Impacts of soil properties on flow velocity under rainfall events: evidence from soils across the Loess Plateau

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Abstract: Flow velocity is one of the most significant hydraulic parameters directly connected to sediment transport-deposition processes. Four soils were collected from north to south of the Loess Plateau, namely Sandy Loess (SL), Loessial Soil (LS), Heilu Soil (HS) and Anthrosol Soil (AS), to examine the impacts of soil property on mean flow velocity in both interrill and rill flows under different simulated rainfall experiments. The mean velocity of interrill flow (*MVIF*) followed the order of LS > HS ≈ AS > SL at 90 mm h^{-1} rainfall intensity and LS > HS > AS > SL at 120 mm h^{-1} rainfall intensity. The mean velocity of rill flow (*MVRF*) decreased as LS ≈ HS > AS at 90 mm h^{-1} and LS ≈ HS > AS > SL at 120 mm h^{-1}. The order of *MVIF* and *MVRF* on four soil slopes is determined by the relations of runoff discharge, Darcy-Weisbach friction factor in interrill area (f_I) and rills (f_R), which are closely related to soil properties. Soil properties also changed the effects of rainfall intensity on flow velocities in different erosion stages, resulting in the increasing trend of *MVIF* on SL, HS and AS slopes and the decreasing trend of *MVIF* on LS slope with the increase of rainfall intensity. Moreover, soil properties may change the variations of *MVIF* and *MVRF* with the increase of slope gradient, by altering the relations of sealing progress and slope effect. The slope effect determined the increasing trend of *MVIF* with the increase of slope gradients. However, the sealing progress may offset the slope effect and cause the decrease of *MVIF* on the critical slopes, and the critical slope decreased from the north (20° and 25 °) to the south (15°). The equal roles of rill bed roughness and slope effect caused the unchanged of *MVRF*on LS and HS slopes, while rill bed roughness dominated the fluctuations of *MVRF* on SL and AS slopes.

Keywords: Loess Plateau; Rainfall impacts; Slope effects; Mean flow velocity; Soil property

1. Introduction

Soil erosion process includes detachment and transport of soil materials by erosive agents, which is closely related to rainfall kinetic energy, flow hydraulics, soil erodibility and their interactions (Bryan, 2000). Flow velocity is a significant parameter in both interrill and rill erosion (Guo et al., 2013;). Many flow hydraulic variables, for instance, Darcy-Weisbach friction factor (f) of overland flow, Manning roughness coefficient (n) of channel flow, Reynolds number (Re), Froude number (Fr), hydraulic shear stress (τ) and stream power (ω) are all calculated and determined by flow velocity (Guo et al., 2013; Stefano et al., 2018). Flow velocity is also directly linked to sediment transport-deposition process and has significant impacts on soil loss and rill development on slopes (Tian et al., 2017). Shen et al. (2016) indicated that rill erosion was sensitive to rill flow velocity and stream power.

Flowvelocity is susceptible to many factors, such as rainfall condition and slope gradient (Tian et al., 2017; Stefano et al., 2018). The complex interactions of surface roughness, flow depth and raindrop impact may result in the differences of flow velocities between rills and interrill areas (Tian et al., 2017). Many previous studies discussed the impacts of raindrop and slope gradient on soil detachment and runoff disturbance, which would lead to a variation of flow velocity (Römkens et al., 2001; An et al., 2010). An et al. (2010) indicated that raindrop impact enhanced flow turbulence to increase flow velocity, and the flow instability could change the flow velocity. So far, there are debates about the slope gradient impacts on flow velocity and roughness in rills (Nearing et al., 1997; Stefano et al., 2018). Flow velocity was found to increase with slope gradient by Foster et al. (1984), whereas Govers (1992) suggested that rill flow velocity tended to be independent of slope gradient, because the variation of bed morphology may increase bed roughness to reduce flow velocity. The effect of slope on flow velocity may be compensated by increasing erosion and bed roughness in rills on steeper slopes (Torri et al., 2012).

Soil property impacts flow velocity directly by altering soil infiltration capacity, soil shear strength and detachment rates, and also influences flow velocity indirectly through the interactions of surface soil with water layer during erosion processes (Dunkerley, 2004; Guo et al., 2013; Fang et al., 2014; Liu et al., 2015; Mahalder et al., 2018). Soil property is a key factor influencing runoff generation and soil erodibilty (Fang et al., 2014). For example, soil particle size distribution, especially the aggregated particle size directly influenced soil detachment and transport processes (Rienzi et al., 2013). Soil texture and porosity across the surface also influenced water infiltration rate (Wang and Shi, 2015). The dispersion of clay particles in the soil led to the blockage of soil pores to reduce infiltration rate, and the increase of soil bulk density could increase the air pressure to decrease infiltration rate (Parker et al., 1995; Liu et al., 2015). Moreover, soil property determined soil surface microtopography, which significantly influenced flow velocity by making differences in both flows and infiltration rates between the lower area and higher area of soil surface (Dunkerley, 2004). Meanwhile, seal or crust is one of the important factors affecting the infiltration rate, hydraulic conditions and surface roughness (Bryan, 2000). Soil texture, such as the content of silt and clay, the sizes of aggregates, had influences on the formation and pattern of seal (Farres, 1978; Fang et al.,2014). It is also reported that the aggregate breakdown process may reduce the particle size and became a component of the surface sealing (Vaezi et al., 2017). Although numerous studies have investigated the features of infiltration, sealing and surface roughness during erosion processes, however, few studies have clarified the actual impacts of soil property on the flow velocity due to the complexity of interrelationships.

As the key agricultural area in northwest China, the Loess Plateau has been suffering from serious erosion for decades, with more than half area being affected by water erosion (Wu et al., 2018). At the same time, soils in the Loess Plateau showed strong zonal distribution characteristics in particle sizes and properties, with a tendency of decreasing sand content (> 0.05 mm), an increasing clay content (<0.002 mm), and an increasing trend of soil organic matter (SOC) content from the northwest to southeast of the Loess Plateau (Li et al., 1985; Wang and Shi, 2015). Although numerous experiments have been carried out in the Loess Plateau to investigate the water erosion process and mechanism (Fang et al., 2014; Shen et al., 2016), it is still unclear how the soil properties changing in different zones affected flow velocity during surface erosion processes. Thus, the primary purpose of this article is to investigate the impacts of the soil properties on flow velocity in the Loess Plateau under different experimental conditions.

2. Materials and methods

2.1 Soil sampling

According to the zonal classifications of soil in the Loess Plateau (Li et al., 1985), four soils were sampled in four zones from north to south across the Loess Plateau (Fig. 1). They are sandy loess (SL) from Suide County (37°31′ N, 110°16′ E) in the sand soil belt, loessial soil (LS) from Ansai County (36°58′ N, 109°20′ E) in the light soil belt, Heilu soil (HS) from Changwu County (35°12′ N, 107°47′ E) in the middle soil belt-II, and Anthrosol soil (AS) from Yangling County (34°16′ N, 108°4′ E) in the heavy soil belt. Farm land soils (20 cm) were collected and transported to the laboratory for the experiments. The sand content of the collected soils decreased from 32.1% (SL) to 6.9% (AS), while the clay content increased from 12.1% (SL) to 26.3% (AS) from north to south of the Loess Plateau (Table 1). The mean weight-diameter (MWD) of aggregates after wet sieving of the four soils also increased from 0.04 (SL) to 0.36 (AS) mm. All soils were firstly air dried to stable moisture content at approximately 10% and then passed through a 10.0 mm sieve.

<Fig. 1 is here>

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2.2 Artificial rainfall experiments

Laboratory experiments were conducted in the simulated rainfall laboratories of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, using artificial rainfall facilities. The height of the down-flow rainfall simulation system was set at 18 m to ensure the raindrops reach their final velocities as natural events. Tap water (conductivity at 0.7 $dS \cdot m^{-1}$) was used for all experiments. The rainfall intensities were set at 90 mm h^{-1} and 120 mm h^{-1}, respectively, with durations of 60 min and 45 min to obtain the equal rainfall amount of 90 mm. Electronic control system was applied to record the rainfall dynamics automatically. The equitability (> 90%) and the deviation (< 5%) were controlled to ensure the homogeneity of the artificial rainfall distribution.

Movable steel boxes (5 m × 1 m × 0.5 m) were used for the experiments. The steel box is tiltable to set the slope gradient at 10°, 15°, 20° and 25°, respectively. Coarse sand was put into the first 10-cm in the bottom of the box to keep the slopes similar to the natural slopes. Also, bulk density was set at 1.13 $g \cdot cm^{-3}$ for SL, LS, AS and 1.25 $g \cdot cm^{-3}$ for HS to ensure the consistency with field situations. Dried soil was weighed and packed into the steel box in six stages (5 cm each time) to ensure the soil bulk density. The coarse sand and the experimental soil were separated by the permeable fine gauze.

The erosion processes were recorded by two video cameras to observe the knickpoints and rills. Runoff samples were collected at 1 min intervals with 1.5 L cylinders at the outlet of the box. Here, the measured runoff discharge (Q_T) is the total discharge of the whole slope, including both the interrill runoff discharge (Q_I) and rill runoff discharge (Q_R). Sediment concentrations were measured using oven-drying (105°C) method after the deposition of the runoff samples. Experiments were repeated 2 times. However, the experiments in LS and AS on 25° slope were unsuccessful due to the sudden collapse in the two sides of the slope.

The maximum flow velocity was measured using the dye method ($KMnO_4$) by recording the travel time of the dye flow through the distance of 0.5 m. Flow velocities were cyclically measured for sites at 1-m intervals, i.e.1 m, 2 m, 3 m and 4 m to the top of the box. Water temperature was measured using a normal thermometer. For comparison, the velocity data were measured simultaneously for interrill flow and rill flow. The dye method can only measure the maximum flow velocity. Therefore, the corrected flow velocity was derived by multiplying a correction factor (Zhang et al., 2010). According to Wang and Shi (2015), the correction factor of 0.466 was chosen for interrill flow and 0.8 for rill flow. To reduce the side-effects of flow velocity changing with slope length, it was decided to calculate the average value of corrected flow velocities in interrill flow on different sites of one slope as the mean velocity of interrill flow (*MVIF*), and the average value of corrected flow velocities in rill flow on different sites of one slope as the mean velocity of rill flow (*MVRF*). The depth of the runoff flow was also measured by the regular ruler when the flow velocity was measured.

2.3 Hydraulic parameters

According to Dunkerley (2004), Darcy-Weisbach friction factor (f) was calculated by equation (1)

$$f = \frac{8gDS}{V^2} \quad (1)$$

where D is the mean flow depth (m), V is the mean flow velocity (m s^{-1}), g is the acceleration due to gravity (m s^{-2}), S is plot gradient (sine).

2.4 Data analyses

All statistical analyses were conducted using SPSS 22.0 software. Analysis of variance (ANOVA) was conducted to examine significant differences of flow velocities (rill/interrill) in four soils with different slope gradients and rainfall intensities. The method of least significant difference (LSD) procedure was used for the multiple comparisons at 95% confidence level, and the Paired-Samples Test was used for two-group comparison. The correlation analysis was conducted by the Pearson correlation method.

3. Results

3.1 Flow velocity on soil slopes

As shown in Fig. 2, *MVIF* ranged at 0.004-0.186 m s^{-1}on SL slope, 0.039-0.349 m s^{-1}on LS slope, 0.010-0.728 m s^{-1} on HS slope and 0.048-0.443 m s^{-1}on AS slope, respectively. In comparison, *MVRF* varied at 0.070-0.377 m s^{-1}on SL slope, 0.209-0.364 m s^{-1} on LS slope, 0.156-0.678 m s^{-1}on HS slope and 0.105-0.400 m s^{-1}on AS slope, respectively. The ranges of flow velocity are consistent with previous studies in the Loess Plateau (Wang and Shi, 2015).

In this study, *MVIF* showed no significant differences between HS (from middle soil belt) and AS (from heavy soil belt) in the south part of the Loess Plateau when rainfall intensity was 90 mm h^{-1}, decreasing as LS > HS ≈ AS > SL (Fig. 2a). Interestingly, the order of *MVIF* values also decreased as LS > HS > AS > SL (Fig. 2b) when rainfall intensity increased to 120 mm h^{-1}. *MVRF* showed no significant differences between LS (from light soil belt) and HS (from middle soil belt) soils in both two rainfall intensities, following the order of LS ≈ HS > AS at 90 mm h^{-1} (Fig. 2c) and LS ≈ HS > AS > SL at 120 mm·h^{-1} (Fig. 2d). No rills occurred on SL slopes at 90 mm h^{-1} rainfall intensity.

<**Fig. 2 is here**>

3.2 Surface runoff discharge from soils

As shown in Fig. 3, average runoff discharge in four soils showed increasing trend from north to south, due to increasing infiltration rate with the rising sand content and decreasing infiltration capacity with the rising clay and silt content (Koiter et al., 2017; Bullard et al., 2018). The *MVIF* under different treatments increased with average runoff discharge on soil slopes in the north part (SL and LS), but did not increase with the rising runoff discharge on HS and AS. In addition, *MVRF* under different treatments increased with the rising average runoff discharge, except for AS. Normally, mean flow velocity is determined by runoff discharge and effective flow depth, which are indirectly influenced by soil property through the interactions of surface soil with water layer during erosion processes, correlating with infiltration capacity and surface roughness (Dunkerley, 2004; Guo et al., 2013; Liu et al., 2015). It is noticeable that the discharge value in Fig. 3 is the total runoff discharge (Q_T) for both interrill flow (Q_I) and rill flow (Q_R), which may affect the relations of the measured discharge and mean flow velocities.

<**Fig. 3 is here**>

3.3 Darcy-Weisbach friction factor from different soils

As shown in Fig. 4, both the calculated Darcy-Weisbach friction factor of interrill flow (f_I) and rill flow (f_R) showed the highest value on SL slope, the lowest value on LS slope and increased from HS to AS. Soil roughness is closely related to the soil texture and rainfall characteristics as well, which means that the response of roughness to soil property is complicated due to the raindrop impacts as well as the rearrangement of sediment during rainfall events (Bedaiwy, 2007; Bullard et al., 2018).

<Fig. 4 is here>

3.4 Rainfall impacts on four soils

MVIF ranged at 0.010-0.728 m s^{-1} under 90 mm·h^{-1} rainfall and 0.004-0.583 m·s^{-1} under 120 mm h^{-1} rainfall, respectively. There is a general increase of *MVIF* with rainfall intensities on soil slopes except for LS (Fig. 5a). Overall, the increasing rainfall intensity will increase flow discharge (Table 2) and supply more energy to disturb the runoff flow, thus increase flow velocity in the shallow overland flow (Bryan, 2000; Nearing et al., 1999; Zhuang et al., 2018). However, the impacts of rainfall intensity on flow velocity changed with soil properties as well as erosion progresses, because the increasing rainfall intensity may increase runoff energy, which in turn enhances the interactions of surface soil with water layer (Liu et al., 2015).

<Table 2 is here>

Before the occurrence of knickpoint, the impacts of rainfall intensity on flow velocity are not significant in *MVIF* on soils from the north of the Loess Plateau (SL and LS). While, for soils HS and AS, *MVIF* in higher rainfall intensity was up to 1.14 times as that in lower rainfall intensity, showing significant differences with rainfall intensity (Fig. 5c).

<**Fig. 5 is here**>

During the erosion stage between the occurrence of knickpoint and rill, the impacts of rainfall intensity on *MVIF* are not significant on four soil slopes (Fig. 5d). In this stage, the knickpoints may increase the infiltration, surface roughness as well as storage capacity to offset the raindrop impacts by destroying soil sealing (Brunton and Bryan, 2000; Römkens et al., 2001).

After the occurrence of rill, *MVIF* decreased with rainfall intensity on LS slope, increased with rainfall intensity on HS slope, and showed no significant differences on AS slope (Fig. 5e). *MVIF* in higher rainfall intensity was up to 1.17 times as that in lower rainfall intensity on HS slope.

3.5 *MVRF* varied at 0.097-0.678 m s^{-1} during 90 mm h^{-1} rainfall and 0.007-0.400 m s^{-1} during 120 mm h^{-1} rainfall, averaging at 0.199±0.003 m s^{-1} under 90 mm h^{-1} rainfall and 0.206±0.004 m s^{-1} under 120 mm h^{-1} rainfall, respectively (Table 2). Due to the insignificant raindrop impacts on rills (Bryan, 2000; Romero et al., 2007; Wirtz et al., 2012), *MVRF* showed no significant differences when rainfall intensity increased from 90 mm h^{-1} to 120 mm h^{-1}, except for AS soil. *MVRF* showed significant increase (1.04 times) on AS slope, when rainfall intensity increased from 90 mm h^{-1} to 120 mm h^{-1} (Fig. 5b). Slope effects on rill and interrill flow

Whether soil property may change the slope gradient effects on flow velocity is also debated in previous studies. Govers (1992) suggested that rill flow velocity is independent of slope gradient and soil properties. However, that conclusion is not supported by other researchers (Abrahams et al., 1996; Nearing et al., 1997). In this study, *MVIF* on SL slope fluctuated with slope gradient in both rainfall intensities, following the order of $10^o < 20^o < 25^o \approx 15^o$ at 90 mm h^{-1} (Fig. 6a) and $10^o \approx 15^o \approx 20^o < 25^o$ at 120 mm h^{-1} (Fig. 6b). The critical slope gradient is 20° and 25° at 90 mm h^{-1} on SL slope. *MVIF* on LS slope showed increasing trend with rising slope gradient in both rainfall intensities, following the order of $10^o < 15^o \approx 20^o < 25^o$ under 90 mm h^{-1} (Fig. 6c) and $10^o < 15^o < 20^o$ under 120 mm h^{-1} (Fig. 6d). *MVIF* on HS slope did not change significantly with slope gradients at 90 mm h^{-1}, ranging from 0.100±0.002 m s^{-1} to 0.113±0.002 m s^{-1} (Fig. 6e). However, it ranged from 0.114±0.002 m s^{-1} to 0.139±0.004 m s^{-1} at 120 mm h^{-1}, with the highest value on 20° (Fig. 6f), the critical slope is 25° on HS slope at 120 mm h^{-1}. *MVIF* on AS slope increased in the order of $15^o < 10^o < 20^o < 25^o$ at 90 mm h^{-1} (Fig. 6g), whereas it followed the order of $10^o < 15^o \approx 20^o$ at 120 mm

h^{-1} (Fig. 6h). The critical slope is 15° at 90 mm h^{-1}. Therefore, in this study, *MVIF* showed increasing trend with fluctuations when rainfall intensity increased, and the critical slope gradient varied with soil properties.

<Fig. 6 is here>

MVRF on SL slope increased as 20° < 25° < 10° ≈ 15° at 120 mm h^{-1}, with the critical slopes on SL slope are 20° and 25° at 120 mm h^{-1} (Fig. 7a). *MVRF* on LS and HS slopes did not change much with slope gradient under both rainfall intensities (Fig. 7b, 7c, 7d and Fig. 7e). *MVRF* on AS slope followed the order of 15° < 10° ≈ 25° < 20° under 90 mm h^{-1} and 10° < 15° ≈ 20° under 120 mm h^{-1}, respectively.

4. Discussion

4.1 Impacts of soil property on runoff, sealing and roughness

The raindrop detachment 'washing in' process may cause surface sealing and affect soil porosity to change the infiltration and surface roughness when aggregate breakdown (Vaezi et al., 2017). It is reported that sealing is prone to develop in soils with high silt content and clay content of 20%-30% (Fang et al., 2014). Thus, the easier development of sealing may also result in higher *MVIF* on HS and AS with higher clay content (> 20%). However, the development of knickpoints and rills may destroy sealing and increase infiltration rate sharply, hence decreasing the *MVIF* on AS (Fig. 3; Luk and Merz, 1992; Fang et al., 2014).

Both f_I and f_R were influenced by soil properties from the north to south of the Loess Plateau. Random roughness increased with the rising proportion of silts and clays, and the sealing is extremely thin on soils with high clay content (Bullard et al., 2018). This leads to the increasing trend of f_I from HS to AS with the increasing content of silt and clay (Fig. 4). Meanwhile structural sealing is easier to form on soils with small aggregate than on those soils with larger aggregate (Farres, 1978). The scale patterning of sealing also impacts the roughness, as suggested by Bullard et al. (2018), rougher surface on soils with more sand may be due to the smaller pattern scale. The smaller aggregate size and highest content of sand at the surface with rapid sieving crusts may result in the highest f_I on SL slope (Fig. 4) in the north part of the Loess Plateau, where the particle composition is dominated by silts as well (more than 50%) comparing with other soils. In addition, the changingmicro-morphology of rill bed may alter bed roughness to further alter rill flow, which is also closely related to soil property (Gimenez and Govers, 2001). The higher content of organic carbon and clay may promote rill developments and decrease flow velocities in the south of the Loess Plateau (Fang et al., 2014). It is assumed that the higher sediment concentration may consume larger flow energy and result in the intermittent sedimentation in rills (Stefanovic and Bryan, 2009). This also increases bed roughness to result in the higher f_R in rill flow on AS slope with more rills (Fig. 4).

The complex functions of runoff discharge, sealing and rill developments resulted in the order of *MVIF* and *MVRF* on four soils. The lowest flow discharge (Q_T) and the highest f_I resulted in the lowest *MVIF* on SL from the sand belt in the north part of the Loess Plateau (Fig. 3). The lowest f_I and f_R resulted in the highest *MVIF* and *MVRF* on LS slope, although its discharge (Q_T) is slightly lower than those on HS and AS slopes. The higher f_I and f_R resulted in the lower *MVIF* and *MVRF* in AS from the heavy soil belt than those in HS from the middle soil belt (Fig. 3 and Fig. 4).

4.2 Rainfall impacts changing with soil property at different erosion stages

The changing roughness and surface sealing may be altered with the rainfall duration, which will further alter the infiltration and hydraulic conditions of runoff flow, and in turn increase or decrease the impacts of rainfall intensity (Römkens et al., 2001; Shen et al., 2016; Fu et al., 2017; Lu et al., 2017). Before the occurrence of knickpoint, the changing *MVIF* with rainfall intensity is directly related with the changing f_I and Q_T, because Q_T is equal to Q_I. As shown in Table 3, Both f_I and Q_T decreased with rainfall intensity, resulting in insignificant decrease of *MVIF* on SL slopes, and the insignificant changing of f_I with small increasing of Q_T resulted in the insignificant increase of *MVIF* on LS slopes. While, the great increase of Q_T (HS and AS) with the insignificant changing of f_I (HS) and decrease of f_I (AS) resulted in the significant increase of *MVIF* on HS and AS, with higher increase rate on AS slopes (Fig. 2). As part of runoff is distributed in rills during the erosion stage between the occurrence of knickpoint and rill ($Q_T > Q_I$), the changing f_I and Q_T is not closely related with the changes of *MVIF*. This is why *MVIF* did not change significantly with rainfall intensity, when Q_T significantly increased and f_I showed insignificant increase with rainfall intensity (Table 3). For the same reason, the changes of f_I and Q_T after the occurrence of rill are not closely related with the changing *MVIF*. f_I showed increasing trends on LS and AS, and a decreasing trend on HS slope with the increase of rainfall intensity, but did not show significant differences (Table 3). Previous investigation indicated that f_I decreased with increasing Reynolds number (Zhang et al., 2014) and increased with increasing rainfall intensity (Li, 2009). Q_T increased significantly with the increase of rainfall intensity on all soil slopes (Table 3). Thus, it is assumed the different partitioning of Q_T between interrill areas (Q_I) and rills (Q_R) resulted in the different changes of *MVIF* on slopes of SL, LS and AS with the increase of rainfall intensity. Although *MVIF* showed different trends in different stages of erosion processes, *MVIF* demonstrated increasing trends on SL, HS and AS slopes and a decreasing trend on LS slope in terms of the whole erosion process. Normally, the concentrated flow dominates the rill velocity and results in the unchanged *MVRF* with rainfall intensity. However, rainfall may enhance the complexity of the final stage of the rill networks or even cause the junction of some rills (Tian et al., 2017). Rills on AS slope are most developed due to its higher contents of clay and organic carbon (Fang et al., 2014). The rainfall intensity could impact the final stage of rills on AS slope and the changing rills may result in higher *MVRF* in higher rainfall intensity on AS slope.

<**Table 3 is here**>

4.3 Slope effects changing with slope property

In general, the slope effect means the increasing flow velocities in both interrill and rill flows with the increase of slope gradient, due to the increasing gravity. However, contradictory results were found due to the complexity of erosion processes (Govers 1992; Nearing et al., 1997). Moreover, the increase of slope gradient may change the infiltration rate through altering surface storage, effective rainfall intensity, and overland flow depth in interrill areas, which may alter the interrill flow velocity (Fox et al., 1997; Liu et al., 2015). It is noticeable that all four soils are susceptible to surface sealing, so the order of *MVIF* is the result of both sealing and slope effects (Luk and Merz, 1992). Sealing process can change f_I, Q_T and the distribution of Q_T between interrill (Q_I) and rills (Q_R). The changing of slope impacts on four soil slopes may be due to the differences in ‘sealing’ development on four soils with different content of clay and silts. As shown in Table 4, f_I did not show significant differences on SL slopes, but showed increasing trend with slope gradient on other soil slopes. The increasing trend of f_I could decrease *MVIF* with slope gradient to offset the increasing of *MVIF* by gravitational force. Q_T fluctuated with slope gradients and showed different critical slopes with changing soil properties (Table 4). Generally, 'slope' effects dominated most slopes and resulted in the general increasing trend of *MVIF* with increase of slope gradients (Fig. 6). In critical slopes, the 'sealing' effects was dominating and resulted in the lower *MVIF* on these slopes (Fig. 6). The critical slope was 20^o and 25^o on SL slope and 15^o on AS slope, showing a decreasing trend from north to south of the Loess Plateau (Fig. 6). The decreasing trend of critical slope is closely related with the increasing trend of sealing process, and the increasing trend of clay and silt content in soils from north to south of the Loess Plateau.

<Table 4 is here>

f_R fluctuated with slope gradient on SL and AS slopes, changed insignificantly with slope gradient on LS slopes and increased with slope gradient on HS slopes (Table 4). Abrahams et al. (1996) suggested that slope gradient and soil property may have equal influences on rill flow velocity. Govers (1992) also indicated that the increasing bed roughness with slope gradient would increase Darcy–Weisbach friction and decrease rill flow velocity, which may even result in the independence of rill flow velocity on slope gradient. In this study, the changing relations of 'slope effect' and 'rill bed roughness' may result in the order of *MVRF* (Fig. 7) with slope gradient (Gimenez and Govers, 2001). Specifically, slope effect and rill bed roughness may play equal roles on soils from LS and HS, and result in the relatively constant *MVRF* with the increase of slope gradient (Fig. 7b,c,e). Compared with 'slope' effect, rill bed roughness may play the dominant roles on the changing *MVRF* with slope gradient on SL and AS slopes, due to the inverse order between *MVRF* with f_R when both fluctuated with the increasing of slope gradient (Table 4 and Fig. 7a,f,g).

4.4 Empirical correlations

The empirical correlations of rainfall intensity (*I*), slope gradient (*S*), mean weight-diameter (*MWD*) with *MVIF*, f_I and f_R were regressed as follows:

$$MVIF=e^{-3.696}S^{0.210}I^{0.260}MWD^{0.188};\ R=0.643;\ n=30;\ \underline{P}=0.0003 \quad (1)$$

$$f_I=e^{-2.914}S^{0.709}I^{-0.086}MWD^{-0.261};\ R=0.539;\ n=30;\ \underline{P}=0.0093 \quad (2)$$

$$f_R=e^{-11.796}S^{1.567}I^{1.451}MWD^{0.259};\ R=0.638;\ n=17;\ \underline{P}=0.0005 \quad (3)$$

4.5 The size of soil particles has positive influence on *MVIF* (equation (1)), however, no such correlations were found with *MVRF*. From equations (2) and (3), it can be deduced that the size of soil particles has negative influence on Darcy-Weisbach friction in interrill erosion and positive influence on Darcy-Weisbach friction in rill erosion.Conclusions

In this study, flow velocities were compared on four soils from north to south of the Loess Plateau under different artificial experiments. The results showed that soil property affected flow velocities in both interrill and rill flows, which were closely related to the interactions of flow discharge and Darcy–Weisbach friction. The mean velocity of interrill flow (*MVIF* was highest in light soil belt and lowest in sand belt. Similarly, the highest mean velocity of rill flow (*MVRF*) was in the light and middle soil belt, and lowest in the heavy soil belt and sand soil belt. Soil property may alter the increasing trend of *MVIF* with rainfall intensity, by changing the distribution of flow discharge between the interrill area and rill area. Soil property may also alter the relation of *MVRF* with rainfall intensity, by enhancing the rill networks in soil from heavy soil belt in the south of the Loess Plateau. Moreover, soil properties may change the slope effect on the mean flow velocities, resulting in the decrease of *MVIF* on critical slopes and the fluctuations of*MVRF* with the increase of slope gradient by changing the sealing progress. These results improved our understanding of soil property impacts on the mean flow velocities in both interrill and rill flows in the Loess plateau. Furthermore, empirical correlations were established for the *MVIF* and Darcy-Weisbach friction factor in interrill erosion and rill erosion, which is improved by considering the size of soil particle. The dynamic partitioning of runoff between interrill and rill area is important and used to determine the *MVIF* after the occurrence of rills. Further research should determine the complex distribution of flows in interrill and rill area, in order to improve the current erosion modelling.

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