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Onset of suffusion in gap-graded soils under upward seepage

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Abstract

Suffusion is an important mechanism that leads to the failure of hydraulic structures such as dams and levees. To evaluate the onset conditions, i.e., the critical hydraulic gradient of the suffusion, a set of laboratory experiments is conducted to explore the internal erosion behaviors under upward seepage conditions. During these experiments, the particle erosion in soils with different particle size distributions and dry densities is investigated. Based on the results of the experiments, a low critical hydraulic gradient (LCHG) and a high critical hydraulic gradient (HCHG) are defined corresponding to the local moving and the global loss of fine particles, respectively. The results show that these two critical hydraulic gradients are significantly influenced by the particle size distribution and the dry density of the soil. Moreover, the experiments reveal that the characteristics of the soil, especially the particle size distribution, have a significant impact on the internal instability of the soil. The effects of the particle size distribution and the dry density on the critical hydraulic gradients are then explained using a capillary model, which is built upon the characteristics of the voids in the soil, including the porosity and the void size distribution.

Keywords: Suffusion; Critical hydraulic gradient; Particle size distribution; Dry density; Void size distribution

1. Introduction

Internal erosion is the main cause of the failure of hydraulic structures like earth-rock fill dams and levees (Foster et al., 2000; Richards and Reddy, 2007; Zhang and Chen, 2006). Internal erosion includes four mechanisms, namely, erosion in concentrated leaks, backward erosion, contact erosion, and suffusion (Bridle and Fell, 2013). In the present study, focus is placed on suffusion. Suffusion is the process by which finer soil particles are moved through constrictions between larger soil particles by seepage forces (Wan and Fell, 2008), leading to changes in the physical and geo-mechanical properties of the soils (e.g., permeability, volume change, compressive strength, and soil grain gradation) (Xiao and Shwiyhat, 2012).

As the seepage forces reach certain critical values, the onset of suffusion in the soils begins (i.e., particle loss occurs). These critical values or conditions play a crucial role in assessing the failure risks of dams and levees (Brivois et al., 2007; Chang and Zhang, 2013a; Kimiaghalam et al., 2016; Mercier et al., 2014; Ojha et al., 2003; Reddi et al., 2000; Richards and Reddy, 2007; Wilhelm and Wilmański, 2002). A common criterion for evaluating the critical conditions for suffusion is the

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critical hydraulic gradient (CHG). The CHG can be related to the intrinsic properties of soils and some external factors. Over the past decades, the influences of the intrinsic properties, such as the particle size distribution (PSD), the gradation, the porosity, and the particle shape, have been extensively investigated via analytical and experimental approaches. These investigations have led to a set of methods for estimating the CHG value and for evaluating the internal stability of soils (e.g., Åberg, 1993; Burenkova, 1993; Kenney and Lau, 1985; Kovacs, 1981; LaFleur, 1999; Skempton and Brogan, 1994).

More recently, research has focused on the effects of external factors such as the stress state and seepage directions. For example, Moffat and Fannin (2006, 2011) investigated the effects of the vertical effective stress on the internal stability in cohesionless soils and proposed a hydromechanical rule that governs the stability of soils. Studies on the stress conditions have thrived due to recent advances in testing apparatuses and approaches. Some stress-controlled apparatuses are capable of imitating the suffusion behaviors under complicated stress paths (Chang and Zhang, 2011; Ke and Takahashi, 2014; Luo et al., 2013a).

While many factors controlling suffusion have been explored during the past decades, the mechanism of the suffusion behaviors under different conditions remains to be understood. One of the reasons that our understanding of the mechanism is hindered is the limited ability of the experimental apparatuses. For example, while the latest apparatuses are capable of implementing suffusion tests under complicated stress paths, the seepage in these apparatuses is often restricted to the downward direction. To the authors' best knowledge, studies on suffusion behaviors in the upward flow with a stress-controlled apparatus are rare. Practically speaking, internal erosion in the upward flow is far more common than that in the downward flow. An example of levee systems is considered for which a continuous internal erosion can be attributed to the escaping upward hydraulic gradient exerted on the fine particles around the erosion outlet, which leads to the loss of fine particles around the outlet. Otherwise, the fine particles near the outlet are likely to have a deterrent effect on the erosion, even if the hydraulic gradients in other areas are large enough to move the particles (Ahmed, 2012; Fleshman and Rice, 2013; van Beek et al., 2014). Therefore, assessing the fine particles escaping in an upward flow from the outlet is essential to understanding the internal stability of levee systems. Another reason is that the hydromechanical principle governing the factors having an effect (e.g., the PSD) on the suffusion behaviors is still unclear, despite the established links between the PSD and the suffusion behaviors via experimental and theoretical works. This predicament arises from the fact that it is difficult to construct an appropriate mathematical model to explain the physics of the suffusion process because of the complexity of the structures and the phenomena at the pore scales.

The focus of this study is the suffusion initiation under upward flow conditions. Firstly, a set of suffusion experiments is conducted with our newly developed apparatus, which has been proven effective in simulating the suffusion in the upward flow direction under a complex stress state. In these experiments, the critical hydraulic gradients that drive the fine particles out of the soil matrix under the upward seepage flow conditions are captured. Based on the results, the effects of the PSD and the dry density are investigated upon the onset of suffusion. Subsequently, a conceptual model is developed to elucidate the mechanism behind the link among the PSD, the dry density, and the suffusion initiation.

2. Upward suffusion experiments

2.1. Apparatus

The newly developed apparatus is employed to conduct suffusion experiments under upward flow conditions. The apparatus is stress-controlled such that the erosion can be studied under different desired stress states on the specimens. Fig. 1 shows a sketch of this apparatus. Generally, the apparatus consists of four components, namely, the water supply system, the loading system, the soil–water separating system, and the water-collecting system. The loading system, including a loading chamber, a vertical loading system, and a confining loading system, is the core of this apparatus. The loading chamber houses the specimen to which stresses are applied (Fig. 2). The stresses, including the confining stress and the vertical stress, are supplied separately. The confining stress is implemented by inflating pressurized nitrogen into a Mariotte's bottle. The Mariotte's bottle is also used to monitor the volumetric strain of the specimen by weighing the liquid in the tube. The vertical stress system includes a servo-compression tester and a controlling unit. The vertical stress is applied on the top of the specimen via a piston connected to the tester (Fig. 2). Besides delivering the desired stresses, the tester is also capable of recording the vertical displacement during loading. An upstream water supply system regulates the desired hydraulic head at the bottom of the specimen to initiate the seepage flow and to trigger suffusion in the samples. The water through the specimen then freely spills out from the top. A soil–water separating system is designed to separate and collect the eroded particles from the outlet flow. This system also monitors the seepage velocity, which is determined by using the mass increment of the collected water in a unit time. More details on this apparatus can be found in Liang et al. (2017).

2.2. Materials and specimen preparation

The soil used for the specimens in these experiments is collected from a beach along the Yangtze River in Chongqing, China. Firstly, the soil is washed with distilled water to