Catena 156 (2017) 197–204

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of gravel on concentrated flow hydraulics and erosion in simulated landslide deposits

Tianyang Li[a,b,c], Binghui He[a,*], Zhanpeng Chen[a], Yi Zhang[d], Chuan Liang[b,c]

[a] College of Resources and Environment, Southwest University, Chongqing 400715, China
[b] State key laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, Sichuan 610065, China
[c] College of Water Resource and Hydropower, Sichuan University, Chengdu, Sichuan 610065, China
[d] Chongqing Branch, Changjiang River Scientific Research Institute, Chongqing 400026, China

ARTICLE INFO

Keywords:
Hydraulic parameters
Gravel content
Soil and water loss
Scouring experiment
Landslide

ABSTRACT

Gravel has an important influence on concentrated flow hydraulics and soil and water loss. We conducted a field investigation and a subsequent simulated scouring experiment with four gravel contents (0, 25, 33.3, 50%) and three inflow rates (4, 8, 12 L/min) under two steep slopes (67.5, 72.7%). We assessed the characteristics of concentrated flow hydraulics, including flow velocity, flow depth, Reynolds number (*Re*), Froude number (*Fr*), Darcy-Weisbach friction coefficient (*f*), and the rate of soil and water loss (*SW*). We observed significant effects of gravel and inflow rate on hydraulics and erosion, as well as interactions between gravel and inflow rate. The mean flow velocity reduced as the gravel content increased. The changes in flow depth fluctuated with gravel content in the order $25 > 0 > 50 > 33.3\%$. *Re* was larger in 0% gravel than in 25, 33.3 and 50% gravel. *Fr* was > 1 in 0% gravel but was approximately equal to 1 in gravel-containing soils. Values of *f* were lowest in 0% gravel. The *f* values for gravel-containing soils not only decreased as the gravel content increased, but also had a significant relationship with the corresponding *Re* values. *SW* was maximal in 25% gravel content and gradually declined for gravel content beyond 25%. *SW* had a significant logarithmic relationship with *Re*. The results have significant implications for predictions of soil and water loss steeply sloping, gravel-rich, soils.

1. Introduction

Rock fragments not only have an important influence on soil characteristics (Epstein et al., 1966; Petersen et al., 1968; Groenevelt et al., 1989; Poesen and Ingelmo-Sanchez, 1992; Torri et al., 1994; Poesen and Lavee, 1994; van Wesemael et al., 1995, 1996; Cerdà, 2001; Shi et al., 2007) but they also play a crucial role in flow hydraulics and soil erosion (Abrahams and Parsons, 1994; Morgan et al., 1990; Baird et al., 1993). For instance, Nearing et al. (1989) found that rock fragments increased hydraulic roughness and friction, leading to decreases in overland flow velocity and sediment yield in the Water Erosion Prediction Project (WEPP) model. Bunte and Poesen (1993) studied the effects of rock fragment cover on erosion and transport of fine, non-cohesive material by shallow overland flow. Up to a threshold of 20% coverage, horseshoe vortex erosion around individual rock fragments led to high local turbulence and increased sediment yield. As rock fragment cover increased above this threshold, the sediment yield decreased. Because of the nonmonotonic variation in sediment yield with rock fragment cover, spatially averaged flow hydraulics could not be used to predict the sediment yield.

The size and spacing of rock fragments has an important effect on the friction and turbulence of flow (Abrahams and Parsons, 1994). Bunte and Poesen (1994) showed that flows over small rock fragments experience greater hydraulic roughness, reducing the capacity for scouring and transport. This is mainly because, for equal rock fragment cover percentages, the shape of the cross-sectional flow area exposed varies greatly with the size of the rock fragments. Small rock fragments distribute the flow into numerous small threads, leading to a larger wetted perimeter than that large rock fragments which smooth the flow and concentrate it into large channels. Other studies have assessed whether slope can be used in prediction models for estimating flow velocity. Some studies found that flow velocity can be independent of slope because the rougher surfaces created by headcuts and other erosion-induced roughness morphologies can counteract the effect of increased slope gradient on velocity (Govers, 1992; Giménez and Govers, 2001; Nearing et al., 1999). However, a different study found that slope and soil materials had almost as much effect on flow velocity as did discharge, either directly or indirectly through bed roughness (Abrahams et al., 1996). Therefore, the impact of rock fragments on hydraulics requires further study, especially in the text of landslide

---

* Corresponding author at: College of Resources and Environment, Southwest University, Beibei District, Chongqing 400715, China.
E-mail address: hebinghui@swu.edu.cn (B. He).

http://dx.doi.org/10.1016/j.catena.2017.04.015
Received 15 September 2016; Received in revised form 1 March 2017; Accepted 9 April 2017

deposits, which have rarely been focus of investigation.

There is consensus that sediment yield decreases with increased rock fragment cover or content regardless of whether the experiments were conducted with rainfall or scouring (Abrahams and Parsons, 1994; Wainwright, 1996; Cerdà, 2001; Mandal et al., 2005; Rieke-Zapp et al., 2007; Martínez-Zavala and Jordán, 2008; Wang et al., 2013). Rock fragments not only increase the roughness of the surface soil, thereby increasing the consumption of flow energy, but also increase the macroporosity of the soil. This increases the infiltration capacity, leading to decreased soil loss as the number of rock fragments increases.

Soil and water loss can occur easily in the surface soil of landslide deposits, such as those triggered by the 8.0 magnitude Wenchuan earthquake that occurred on May 12th, 2008. The Wenchuan area receives a lot of rainfall and the landslide deposits have a loose structure composed primarily of soil and gravel. The scouring flows concentrated in the catchment area caused rill erosion, thus a large amount of sediment was carried into the river channels, with subsequent aquatic eutrophication and severe effects on river transport capacity and river morphology (Zhao et al., 2009; Ding et al., 2014). The overall quantity and distribution of soil erosion and the volume of landslide deposits in the Wenchuan area have recently been reported (Xu et al., 2009; Chen et al., 2009; Xu et al., 2011; Chen et al., 2013) and some studies have also reported the soil and water loss from the Wenchuan earthquake landslide deposits (Hu et al., 2010; Xu et al., 2012). However, there is little information available on the interaction between concentrated flow hydraulics and the gravel-containing soils on the surface of steep landslide deposits.

In this study, we studied a total of 12 landslide deposits distributed along a 56 km stretch of National Road 213 that crosses Wenchuan County from south to north. Based on the information from our field investigation, we used a laboratory flume (rectangular water channel) to simulate the surface conditions of landslide deposits and conducted a sequence of experiments to investigate the effects of gravels on the characteristics of concentrated flow and soil and water loss on steeply sloping landslide deposits. The specific objectives of this study were: (1) to examine flow properties such as mean flow velocity, flow regimes, and flow friction under different gravel contents, (2) to evaluate the effects of gravel content on the rate of soil and water loss on the sloping surface of landslide deposit, and (3) to employ hydraulic parameters to predict the soil and water loss.

2. Materials and methods

2.1. Investigation area

The investigation area included the towns of Yingxiu, Yinxing, Caopo, Miansi, and Weizhou in Wenchuan County (Fig. 1). The area forms a typical mountain ravine with a maximum elevation of > 2000 m; the northwest side is higher than the southeast side. The average elevation of Weizhou town in the center of Wenchuan county is 1325 m. Northern Wenchuan county, including Weizhou and Miansi, has a warm temperate climate with an annual average precipitation of 528.7 mm. Southern Wenchuan county is in a mountainous subtropical humid monsoon climate zone with an annual average precipitation of 1332.2 mm. The dominant mountain slopes range from approximately 46.6 to 142.8%. The average slope of Minjiang River along the National Road is 8‰. The maximum flow in Minjiang River is 1980 $m^3 \cdot s^{-1}$ and the minimum flow is 49.3 $m^3 \cdot s^{-1}$ and the river is approximately 80 to 100 m wide. The water supply is from rainfall in the wet season; melting snow and groundwater provide the water supply in the dry season. Granite is the dominant rock type, but sandstone, dolomitic limestone, dark gray shale, and dark siliceous shale are also found in this area (Chen et al., 2013). The soil is mainly mountain yellow-brown soil.

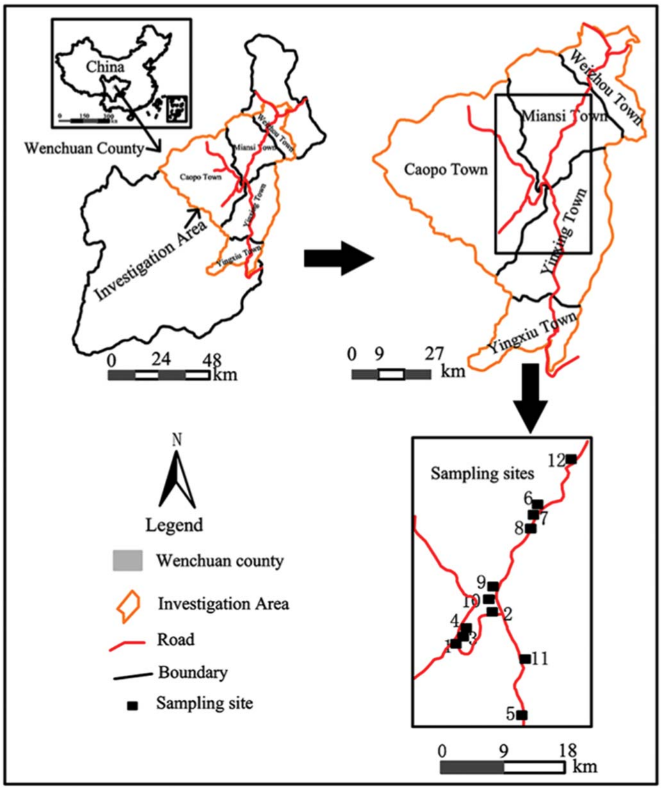

Fig. 1. Study area in Wenchuan county, Sichuan province, China.

2.2. Characteristics of landslide deposits

Because of the steep topography in the investigation area and the fact that landslide deposits are distributed mainly along the rivers and tributary valleys, we used the global positioning system (GPS) and a gradiometer to survey 12 groups of typical landslide deposits. Soil and gravel samples were collected from the 0 to 30 cm layer in each landslide deposit. We analyzed the gravel content, soil particle size distribution (determined by the pipette method (ISSCAS, 1978)), and gravel characteristics in these samples (Table 1). The landslide slope ranged from 62.5 to 83.9%. The bulk density of gravel-containing soils was 1.43 to 1.80 $g \cdot cm^{-3}$. The percentage weight from gravel (2–7 mm diameter) was 20.33 to 68.5%. Correspondingly, the percentage weight of soil (diameter is < 2 mm) was 31.5 to 79.67%. Vegetation coverage rates ranged from 3 to 60%.

2.3. Experimental setup

The laboratory scouring experiments were conducted in the artificial rainfall hall at Southwest University, Beibei District, China. In order to simulate the hydrological and erosion processes in landslide deposits, a water pump was placed inside a filled water pool and connected via pipes to a constant head scouring setup that controlled the inflow rate at the top of flume. A steel catchment collector was placed at the base of the soil flume (3.5 m long, 0.1 m wide, 0.5 m deep) to channel runoff and sediment into a plastic container set at the bottom end of flume, as shown in Fig. 2. The slope of the flume could be altered and there were holes at the bottom of the flume so that the gravity water could drain freely.

2.4. Scouring experiment

The mixtures of soil and gravel used for the scouring experiment were collected from landslide deposits in the Wenchuan earthquake area. The mixtures were passed through 2 mm and 7 mm sieves in order