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Splash erosion of clay–sand mixtures and its relationship with soil physical properties: The effects of particle size distribution on soil structure

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ABSTRACT

Large quantities of disturbed soils and residues derived from engineering constructions have provided material resources for soil erosion and geological disasters, which is becoming a serious problem in China. To date, studies on the erosion mechanism of these soils in a wide particle size distribution (PSD) are limited, and the relationships between soil PSD and physical characteristics are not explicit. Here, we analyzed the effects of PSD on structural and mechanical parameters and attempted to quantify their relationships by blending silty clay soil and engineering sand as clay–sand mixtures with various sand mass proportions ranging from 0 to 90% at a 10% increment in a wet and a dry mixing type (MT). In addition, the effect of PSD on splash erosion was measured under simulated rainfall. Changes of bulk density and porosity of soil mixtures (for clay contents more than 13%) with clay content displayed apparent differences separately in the wet and dry mixing types mainly due to the deformation and reorganization of soil grains. Internal friction angle φ and cohesion c of saturated soils showed a parabolic trend and an exponential increase with clay content respectively, while cohesion c was better quantified by particle fractal dimension D than clay content. Shear strength indexes in the wet mixing type were generally larger than those in the dry mixing type when clay content was larger than 13%. Splash erosion temporal variation was significantly affected by PSD, MT, rainfall duration (RD) and their interaction effects (PSD × MT, PSD × RD), among which MT was the most prominent source of variation ($F = 99.97$, $p < 0.001$). Stepwise multiple regression analysis indicated that splash erosion rate was negatively correlated with cohesion ($p < 0.001$) and the coefficient of variations (CVs) of splash erosion rate were positively related with non-capillary porosity ($p < 0.01$). Simple equations were proposed for predicting physical parameters (bulk density ρ, porosity e, φ, c, splash erosion rate) as a function of soil PSD characteristics. These obtained results are useful to supplement the erosion knowledge of disturbed soils, facilitate soil erosion prediction and provide technical guidelines for soil and water conservation in engineering construction areas.

1. Introduction

There is an increasing quantity of waste soils and residues derived from construction projects along with the acceleration of industrialization and urbanization in most areas of China. Engineering accumulation is being stock piled from foundation excavation and forms a special geomorphic unit (Dimitrova and Yanful, 2012; Hamidi et al., 2012; Li et al., 2013a). Due to the nature of open and loose packing structure, engineering accumulation is sensitive to soil erosion and has become one of the main sources of soil erosion (Halvorson et al., 1997; Lin, 2008).

Soil erosion process in construction areas has different forms and shows distinct characteristics. As the first process of soil erosion, splash produces detached materials that can be transferred by the overland flow and affects further erosion such as sheet erosion and rill erosion (Kinnell, 1990; Legout et al., 2005). Engineering accumulation (disturbed soils) with different compactness and in a wide range of texture makes it become the most commonly encountered materials generating splash erosion easily (Song et al., 2007). Prior studies have shown that large aggregate sizes and high organic matter contents can protect soils against splash detachment (Ekwue, 1991). Legout et al. (2005) also found that clay content could be used to predict the size distribution of splashed soil fragments and aggregate structural stability is the limiting factor for the splash transport. Mamedov et al. (2006) emphasized that the surface conditions, especially the antecedent moisture content and aging, affect the soil surface structural stability as well as its resistance to seal development and soil losses. A systematic study about the erosion discipline of engineering accumulation in the wide range of particle size distribution (PSD) has barely been conducted,

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especially for construction projects. Given the above situation, it is advisable to carry out relevant research about the erosion discipline based on engineering accumulation to facilitate erosion prediction in construction areas.

Studies on the soil erosion have indicated significant relationships between the mass of splashed soil and soil strength, and soil erodibility associated with the rainfall-driven erosion processes can decline with an increase in soil strength (Rose et al.1990; Misra and Rose, 1995; Mouzai and Bouhadef, 2011). The influence of particle size distribution on the shear strength of soil has been well established (Li et al., 2013a). Increasing sand content or decreasing clay content would decrease cohesion and increase friction (Al-Shayea, 2001; Dimitrova and Yanful, 2012). Soil shear strength depended greatly upon the relative contents of coarse and fine particles (Vallejo and Mawby, 2000). Salgado et al. (2000) reported that, for silty sand, fine particles entirely control the soil behaviors in terms of shear strength when their content is more than 20%. However, these studies about soil shear strength commonly focused on the soils with a narrow range of clay content, whether these obtained results could be applied to engineering accumulation need to be verified.

As one of the most important physical attributes, particle size distribution (PSD) reflects soil particle composition and has great influence on soil properties related to soil erosion (e.g. Fiès and Bruand, 1998; Montero, 2005; Rahardjo et al., 2008; Zhao et al., 2009). Prior studies have shown that clay content (less than 2 μm) is a critical factor for the engineering behavior of soils (Al-Shayea, 2001). Compared with the traditional presentation of PSD by a given size fraction, fractal dimension has been demonstrated to be a better tool used to characterize soil structure, soil erodibility and soil permeability (e.g., Tyler and Wheatcraft, 1992; Perfect, 1997; Huang and Zhan, 2002; Filgueira et al., 2006).

Existing articles about engineering accumulation focused on their engineering behaviors in most cases. The erosion knowledge of engineering accumulation is insufficient. Moreover, the investigated materials are mostly related to a narrow range of textures and there are few quantitative relationships between soil physical parameters and PSD, which hampers the generalization and application of aforementioned knowledge. With an attempt to probe into the influence of PSD on physical properties and soil erosion of the engineering accumulation, synthetic clay–sand mixtures with different PSDs were prepared by mixing various proportions of selected clay soil and engineering sand. Experiments were conducted to determine soil structure and splash erosion under simulated rainfall for various clay–sand mixtures in both a wet and a dry mixing type (simulating natural disturbed soil conditions). Efforts were also made to quantify the relationships between the physical properties and PSD, and explore the splash erosion mechanism of clay–sand mixtures. These obtained results are useful to supplement the erosion knowledge of soil mixtures and lay the foundations for the establishment of appropriate soil erosion prediction models, and provide technical guidelines for soil and water conservation in engineering construction areas.

2. Materials and methods

2.1. Soil mixtures

The tested samples in different particle size distributions were obtained by mixing clay soil and engineering sand (taken from a building site) at various sand mass proportions. The soil in texture of silty clay was taken from the surface layer (0–15 cm) of cultivated land with a relative elevation of 30–80 m and a gentle inclination (<20%) in Xianning County (29°39′–30°02′N and 114°06′–114°43′E), Hubei, China, with an annual average precipitation of 1572 mm. It was derived from Quaternary red clay. The silty clay soil was air dried and ground to pass through a 2 mm sieve. The air-dried engineering sand material was yellowish-brown in color with an angular particle shape, and the portion with a diameter of 0.25–2 mm was reserved after sieving. The physical and chemical properties (Table. 1) of the silty clay soil and engineering sand were determined using the standard analytical methods (Institute of Soil Science, Chinese Academy of Sciences, 1978). Particle-size distributions are presented in Fig. 1.

Ten soil mixtures were prepared by blending the silty clay soil (<2 mm) and the engineering sand (0.25–2 mm) thoroughly at different engineering sand contents, i.e., ranging from 0 to 90% at a 10% increment on a dry mass basis. To explore the cementing effect of clay on soil structure, each sample of soil mixtures was blended in both a dry and wet mixing type (MT) (Consoli et al., 2011), i.e., the silty clay soil and engineering sand were mixed with no or a certain amount of water added to the mixtures.

2.2. Measurements

2.2.1. Particle-size distributions

Soil mixtures were dispersed with sodium hydroxide. After pretreatment, sieve analysis was performed for particle sizes larger than 0.25 mm and the hydrometer method was used for particle sizes smaller than 0.25 mm, so that a distribution of particle sizes below and over 0.25 mm was obtained. Also the temperature was recorded at each time to allow viscosity and density corrections (Gee and Bauder, 1986).

Percentages of clay, silt, and sand of soil mixtures analyzed in this study are summarized in Table. 2; they were classified in accordance with USDA soil classification and their distribution in the soil textural triangle is shown in Fig. 2 (Staff, 1993). In order to obtain detailed information of soil PSD, fractal techniques were introduced from information science to soil science (Montero, 2005). The fractal dimension D was commonly used to evaluate particle size distributions in many reports (e.g. Turcotte, 1992; Tyler and Wheatcraft, 1992). We adopted the D index to quantify PSD to facilitate the development of mathematic models for further research.

2.2.2. Bulk density and porosity

Pretreatment showed that the optimal initial water content added for each wet-mixing soil sample equaled to its plastic limit, and then stored in plastic bags for about one day before test. Both dry and wet soil mixtures were compacted into standard cylinders (50.46 × 50 mm, consisting of top and base caps) with filter paper covering the bottom. Each sample was filled with 3 layers of equal thickness, and compacted at a normal pressure of 50 N (2600 Pa). Afterward, the excess portions above the ring edge were removed by a profile knife.

The weights of each sample were recorded under following conditions:(i) 24 h saturation, (ii) 2 h filter-drying for capillary (e_c) and non-capillary porosity (e_n) and (iii) 12 h oven-dried at 105 °C for bulk density (ρ) and total porosity (e). Each process was repeated three times (n = 3). Soil bulk density and porosity were estimated using the following formulas (ASTMD 698, 2000).

$$\rho = \frac{W_d}{V} \tag{1}$$

$$e = \left(1 - \frac{\rho}{2.65}\right) \times 100 \tag{2}$$

$$e_c = \frac{W_c - W_d}{V} \times 100 \tag{3}$$

$$e_n = e - e_c \tag{4}$$

where, ρ, bulk density, $g \cdot cm^{-3}$; W_d, the oven-dried soil mass, g; V, soil volume, cm^3; e, total porosity, %; e_c, capillary porosity, %; W_c, the soil mass after 2 h filter-drying from saturation, g; e_n, non-capillary porosity, %.