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The abrasion of soil aggregate under different artificial rough beds in overland flow

Jun-guang Wang[a], Bing Yu[a], Wei Yang[b], Jia-ning Cheng[a], Yun-rui Song[a], Chong-fa Cai[a,*]

[a] *Key Laboratory of Arable Land Conservation (Middle and Lower Reaches of Yangtze River) of the Ministry of Agriculture, Soil and Water Conservation Research Centre, Huazhong Agricultural University, Wuhan 430070, People's Republic of China*
[b] *Hubei Water Resources Research Institute, Wuhan 430070, People's Republic of China*

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ABSTRACT

During slope erosion, the travel and abrasion of aggregate during transport may produce finer and more transportable particles, causing a significant effect on the sediment transport capacity and erosion intensity. Little information is available on the effect of roughness on aggregate abrasion in overland flow. This study investigated the potential effects of slope gradient, flow discharge, and roughness on aggregate abrasion and hydraulic characteristics in overland flow. These factors were studied with a series of aggregate abrasion experiments in a 3.8 m long flume at four slope gradients (8.7%, 17.6%, 26.8%, 36.4%), five discharges ($0.4\,\mathrm{L\,s^{-1}}$, $0.6\,\mathrm{L\,s^{-1}}$, $0.8\,\mathrm{L\,s^{-1}}$, $1.0\,\mathrm{L\,s^{-1}}$, $1.2\,\mathrm{L\,s^{-1}}$), and five surfaces of artificial rough beds. The results indicated that the different roughness conditions (with contributions of 63.5%) had obvious effects on the abrasion of aggregate compared to the slope gradient and discharge. Regardless of the discharge and slope gradient, the abrasion degree of aggregate gradually increased as the roughness increased. The changes in the abrasion degree of the aggregate were not the same at the different combinations of discharge and slope for each artificial rough bed. Flow depth can well explain the extent of abrasion of the aggregate for the single fixed rough bed. However, the abrasion degree of the aggregate had no significant variation with increases in the flow depth from all the data of the five artificial rough beds. The ratio between the residual weight and initial weight of soil aggregates (Wr/Wi) decreased in a power function with increase in the friction factor and shear stress from all the data of the five artificial rough beds. The friction factor and shear stress should be appropriate indicators to reflect aggregate abrasion under various roughness conditions in overland flow. The information of the analysis of the abrasion of soil aggregate under different artificial rough beds can be useful for the development of soil process-based erosion models.

1. Introduction

The basic processes of soil erosion by water that occur on hillside fields involve detachment, transport and deposition (Meyer and Wischeier, 1969; Rose, 1985; Hairsine and Rose, 1992). Detachment occurs when the erosive forces of raindrop impacts and the transport of detached particles take place due to raindrop splashes and overland flow (Kinnell, 2005, 2009). Many soil properties influence erosion processes and soil erodibility directly or indirectly. However, some studies have noted that slope erosion is considered to be the most dependent on the soil structure and strength (Zhang et al., 2007; Shi et al., 2010). Stable aggregate can reduce the possibility of forming surface crusts and seals, and the stability of soil aggregate is one of the most important factors for controlling soil erosion (Martínez-Mena et al., 1999; Valmis et al., 2005). The responses of soil aggregate to water erosion processes include the resistance to splash erosion dispersion under the action of rainfall and the transformation of the aggregate particles during the transport processes in overland flow.

Le Bissonnais (1996) showed that the breakdown of soil aggregate mainly results from four mechanisms during detachment and transport by water erosion: slaking due to the compression of entrapped air during wetting, micro-cracking, mechanical breakdown by raindrop or runoff impacts, and physical–chemical dispersion. Over recent years, some scholars have elaborated on the breakdown of aggregates by raindrop splash (Legout et al., 2005; Wuddivira et al., 2009; Mahmoodabadi and Sajjadi, 2016), the influence of aggregate breakdown under different particle sizes and moisture rates to soil water infiltration (Lado et al., 2004; Abu-Hamdeh et al., 2006; Warrington

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* Corresponding author at: College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, People's Republic of China.
E-mail addresses: jgwang@mail.hzau.edu.cn (J.-g. Wang), yu20008bing@webmail.hzau.edu.cn (B. Yu), yw-883@163.com (W. Yang), 1151615395@qq.com (J.-n. Cheng), 1243078296@qq.com (Y.-r. Song), cfcaihzau@163.com, cfcai@mail.hzau.edu.cn (C.-f. Cai).

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et al., 2009) and the quantitative relationship between aggregate stability and the erodibility index of interrill erosion (Fox and Le Bissonnais, 1998; Yan et al., 2008; Shi et al., 2010). The above studies are focused on an analysis of aggregate breakdown mechanisms and soil detachment in the process of erosion under rainfall conditions. However, little is known about soil aggregate dynamics within overland flow just after their detachment from the soil matrix (Wendling et al., 2016). As sediment particles are transported in overland flow, many studies mainly focused on the analysis of the quantitative relationship between the cohesionless fine sediment transport capacity and hydraulic parameters (Prosser and Rustomji, 2000; Abrahams et al., 2001; Zhang et al., 2009; Ali et al., 2013). Studies on the transport characteristics of aggregate are not very common in overland flow. There are some scholars that only select materials that have a similar geometric morphology with aggregate (such as aggregates of paint package, brickbat, and so on) in order to study transport processes and transport forms in overland flow (Giménez et al., 2007; Nord et al., 2009). However, these studies did not consider the break characteristics of the aggregate itself in the transport process.

Wang et al. (2012, 2013) showed that abrasion is one of the ways that the aggregate can be destroyed in overland flow, which is often used to explain the process of a pebble in a natural river (Naaim-Bouvet et al., 2011), and it is due to the friction and collisions that occur between aggregates and between one aggregate and the bed, leading to a reduction in the size of the aggregate. The abrasion regularities of the aggregate and the relationship between aggregate abrasion and some related hydraulic parameters have been obtained and interpreted under conditions of a certain slope surface roughness in overland flow (Larionov et al., 2007; Wang et al., 2012, 2013). These studies reflected over the process by which the aggregate is subjected to chip and grind and does not split rapidly. However, the single underlying surface condition makes difficult to adequately understand the process of actual slope erosion.

Soil surface roughness is identified as one of the controlling factors because it influences overland flow and soil loss and improves the understanding of the mechanisms of soil erosion (Jester and Klik, 2005; Zheng et al., 2014; Vermang et al., 2015). Previous researchers defined several types of soil surface roughness, each type representing a different order of magnitude in size. The first type of roughness constitutes microrelief variations due to individual grains, microaggregates or aggregate sizes, which are on the order of 0 to 2 mm. The second type is surface variations due to cloddiness and range in size from 100 to 200 mm (Römkens and Wang, 1986). The first two types are uniform in all directions and therefore are called random roughness. Many researchers characterized the effects of soil surface roughness on runoff and soil erosion rates under simulated rainfall (Helming et al., 1998; Zheng et al., 2014; Vermang et al., 2013, 2015). Some authors showed that because surface roughness reduces the flow velocity, the erosive power and the transport capacity of the flow is decreased, leading to a decrease in soil loss (Cogo et al., 1984; Zheng et al., 2014). Others suggested that a higher degree of soil surface roughness can also increase soil erosion by concentrating flows and possibly increasing scouring action, headcut development and rilling (Helming et al., 1998; Römkens and Helming, 2002). In general, the soil surface roughness greatly affects surface sealing, runoff generation, and soil erosion. According to a few researchers, a soil surface roughness ranging from millimeter to centimeter scales reduces runoff velocity. They showed the relationship of the bed roughness to the particles transported on an artificially roughened surface bed (Darboux et al., 2002; Farenhorst and Bryan, 1995). Therefore, the objectives of this study are: (1) to estimate the aggregate abrasion for the combinations of slope gradient and discharge under different artificial rough beds; and (2) to quantify the relationship between aggregate abrasion and the three main hydraulic parameters (flow depth, friction factor and shear stress) under different artificial rough beds.

2. Material and methods

2.1. Soil aggregate samples

Soil aggregate samples for the measurement of overland flow were collected from Xianning City in Hubei Province, China. The site has a subtropical monsoon humid climate with an annual average temperature of 16.8 °C and average annual precipitation of 1572 mm, of which > 70% falls between April and August. The landscapes of this area are hills with different degrees of erosion. There are rills and gullies that have developed on the ground surface as a result of washing by abundant rainfall. The vegetation mainly consists of evergreen broadleaf forests, deciduous broadleaf forests and coniferous forests. The selected soil parent material is derived from Quaternary red clay, which is the main parent material in this region.

Soil samples were taken from the surface layer (0–15 cm) in the field and then the samples were carried to the laboratory in rigid boxes and immediately air-dried. Large clods were broken by hand when they reached the proper moisture content (18% to 21%). The air-dried materials were sieved through screens with different mesh sizes. The physical and chemical properties of soils were determined using the routine methods (ISSAS, 1978). The mechanical composition of the soil was measured by the pipette method. The soil pH was measured with a pH meter in a 1:2.5 soil to water mixture.

The aggregate stability was measured with LB-method, which was proposed by Le Bissonnais (1996) and tested by Amezkéta et al. (1996). Aggregates (3–5 mm) of air-dried soil samples were selected and were oven-dried at 40 °C for 24 h. Then these soil samples were tested with fast wetting (FW), slow-wetting (SW) and stirring pre-wetted (WS) aggregates. The operation procedure was the same as that described by Wang et al. (2013). Each treatment was replicated 3 times. Aggregate stability was expressed using the mean weight diameter (MWD).

$$\mathrm{MWD} = \sum_{i=1}^{7} x_i w_i \tag{1}$$

where x_i is the mean diameter of each size class (< 0.05 mm; 0.05–0.1 mm; 0.1–0.25 mm; 0.25–0.5 mm; 0.5–1 mm; 1–2 mm; > 2 mm), and w_i is the weight fraction of aggregates in the size class *i*.

The mechanical breakdown index (RMI) proposed by Zhang and Horn (2001) was used to determine the resistance to the mechanical breakdown of the soil. The relationship is:

$$\mathrm{RMI} = \frac{\mathrm{MWD_{SW}} - \mathrm{MWD_{WS}}}{\mathrm{MWD_{SW}}} \tag{2}$$

where $\mathrm{MWD_{SW}}$ and $\mathrm{MWD_{WS}}$ are the mean weight diameters obtained by the slow-wetting and stirring treatments, respectively. An increase in the RMI-value indicates that the aggregates are increasingly more susceptible to mechanical breakdown.

Table 1
Basic properties and aggregate stability of test soils.

Soil	Mechanical composition ($g\ kg^{-1}$)			Texture	pH (H_2O)	MWD_{FW} (mm)	MWD_{SW} (mm)	MWD_{WS} (mm)	RMI
	Sand	Silt	Clay						
Q	86 ± 13	375 ± 26	539 ± 34	Clay	4.51 ± 0.14	1.85 ± 0.17	2.71 ± 0.03	1.88 ± 0.02	0.31