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Rill erosion processes on a steep colluvial deposit slope under heavy rainfall in flume experiments with artificial rain

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ABSTRACT

Understanding rill erosion processes is important in the prediction of soil erosion and the prevention of soil loss. However, limited information is available concerning the impacts of rainfall on rill erosion on steep slopes. Colluvial deposits with steep slopes make up the packed material underlying the collapsing walls in *benggang*, which collapse due to hydraulic pressure and gravity. They contain loose materials and large amounts of coarse particles. The objectives of this study were to investigate the impacts of rainfall intensity and slope gradient on the rill erosion process, rill development and rill flow dynamic mechanisms on the steep slopes of colluvial deposits. The colluvial soils were subjected to simulated rainfall in a 5-m^2 (5-m by 1-m) flume at heavy rainfall intensities (100, 120, and 140 mm h^{-1}) and on five steep slopes (20, 25, 30, 35, and 40°). Rill erosion contributed significantly to colluvial slope erosion; on average, rills accounted for 61% of the soil loss, and the effects of slope gradient were greater than those of the rainfall intensity. After rill development, rill density, rill length, width, and depth all significantly increased. Correspondingly, the soil loss rate sharply raised and irregularly fluctuated. Moreover, the collapse of rill heads or sidewalls tended to increase the relative contribution to rill erosion and rill development. The rill flow was characterized by transitional and subcritical flow regimes. The rill flow velocity was the most sensitive hydraulic parameter, and the unit stream power provided the optimal hydrodynamic parameter to characterize the dynamic mechanisms of rill erosion on colluvial deposits. The collapse of rill heads or sidewalls could result in negative values for critical shear stress, critical stream power, and critical unit stream power of rill erosion, which were −19 Pa, −5.3 N m^{-1} s^{-1}, and −0.09 m s^{-1}, respectively. These results provide a better understanding of the mechanism of rill erosion on steep slopes.

1. Introduction

Bare slopes are very sensitive to runoff and soil loss processes (Fang et al., 2015). Soil erosion can quickly evolve from splash or sheet erosion to rill erosion during high intensity rainfall (Di Stefano et al., 2013; Shen et al., 2016). Rill erosion greatly affects runoff, soil loss, morphology and the dynamic characteristics on slope surfaces (Morgan, 1977; Lei and Tang, 1998; Govers et al., 2007; Dunkerley, 2008; Wirtz et al., 2012). Therefore, it is important to understand rill erosion processes in order to predict soil erosion and prevent soil loss.

A number of experiments have been performed to examine the process of rill erosion (Torri, 1987; Rauws and Govers, 1987; Le'onard and Richard, 2004; Berger et al., 2010). Some researchers documented that rill erosion easily occurs with increasing flow (Mancilla et al., 2005), rainfall intensity (Brunton and Bryan, 2000) or slope gradient (Berger et al., 2010). However, Wirtz et al. (2012) showed that rill erosion is not a simple function of excess rainfall or slope gradient; instead, it is a complex process that is dominated by surface sealing, rill development, headcut incision, and sidewall collapse. Therefore, rill erosion also greatly affects the micro-morphology of the slope surface (Berger et al., 2010). Rill morphology contributes to an increase in runoff connectivity and concentration of flow along the channeling network (Heras et al., 2011), and it significantly determines surface soil loss from hillslopes (Shen et al., 2016). The characteristics of rill have often been described by the value of different statistical indicators, including rill length, width, depth, and the space filling tendencies of networks (Raff et al., 2004). Rill erosion enhanced soil loss is also closely linked to the hydraulic and dynamic characteristics of rill flow (Gilley et al., 1990; Govers, 1992; An et al., 2012). The flow velocity, Reynolds number, Froude number, Darcy-Weisbach resistance

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coefficient and other indicators derived from these variables, such as shear stress, stream power, and unit stream power, are basic hydraulic and dynamic parameters (Torri, 1987; Govers, 1992; Abrahams et al., 1986; Nearing et al., 1997). Some researchers (Reichert and Norton, 2013) considered that the Darcy-Weisbach resistance coefficient is the most diagnostic of the rill flow hydraulic parameters. However, Lei and Tang (1998) suggest using Reynolds number as the criterion parameter of rill initiation, and Govers (1992) showed that mean flow velocity can be related to the discharge of rills eroding loose, non-layered materials such as agricultural soils. As for the hydrodynamics mechanism of rill erosion, Nearing et al. (1997) reported that stream power was an appropriate predictor for unit sediment load; whereas Giménez and Govers (2002) showed that shear stress was capable of directly accounting for variations in bed geometry. The above shows that numerous studies have characterized rill erosion, but the results of these studies differ because they employ different soil types, experimental conditions and spatial scales. Furthermore, previous studies have mainly focused on the impacts of rainfall on rill erosion at relatively gentle slopes (< 20°). The rill erosion process and its dynamic mechanism on steep slopes need to be further researched.

A type of erosion that is characterized by gullies with steep collapsing walls is common in the red soil region of southern China (Jiang et al., 2014; Lin et al., 2015). These gullies are locally termed *benggang*, and they are also known as collapsing gullies (Fig. 1A) (Xu, 1996). These gullies develop quickly, and their walls fail suddenly. The topographic expression of these collapsing gullies is similar to that of "*lavaka*" in Madagascar (Cox et al., 2010) and "*calanchi*" in central Italy (Moretti and Rodolfi, 2000). Mean soil loss rates in areas with collapsing gullies exceed 500 Mg ha^{-1} y^{-1}, and these rates are at least 50-fold greater than those that occur on gentler slopes or slopes with dense vegetation (Xu, 1996; Zhong et al., 2013). This particular type of collapsing gully generally consists of an upper catchment, a collapsing wall, a colluvial deposit, a scour channel, a gully mouth, and an alluvial fan (Fig. 1) (Jiang et al., 2014; Xia et al., 2015). Colluvial deposits make up the packed material underlying the collapsing walls (Fig. 1B), which collapse due to hydraulic pressure and gravity. As a type of disturbed soil, colluvial deposits feature high contents of gravel, sand, and loose materials that have a weak structure, low cohesion, poor stability, and high erodibility. After water immersion, colluvial deposits disintegrate rapidly, and particle sizes become more ideal for water transportation. Furthermore, rainfall splash erosion and runoff scouring occur easily because of the steep slope (generally between 20° and 40°) and lack of plant roots and organic matter. Therefore, several to tens of rills (Fig. 1C), which are small channels eroded by concentrated flow, occur on the colluvial deposits. Large amounts of sediment are generated by rill erosion; colluvial deposits contribute > 50% of the total soil loss associated with collapsing gullies (Liu et al., 2015). Previous studies have examined the characteristics of runoff and sediment production on colluvial deposits (Jiang et al., 2014; Liu et al., 2015; Lin et al., 2017). Jiang et al. (2014) reported that runoff volume and soil loss increased with rainfall intensity up to critical slope gradients of 58% and > 47%, respectively, whereas Liu et al. (2015) noted a negative linear correlation between time to runoff initiation and slope gradient. Lin et al. (2017) also indicated that the sediment yield in colluvial deposit slopes increased with flow discharge and slope and that the effect of flow on the sediment yield was greater than that of the slope. However, there is little information available on the processes of rill erosion and the mechanisms acting on steep colluvial deposits.

For the issues mentioned above, most previous studies focused on relatively gentle slopes. However, there are differences in rill erosion processes and flow hydraulics between gentle slopes and steep slopes. Rainfall simulation is an ideal research method for rill erosion by replicating rill erosion processes. Therefore, a laboratory study was conducted under controlled experimental conditions on steep colluvial deposits (ranging from 20° to 40°) to address these issues. This paper aimed to define relationships between colluvial deposit characteristics, rainfall characteristics and rill behavior by considering rill shape and analyzing the hydraulic characteristics of rill flow and the dynamic mechanisms of rill erosion on steep colluvial slopes.

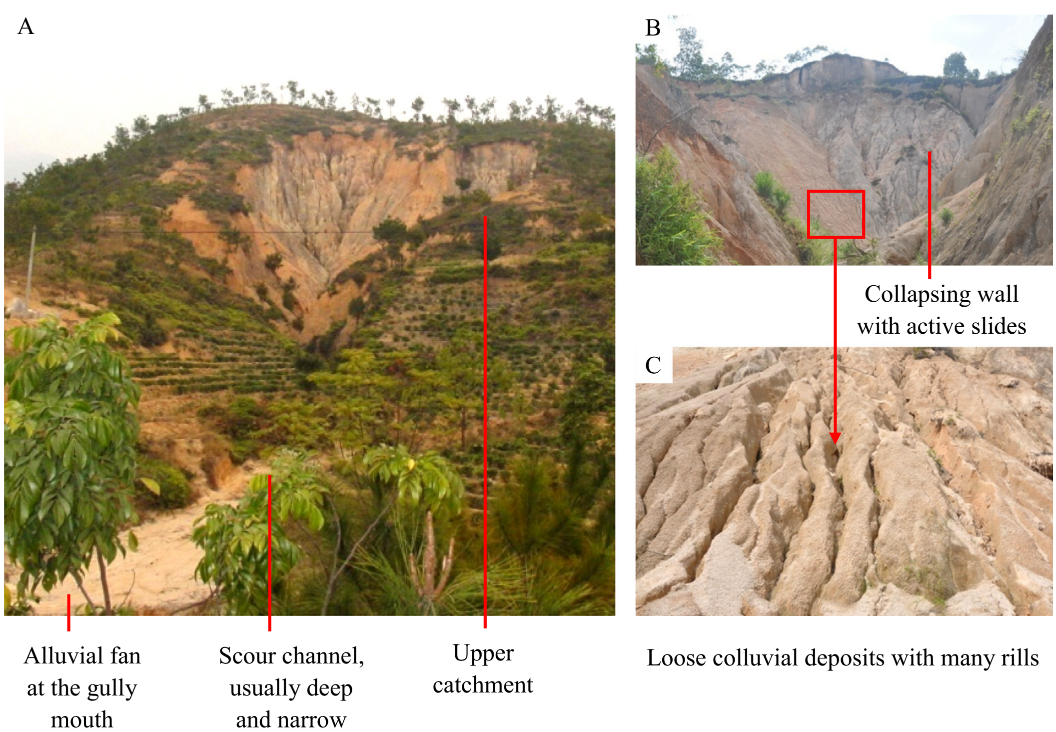

Fig. 1. (A) A view of a typical gully in the study area showing a gully landscape with a large gully dividing the hill slope, which is locally called *benggang*. (B) Example of the collapsing wall and loose colluvial deposits. (C) Loose colluvial deposits with many rills.