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Soil internal forces contribute more than raindrop impact force to rainfall splash erosion

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ABSTRACT

Soil internal forces, including electrostatic, hydration and van der Waals, play critical roles in aggregate stability, erosion, and other processes related to soil and water. However, the extent to which soil internal forces influence splash erosion during rainfall remains unclear. In the present study, we used cationic-saturated soil samples to quantitatively separate the effects of soil internal and raindrop impact forces (external) on splash erosion through simulated rainfall experiments. An electrolyte solution was employed as rainfall material to represent the combined effects of soil internal and external forces on splash erosion. Ethanol was used to simulate the sole effect of soil external force on splash erosion. The soil splash erosion rate increased with increasing rainfall kinetic energy in experiments with electrolyte solution and ethanol and was also greatly influenced by soil internal forces. Moreover, the soil splash erosion rate increased first (from 1 to 10^{-2} mol L^{-1}) then leveled off (from 10^{-2} to 10^{-4} mol L^{-1}) with decreasing electrolyte concentration in the bulk solution. This finding was in agreement with the theoretical analysis of soil internal forces. The contribution rate of soil internal forces on splash erosion was > 65% at a low electrolyte concentration (< 10^{-2} mol L^{-1}) and only 3%–25% at an electrolyte concentration of 1 mol L^{-1}. Even though the electrolyte concentration of the soil bulk solution reached 10^{-1} mol L^{-1}, the contribution rate of soil internal forces to splash erosion was > 50%. Hence, soil internal forces exerted higher contribution to rainfall splash erosion than raindrop impact force under most field conditions. This work provides new understanding of the mechanism of soil splash erosion and establishes the possibility of controlling splash erosion by jointly regulating the soil internal and external forces.

1. Introduction

Splash erosion mainly caused by raindrop impact is an important process and the first step of soil erosion during rainfall (Legout et al., 2005a, 2005b; Vaezi et al., 2017; Fernández-Raga et al., 2017). Splash erosion has two main direct consequences, namely, breakdown of top soil aggregates and movement of finer soil particles (Legout et al., 2005a; Warrington et al., 2009; Angulo-Martínez et al., 2012), which may lead to surface sealing, decrease in soil porosity, increase in runoff and sediment, and negatively influence on the sustainable development of agriculture and ecological environment (Le Bissonnais, 1996; Uri, 2000; Falsone et al., 2012; Vaezi and Bahrami, 2014; Mekonnen et al., 2015; Parras-Alcántara et al., 2016; Zhang et al., 2017; Yaghobi et al., 2018). Therefore, an effective method must be developed to protect aggregates against the disruptive effects of raindrop impact, shear strength of flowing water, and freezing/thawing cycles.

Splash erosion starts with the disintegration of soil aggregates into small particles (Shainberg et al., 1992); in this regard, soil aggregate stability is often used as an indicator of soil erodibility (Barthès and Roose, 2002; Wuddivira et al., 2009; Ma et al., 2014; Xiao et al., 2017, 2018). The interaction of internal forces (electrostatic, hydration and van der Waals force) are crucial for initiation of the soil aggregate breakdown (Hu et al., 2015; Xu et al., 2015; Huang et al., 2016). Among these soil internal forces, electrostatic and hydration forces are repulsive and induce soil aggregate breakdown; meanwhile, van der Waals force is attractive and restrains aggregate dispersion (Huang et al., 2016). In general, as rainfall enters the soil, strong hydration and electrostatic forces between soil particles in the aggregates build up

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rapidly with decreasing electrolyte concentration in the soil bulk solution; this phenomenon leads to the breakdown of aggregates and the immediate release of micro-aggregates/finer particles (Hu et al., 2015). Theoretically, soil internal forces could reach as high as hundreds of thousands of atmospheric pressure among soil particles (Li et al., 2013). The net pressure, i.e. the sum of electrostatic, hydration and van der Waals forces among soil particles, controls aggregate swelling, dispersion, or breakdown. Holthusen et al. (2010) measured the rheological parameters for soils with different salt concentrations; the results indicated that soil aggregate stability at the microscale increased with increasing potassium concentration in the soil solution due to the change in the soil particle interaction forces. Li et al. (2013) reported that the net pressure of soil internal forces among particles strengthened with decreasing electrolyte concentration in the bulk solution, resulting in increased soil particle transport during simulated rainfall. Yu et al. (2017) found that the removal of soil organic matter decreased the soil aggregate stability mainly due to the decreasing van der Waals force among soil particles. These studies indicate that soil internal forces could significantly affect aggregate stability and thus splash erosion during rainfall. In our recent study, through the simulated rainfall experiments, we demonstrated that splash erosion could be due to the coupling effects of soil internal and raindrop impact forces (Hu et al., 2018). During splash erosion, soil internal forces mainly induce aggregate breakdown and release of fine soil particles when the soil is wetted; this process supplies the original material for rainfall splash erosion.

Besides, raindrop impact force is the driving mechanism that causes soil particle movement (Le Bissonnais and Singer, 1993; Kinnell, 2005; Legout et al., 2005a; Oliveira et al., 2013). This type of force is regarded as the main external factor that affects splash erosion. If raindrop impact would be totally eliminated, then splash erosion will not occur during rainfall. Rainfall properties, such as shape and size, intensity, kinetic energy, and their various combinations, exert important effects on splash erosion (Jayawardena and Rezaur, 2000; Wei et al., 2007; Lu et al., 2008; Pieri et al., 2009; Ziadat and Taimeh, 2013; Fu et al., 2016). In any case, the most important parameter that influences splash erosion is raindrop kinetic energy (Fernández-Raga et al., 2010; Vaezi et al., 2017). In general, the splash erosion rate increases with increasing raindrop kinetic energy (Hu et al., 2016). Raindrop impact has two main consequences: breakdown of surface soil aggregates and movement of fine particles (Legout et al., 2005a, 2005b). But, unlike soil internal forces, raindrop impact force mainly influences the movement of fine particles (Hu et al., 2018).

Overall, rainfall splash erosion is affected by two erosive factors: soil internal and raindrop impact (or external) forces (Hu et al., 2018). Soil internal forces induce aggregate breakdown, which could supply certain amounts of fine soil fragments for splash erosion. Soil external forces, i.e., raindrop impact force, induce the movement of soil fragments (Legout et al., 2005a; Fernández-Raga et al., 2017). Hence, soil internal forces determine the "source" (the amount of fine soil particles released from macro-aggregates) of splash erosion; meanwhile, soil external force controls the movement of fine particles. Therefore, the coupling effect of soil internal and external forces could result in splash erosion. However, the extent to which soil internal forces influence splash erosion during rainfall remains unclear. Determining the contribution of soil internal forces to splash erosion will improve our knowledge on the nature of erosivity and its influencing factors. Results could also provide a basis for developing a more effective method for controlling the risk of soil erosion by jointly regulating the soil internal and external forces.

Thus, we hypothesize that soil internal forces have higher contribution to splash erosion rate during rainfall than raindrop impact force. In this study, electrolyte solution was used as rainfall material to represent the combined effects of soil internal and external forces on splash erosion. Ethanol was employed to simulate the sole effect of soil external force (raindrop impact) on splash erosion. This work aims to quantitatively evaluate the effects of soil internal forces on splash erosion through simulated rainfall experiments.

2. Materials and methods

2.1. Materials

Soil samples were collected from Yangling (108°2′30″E, 34°18′14″N), Shaanxi Province, which is located in the south of the Loess Plateau in China. Soil erosion in this area is usually serious during the rain period (from July to September). The major crops planted in this region are winter wheat (*Triticum aestivum* Linn) and maize (*Zea mays* L.). The studied soil is Lou soil, which is classified as Calcic Cambisols (according to the FAO soil classification). Soils were sampled from the top 0–20 cm layer of three representative cultivated lands and mixed. X-ray diffraction analysis showed that the dominant clay minerals of the soil were illite, kaolinite, chlorite, and montmorillonite. The contents of clay, silt, and sand in the soils were 25.4%, 40.5%, and 34.1%, respectively, which were measured using a Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments Ltd., UK). According to the combined method for determination of surface properties proposed by Li et al. (2011), the cation exchange capacity (CEC) and specific surface area (SSA) of the soil were 23.2 $cmol_c\,kg^{-1}$ and 41.5 $m^2\,g^{-1}$, respectively. The pH and soil organic matter content were 8.01 and 6.1 $g\,kg^{-1}$, which were measured using traditional methods (Sparks et al., 1996).

2.2. Soil sample treatments

Other factors should be kept as constant as possible for investigating the effects of soil internal forces on splash erosion. Thus, soil samples were first saturated with the given cation species. According to previous studies (Li et al., 2015; Yu et al., 2016), Na^+ shows weak polarization at the interface of soil colloids and is thus a better choice for determining the effects of soil internal forces on splash erosion. Na^+-saturated soil samples were used throughout the study. Herein, Na^+-saturated soil samples were prepared as described in our previous study (Yu et al., 2016). Soil samples of about 1.5 kg were exchanged with Na^+ by adding 0.5 $mol\,L^{-1}$ NaCl solution, and this procedure was repeated for three times. The samples were then washed with deionized water to remove excess Na^+ in the suspension, oven dried at 60 °C, and crushed through a 5 mm sieve to collect model aggregates with diameter of < 5 mm for the experiments.

2.3. Experimental method for rainfall splash erosion

The experimental procedures for splash erosion were the same as those in our previous study (Hu et al., 2018). Herein, we briefly introduce the procedures. The devices for splash erosion (shown in Fig. 1) consist of rainfall simulator and splash pan. The rainfall simulator is a cylindrical box with an open top. Syringe needles with a diameter of 0.6 mm were installed uniformly at the bottom of the cylinder. The rainfall intensity was controlled by adjusting the water head through a hole in the cylinder. The splash pan was made up of collecting and test areas. The collecting area was an inclined plane holder with an outlet connected to the lowest point of the plane. Any splashed material was collected from the test area during rainfall simulation. The test area was a circular sieve with a diameter of 10 cm and a height of 1 cm. The mesh size was 0.25 mm to prevent the effect of water film on raindrop impact.

Electrolyte solution and ethanol were employed as rain materials to quantitatively distinguish the contribution of soil internal and external forces to splash erosion. The electrolyte solution as rain material represents the combined effects of soil internal and raindrop impact forces on splash erosion. Thus, we can quantitatively evaluate the combined effects of soil internal and raindrop impact forces on splash