Geomechanics and Engineering, *Vol. 14, No. 3 (2018) 283-291*
DOI: https://doi.org/10.12989/gae.2018.14.3.283

Experimental study on water exchange between crack and clay matrix

Lei Song[1], Jinhui Li[*1], Ankit Garg[2] and Guoxiong Mei[3]

[1]*Department of Civil and Environmental Engineering, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen, China*
[2]*Department of Civil Engineering, Indian Institute of Technology, Guwahati Assam, India*
[3]*Department of Civil Engineering, Guangxi University, Guangxi, China*

(Received September 7, 2016, Revised April 7, 2017, Accepted July 24, 2017)

Abstract. Cracks in soil provide significant preferential pathways for contaminant transport and rainfall infiltration. Water exchange between the soil matrix and crack is crucial to characterize the preferential flow, which is often quantitatively described by a water exchange ratio. The water exchange ratio is defined as the amount of water flowing from the crack into the clay matrix per unit time. Most of the previous studies on the water exchange ratio mainly focused on cracked sandy soils. The water exchange between cracks and clay matrix were rarely studied mainly due to two reasons: (1) Cracks open upon drying and close upon wetting. The deformable cracks lead to a dynamic change in the water exchange ratio. (2) The aperture of desiccation crack in clay is narrow (generally 0.5 mm to 5 mm) which is difficult to model in experiments. This study will investigate the water exchange between a deformable crack and the clay matrix using a newly developed experimental apparatus. An artificial crack with small aperture was first fabricated in clay without disturbing the clay matrix. Water content sensors and suction sensors were instrumented at different places of the cracked clay to monitor the water content and suction changes. Results showed that the water exchange ratio was relatively large at the initial stage and decreased with the increasing water content in clay matrix. The water exchange ratio increased with increasing crack apertures and approached the largest value when the clay was compacted at the water content to the optimal water content. The effective hydraulic conductivity of the crack-clay matrix interface was about one order of magnitude larger than that of saturated soil matrix.

Keywords: clay; crack; water exchange; wetting front; seepage; hydraulic conductivity

1. Introduction

Cracks are prone to develop in clay due to wetting-drying cycles, freezing-thawing cycles or differential settlement (Benson and Othman 1993, Jessberger and Stone 1991, Melchior 1997, Omidi *et al.* 1996, Smith *et al.* 1997, Suter *et al.* 1993, Xue *et al.* 2014). These cracks provide preferential pathways for contaminant transport and rainfall infiltration (Albrecht and Benson 2001, Galeandro *et al.* 2013, Li *et al.* 2011a, Sajjadi *et al.* 2016). The quantification of preferential flow is dependent on the water exchange between the crack and soil matrix. The water exchange between the cylindrical cracks and sand matrix has been studied experimentally, numerically and theoretically (Castiglione *et al.* 2003, Gerke and Van Genuchten 1993a, Ghodrati *et al.* 1999, Kohne *et al.* 2005, Logsdon, 1995, Mohanty *et al.* 1997). The studies on water exchange between the cracks and clay matrix are rare due to two reasons: (1) the dynamic process of the crack which open upon drying and tend to close upon wetting is hard to be simulated; (2) a crack in clay is often plane shape with small apertures instead of a cylinder shape in sand (Li *et al.* 2011b). The aperture of a desiccation crack in clay (generally 0.5 mm to 5 mm, Li and Zhang 2010) is much smaller than that in sand. These features of desiccation cracks in clay result in difficulties in characterizing the water exchange between cracks and clay matrix.

The water exchange between the crack and soil was often quantified by water exchange ratio as shown in Eq. (1)

$$\frac{\partial \theta_m}{\partial t} = \frac{\partial}{\partial z}(\mathrm{K}_m \frac{\partial h_m}{\partial z} + \mathrm{K}_m) + \frac{\Gamma_w}{1 - w_f} \tag{1}$$

where θ_m is the volumetric water content, K_m is the hydraulic conductivity of the soil (m/s), t is time, z is the distance (m), w_f is the volumetric fraction of crack domain ($0 \le w_f \le 1$), Γ_w is the water exchange ratio (T^{-1}). Eq. (1) showed that the change of volumetric water content in soil during unit time was equal to the amount of water content change in soil itself plus the amount of water flowing into the soil from cracks. However, the water exchange ratio Γ_w between the plane crack and clay matrix was often based on assumptions. For example, the water exchange ratio was assumed to be a constant value in van Dam *et al.* (1997). This over-simplified assumption had not been supported by any experiment. Alternatively, the water exchange was numerically simulated by treating the water flux in cracks as a steady hydraulic boundary (Novak *et al.* 2000, Krisnanto *et al.* 2016). This assumption of steady state may not be applicable for cracks in clay, where hydraulic boundary was of dynamic nature due to deformation of crack.

The main objective of this study is to investigate the water exchange between the crack and the clay matrix. An

∗Corresponding author, Professor
E-mail: jinhui.li@hit.edu.cn

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

experimental apparatus equipped with soil volumetric water content and matric suction measuring system was developed. The water exchange ratio between the crack and clay matrix was quantitatively calculated using the monitored data in the experiments. The influence of the initial water content and the apertures of crack were also investigated. This study provides a method to determine the water exchange ratio, which can improve the understanding of the preferential flow through cracks in clayey soil.

2. Material and methods

2.1 Soil type and properties

The soil (30% sand, 56% silt, 14% clay) used in this study was residual soils from an excavation site in Hebei Province, China. The soil was classified as inorganic clay of low plasticity (CL) according to the Unified Soil Classification System (USCS). Plastic limit and liquid limit of soil were 16% and 35% respectively. The basic soil properties were investigated and summarized in Table 1. The saturated vertical hydraulic conductivity k_s of the clay at relative compaction of 90% was measured according to the ASTM Standard D5084-10. The compaction energy used to achieve the maximum dry density and the optimal water content of the soil was 0.57 kJ according to the ASTM Standard D698-12e2 (ASTM D698-12e2, 2012).

2.2 Experimental setup

The experimental setup (Fig. 1) contained three parts: test box, measuring system and data collecting system. The test box was made of acrylic. The soil sample in the test box was 500 mm long, 500 mm wide, and 400 mm high. In traditional permeability test for saturated soils, the soil sample often has a diameter of 100 mm (ASTM D5084-10, 2010). For unsaturated soils with micro-cracks, ASTM D7664-10 (2010) recommends a minimum diameter of 200 mm to capture the effects of preferential flow paths and to minimize boundary effects. The large soil sample used in this study is considered to be enough and can eliminate any possible boundary effects. A ruler on the front of the box was used to measure the development of wetting front in horizontal direction. The measuring system consisted of three volumetric water content sensors (EC-5) and three soil suction probes (2100F tensiometers; Soil moisture equipment Corp.). Six holes were fabricated on the front of the soil column to accommodate the measuring system. The hole for a volumetric water content sensor was rectangle (length of 17 mm, and width of 10 mm). The hole for the soil suction probe was circle with diameter of 10 mm. The soil suction probes were equipped with pressure transducers to enhance the accuracy of the suction measurements. The three volumetric water content sensors were located at 5 cm, 10 cm, 15 cm depths from the surface of soil and spaced 2 cm away from the center of the crack (as shown in Fig. 1). The soil volumetric water content was monitored every 2 seconds, which could measure the change of water content in the interdomain between the soil matrix and crack. The region around the crack was crucial to characterize the water exchange between the crack and the clay matrix. Hence, the clay matrix that was 1 cm away from the boundary of crack was regarded as interdomain (Kohne *et al.* 2005). The range of the volumetric water content sensors was 0%-100% and its accuracy was ±1%-2% of the range. Soil matrix suction was also monitored

Table 1 Basic physical properties of soil specimen

Soil type	Saturated water content (%)	Saturated vertical hydraulic conductivity (m/s)	Maximum dry mass density (g/cm^3)	Optimal water content (%)	Liquid limit (%)	Plastic limit (%)	Free swell ratio (%)
clay	32#	2.32×10^{-8}	1.727	16.3#	35.0	16.0	8.9

The saturated volumetric water content of the soil is 50% g/g; the optimal volumetric water content of the soil is 25% g/g

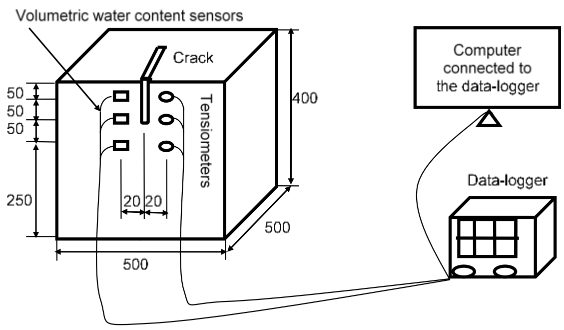
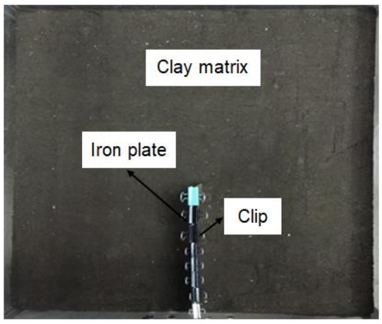
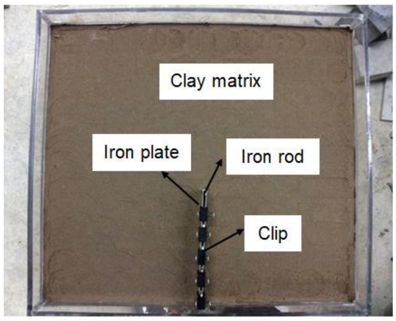


Fig. 1 Sketch of experimental set up for investigating water exchange between crack and clay matrix (Unit: mm)

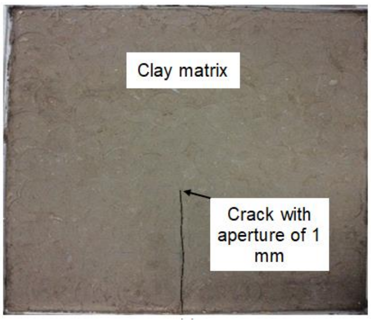


(a)

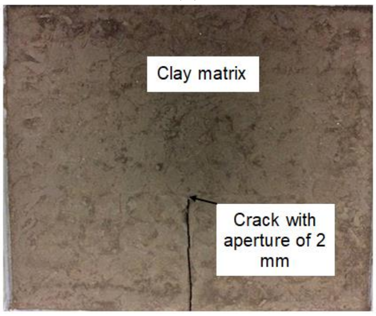


(b)

Fig. 2 Overview of the set up (iron rod, plate, clips) for simulating crack with aperture sizes of (a) 1 mm and (b) 5 mm



(a)



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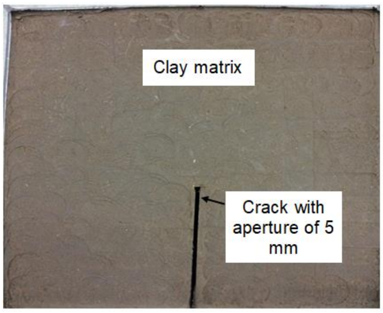

(c)

Fig. 3 Overview of the simulated crack with aperture sizes of (a) 1 mm, (b) 2 mm and (c) 5 mm

every 2 seconds at the symmetrical position of volumetric water content sensors from the center of the artificial crack using the three tensiometers. The range of the tensiometer was 0-100 kPa and the accuracy of the tensiometer was ±0.25 kPa. The data collecting system was consisted of data-logger and computer. The experimental data could be automatically recorded by the collecting system.

2.3 Artificial cracks with different aperture sizes

The cracks in natural clays are always randomly distributed and in the form of network. It is hard to arrange sensors in the randomly distributed crack network and characterize the water exchange between a crack and the clay matrix. In this study, an artificial plane crack was designed to represent the typical feature of an actual crack in clay (Krisnanto *et al.* 2016).

The aperture of desiccation cracks in clay was often found to be smaller and deformable comparing with the crack in sand. Therefore, the existing methods for manufacturing large cracks in sand (Czapar *et al.* 1992, Hu and Brusseau 1995, Li and Ghodrati 1997) could not be applied directly in this study. In clay, Kuna *et al.* (2013) drove pre-cut pieces of 12 mm nominal thickness plywood into the clay using sledgehammers and hand-compactors. The boards were extracted with a hydraulic jack to fabricate an artificial crack with the aperture of 12 mm. This method may create rupture near the surface in the near vicinity of the crack (Kuna *et al.* 2013). In this study an alternative method was designed to fabricate cracks with different apertures (1 mm, 2 mm, 5 mm) without disturbing the clay.

The model for simulating crack with aperture of 1 mm or 2 mm used 10 little plates (20 mm long, 1 or 2 mm wide, 150 mm high). The width of each iron plate was the same as the aperture of the required crack. Each plate was covered with plastic tape in order to minimize the friction between the iron plate and soil. Clips were used to stabilize the shape of crack model as shown in Fig. 2(a). The crack model was placed in the predetermined location during the compaction of the soil sample. Each iron plate was removed one by one carefully after the compaction was finished. After removal of the plates, the gap left in the clay sample was the artificial crack. Fig. 3(a) and 3(b) showed the geometry of the artificial cracks with the aperture of 1 mm and 2 mm, respectively. Procedure for simulating the crack with aperture of 5 mm was different from that for 1 mm (or 2 mm) aperture. This was because that the extraction of 5 mm thick iron plate was likely to disturb the soil. Two iron plates (200 mm long, 0.7 mm wide, 150 mm high) and five iron bars (3.6 mm diameter, 200 long) were used to fabricate the crack with aperture of 5 mm. The plates and bars were wished-in-placed during compaction (Fig. 2(b)). When the compaction was completed, the iron bars were first pulled out and then the plates were taken out. This process avoided the disturbance to the surrounding soils. Gap left in the clay matrix was the artificial crack with aperture of 5 mm (Fig. 3(c)).

2.4 Experimental procedure

The experiment with initial volumetric water content 0.25 g/g and the crack aperture of 1 mm was used as an example to describe the experimental procedure. The clay with volumetric water content of 0.25 g/g was prepared first. Then the clay was placed in the test box and compacted in multiple layers with each layer of 5 cm. The degree of compaction is 90%. The clay samples with designed crack model were first prepared. Then the clay sample was covered with plastic sheet to minimize evaporation. This also helped the equilibrium of water content throughout the soil. Then the water content sensors and suction sensors were inserted into the clay. In order to achieve close contact between the soil and the tensiometer, a tube with diameter of the tensiometer was used to core a hole in the soil first. The porous ceramic cup was inserted into the hole and then refilling it with clay. During monitoring, tensiometers were carefully observed and were resaturated if any bubbles were observed. After the equilibrium of water and air was reached, a high-precision injection was used to fill water into the crack. The injection had a range of 150 ml and an accuracy of 1 ml. A soft tube was connected to the end of the injection and water flowed out from the tube to the bottom of the crack gently, which avoid scouring to the crack. A constant hydraulic head in the crack was controlled manually by continuously filling the crack with water throughout the experiment. The total volume of water injected into the crack was recorded by the high-precision injection. The experiment terminated when the amount of water flowing from the crack into the soil was less than 1 ml per minute. Soil suction and volumetric water content were monitored throughout the experiment.

3. Results

3.1 Observed wetting front in cracked clay during infiltration

There were several ways to describe the water exchange between the soil matrix and crack. The most convenient way was to visually observe the wetting front in the process of the experiment. The wetting front can be observed visually through the change in color of clay as water continuously flowed into the clay from the crack. Fig. 4 presents the change of wetting front at four different time intervals (i.e., 2 min, 20 min, 40 min and 60 min) of the experiment. At the initial 2 minutes of the experiment, the shape of the wetting front appeared as a bulb (shown as the white line in Fig. 4(a)). As the experiment continued, the wetting front gradually changed from bulb shape to parabolic shape (Fig. 4(b), (c) and (d)). The developing of wetting front in horizontal direction was faster than that in vertical direction. This phenomenon was similar to the wetting front observed in Allaire-Leung (2000). It meant that water flowed from crack to soil mainly in horizontal direction (Chai *et al.* 2015). This observation verified the assumption in Gerke and van Genuchten (1996). The development of wetting front in horizontal direction was showed in Fig. 5. The development of wetting front gradually slowed down after 40 minutes. The crack tended to close as the water flowed into the clay. This phenomenon was different from that of wetting front in sandy loam, where development of wetting front continued as water flowed into soil (Bauters *et al.* 2000). This was because cracks in clay tend to close upon wetting and in turn, gradually reduced the water exchange.

3.2 Measured volumetric water content and soil suction in vicinity of crack

The observation on wetting front indicated the unique feature of water exchange between crack and clay matrix. In the seepage analysis for cracked soils, the water exchange ratio was a necessary input in Eq. (1). To calculate the water exchange ratio, the water content and hydraulic pressure in the interdomain between the soil matrix and crack were key variables. Fig. 6 shows the variation of volumetric water content at different depths (5 cm, 10 cm and 15 cm). The volumetric water content increased rapidly as water continuously flowed into soil from the crack. The volumetric water content of soil between the sensors and the crack approached a stable value finally. The change of water content was faster at the depths of 5 cm, and 10 cm than that at the depth of 15 cm. This was because the volumetric water content sensor at 15 cm depth (i.e., 5 cm away from the crack) was farther than those at 5 cm and 10 cm (i.e., 2 cm away from the crack).

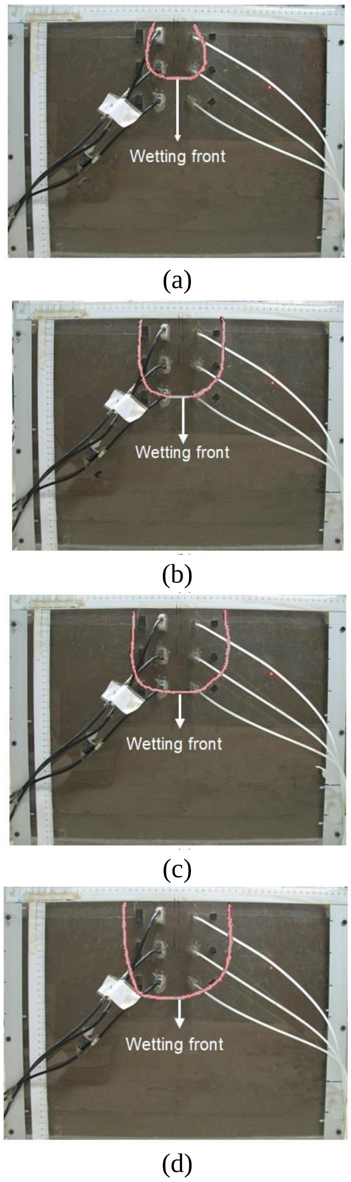

Fig. 4 Development of wetting front during infiltration experiment in cracked clay (aperture size1 mm) at (a) 2 min, (b) 20 min, (c) 40 min and (d) 60 min

Fig. 7 presents the change of suction at different depths in the clay. The suction decreased first and then reached a stable value. As expected, the increase in water content (Fig. 6) was accompanied by the decrease in suction (Fig. 7).

The monitored water contents at different times were utilized to calculate the rate of water content change, α_w

$$\alpha_w = \frac{V_{t+\Delta t} - V_t}{\Delta t} \tag{2}$$

where $V_{t+\Delta t}$ and V_t represent the water content values at time t+Δt and t. The rate of water content change was calculated at different time for the three sensors which located at depths of 5 cm, 10 cm, 15 cm (as shown in Fig. 8). At all depths, the rate of water content change increased to a peak value initially and then decreased to zero. The peak value of the rate of water content change at the three depths is 2.5×10^{-3} s^{-1}, 1.6×10^{-2} s^{-1}, 3×10^{-4} s^{-1}. The peak value of the rate of water content change at 10 cm depth was the largest. This was because the hydraulic gradient between the clay at depth of 10 cm and the edge of crack was the largest. The time required to achieve the peak value of the rate of water content change was about 40 seconds at 5 cm and 10 cm depths. However, it was much longer (i.e., 500 seconds) for the sensor at 15 cm depth. Moreover, the wetting front between 5 cm and 10 cm depths approximately lied in a straight line (Fig. 4). It indicated that the change of water content at the depths of 5 cm and 10 cm is similar. The hydraulic head of the clay at 5 cm and 10 cm depth were similar. As a result, the values of water content and suction at the depths of 5 cm and 10 cm were utilized to calculate the water exchange ratio between the crack and the soil matrix.

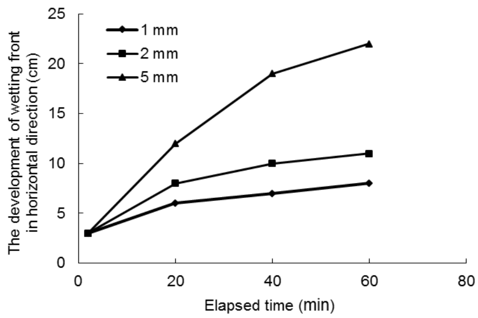

Fig. 5 The development of wetting front in horizontal direction for cracks with different apertures (initial volumetric water content of 0.25 g/g)

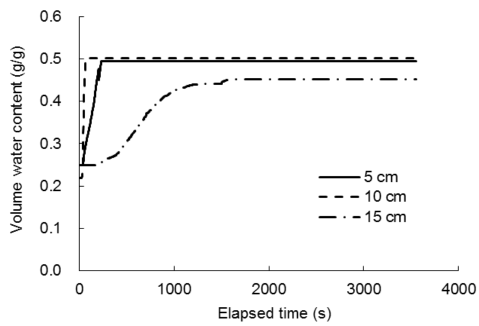

Fig. 6 Variation of measured soil volumetric water content at different depths with time during infiltration experiment in cracked soil (for crack with aperture of 1 mm)

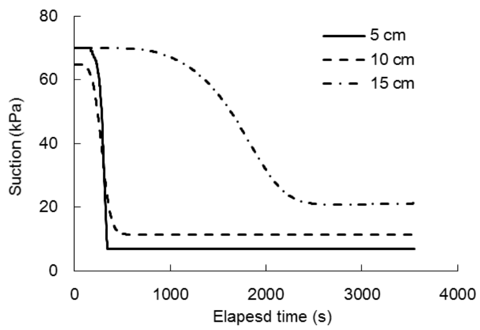

Fig. 7 Variation of measured soil suction at different depths with time (for crack with aperture of 1 mm)

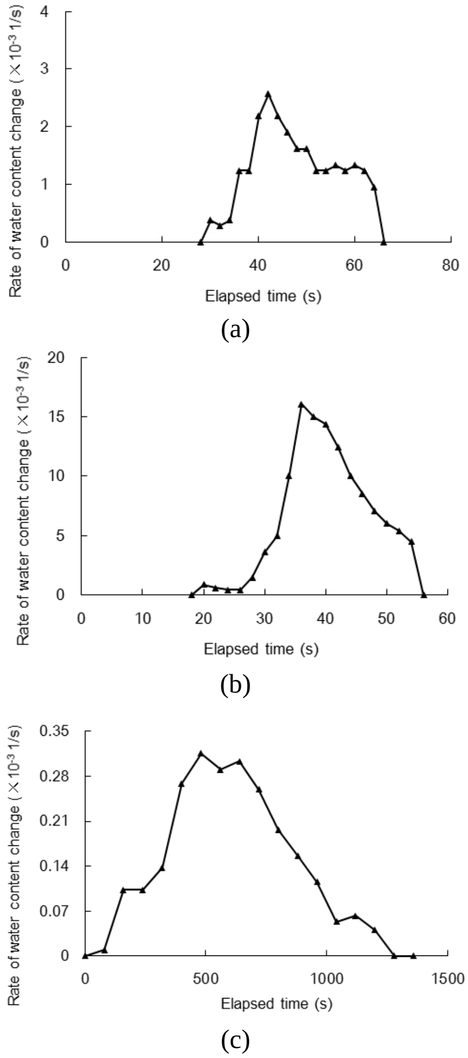

Fig. 8 Rate of water content change with time at depths of (a) 5 cm, (b) 10 cm, (c) 15 cm (for crack soil with aperture of 1 mm)

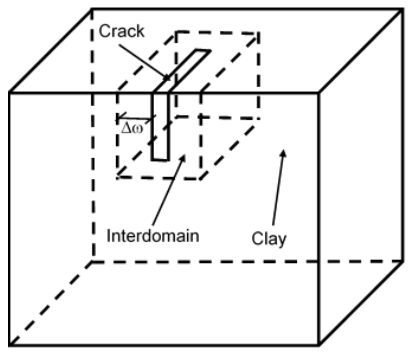

Fig. 9 Sketch of the interdomain between the crack and the clay

3.3 Water exchange ratio between crack and clay matrix

The water exchange ratio was defined as the amount of water flowing from the crack into the clay matrix per unit time

$$\Gamma_w = \frac{\Delta V_w}{\Delta t \cdot \Delta V} \tag{3}$$

where ΔV_w(cm^3) is the volume of water flowing into soil in time interval Δt. The time interval is set as 300 s in this study. ΔV(cm^3) is the volume of clay in the interdomain between the crack and the clay (as shown in Fig. 9). The interdomain is defined as the clay matrix which is 1 cm away from the boundary of the crack (Kohne *et al.* 2005). Then, Eq. (3) could be written as

$$\Gamma_w = \frac{\Delta V_w}{\Delta t \cdot A \cdot \Delta\omega} \tag{4}$$

where A(cm^2) is the total surface area between the crack and the clay matrix. $\Delta\omega$ is the thickness of the interdomain which is 1cm.

Eq. (4) indicates the water exchange ratio is closely related with the volume of water that flowing into the surroundings soil, ΔV_w. The accumulated volume of water that flowing into the soil could be obtained by the change of water volume through the crack. Fig. 10 presents the relationship between the accumulated infiltration and the elapsed time. The accumulated infiltration increased with the process of the experiment and reached 440 ml at the end of the experiment. Meanwhile the infiltration rate reduced gradually from 60 ml/min to 1.8 ml/min at the end of the experiment. The infiltration rate decreased during the process due to: (1) the crack gradually closed with the increasing water content in the soil which reduced water flowing into the soil; (2) the water content of the soil surrounding the crack gradually approached saturated condition.

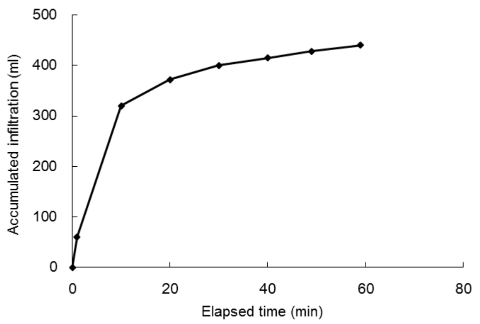

Fig. 10 Development of typical accumulated infiltration with the elapsed time (for crack with aperture of 1 mm)

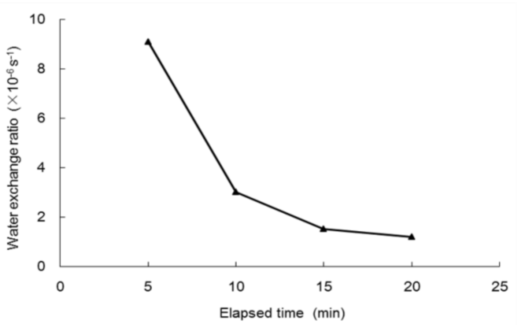

Fig. 11 Development of water exchange ratio with the elapsed time (for crack with aperture of 1 mm)

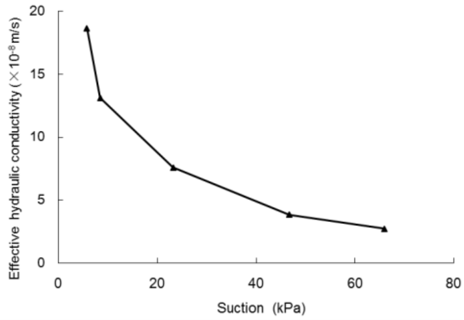

Fig. 12 Change of effective hydraulic conductivity at crack-clay matrix interface (for crack with aperture of 1 mm)

The water exchange ratio was calculated according to Eq. (4). In the first 20 minutes, the wetting front was far away from the boundary of the test box (Fig. 4). Hence the experimental results in the first 20 minutes were used to avoid the possible boundary effects. Fig. 11 shows the water exchange ratio in the initial 20 minutes. The water exchange ratio was high initially and gradually decreased to a stable value of 1.2×10^{-6} s^{-1}. The results indicate that it is not reasonable to assume the water exchange ratio as a constant value or a linear function.

3.4 Effective hydraulic conductivity of crack-clay matrix interface

The hydraulic conductivity of soil is a key parameter to investigate the seepage of water in soil. In this study the effective hydraulic conductivity of the crack-clay matrix interface, k, was an essential parameter to describe the water exchange between the crack and the clay matrix. Based on Darcy's Law, the effective hydraulic conductivity of the crack-clay matrix interface could be defined as

$$k = \frac{\Delta V_w}{i \cdot A \cdot \Delta t} \tag{5}$$

where i is the hydraulic gradient within the interdomain from the edge of the crack to the position of the tensiometers. The hydraulic gradient i can be defined as

$$i = \frac{1}{2}\cdot\left(\frac{h_{favr}^{t+\Delta t} - h_{mavr}^{t+\Delta t}}{l} + \frac{h_{favr}^{t} - h_{mavr}^{t}}{l}\right) \tag{6}$$

where l is the distance from the edge of crack to the position of the tensiometers. h^t_{favr} is the average hydraulic head in crack. h^t_{mavr} is the average hydraulic head in clay. They can be calculated as follows

$$h_{mavr}^{t} = \frac{h_{m1}^{t} + h_{m2}^{t}}{2} \tag{7}$$

$$h_{favr}^{t} = \frac{h_{f1}^{t} + h_{f2}^{t}}{2} \tag{8}$$

where h^t_{m1} and h^t_{m2} are the hydraulic head at the depths of 5 cm and 10 cm at time t in clay. h^t_{f1} and h^t_{f2} are the hydraulic head at the depths of 5 cm and 10 cm at time *t* in crack. Substituting Eq. (4) into Eq. (5), we can obtain

$$k = \frac{\Gamma_w}{i} \tag{9}$$

The water exchange ratio was closely related with the effective hydraulic conductivity of the crack-clay matrix interface. Using the results of water exchange ratio and Eq. (9), the effective hydraulic conductivity of the crack-clay matrix interface was calculated. Fig. 12 shows the value of the effective hydraulic conductivity of the crack-clay matrix interface. The effective hydraulic conductivity of the crack-clay matrix interface increased with the decreasing suction in soil, which was also found by Hardie *et al.* (2011). A maximum value of 1.9×10^{-7} m/s was reached finally. This maximum value was higher than the saturated vertical hydraulic conductivity of the soil (2.32×10^{-8} m/s). The reason for the relatively large effective hydraulic conductivity may lie in that the effective hydraulic conductivity mainly related with the saturated hydraulic conductivity in horizontal direction of clay matrix. The horizontal hydraulic conductivity is often larger than the vertical hydraulic conductivity. This result indicates the effective hydraulic conductivity may closely relate with the largest hydraulic conductivity of soil matrix. The relatively large effective hydraulic conductivity of the crack-clay matrix interface was also supported by Gerke and Genuchten (1993b). They assumed the effective hydraulic conductivity was the arithmetic mean value of the hydraulic conductivity of the crack (5.52×10^{-3} m/s) and the hydraulic conductivity of soil (2.90×10^{-6} m/s). Hence the effective hydraulic conductivity in their research was three magnitudes larger than that of the soil matrix. The experiment in this study found that the effective hydraulic conductivity was only one magnitude larger than that of the clay.

3.5 Influence of crack aperture and initial water content

The initial water content of soil and aperture of crack varied significantly in soils. Two series of tests were conducted to investigate the influence of initial water contents and crack apertures on water exchange between crack and clay matrix. The first series aimed to investigate the effects of initial volumetric water content on water exchange. The second series of tests were to investigate the effects of aperture sizes. In each of these tests, only crack was subjected to wetting. The parametric study was listed in Table 2. There were five experiments with identical dry mass density of soil. The experiments to investigate the influence of initial volumetric water content were conducted for the crack with aperture of 5 mm. The experiments to investigate the influence of crack apertures were conducted in the clay with initial volumetric water content of 0.25 g/g.

Fig. 13 presents the water exchange ratio in the experiments with three different initial volumetric water contents. At initial, the water exchange ratio in the experiment with initial volumetric water content of 0.25 g/g

Table 2 The initial conditions of the five experiments

Cases	Initial volumetric water content (g/g)	Artificial crack aperture (mm)
I	0.2	5
II	0.25	5
III	0.3	5
IV	0.25	1
V	0.25	2

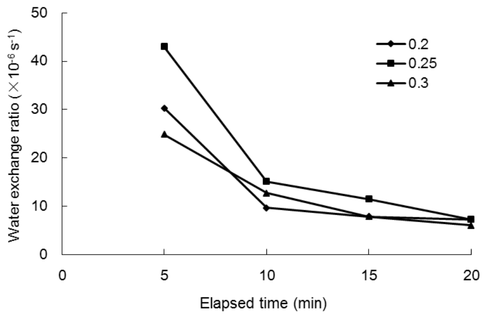

Fig. 13 Water exchange ratio for clay with different initial volumetric water contents (for crack with aperture of 5 mm)

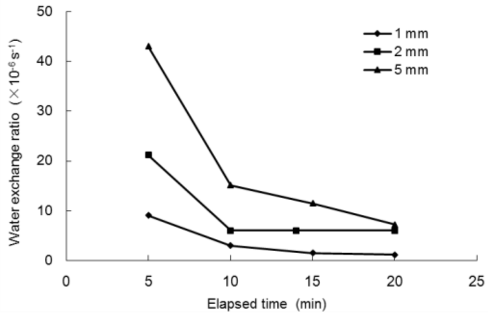

Fig. 14 Water exchange ratio for cracks with different apertures (initial volumetric water content of 0.25 g/g)

(the optimal water content) was higher than the other two experiments. The reason was probably that the clay sample with the optimal water content received the smallest energy when it was compacted to the identical dry mass density. Therefore more flowing paths for infiltrating may exist in this soil. The water exchange ratios of the three experiments all gradually decreased to a stable value of 7×10^{-6} s^{-1}.

Fig. 14 compares the results of the water exchange ratio for cracks with different apertures. The water exchange ratio increased with increasing aperture. This was because it took more time for the crack with larger apertures to close comparing with that with smaller apertures. This enabled more water flowing into the clay. At initial, the difference between the magnitudes of water exchange ratio was large. This difference gradually decreased with the process of infiltration. This was because the cracks were all closed at the end of the experiment despite of their difference in the initial crack apertures.

4. Conclusions

This study developed an experimental method that could investigate the water exchange between the deformable crack and the clay matrix. A method was proposed to fabricate the crack with small apertures without disturbing the surrounding clay. A water content and suction monitoring system was instrumented and enabled to quantitatively determine the water exchange ratio. The influence of initial water content and aperture size on the water exchange was explored. The following conclusions could be drawn:

• The water exchange ratio was large at the initial infiltration when the soil was relatively dry. It decreased dramatically as the water content increased. The water exchange ratio decreased because the crack in clay closed gradually with the increasing water content. This observation indicated that it was not reasonable to assume the water exchange ratio between crack and the clay matrix as a constant.

• The effective hydraulic conductivity of the crack-clay matrix interface was about one magnitude larger than the saturated hydraulic conductivity of the clay.

• The water exchange ratio was the largest in the experiment with the initial volumetric water content of 0.25 g/g (the optimal water content). Meanwhile the water exchange ratio increased with the increasing apertures of crack.

Acknowledgments

The research described in this paper was financially supported by the National Natural Science Foundation of China (Grants No.51379053, 51679060) and Shenzhen Science and Technology project (No. CXZZ2015 1117 174345411).

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