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Resistance of Coarse-grained Particles against Raindrop Splash and Its Relation with Splash Erosion

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ABSTRACT

Raindrop splash, which is the most critical factor determining detachment rate of soil particles, is the result of complex interplay between the erosivity of raindrops and splash detachability of soils. When the applied erosivity exceeds the intrinsic resistance (splash detachability) of soils, raindrop splash erosion will be initiated. However, studies on the elucidation of underlying process in the soil detachment by raindrop splash are very limited. This study investigated the resistance of coarse-grained particles to raindrop splash through both theoretical analysis and experiments. In addition, the splash erosion rate was evaluated by employing both erosivity (property of raindrop) and splash detachability (property of soils) variables. Results indicated that the median sand particle size was the primary variable determining the splash rate of coarse-grained particles, while, the effect of particle shape and relative density on raindrop splash was minimal. Thus, threshold kinetic energy and splash detachability factor were expressed in terms of median sand particle size. Finally, experimental results were compared with the theoretical model through the comparison of the border between splash and no splash, and a good agreement between those two was observed in this study.

1. Introduction

Raindrop splash is known as the most critical factor determining detachment rate of soil particles (Ahn et al. 2013; Dunne et al. 2010; Fu et al. 2017; Lu et al. 2016; Morgan 2005; Park et al. 1982). These particles, detached due to the raindrop impact / lateral spreading can be easily transported by runoff fluid, resulting in the deterioration of aquatic ecosystems, increased oxidization of biomass carbon in soil, and in the worst case, can contribute to interrill erosion (Hu et al. 2018; Levy et al. 1994; Phillips et al. 1993; Pimentel and Kounang 1998). Numerous studies on raindrop splash have been performed since the 1940s, reflecting the importance and complex nature of raindrop splash (Al-Durrah and Bradford, 1981; Terry 1998). Most previous studies mainly focused on the effect of raindrop erosivity such as raindrop size, drop velocity, drop shape, drop kinetic energy, and drop momentum on raindrop splash of soil particles; however, studies focused on the effect of splash detachability of soils (e.g., soil type, particle size, water content, soil fabric, strength, stiffness, and so on) on raindrop splash are relatively limited (Al-Durrah and Bradford, 1982b; Bryan et al. 1989; Misra and Teixeira 2001; Wei et al. 2015; Xiao et al. 2018).

Notably, some studies (Al-Durrah and Bradford, 1982b; Cruse and Larson 1977; Mouzai and Bouhadef 2011; Nearing and Bradford 1985) considering both erosivity and splash detachability attempted to link splash rate with geotechnical strength parameters obtained from fall cone tests, under the assumption that they are affected by similar governing mechanisms. Though these attempts to link those two mechanisms elucidated the importance of resistance / strength of soils on raindrop splash, these relationships between the geotechnical shear strength parameter and splash rate are for fine grained soils such as silts, clays, and sand-silt or sand-clay mixtures only. Additionally, there is no direct relationship between the geotechnical shear strength parameter and splash rate, which has resulted in a lack of physical meaning of soils' resistance to raindrop splash. Therefore, this study investigated the resistance of coarse-grained particles (sand) to raindrop splash through both theoretical analysis and experiments.

The mathematical model describing the detachment of soil particles can be generally expressed according to the following power law relationship (Meyer 1981):

$$D_s = K' \bullet E^b \tag{1}$$

where D_s = splash detachment rate (mass of soil particles detached by raindrop); K' = splash detachability (erodibility) factor, which is a function of soil property; E = erosivity (kinetic energy or momentum); b = empirical constant. However, more recent studies recognized the

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Nomenclature

A	projected cross sectional area
B	width of soil under consideration
C	cohesion of soil
C_c	coefficient of curvature
C_D	drag coefficient
C_s	channel shape factor
C_u	uniformity coefficient
D	waterdrop diameter
D_r	relative density
D_s	splash detachment rate
D'	lateral spreading distance
d_{50}	median particle size
E	erosivity
E'	elastic modulus
e	void ratio
e_{max}	maximum void ratio
e_{min}	minimum void ratio
G_s	specific gravity
i	hydraulic gradient
IR	infiltration ratio
K	hydraulic conductivity
K' and Ka	splash detachability (or erodibility) factor
KE	kinetic energy
KE^*	critical (threshold) kinetic energy
K_p	coefficient of passive earth pressure
M	momentum
N_c,	$N\gamma$, and Nq = bearing capacity parameters
n	porosity
R	roundness
S_0	volumetric specific surface
T	tortuosity
u	drop velocity
u_L	lateral flow velocity
u_t	terminal drop velocity
u_δ	penetration velocity
p	pressure due to water hammer effect
q	dynamic pressure
q_u	bearing capacity
q'	surcharge
t	impacting time
V_D	volume of single water drop
V_I	volume of infiltration
V_L	volume of later flow
δ	infiltration depth
μ	fluid viscosity
γ	unit weight of soil
ζ	lateral water flow thickness
θ	angle of crater slope
φ	friction angle
ρ_w	density of water

intrinsic resistance of soils against raindrop splash; therefore, Equation (1) was modified to employ the concept of threshold describing the minimum erosivity to initiate the detachment of soil particles (Kinnell 2005; Sharma and Gupta 1989; Sharma et al. 1991):

$$D_s = K_a \bullet (KE - KE^*) \tag{2}$$

where K_a = splash detachability (erodibility) factor, indicating the slope of the linear relationship between splash rate (detachment) and applied kinetic energy; KE^* = critical (threshold) kinetic energy. Equation (2) clearly demonstrated that the splash of soil particles will not occur when the applied erosivity (e.g., kinetic energy) is smaller than critical erosivity. Once applied erosivity is greater than the critical value, the splash rate of soil particles will increase with an increase in erosivity, and its increase rate will be proportional to the splash detachability factor (K_a). Therefore, the critical erosivity and splash detachability factor in Equation (2) are a function of the splash detachability of soils, reflecting the resistance of soils to raindrop splash (Sharma and Gupta 1989). Consequently, splash resistant soils will exhibit greater critical erosivity but smaller erodibility factor compared to easily detachable soil particles.

2. Theoretical analysis of raindrop splash subprocesses

The theoretical analysis was divided into two sections: crater formation and raindrop splash of particles. Through the particle-level analysis, the mechanism and physical meaning of crater formation and resistance of a soil particle to raindrop splash were derived. However, it is important to note that the purpose of this analysis was not to predict exact field values, but to elucidate the complex interplay between erosivity (property of raindrop) and splash detachability (property of soils). Due to the complexity of the mechanisms controlling raindrop splash, this analysis represents a simplification of the operative issues.

2.1. Crater Formation

Bearing capacity theory of soils quantifies the ability of soils to sustain a load applied to the ground, and can be employed as an indicator of shear failure in the case of raindrop impact. Bearing capacity for a strip shaped loading (ratio of width to length ~ 0) can be derived from wedge theory with equilibrium analysis (Terzaghi 1943):

$$\frac{q_u}{B} = C \bullet N_c + \frac{1}{2} \bullet \gamma \bullet B \bullet N_\gamma + q' \bullet N_q \tag{3}$$

where q_u = bearing capacity; B = width of soil under consideration; C = cohesion of soil; γ = unit weight of soil; q' = surcharge; N_c, N_γ, and N_q = bearing capacity parameters (function of friction angle φ). In the case of circular loading, the above equation can be modified (Das 2010; Lambe and Whitman 1969):

$$q_u = 1.3 \bullet D \bullet N_c + 0.6 \bullet \frac{1}{2} \bullet \gamma \bullet D \bullet N_\gamma + q' \bullet N_q \tag{4}$$

In addition to the negligible cohesion ($C \approx 0$, valid for coarse-grained particles), waterdrop impact occurs at the soil surface level; therefore, the surcharge term can also be neglected ($q' N_q \approx 0$) and the bearing capacity is reduced to:

$$q_u = 0.6 \bullet \frac{1}{2} \bullet \gamma \bullet D \bullet N_\gamma \tag{5}$$

where D = waterdrop diameter; $N_\gamma = 0.5 \bullet (K_p{}^{2.5} - K_p{}^{0.5})$ and K_p = coefficient of passive earth pressure ($K_p = \tan^2(45 + 0.5 \bullet \varphi)$). The initial contact area when the raindrop impacts the soil surface is much smaller than the circular area based on D. However, the contact area will increase during the impacting time; thus, it is assumed that Eq. (5) is based on waterdrop diameter. In other words, it is assumed in Eq. (5) that the area affected by raindrop is equivalent to the waterdrop cross sectional area.

The applied load on the soil surface due to raindrop impact can be calculated from the dynamic pressure, from Bernoulli's equation, and can be derived from the conservation of energy under the assumption of that the raindrop impacting area is equivalent to the waterdrop cross sectional area:

$$q = \frac{1}{2} \bullet \rho_w \bullet u^2 \tag{6}$$

where q = dynamic pressure in Pa; ρ_w = density of water in kg/m^3; and