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An experimental testing apparatus for study of suffusion of granular soils in geological structures

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ABSTRACT

This study mainly focuses on the suffusion process of granular soils, especially that filled in geological structures, such as faults and karst conduits. As current devices only can be used for suffusion tests on cylindrical soil specimens, an experimental testing apparatus has been designed and developed for systematic research on the suffusion of granular soils filled in fractures and fractures subjected to unidirectional seepage flow. The permeameter cell is designed to enable free rotation so that unidirectional seepage can be imposed at any angle from 0° to 90°. Experiments on granular soils were carried out under different axial stresses to verify the operability and repeatability of the designed apparatus. The water pressure and axial stress applied on soil specimens were controlled during testing, and the variations of flow rate and hydraulic conductivity with water pressure under different axial stresses were analyzed to study the effect of axial stress on the suffusion of granular soils.

1. Introduction

The knowledge of the internal instability of granular soils is a key factor in the design of granular or geotextile filters (Moraci, 2010; Moraci et al., 2012). In addition, while tunneling in karst terrains and mountainous areas, engineers may encounter unpredictable fractures, faults and well-developed karst conduits, which may be filled with different packing media, such as clay, granular soil and fault gouge (Li et al., 2013, 2016; Zhou et al., 2015). The failure of filling materials in geological structures under high water pressure may induce serious geological disasters, such as water inrush in tunnels. This study mainly focuses on the suffusion process of granular soils, especially that filled in faults or karst conduits.

Granular soil is comprised of gravel, sand and silt, and its gradation curve can be split into two parts: the coarse fraction and the fine fraction. The coarse particles constitute the skeleton of the soil and carry the major part of the overburden load. The fine particles can move within the matrix of the coarse particles under seepage flow, which takes different forms and can be described by several terms, such as suffusion (Kovacs, 1981; Bendahmane et al., 2008) and suffosion (Kenney and Lau, 1985; Chapuis, 1992). The term suffusion refers to the redistribution of the fine fraction within the coarse fraction, yielding a relatively small and slow change in local hydraulic conductivity and permeability. The total specimen volume will remain the same without any reduction during suffusion process, because only fine particles move within the voids of coarse particles and no displacement occurs for coarse particles which constitute the soil skeleton. Suffusion may cause a loss of particles and instigate a process of undermining, termed suffosion, where particle migration yields a reduction in total volume and a consequent potential for collapse of the soil skeleton, yielding a relatively large and fast change in local hydraulic conductivity and permeability (Moffat and Fannin, 2006; Richards and Reddy, 2007; Moffat et al., 2011). The potential of suffusion of a granular soil is mainly controlled by its particle size distribution (PSD), and the onset of suffusion is governed by the hydromechanical conditions within the soil skeleton and initiates when the seepage force exceeds a critical threshold (Moraci et al., 2012, 2014). Previous laboratory studies were conducted primarily to quantify the potential of suffusion by means of geometric analysis of the particle size distribution (Kezdi, 1979; Kenney and Lau, 1985; Honjo et al., 1996; Wan and Fell, 2008), and thereafter several apparatuses have been designed for experimental tests to investigate both the initiation and development of suffusion under multi-stage seepage flow and complex stress states (Tomlinson and Vaid, 2000; Bendahmane et al., 2008; Richards and Reddy, 2010; Moffat and Fannin, 2011; Moffat et al., 2011).

Filtration tests on four sandy gravels were performed by Skempton

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and Brogan (1994) with an upward seepage flow and with no confining stress applied to the top surface of the specimen. Bendahmane et al. (2008) developed a new experimental device for sandy-clay samples to investigate the initiation of internal erosion and to characterize the erosion evolution of cohesive soils. Internal erosion tests under isotropic stress conditions subjected to a hydraulic action in a downward direction were conducted to examine the influence of hydraulic gradient, confining pressure and clay content on clay and sand erosion mechanisms. Richards and Reddy (2010, 2012) developed a new apparatus named True Triaxial Piping Test Apparatus (TIPTA), which is capable of applying variable confining pressure conditions along three mutually perpendicular axes, as well as pore water pressure and seepage flow rate, for the evaluation of non-cohesive as well as cohesive soils prone to backwards erosion subjected to a variety of hydraulic conditions and confining stresses. A permeameter device was designed by Moffat and Fannin (2006) to examine hydromechanical conditions prevailing at the onset of suffusion in cohesionless soils subjected to multi-stage seepage flow. Experimental tests were performed by Moffat and Fannin (2011) and Moffat et al. (2011) on four widely-graded cohesionless soils to investigate their susceptibility to internal erosion and the spatial and temporal progression of seepage-induced instability. Chang and Zhang (2011) developed a stress-controlled internal erosion apparatus, which allows independent control of hydraulic gradient and stress state, to systematically investigate the initiation and development of internal erosion subjected to multi-stage seepage flow and complex stress state and the effect of stress states on critical hydraulic gradients. A series of laboratory internal erosion tests on gap-graded granular soils have been conducted by Chang and Zhang (2013) under three stress paths: isotropic, triaxial compression and triaxial extension. A laboratory apparatus, which can provide a constant hydraulic gradient, was designed and constructed by Fleshman and Rice (2013) to measure the critical hydraulic gradient close to the microscopic grain-size scale in sandy soils.

Experimental tests on the internal instability of granular soils have been conducted by many researchers using the aforementioned apparatuses and devices. However, most were carried out on cylindrical samples. This study mainly focuses on the suffusion of granular soils filled in geological structures, such as fractures and faults, which are narrow in one direction compared to their extended length. Therefore, an apparatus which allows independent control of seepage direction, has been designed and developed in the present study for systematic research on the suffusion of cuboid specimens of granular soils filled in fractures subjected to unidirectional seepage flow. Experiment tests on granular soils under different axial stresses were carried out first using the new-developed apparatus, and the effect of axial stress on suffusion process was studied.

2. Experimental testing apparatus

A new apparatus has been designed and developed to enable systematic investigation of the initiation and development of suffusion of granular soils filled in geological structures subjected to unidirectional seepage flow. The design was based on earlier experiences reported by Moffat and Fannin (2006) and Chang and Zhang (2011), and was a combined effort of researchers from Shandong University in China and Monash University in Australia. A schematic diagram of the testing apparatus is shown in Fig. 1, and a picture of the set-up is provided in Fig. 2. It comprises an axial load apply system, a pressurized water supply system, a permeameter cell, a particle collection system, a water collection system and a data acquisition system. Same to the device developed by Chang and Zhang (2011), the apparatus also allows independent control of water pressure and axial stress. In particular, the axial load application system and the permeameter cell can be freely rotated together to enable investigation of the impact of seepage direction ranging from 0° to 90° on the suffusion phenomenon, as shown in Fig. 3. The design and operation of each component is presented in detail as follows.

2.1. Permeameter cell

The permeameter cell is designed with an aluminum frame and transparent Perspex screen to enable observation of the spatial and temporal variation of particle migration along the specimen, and to enable free rotation so that unidirectional seepage can be imposed at any angle ranging from 0° to 90°. The axial load apply system and the permeameter cell are mounted on the bed frame with two all-thread bolts, as shown in Fig. 1. Once loosing these two bolts, the axial apply system and the permeameter cell can be rotated together to the specified angle, and then tighten the bolts so that the permeameter cell can be fixed and the unidirectional seepage flow with specified angle can be applied during testing. It accommodates a specimen with a length of 250 mm and a width of 25 mm, which is reconstituted and compacted to an initial height of about 200 mm. The cell has an aluminum frame and Perspex screen with the material properties shown in Table 1 (Ranjith et al., 2013). The aluminum frame is designed in two sections, and the back panel has cross-sectional dimensions of 25 mm × 50 mm and the front panel has cross-sectional dimensions of 40 mm × 25 mm. The aluminum window area has dimensions of 360 mm × 360 mm. The Perspex screen area is designed to be 625 cm^2, with a total area of 900 cm^2 and a thickness of 4 cm. The top cap is sealed by means of O-rings, and is held in place with several external all-thread bolts. The inside of the permeameter cell comprises a perforated plate I, an upper wire mesh, four pieces of flexible membrane, the soil specimen, a lower wire mesh and a base pedestal, as shown in Fig. 1. The design of each component is presented in detail as follows.

Perforated Plate I. The perforated plate I is made of aluminum (10 mm in thickness, 250 mm in length and 25 mm in width) and seated against an upper wire mesh screen on the top surface of the specimen. It has 33 symmetrically-located holes, 8 mm in diameter, to allow for circulated water flow and the transmission of axial stress to the soil specimen.

Upper Wire Mesh. This is placed between the perforated plate I and the top surface of the specimen to prevent clogging of the perforated plate by coarse particles. The opening size of the screen is selected in accordance with the particle size distribution of the specimen to be tested.

Soil Specimen. The tested specimen is reconstituted on a lower wire mesh screen and supported on a base pedestal that provides a reaction to the self-weight of the specimen and the axial force imposed using the loading rod.

Flexible Membrane. No flexible membrane is designed inside the permeameter cell at first, resulting that water flows quickly between the soil specimen and the side wall during the apparatus test. Therefore, to prevent the sidewall preferential flow, four pieces of PDMS flexible membrane with a thickness of 1 mm are used to minimize potential interface leakage between the rigid wall and the soil specimen.

The PDMS flexible membranes are made from two kinds of solutions and can be placed in the permeameter cell as follows: (a) Divide the permeameter cell into three separate components (the back panel, the front panel and the Perspex screen) firstly, and then place and fix them horizontally. (b) Mix these two solutions in a certain proportion and pour them on the inner surfaces of the back panel and the Perspex screen, and place the components in the air for several days until the solutions are completely solidified. (c) Assemble the back panel, the front panel and the Perspex screen together with all-thread bolts.

Lower Wire Mesh. A lower wire mesh is placed on the base pedestal to hold the coarse fraction of the soil and allow the fine fraction to erode by seepage flow. The opening size of the lower screen is