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Effects of transport distance and flow discharge of overland flow on destruction of Ultisol aggregates

Junguang Wang, Zhaoxia Li, Chongfa Cai*, Wei Yang

Key Laboratory of Arable Land Conservation (Middle and Lower Reaches of Yangtse River), Ministry of Agriculture, Huazhong Agricultural University, Wuhan 430070, China

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ABSTRACT

The destruction of soil aggregates upon transport by overland flow may produce a significant effect on sediment transport capacity and general intensity of erosion. The particle size distribution of destructed soil aggregates has a close relation to the surface runoff and permeability of soils. The objective of this study is to quantify the effects of transport distance and flow discharge of overland flow on the destruction of aggregates of Ultisols in a 3.8 m long flume with a fixed bed. A series of experiments were carried out at a slope of 17.6%, including six transport distances (9–108 m) and eight discharges (0.4–1.2 L/s). The results indicate that (1) the extent of the destruction of aggregates became weaker with the decrease in size over the same transport distances or at the same discharges; (2) the aggregates derived from Shale were rapidly abraded and had more serious destruction as compared to the aggregates from Quaternary red clay during the transport process, which was relevant to the stability difference of the two parent materials; (3) two stages of aggregate breakdown could be identified in terms of the coefficient α during transport, that is, the aggregates were rapidly abraded and became round and were predominantly broken down into smaller fragments at the first stage, while the smaller fragments and the round aggregates were weakly abraded with reduction in weight and their shape became regular; and (4) the extent of the destruction decreased with increasing discharge, which was due to the changes in the hydraulic properties (flow depth and friction factor) and in movement modes during the transport process. The analysis of the characteristics on aggregate destruction by overland flow can contribute to the development of soil erosion models.

1. Introduction

Aggregate is the fundamental structural unit of soil, which has an influence on several aspects of the physical behavior of soil, in particular, on water infiltration and soil erosion (Legout, Leguédois, & Le Bissonnais, 2005). Soil loss can be described as a net balance of the detachment of in situ soil fragments by splash and overland flow, the transport of the previously detached sediment and the deposition. These erosion processes depend on size distribution of available soil fragments provided by the breakdown of the soil (Leguédois & Le Bissonnais, 2004; Rose, 1985). Stable aggregates can reduce soil detachment caused by raindrop impact and transport by overland flow (Martínez-Mena, Deeks, & Williams, 1999). It is generally accepted that soil aggregate breakdown and particle size distribution may produce an effect on sediment transport capacity and the intensity of erosion.

The major mechanism that causes aggregate breakdown during detachment and transport by water includes slaking due to the compression by entrapped air during wetting, breakdown by differential swelling, mechanical breakdown due to raindrop and runoff impact, and physical–chemical dispersion (Le Bissonnais, 1996). Over recent years, some studies have better documented aggregate breakdown by splash (Legout, Leguédois, Le Bissonnais, & Malam, 2005; Wuddivira, Stone, & Ekwue, 2009) and the effect of aggregate size on infiltration and erosion characteristics under simulated rainfall (Abu-Hamdeh, Abo-Qudais, & Othman, 2006; Lado, Paz, & Ben-Hur, 2004; Warrington, Mamedov, Bhardwag, & Levy, 2009). The relationship between aggregate stability and erosion has generally been obtained from empirical information without considering the models for aggregate breakdown (Fox & Le Bissonnais, 1998; Valmis, Dimoyiannis, & Danalatos, 2005). Furthermore, new formulae have also been developed to evaluate interrill erosion rate by considering the aggregate breakdown mechanisms (Yan, Shi, Li, & Cai, 2008). Most studies on aggregate breakdown and the effect of aggregate stability on erosion focused on the detachment processes due to raindrop. However, little information about the destruction characteristics and movement modes of aggregates by overland flow is found.

In addition, various experiments on sediment transport by shallow flow were carried out, but most of attention were paid to

* Corresponding author. Tel.: +86 27 87288249; fax: +86 27 87671035.
E-mail addresses: cfcaihzau@163.com, cfcai@mail.hzau.edu.cn (C. Cai).

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Table 1
Physical and chemical properties of experimental soil.

Soils	Sample composition (g/kg)			pH (H_2O)	SOM (g/kg)	CEC (cmol/kg)
	Sand	Silt	Clay			
S	235 ± 8	439 ± 14	326 ± 12	4.52 ± 0.25	16.35 ± 0.41	14.35 ± 1.65
Q	189 ± 7	313 ± 11	498 ± 16	4.39 ± 0.21	17.55 ± 0.35	15.18 ± 1.57

Values are expressed as mean ± standard error ($n = 5$). SOM, soil organic matter; CEC, cation exchange capacity.

fine sediment transport capacity predicted by several hydraulic parameters such as shear stress (Alonso, Neibling, & Foster, 1981; Foster & Meyer, 1972; Yalin, 1963), stream power (Abrahams, Li, Krishana, & Atkinson, 2001; Prosser & Rustomji, 2000), and particle size distribution in different channel roughness (Farenhorst & Bryan, 1995; Foster & Meyer, 1972; Giménez, Léonard, Duval, Richard, & Govers, 2007). Some studies indicated the effect of the presence of sediment load on soil detachment (Merten, Nearing, & Borges, 2001; Zhang, Liu, Han, & Zhang, 2009). Little information about coarse sediment transport and destruction, such as aggregates, is found. The total amount of sediments in the flow and the relationship between the suspended load and bed load may affect the general intensity of erosion and the transport capacity of the flows. Thus, the effect of destruction of soil aggregates transported by overland flow is of great interest.

Due to the presence of abundant water-stable micro-aggregates, the effect of aggregate stability on soil erosion in Ultisols is obvious and vastly different from soils found in the temperate zone (Yan et al., 2008). Thus the objectives of this work are: (1) to investigate the effect of aggregate stability on the destruction of aggregates in Ultisols of subtropical China; and (2) to analyze the destruction regularities and movement modes of aggregates with different sizes over different transport distances and at different flow discharges.

2. Materials and methods

2.1. Soil aggregate samples

Two soil aggregate samples for overland flow measurement were selected from Xianning County, the southeast of Hubei Province, China. The selected soils were derived from shale and Quaternary red clay and were classified as Ultisols according to the U.S. Soil Taxonomy (USDA, 1999), Acrisols and Cambisols in the FAO legend (FAO-UNESCO, 1988). In this paper, soil aggregates refer to their parent materials, i.e., S and Q indicate soils derived from shale and Quaternary red clay, respectively.

Samples were taken from the surface layer (0–15 cm) in the field, and then carried to the laboratory in rigid boxes and immediately air-dried. Large clods were broken by hand when they were of the proper moisture content. The air-dried materials were sieved through screens with mesh sizes of 2–7 mm. Aggregates with characteristic sizes of 7–5, 5–3, and 3–2 mm were used for analyzing the destruction characteristics in overland flow, and 5–3 mm aggregates were used for stability test.

Selected physical and chemical properties of soils were determined using the routine method (ISSAS, 1978). Average values (five replicates) of each soil are given in Table 1. The two kinds of soils were strongly acidic, poor in soil organic matter and relatively low in total exchangeable bases, which are typical of Ultisols from southeastern China (Yan et al., 2008). The clay content was high in the soil derived from Quaternary red clay. The soil texture of Quaternary red clay was clay and shale was clay loam.

2.2. Aggregate stability tests

Aggregate stability was measured by slow-wetting (SW) aggregates and by stirring pre-wetted (WS) aggregates of the LB-method, which was proposed by Le Bissonnais (1996) and tested by Amezkéta, Singer, and Le Bissonnais (1996). Five grams of 5–3 mm aggregates was oven-dried at 40 °C and then tested for the following two treatments: slow-wetting (SW) and stirring pre-wetted (WS) aggregates. The operation procedure was the same as that described by Yan et al. (2008) and Wang et al. (2011). Each treatment was replicated 3 times. Aggregate stability for each sample was expressed in terms of the mean weight diameter:

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

where w_i is the weight fraction of aggregates in the size class i (<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) with diameter x_i.

The relative mechanical breakdown index (*RMI*) proposed by Zhang and Horn (2001) was used to determine the mechanical breakdown of the soils according to the following relation:

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

where MWD_{SW} and 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.

2.3. Measurement of destruction of soil aggregates

Fig. 1 shows the destruction of soil aggregates by overland flow in a hydraulic flume with a length of 3.8 m, a bottom width of 0.2 m

Fig. 1. Destruction of soil aggregates measured in a laboratory flume with constant roughness.