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Soil internal forces initiate aggregate breakdown and splash erosion

Feinan Hu[a,b], Jingfang Liu[c,a], Chenyang Xu[c], Zilong Wang[c,a], Gang Liu[a,b], Hang Li[d], Shiwei Zhao[a,b,c,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences, Ministry of Water Resources, Yangling, Shaanxi 712100, China
[c] College of Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, China
[d] Chongqing Key Laboratory of Soil Multi-Scale Interfacial Process, College of Resources and Environment, Southwest University, Chongqing 400715, China

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ABSTRACT

Soil erosion is a severe ecological and environmental problem and the main cause of land degradation in many places worldwide. Soil aggregate breakdown is the first key step of splash erosion and is strongly influenced by soil internal forces, including electrostatic, hydration, and van der Waals forces. However, little is known about the influence of soil internal forces on splash erosion. In this study, we demonstrated that both splash erosion rate (SER) and soil aggregate breaking strength (ABS) were significantly affected by soil internal forces. SER and ABS increased first (from 1 to 10^{-2} mol L^{-1}) then became stable (from 10^{-2} to 10^{-4} mol L^{-1}) with decreasing electrolyte concentration in bulk solution. The electrolyte concentration of 10^{-2} mol L^{-1} in bulk solution was the critical point for both soils in splash erosion and soil aggregate stability. The experimental results can be well interpreted by the theoretical analysis of soil internal forces. The surface potential and electric field around soil particles increased with decreasing electrolyte concentration, thereby increasing the electrostatic repulsive force among soil particles. This phenomenon led to soil aggregate breakdown and release of fine soil particles. Soil splash erosion rate and aggregate stability showed a linear relationship ($R^2 = 0.83$). Our results suggest that soil internal forces induce soil aggregate breakdown and then release of fine soil particles when the soil was wetted, supplying the original material for splash erosion. Furthermore, the raindrop impact force is the driving mechanism causing soil particle movement. In summary, splash erosion could be due to the coupling effects of soil internal forces and the raindrop impact force. Our study provides a possible internal controlling method for reducing splash erosion by adjusting soil internal forces between soil particles.

1. Introduction

Soil erosion is the main reason of land degradation and has posed a major threat to many agricultural and environmental safeties (Mhazo et al., 2016; Vaezi and Bahrami, 2014; Ochoa-Cueva et al., 2015). In rain-induced erosion, splash erosion is an important process and the initial step of inter-rill erosion (Legout et al., 2005b; Fernández-Raga et al., 2017). In general, splash process could result in two main consequences: top soil aggregate breakdown and soil fragment movement (Rose et al., 1983; Legout et al., 2005a; Warrington et al., 2009). These phenomena may further affect soil porosity, hydraulic conductivity, surface sealing or crusting, runoff, and soil erosion (Ramos et al., 2003; Falsone et al., 2012; Vaezi et al., 2017; Sachs and Sarah, 2017). Thus, splash erosion is a vital issue that should be considered in soil erosion management and reliable prediction model development.

Splash erosion begins with the breakdown of soil aggregates into small particles (Shainberg et al., 1992; Legout et al., 2005b). In rain-induced erosion, soil aggregate stability mainly depends on changes in rainfall properties (Kinnell, 2005; Ghahramani et al., 2012), such as raindrop shape and size, kinetic energy, intensity, and their various combinations (Jayawardena and Rezaur, 2000; Martinez-Mena et al., 2002; Wei et al., 2007; Pieri et al., 2009; Ziadat and Taimeh, 2013; Fu et al., 2017). Several studies also reported that raindrop force could directly break down soil aggregates and initiate soil erosion (Ekern, 1951; Kinnell, 1990; Van Dijk et al., 2002; Wang et al., 2014). Although rainfall properties are important factors to influence splash erosion, according to the study of Nearing et al. (1987), the raindrop impact pressure was only about 1 to 3 atm. Therefore, it is still not sure whether the raindrop impact force is strong enough that could directly destroy soil aggregate.

* Corresponding author at: No. 26, Xi'nong Road, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China.
E-mail address: swzhao@nwafu.edu.cn (S. Zhao).

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Table 1
Basic physical and chemical properties of soil samples in this study.

Soil type	pH	SOM	CEC	SSA	Particle size distribution		
		(g kg^{-1})	(cmol$_c$ kg^{-1})	(m^2 g^{-1})	Clay (%)	Silt (%)	Sand (%)
Loessal soil	8.60	4.6	7.2	23.0	10.6	13.3	76.1
Lou soil	8.01	6.1	23.2	41.5	27.3	41.5	31.2

On the other hand, splash erosion is also affected by soil properties, such as clay content, soil organic carbon, cation exchange capacity, soil water content (Le Bissonnais and Singer, 1992; Le Bissonnais et al., 1995; Wuddivira et al., 2009; Saedi et al., 2016). These soil properties mainly affect soil aggregate stability, which is often employed as an indicator of soil erodibility (Barthès and Roose, 2002; Ramos et al., 2003; Shi et al., 2010). Soil aggregate breakdown during rainfall could be ascribed to slaking, differential clay swelling, and physical–chemical dispersion (Le Bissonnais, 1996; Levy et al., 2003). For soil aggregate stability under a fast wetting process, the mechanisms of soil aggregate breakdown are always ascribed to the slaking effect (Grant and Dexter, 1990; Le Bissonnais, 1996; Zaher and Caron, 2008; Wuddivira et al., 2010). Ramos et al. (2003) investigated the effects of different disaggregation forces on soil aggregate stability and found that most of the studied soils are susceptible to the loss of stability caused by slaking. Wu et al. (2017) reported that slaking is the most disruptive mechanism in aggregate breakdown in soils with the main clay types being kaolinite and illite which were sampled from Central-South China. Slaking is a physical process where soil aggregates are disintegrated either by forces exerted by clay swelling during wetting or by compressed air in aggregate (Zaher and Caron, 2008; Wuddivira et al., 2010). Furthermore, Dinel and Gregorich (1995) found that swelling exerts more effect on aggregates than alterations caused by compressed air during rapid wetting. Clay (e.g. montmorillonite and illite) swelling is mainly due to surface hydration and the overlap of diffused double layer when the clay is immersed into water (Abu-Sharar et al., 1987; Wilson and Wilson, 2014; Hu et al., 2015). The hydration force mainly induces soil aggregate swelling (Hu et al., 2015). Levy et al. (2003) reported that the slaking effect can be affected by soil electrolyte concentration due to their influences on the diffuse double layer. These studies indicated that the slaking effect essentially originated from soil internal forces, especially electrostatic repulsive force and hydration repulsive force, because of the overlap of diffused double layer of colloidal particles.

From the viewpoint of colloidal surface chemistry, soil internal forces, including electrostatic, van der Walls, and hydration forces, considerably affect soil aggregate stability (Farres, 1980; Itami and Fujitani, 2005; Hu et al., 2015; Rengasamy et al., 2016). Among these forces, electrostatic and hydration forces are repulsive forces, inducing soil aggregate breakdown; meanwhile, van der Waals force is an attractive force that restrains aggregate dispersion (Hu et al., 2015). Theoretically, these soil internal forces could produce interparticle pressure as high as 100–1000 atm (Li et al., 2013; Hu et al., 2015); by contrast, raindrop impact pressure is only 1–3 atm (Nearing et al., 1987). Evidently, the raindrop impact force is lower than soil internal forces. Therefore, soil internal forces are more important for soil aggregate stability than raindrop impact force and other factors. Previous studies demonstrated that these soil internal forces are responsible for soil aggregate stability and soil water movement (Hu et al., 2015; Xu et al., 2015; Li et al., 2013; Rengasamy et al., 2016; Yu et al., 2016). However, few works have directly focused on the effect of soil internal forces on splash erosion; future studies on this aspect could improve our knowledge on splash erosion and soil erosion risk prediction.

Here, we hypothesize that soil internal forces could be the initial forces causing aggregate breakdown and subsequent splash erosion due to raindrop impact. Moreover, splash erosion could be due to the coupling effects of soil internal forces and raindrop impact force. Therefore, in this work, we aimed to investigate the influence of soil internal forces on splash erosion, and probe into the background mechanism of rainfall splash erosion.

2. Materials and methods

2.1. Materials

Soil samples were collected from Ansai (109°19′21″E, 36°51′50″N) and Yangling (108°2′30″E, 34°18′14″N) within the Shaanxi Province, which is located in the south of Loess Plateau and is a traditional agricultural planting region in China. Soil erosion in these areas is usually serious in the rainy periods from July to September. The studied soils are Loessal soil and Lou soil, which are developed from loess parent materials and are classified as Calcic Cambisols according to FAO soil classification. Soil texture for Loessal soil and Lou soil are sandy loam and clay loam, respectively. The major crops planted in this region are winter wheat (*Triticum aestivum Linn*) and maize (*Zea mays L.*). For each type of soil, samples were collected from the top 0–20 cm layer of three representative cultivated lands and were then mixed for further use. X-ray diffraction analysis showed that the dominant clay minerals in the two soils were illite (~40%), kaolinite (~20%), chlorite (~20%), montmorillonite (~10%) and vermiculite (~5%). The cation exchange capacity (CEC) and specific surface area (SSA) were measured using the combined method for surface properties determination which proposed by Li et al. (2011); the detailed steps were given in our previous studies (Liu et al., 2013; Tang et al., 2015). The pH, soil organic matter (SOM) and particle size distribution were analyzed using the traditional methods and shown in Table 1.

2.2. Sample preparation

To quantitatively evaluate the effects of soil internal forces on splash erosion and soil aggregate stability, soil samples were saturated by replacing the originally heterogeneous ions adsorbed on the particle surface with specific ion specie, e.g. Na^+. On the other hand, previous studies (Li et al., 2015; Yu et al., 2016) have revealed that Na^+ is a preferable choice to investigate the effects of soil internal forces on aggregate stability due to its weak polarization at the interface of soil colloids. Therefore, Na^+-saturated soil samples were used in the present study. Here, Na^+-saturated soil samples (model aggregates) were prepared following the procedure described by Hu et al. (2015) and Li et al. (2013). In brief, the air-dried soil samples were firstly exchanged with NaCl solution, subsequently washed with deionized water to remove excess Na^+ in the suspension, then oven dried at 60 °C, and finally crushed and sieved to gain model aggregates (1–5 mm in diameter) for the evaluation of splash detachment and aggregate stability.

2.3. Experimental methods

The experiment on raindrop splash erosion was conducted using the combination of rainfall simulator and splash pan. The rainfall simulator was a cylindrical box with an open top. At the bottom of the cylinder, 22 syringe needles with a diameter of 0.6 mm were installed uniformly. During the rainfall, a constant water head was maintained through a hole in the cylinder. The splash pan used was modified according to the