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Research Article

Experimental Study of Rainfall Infiltration in an Analog Fracture-matrix System

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In this study, an experimental apparatus was developed to investigate unsaturated infiltration in an analog fracture-matrix system. Fracture and adjacent matrix is simulated by sands with various particle sizes. Four rainfall infiltration experiments were performed on the analog fracture-matrix system at a constant rainfall rate of 100 mm/h. The process of rainfall infiltration is measured by a combination method of tensiometers and quick moisture apparatus. The measured results reveal that fracture-matrix interactions certainly exert influences on the hydraulic behaviour of unsaturated fractured matrix, and the fluid flow mainly infiltrates along the nonuniform paths within the matrix. Moreover, it is observed that the influences are greater when using a coarser sand to mimic the fracture. Specifically, the wetting phase in the matrix moves faster than that in the fracture; the fracture, therefore, acts as a vertical capillary barrier, but there exists lateral water exchange from the matrix to the fracture. Overall, this study has demonstrated the importance of fracture/matrix interactions, which should be considered when dealing with unsaturated flow through permeable matrices.

1. Introduction

Unsaturated zone is widely distributed in geoformation, and the fluid flow in unsaturated zone is different from that in the saturated zone. Exploration of unsaturated fluid flow in fractured rocks is of special interest to several fields, including the disposal of nuclear waste [1–3] and subsurface contaminant remediation [4–8].

The experiment plays a fundamental role in understanding flow processes in unsaturated fractured rocks, and it usually starts with the research on fluid flow through a single fracture, which has attracted substantial attentions since Lomize firstly introduced a conceptual model of using parallel glass plates to fabric open fractures [9]. Henceforth, a bunch of experiments have been carried out with remarkable progresses achieved [5, 10–15]. Nicholl and Glass developed an optical visualization technique to explore the wetting phase flow through two-phase structures (water and gas) in an analog rough-walled fracture [16]. The experimental scenario was analogous to single-phase flow through fractures, where the gas phase was invariant under steady-state conditions. The measured relative permeability was proportional to saturation (wetting phase) by third order. Brown et al. studied fluid flow paths within a fracture plane fabricated by assembling two transparent epoxy fracture surfaces together [17]. The measured fluid velocities were found to range over several orders of magnitude, and the maximum velocity was five times larger than the average velocity, indicating that channeling flow in fractured media could cause the fast breakthrough of contaminants. Su et al. performed flow visualization experiments on a fracture replica to study the liquid distribution and behaviour of seepages [18]. It was observed that infiltrating water advanced in unsaturated fractures along highly localized, nonuniform flow paths. Sun et al. developed an experimental device to explore rainfall infiltration in an artificial fracture [19]. The obtained relationships of saturation to capillary pressure and saturation to unsaturated hydraulic conductivity were both found to be nonlinear. Hu et al. developed an experimental apparatus for the determination of the unsaturated hydraulic properties of an analogous fracture [20]. They reported that there exists hysteresis between drainage and imbibition processes. Qian et al. conducted laboratory experiments to investigate fluid flow through a single fracture with various surface roughnesses and apertures [15]. An empirical exponential function was found to fit well the relationship between the mean velocity and the hydraulic gradient, and the fitting parameter for the exponential function was around 0.5 when hydraulic gradients ranged from 0.003 to 0.02.

The aforementioned experiments usually neglect fracture/matrix interactions, but both field and laboratory tests have addressed the significant influence of fracture/matrix interactions on unsaturated seepage through fractured media [21–23]. Salve et al. performed liquid-release tests in highly fractured welded tuffs at Yucca Mountain. They revealed that both fracture flows and faults-matrix interactions play critical roles in the wetting-phase movement within unsaturated fractured rocks [22]. Salve et al. carried out field tests by releasing water directly into nonwelded tuffs at Yucca Mountain [23]. The field tests suggested when the matrix and fault were dry, water injected into the fault was mostly absorbed by the adjacent matrix. Moreover, although the fault started to dry immediately after one infiltration event, the surrounding matrix would retain moisture for a few months. Roels et al. further performed moisture uptake experiments in a rough fracture fabricated by two halves of a fractured brick [24]. They observed that the wetting front in the fracture with aperture of 0.01 mm fell behind the wetting front in the matrix. Sakaki conducted wetting experiments of a rock matrix adjacent to a single vertical fracture to understand some of the fundamental mechanisms controlling fracture-matrix interactions [25]. Results showed that the wetting front within the matrix was approximately parallel to the fracture and propagated mainly in the horizontal direction, indicating that water absorption was predominantly one-dimensional orthogonal to the vertical fracture. Rangel-German et al. developed a two-dimensional micromodel to simulate moisture uptake from fracture to surrounding matrix [26]. The experimental results showed that the water uptake rate was depended critically on the water infiltration rate through fractures. Huang et al. designed an experimental apparatus to investigate the transport of vertical flow in unsaturated fractured sandstone [13]. It was observed that the fracture enlengthened the time for the wetting phase to break through the matrix, arising the accumulation of water in the matrix around the inlet end of the fracture, which tended to enhance the local flow in the matrix.

Even though substantial efforts have been made to uncover the hydraulic behaviours of unsaturated flow through the single fracture-matrix system [7, 27–30], there is still a lack of laboratory experiments for the determination of unsaturated hydraulic properties, including suction and saturation, under fracture/matrix interactions. Here, we followed the methods of Zhong et al. [31] to present an experimental apparatus for assessing unsaturated fluid flow through an analog fracture-matrix system. Sands with different particle-size ranges are used as an analog to simulate the fracture and matrix, respectively. The apparatus is capable of taking fracture/matrix interactions into considerations; then, rainfall infiltration tests, aiming at exploring the impact of fracture/matrix interactions on the hydraulic behaviours of the unsaturated matrix and fracture, are conducted.

2. Materials and Methods

It is usually difficult to install time domain reflectometry (TDR) probes in rock mass to measure unsaturated hydraulic properties, and accuracy of the measurement is sensitive to the contact between the probe and the rock. Here, an experimental model is designed to use sand with different particle sizes to mimic the fracture and the matrix, respectively. This is feasible with respect to the facts that unsaturated seepage within the fracture and sand are both under joint actions of capillary and gravity forces [32]. Table 1 summarizes physical properties of sand, which was sieved into three grain size fractions: 0.315~0.63, 0.63~1.25, and 1.25~2.50 mm, and it was classified into medium sand (MS), coarse sand (CS), and very coarse sand (VS) according to particle size ranges.

As illustrated in Figure 1, the experimental system consists of a water supply tank, a sand tank, two stainless-steel holders, and measuring devices. Figure 2 shows the detail drawing of the water supply tank and the sand tank. The water supply tank, with a length × width × height of $0.62\,\mathrm{m} \times 0.62\,\mathrm{m} \times 0.20\,\mathrm{m}$, stands on the high stainless steel holder, and it has twenty-five needles (an inside diameter of 0.5 mm) uniformly distributed at its bottom to generate rainfall for the sand tank, which is situated at the low stainless steel holder right below the water supply tank. The water supply tank has a spillway at its front wall to obtain stable overflow. The sand tank (0.42 m in length, 0.42 m in width, and 0.6 m in height) is made of transparent plexiglass to make direct observation of the fluid flow processes possible. The sand tank has two layers along its height, noted as the upper and lower layers. Both layers are partitioned into 3 zones, named zone F, M1, and M2, respectively, by the glass sheet (see Figures 1 and 2). Zone M1 and zone M2 of the upper layer are packed with a finer sand of height 0.35 m to mimic "matrix." Consequently, a vertical gap (30 mm in thick) is created in the middle, and a coarser sand is used to fill the gap (Zone F) to form "fracture" [33]. The aperture of fracture is approximately estimated by multiplying the gap thickness by coarse sand's porosity [34]. The lower layer is used to collect the water drained from the sample. During the experiments, the capillary pressure of the fractured matrix is measured by nine tensiometers (TEN, TOP Instrument Co., Ltd.) distributed at various depths within the fracture and matrix, while the saturation is monitored by quick moisture apparatus (TZS-1K, TDR, TOP Instrument Co., Ltd.) through the observation holes drilled at the backside of the sank tank.

Four experiments, indicated as experiments A, B, C, and D, respectively, were carried out under an invariant rainfall rate of 100 mm/hr. The top boundary of the sample could be considered as a boundary of constant flux boundary conditions (100 mm/hr) under unsaturated flow, while four sidewalls are subjected to zero-flow boundaries. Experimental scenarios based on different combinations of sand

Table 1: Physical properties of sand with various ranges of particle size.

Sand classification	Particle size ranges (mm)	Bulk density (g/cm^3)	Porosity	Saturated conductivity (cm/s)
Medium sand (MS)	0.315~0.63	1.99	0.25	$2.1e-3$
Coarse sand (CS)	0.63~1.25	1.72	0.35	$3.5e-3$
Very coarse sand (VS)	1.25~2.50	1.59	0.40	$5.2e-3$

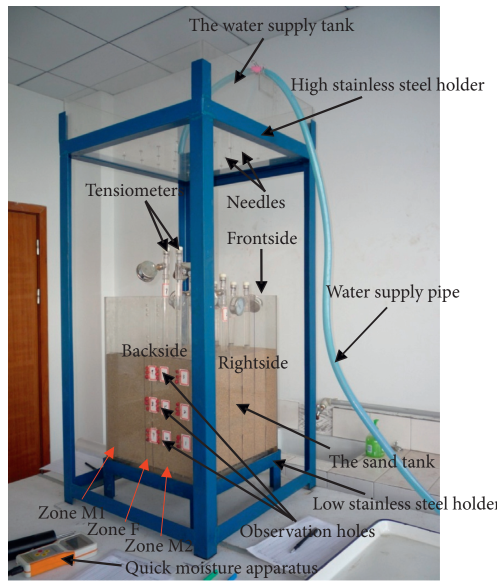

Figure 1: Illustration of the experimental setup.

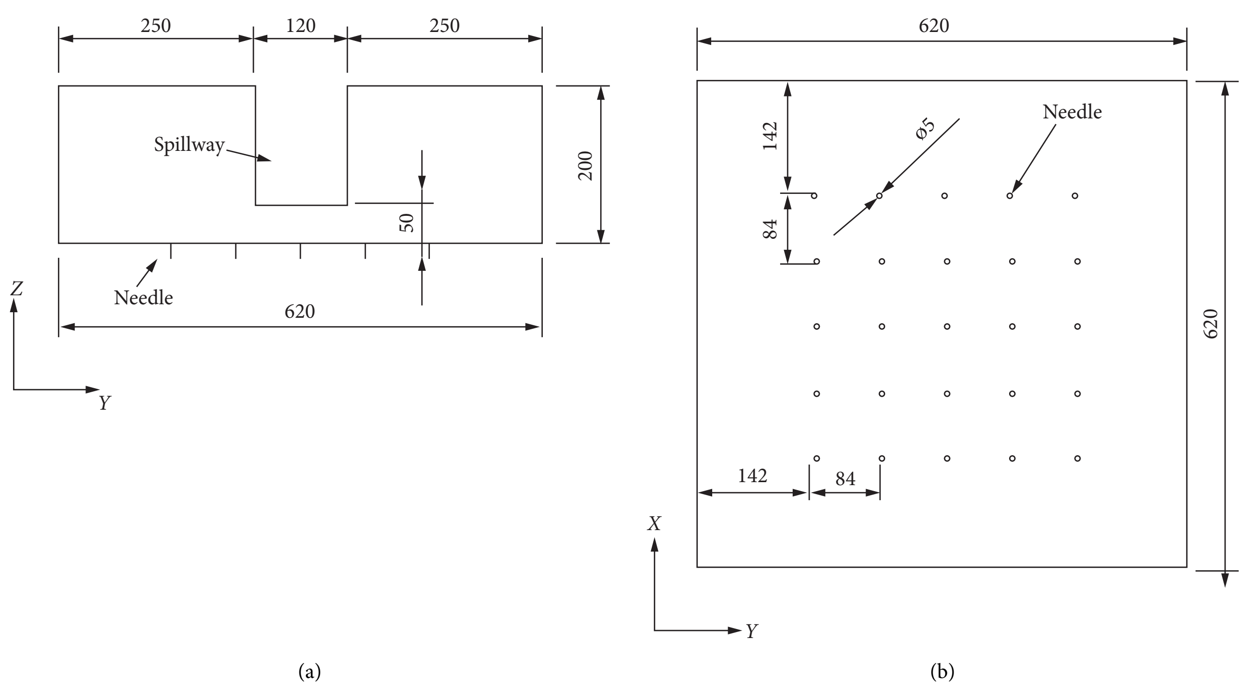

Figure 2: Continued.

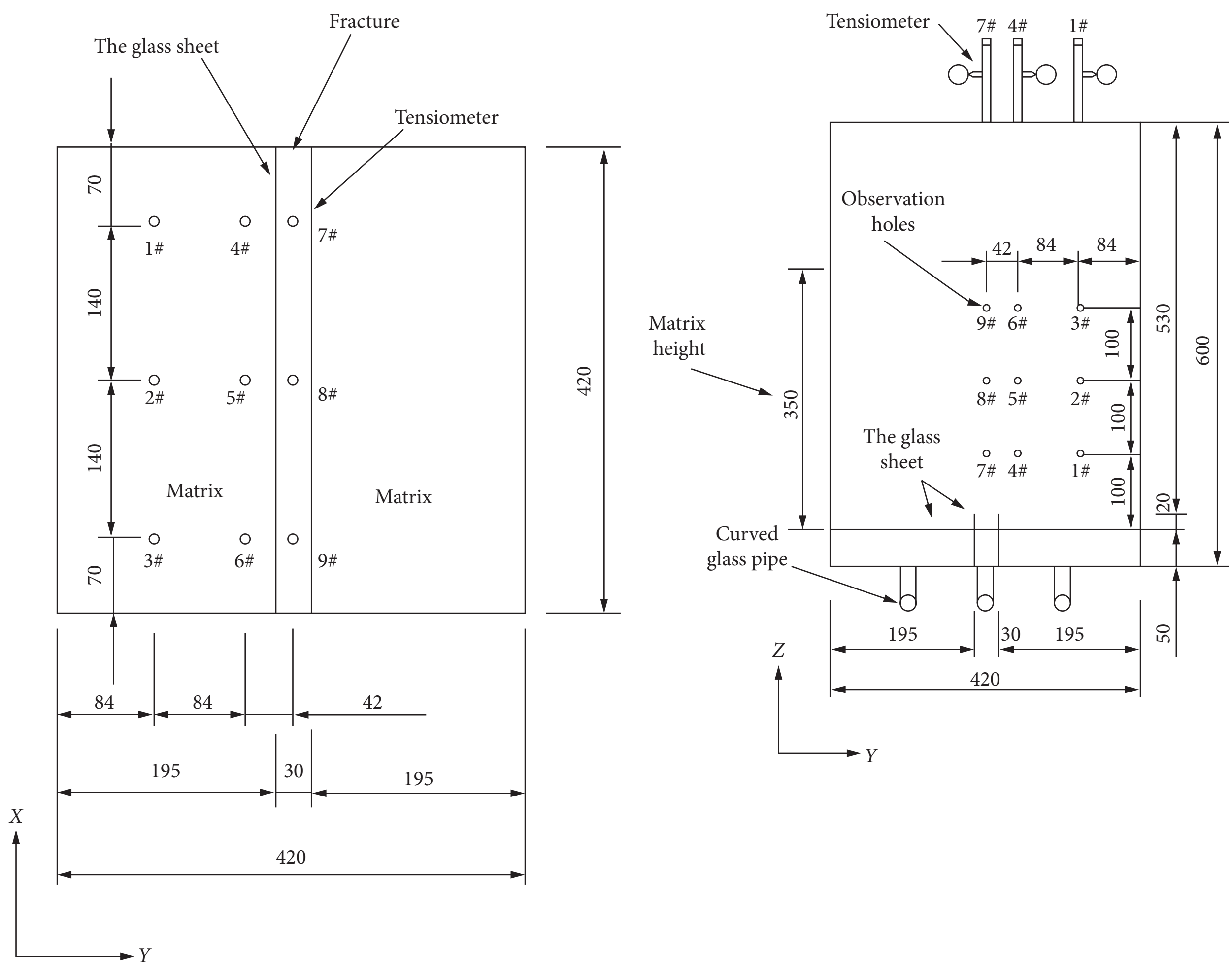

Figure 2: Annotated sketches of the experimental apparatus: (a) sectional view and (b) top view of the water supply tank; (c) top view and (d) sectional view of the sand tank, unit (mm).

are displayed in Table 2. The initial suction and saturation are recorded using the tensiometer and quick moisture apparatus located at various depths, respectively. Water is delivered continuously to the water supply tank via a water supply pipe during the experiment, and the constant rainfall is obtained when water level keeps constant. The real-time capillary pressure and water saturation at different positions are consistently monitored during the rainfall infiltration within the fractured matrix. Effluent from the coarse- and fine-grained sand were collected separately and measured.

3. Results and Discussion

Experiment A, B, and C, using MS with particle sizes in the range of 0.315~0.63 to represent the matrix, are performed to assess the influence of fracture flow on the hydraulic behaviour of the matrix. Figure 3 shows matrix suction-time curves for tensiometers located at 1#, 4#, 2#, and 5#, and it is obvious that fracture aperture has significant impacts on hydraulic properties of matrix, since it takes fewer time for matrix to get full saturated (suction drop to zero) as fracture aperture becomes larger. This might be caused by the joint effects of capillary barrier of fracture and fracture/matrix interactions. Specifically, it is easier for the rainfall to penetrate the matrix with smaller pores compared to the fracture with larger pores; besides, the rainfall falling on the fracture tend to accumulate around the upper boundary of the fracture induced by the capillary effect, and accumulated water is absorbed by the matrix through both sides of the fracture-matrix interface. Consequently, infiltrated rainfall mainly travel through the fractured matrix along the vertical paths within the matrix, while fracture acts as a barrier, where accumulated water will flow to the matrix. The amount of water, flowing from fracture to surrounding matrix, increases with an increase in fracture aperture, and small portion of the water, driven by the hydraulic gradient between fracture and matrix, will return to the fracture (see inset A in Figure 4(a)).

Matrix suction is plotted against saturation in Figure 5. The evolution of matrix suction experiences two periods as water advancing the matrix and fracture. It decreases gradually at first before drops dramatically to zero.

Table 2: Experimental conditions showing different combinations of sand selected to mimic “Fracture” and “Matrix.”

Experiments	Sand used to mimic “fracture”	Fracture aperture/mm (gap thickness × sand porosity)	Sand used to mimic “matrix”
A	MS	7.5	MS
B	CS	10.5	MS
C	VS	12.0	MS
D	CS	10.5	CS

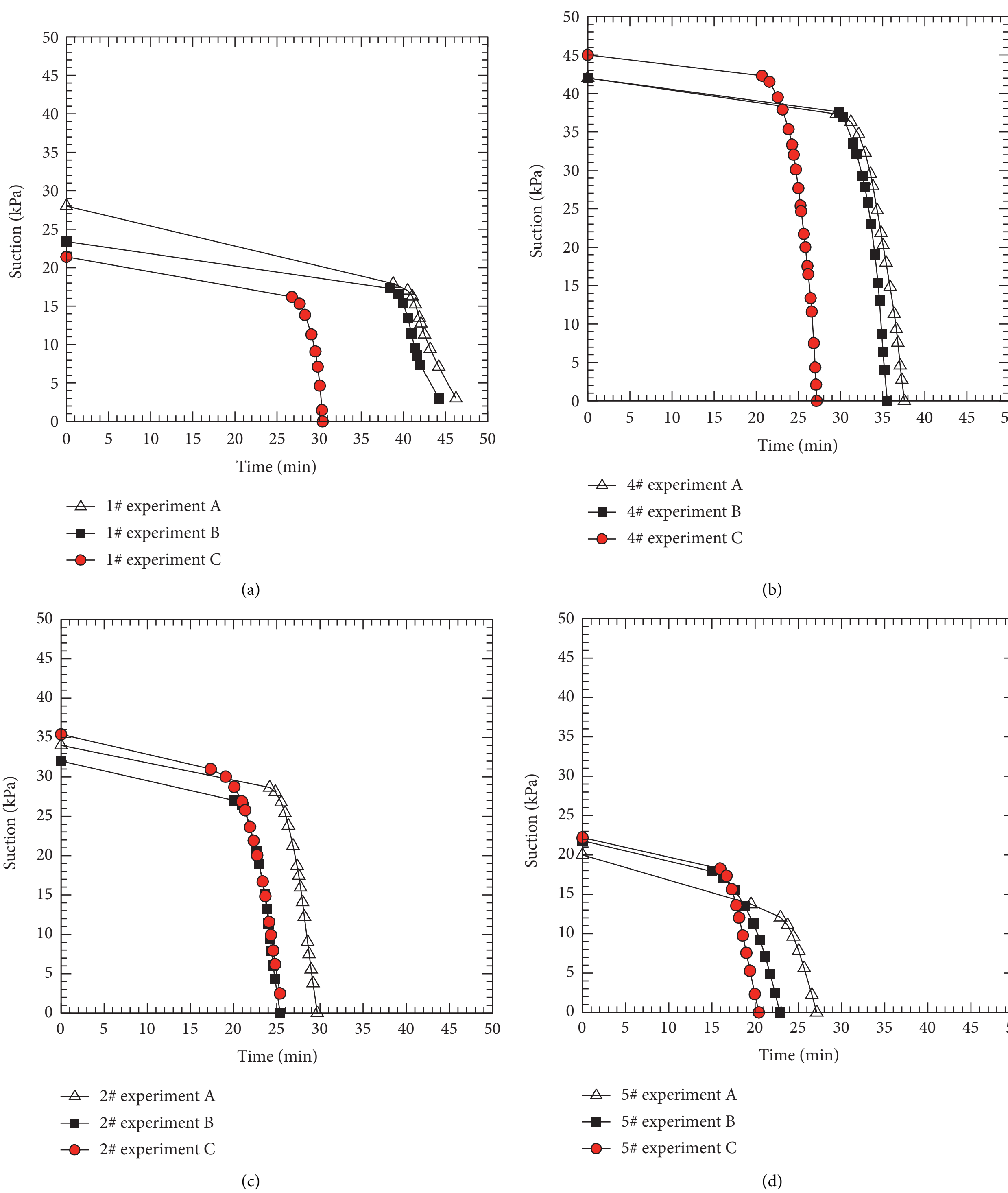

Figure 3: Evolution of matrix suction measured with tensiometers located at various depths of: (a) 1# (250 mm depth); (b) 4# (250 mm depth); (c) 2# (150 mm depth); (d) 5# (150 mm depth).

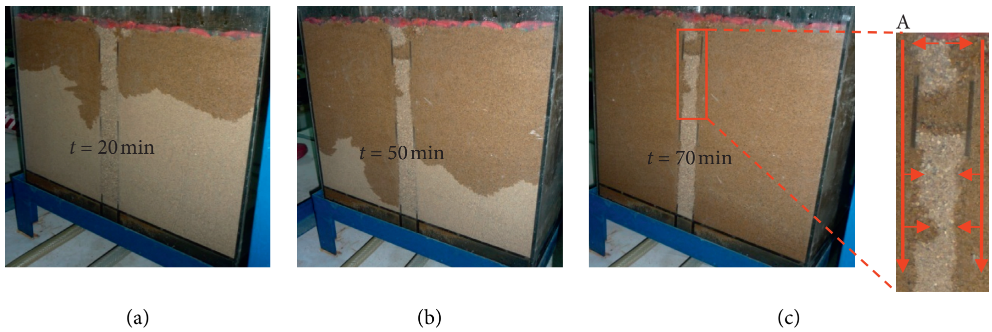

FIGURE 4: Vertical infiltration of water into an analog fracture-matrix system. A is the flow direction of the partial enlargement of main plot at 70 min.

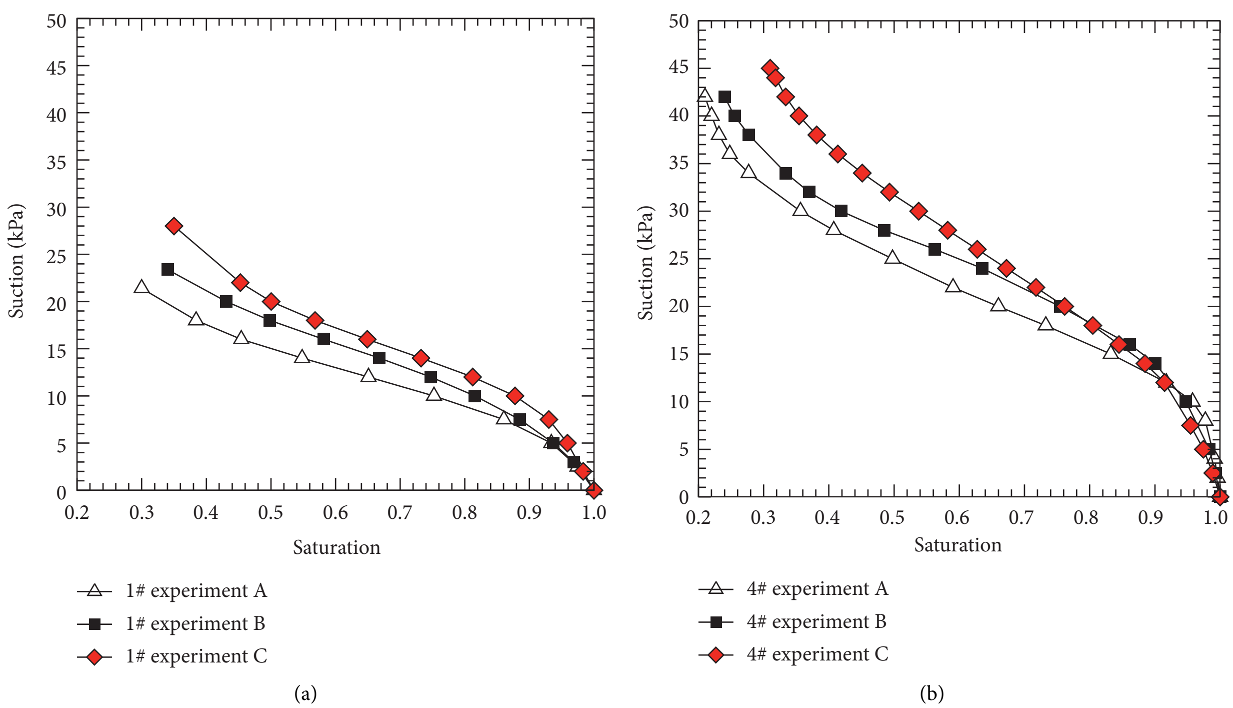

FIGURE 5: Continued.

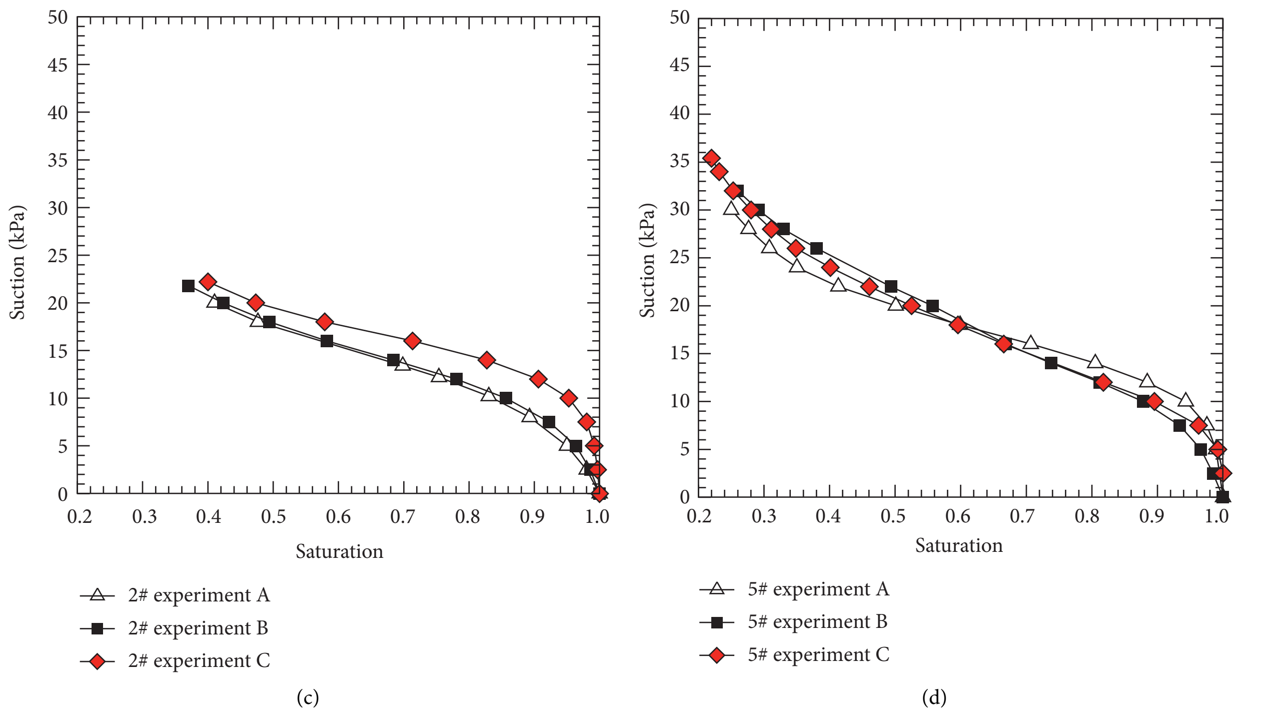

Figure 5: Relationships between matrix suction and saturation tensiometers located at different depths of (a) 1# (250 mm depth), (b) 4# (250 mm depth), (c) 2# (150 mm depth), and (d) 5# (150 mm depth).

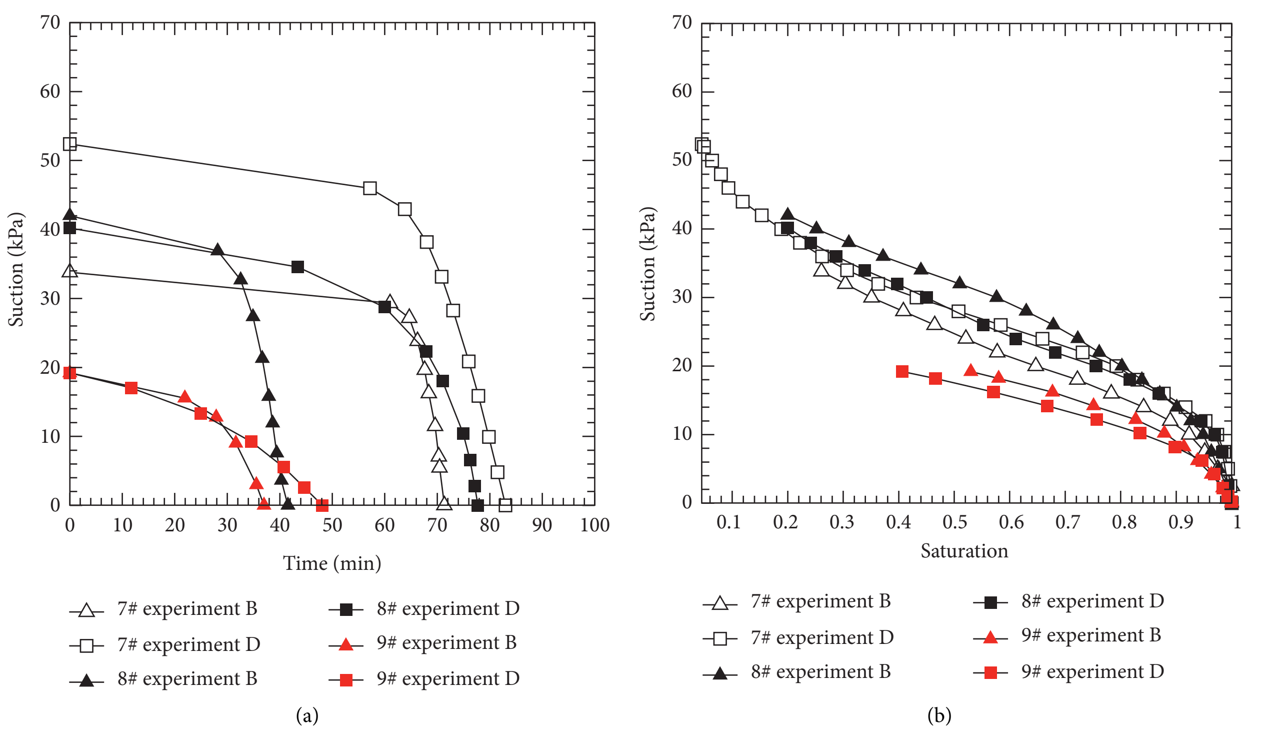

Figure 6: Plot of the experimental results for tensiometers in the fracture: (a) suction versus time; (b) suction versus saturation.

The results of experiment B and D with CS to simulate fracture are compared in Figure 6. Figure 6(a) describes evolution of capillary pressure (suction) in fracture. At the beginning of rainfall, both fracture and matrix are dry with low saturation, so infiltrated rainfall tend to occupy the matrix with smaller pores, leaving fracture with larger pores remain in dry. This can result in a hydraulic connection between fracture and adjacent matrix, fracture start to absorb water from matrix because of hydraulic gradient between them. The matrix provides an extra source of water for the fracture under this circumstance, and it would be easier for water to move from a finer matrix to the fracture. The finer the matrix, the quicker the suction in fracture drops to zero. Since both the fracture and matrix are actually porous media (sand), the fracture's suction-saturation curves, as indicated in Figure 6(b), are similar to those of the matrix.

The wetting front evolution of the experiment C is displayed in Figure 4. It is observed that infiltrated water mainly travels through unsaturated fracture-matrix system along nonuniform, localized preferential flow paths. Inset A in Figure 4 is a close-up view of rainfall infiltration at 70 min, and it can also be concluded that flow primarily migrates downwards via the matrix in the direction parallel to the fracture, and the wetting phase within the matrix moves quicker than that in the fracture, even though some portion of water is driven back to fracture because of the hydraulic gradient between fracture and matrix. Those observations are similar with that observed in [24].

4. Conclusions

This paper presents a new experimental apparatus to study unsaturated flow in fractured rock. Sands with various ranges of particle sizes are chosen as analogous materials to mimic fracture and matrix, respectively. Then, rainfall experiments were performed on an analog fracture-matrix system to evaluate unsaturated infiltration processes in both "fracture" and adjacent "matrix." It is observed that unsaturated flow primarily migrate downwards via the matrix along nonuniform, localized preferential flow paths, which is quite different from the results from saturated flow, where the fracture is usually considered as a major conduit. Moreover, the preferential flow in the matrix will be enhanced since the fracture acts as a capillary barrier, and this enhancement is greater by using a coarser sand to simulate the fracture. Besides, there also exists hydraulic connection between the fracture and adjacent matrix, and fluid flow tends to transport from the fracture to the matrix due to hydraulic gradient between them, bringing in additional water supply for the fracture along the direction transversal to it. In general, it is suggested that hydraulic connection between fracture and surrounding matrix should not be ignored in unsaturated flow, especially when the matrix is permeable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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