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Rainfall infiltration performance and its relation to mesoscopic structural properties of a gravelly soil slope

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A R T I C L E I N F O

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A B S T R A C T

Soil infiltration performances under rainfall affect shear strengths and play a crucial role in landslide problems. In this paper, the infiltration performances of gravelly soils under different rainfall conditions were investigated by 1D and 2D seepage tests. Computed tomography (CT) scans were adopted to identify the mesoscopic structural properties of gravelly soils. The significances of mesoscopic properties on the saturated coefficient of permeability (k_s) were subsequently analyzed. The results showed a temporal and spatial variation of infiltration performances of a gravelly soil slope. The infiltration performances measured by 1D infiltration tests were different from those obtained from 2D tests. An exponential relationship between 1D and 2D infiltration rates was observed. The results further highlighted that void area ratio, uniformity coefficient, and gravel content were three most significant factors to k_s. Three permeability formulas that respectively expressed by gravel content, initial dry density and two mesoscopic properties were proposed in this paper.

1. Introduction

The soil with 50% or more of coarse fraction retained on the 4.75 mm (No. 4) sieve is referred to as gravels (ASTM D2487, 2011), or gravelly soils in some literature (Chen and Chu, 2011; Chang and Phantachang, 2016). Natural gravelly soils are widely distributed around the tropical and subtropical regions as a slope material formed by complex factors, such as weathering and accumulation of residual and colluvial deposits (Chang et al., 2014; Chang and Cheng, 2014). The failure of gravelly soil slopes can broadly be attributed to the convergence of three factors, i.e., rainfall, the inclination of slope, and soil geological profile. Among these, rainfall is considered to be the most significant triggering factor for slope failures (Lee et al., 2011; Cuomo and Della Sala, 2013; Dou et al., 2015). Practical experience has shown that many slope failures occurred during or shortly after rainfall (Gavin and Xue, 2008). Actually, the soil infiltration performances under rainfall determine water contents and pore pressure gradients, hence, affect the soil shear strength and play a crucial role in landslide problems (Rahimi et al., 2010; Lee et al., 2011). Therefore, it is essential to evaluate the rainfall infiltration performance of unsaturated gravelly soils for prevention of geological disasters such as landslides and debris flows.

In the literature, laboratory experiments, field tests, numerical analyses and analytical methods were employed to offer insights into the process of rainfall infiltrations and runoffs, and relevant conclusions were reported. By parametric analyses, on the one hand, rainfall duration, rainfall intensity and antecedent soil moisture were found to affect the soil cumulative infiltration (Wang et al., 2013). On the other hand, $CaCO_3$ content, primary particle size distribution (PSD) and texture of soil were reported to evidently influence the infiltration rate (Mazaheri and Mahmoodabadi, 2012). The numerical work by Cuomo and Della Sala (2013) showed that slope angle and rainfall intensity are two important factors for the runoff generation: the greater the slope angle and rainfall intensity, the earlier the runoff to start. Additionally, the influence of the presence of vegetation on the infiltration rate and surface runoff was also pointed out in previous works (Zhan et al., 2007). The study by Wu et al. (2016) reported that the coupling of seepage and deformation plays a notable role in the movement of wetting fronts, the distribution of pore water pressure and the slope stability, especially for a combination of short-duration heavy rain and high initial suction. To predict the water infiltration and estimate the travel time of wetting fronts, Green and Ampt (1911), Philip (1957), Latifi et al. (1994), and Gavin and Xue (2008) proposed some analytical and empirical models. Some other researchers put emphasis on air entrapment effects. Wang et al. (1998) found that the infiltration rate was controlled by air outflow and it decreased threefold to tenfold

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when considering air entrapment. Latifi et al. (1994) noted that the air pressure buildup was more pronounced in soil columns of two layers than that in soil columns of one homogenous layer, and the flow condition and pressure buildup in the bottom layer retarded the wetting front. The process of rainfall infiltration into gravelly soils is an extremely complex problem due to the non-linearity of hydraulic properties.

The coefficient of permeability (or hydraulic conductivity) is one of the most important hydraulic properties of soil (Cai et al., 2014). The value of permeability coefficient is in relation to pore fluid types (e.g. air, water and oil), soil solid types (e.g. gravel, sand, silt and clay) and external conditions (e.g. deformation, stress and strain) (Fredlund and Rahardjo, 1993; Huang et al., 1998; Lei et al., 2016). With respect to gravelly soils, owing to the presence of oversized gravel particles, special sampling tools and large-scale testing apparatus are required to measure the coefficient of permeability. Li et al. (2009) developed a soil column device equipped with suction and water content monitoring sensors to measure the coefficient of permeability of the soils from clay to gravel. Heeren et al. (2013) proposed a method for field measurement of permeability with a temporary berm constructed of a water-filled 15 cm diameter vinyl hose with the edges sealed to the soil using bentonite. The berm was reported to be capable of confining infiltration plot areas of various sizes (e.g. 1 × 1 and 3 × 3 m^2 areas). Wang and Huang (1984) developed a relation between the coefficient of permeability and classification properties of soil based on experimental results. By testing the permeability of the materials ranging from sand to rock-fill, Côté et al. (2011) observed that the intrinsic permeability of soil went up with increasing effective grain size (d_{10}). Shelley and Daniel (1993) investigated the effect of gravel content on the hydraulic conductivity of soil/gravel mixtures. They found that when gravel content was greater than 50% - 60%, the clayey soil did not fill the voids between gravel particles resulting in a high hydraulic conductivity. The authors also highlighted that the soil permeability function may change spatially due to uncertainties in soil fabric. Recently, mesoscopic structural properties of soils derived from CT scans were introduced to estimate the coefficient of permeability, while few efforts have been made for gravelly soils (Dal Ferro et al., 2015; Tracy et al., 2015; Mossadeghi-Björklund et al., 2016).

The aim of this study was to comprehensively examine the rainfall infiltration performance of gravelly soils and provide insight into the relationship between the permeability and the mesoscopic structural properties. To this end, 1D and 2D seepage tests considering different rainfall conditions were carried out on gravelly soils. And then the infiltration rates, infiltration depths and surface settlements were analyzed. Afterwards, CT scans combined with image processing techniques were employed to quantify the mesoscopic structural properties of gravelly soils. The significances of the obtained mesoscopic properties to the saturated coefficients of permeability (k_s) were subsequently assessed by range analyses, variance analyses and gray relational analyses. Finally, three empirical permeability formulas that expressed by gravel content, initial dry density and two mesoscopic structural properties, respectively, were proposed.

2. Material and methodology

2.1. Material properties

The materials studied were sandstone residual gravelly soils derived from a slope beside the entrance of the Shuizhuwan tunnel (GPS coordinates: 27°58′N, 113°01′E) in Xiangtan, China (Fig. 1). Three soil-collecting areas were selected in every 4 m from the top to the bottom of the slope, and marked by "slope top", "middle slope" and "slope toe", respectively. The physical properties of gravelly soils measured in the laboratory are listed in Table 1. It is noteworthy that gravel content in this study was defined as the mass percentage of coarse grain with a size greater than 2.0 mm.

Prior to the infiltration tests, a proper range of sample grain size must be determined. When using the column permeameter to measure the soil permeability, the maximum grain size of samples usually should not exceed 1/5 of the internal diameter of the permeameter so that the size effect could be controlled to the minimum. The maximum grain size of the raw gravelly soils was up to about 80 mm. In view of the size limitation of our laboratory samples, the replacement technique was adopted to remove the oversized grains. In other words, we removed the oversized grains (whose sizes were larger than 60 mm) by proportionally replacing them with small grains in equivalent mass. Fig. 2 shows the grain size gradation of oversized-grain-removed gravelly soils.

2.2. Setups and programs for infiltration tests

2.2.1. 1D infiltration tests

2.2.1.1. Instrument description. An infiltration-settlement testing instrument was self-designed to meet the experimental requirements. As shown in Fig. 3, the instrument was principally composed of three parts: a circulating water supply device, an infiltration-settlement column cell, and a measurement system. The circulating water supply device consisted of a water pump with frequency control and constant pressure, a water tank and water supply pipelines. Distilled water was used in our tests to eliminate the effect of bubbles in tap water. The infiltration-settlement column cell consisted of a plexiglass column, an artificial rainfall device, and an instrument support. The plexiglass column was 300 mm in internal diameter and 850 mm in height. The artificial rainfall device was made up of mist rainfall nozzles and hoses. The measurement system was designed for evaluating head pressures, water flows, infiltration rates, infiltration depths, permeabilities and settlements of gravelly soils. The head pressures were measured by 4 glass piezometric tubes that connected to the infiltration-settlement column cell by valves and hoses. Another hose with one end connected to the plexiglass column at the bottom could enable excessive water flow into the water collection cup. This hose could also be adjusted up and down according to the scale bar to meet the desired water head. The water flow was evaluated by weighing the mass of outflow water in the water collection cup. k_s was then calculated according to Darcy's law. The settlement of gravelly soils was measured with a digital caliper. A camera was used to photograph the infiltration process of rainwater, thus infiltration rates and depths could be obtained by analyzing the digital images.

2.2.1.2. Test program. 1D infiltration tests were performed to investigate the infiltration performance and settlement of gravelly soils (Table 2). In the tests, 3 torrential rainfall conditions with the intensities of 1.2 mm/min, 1.6 mm/min and 2.0 mm/min were considered. The material adopted was oversized-grain-removed gravelly soils that collected from the slope top. Every test followed these procedures: (i) The experimental soil was filled into the infiltration-settlement column cell in layers. Each layer of the soil was shaved and compacted by modeling tools to ensure the uniformity and integrity of the soil sample. After preparing the sample, we let it stand for 24 h. (ii) The rainfall intensity was calibrated according to the test requirements, and artificial rainfall was subsequently simulated. A camera was started to record the whole testing process. (iii) The soil sample was gradually saturated with low water head. After standing for another 12 h, k_s and the saturated water content of the sample were measured. (iv) After a test, we removed the soil sample and went on to the next.

2.2.2. 2D seepage tests

2.2.2.1. 2D physical model. 2D seepage tests were carried out on slope models under plane strain conditions. The gravelly soil slopes were modeled in a rectangle toughened glass container with angle steel and channel steel skeletons (see Fig. 4). The experimental container had a