Simulation of Contaminant Transportation in Saturated Transparent Rock Fractures

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ABSTRACT

This paper presents an experimental investigation of flow of contaminated water in saturated rock fractures by using a transparent fractured rock replica for visualizing contaminant transport. The transparent fractured rock model is composed of transparent silica blocks and matched refractive index pore fluids. A dyed fluid is used for simulating contaminants. The experimental setup consists of a Plexiglas container, a contamination injection system and three CCD cameras. The transport images during testing are captured by the three cameras in orthogonal directions. Digital image processing is applied to analyze the greyscale to detect the edge of the transportation front and to calculate penetration length and area at different times. A roughly circular plume is found when the fractures filled with transparent silica grains. The results indicate a square relationship between the penetration length and the cubic root of injection time, and a square relationship between the propagation area and the injection time in the fractures. The results also verified the possibility for simulation of contaminant transport in a fractured rock mass by using a transparent rock replica.

Keywords: Contaminant transport; rock fracture; digital image correlation; transparent rock replica; transparent soil

INTRODUCTION

In recent years, transparent models have been successfully applied to investigate contaminant transport in porous media (Mannheimer and Oswald 1993; Iskander et al. 2003; Liu et al. 2005; Lo et al. 2008; Fernandez et al. 2011; Liu et al. 2013). However, the transparent model has not been used to study contaminant transport in fractured rock mass. The difficulty of the visualization inside a rock mass limits the understanding of contaminant transport during water drainage due to mining. This paper presents a preliminary extension of the transparent soil modelling techniques to simulate contaminant transport in rock fractures. A transparent rock replica is constructed to document contaminant propagation in saturated fractures filled with fused silica grains.

EXPERIMENTAL SET UP AND PROCEDURE

Experimental setup and transparent model preparation

The experimental setup consists of a transparent fractured rock replica, an injection system, an optical detecting system and data collectors. All of the experimental devices were built on a vibration isolation optical platform.

Transparent fractured rock model

Silica blocks that were 2 cm (length) × 2 cm (width) × 2 cm (depth) in size were used to replicate fractured rock in this experimental investigation. The apertures between silica blocks were considered as rock fractures. A regular fracture network could be built when the silica blocks were placed in order. The fractures in the blocks were filled with fused silica grains with a particle size between 0.1 to 1 mm. The refractive index (RI) of the fused silica was 1.4585. The related physical properties of the fused silica can be found in Liu et al. (2013) and were generally similar to those of Chinese standard sand. Calcium bromide solution was applied as pore fluid, which can be made the same RI as the fused silica and can be completely mixed with the fused silica. $CaBr_2$ which is white powder or crystals with a purity of more than 96% was used to prepare the calcium bromide solution. A series of trial and error tests shows that the RI of calcium bromide solution reached 1.4585 at a concentration of approximately 65% thus the best transparency achieved. An ink-dyed calcium bromide solution was used to simulate the contaminant. When the contaminant propagates among the fractures, the position of the contaminant front in every fracture could be easily observed and recorded since the fractured rock replica is transparent.

The injection system and the optical detecting system

Fig. 1 shows an overall schematic of experiment set up. A similar drip injection method was used by Hayashi, et al. (2006). The injection pressure was about 1500 mm high which approximates a pressure of 15 kPa. An injection needle with an inner diameter of 1.2 mm was inserted into the model at a depth of 25 mm below the sample surface. The injection system was connected with transparent pneumatic tubes. A point contaminant source was then simulated by the injection at the end of the needle.

The optical system was a modified particle image velocimetry (PIV) system. Three black and white Charge Coupled Device (CCD) cameras were connected to a computer for image capturing and collecting. The CCD cameras had a resolution of 1024 × 768 pixels and a maximum frame rate of 30 frames per second (fps). The CCD cameras were controlled by a computer through the MV Capture 2.0 program.

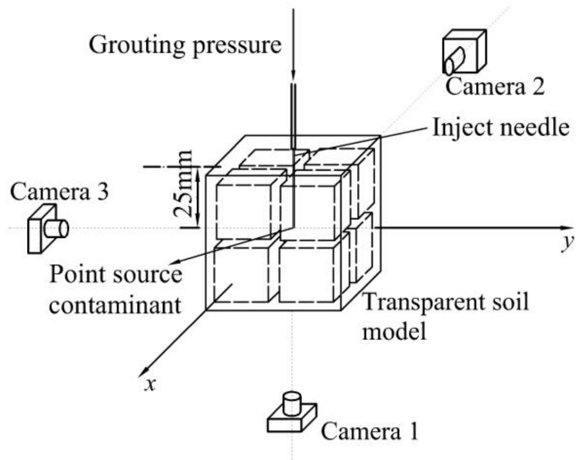


Figure 1 Schematic of experimental set up

Transparent model preparation

The transparent model was constructed in a transparent Plexiglas mold with an inner size of 5 cm (length) × 5 cm (width) × 5 cm (depth). Four silica blocks were evenly and symmetrically packed in blocks of 2 × 2 to form a layer of the rock replica. The fractures with an aperture of about 3 mm were filled with fused silica grains and pore fluid. The model was then de-aerated by using a vacuum pump to achieve the best transparency. Fig. 2 shows the transparent replica and its transparent effect.

Test procedure

A background image was taken before the injection. Once the injection pipe was turned on, a series of images were then captured during the injection at a frame rate of 30 fps until the test stopped after 22 s of contaminant injection.

RESULTS AND ANALYSIS

Propagation characteristics of contaminant front

Fig. 3 shows some images captured by Camera 2 at different times during the experiment, in which the contaminant transport process lasted for about 22 s and approximately 2000 images were captured. The contaminant propagates almost symmetrically. The contaminant first penetrates in a nearly circular shape inside the fractures; see Figs. 3(a) to 3(e). However, the contaminant did not propagate in an entirely circular shape; see Figs. 3(f) to 3(j). The contaminant front appeared inside the fractures where the penetration was faster. With a longer time, the propagation boundary became more irregular. The pore structure of the fused silica sands themselves caused the plume-shaped edges of the propagation front.

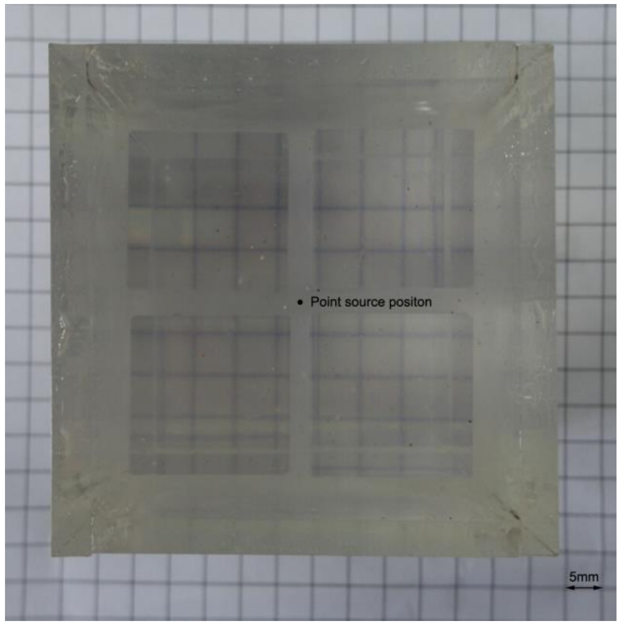


Figure 2 Transparent silica rock replica

Contaminant penetration length and propagation area

The images captured in the test were analyzed by digital image process software. The propagation front was traced to acquire perimeter. The propagation area was calculated according to the traced data. Table 1 lists the image scale coefficients calculated in accordance with the pixel value and real size of the silica blocks.

Table1 Scale coefficients of images in accordance with size of silica block

Location	Pixel value	Real size (cm)	Length scale coefficient (cm^{-1})	Area scale coefficient (cm^{-2})
Camera1, underneath the model	256	2	128	16384
Camera 2, behind the model	233	2	116.5	13572
Camera 3, on the left of the model	233	2	116.5	13572

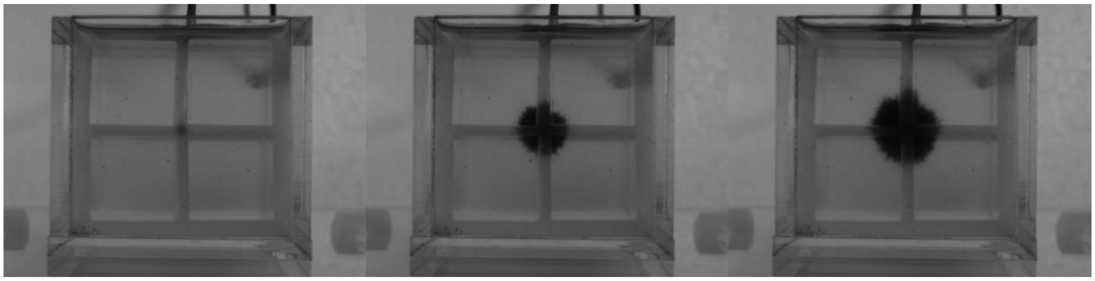
Fig.4 shows the maximum penetration length of the contaminant in the images. The equations are as follows

$$L_N = -2.31t^{2/3} + 18.01t^{1/3} - 13.16 \quad (1)$$

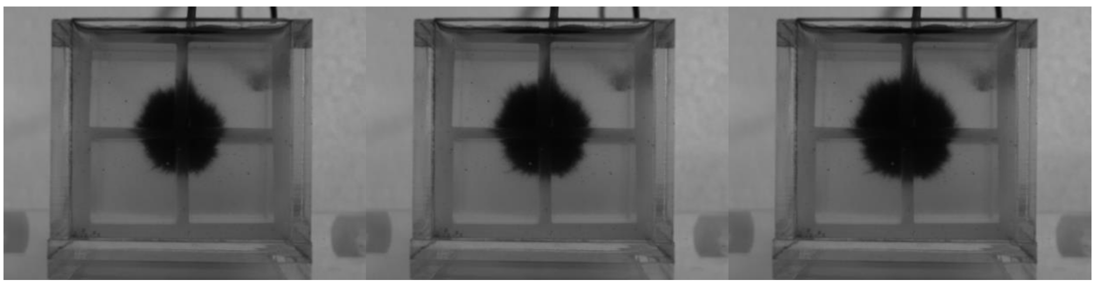
$$L_B = -1.18t^{2/3} + 11.52t^{1/3} - 7.96 \quad (2)$$

$$L_L = -1.23t^{2/3} + 12.76t^{1/3} - 8.71 \quad (3)$$

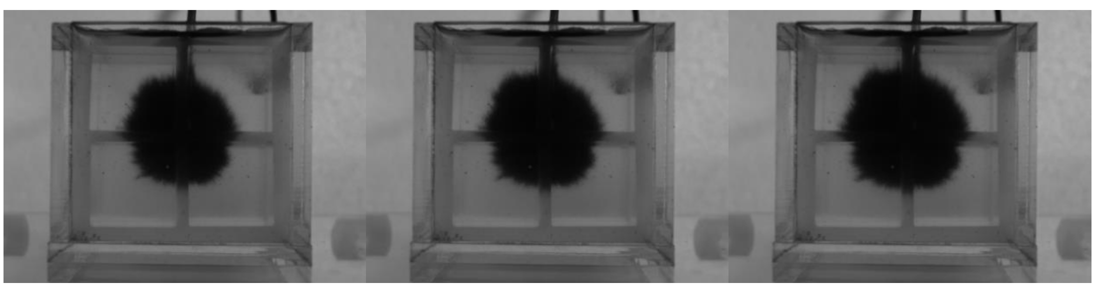
Where L_N = contaminant penetration diameter taken from underneath the model, mm; L_B = contaminant penetration diameter taken behind the model, mm; L_L = contaminant penetration diameter taken on the left side of the model, mm; and *t* = injection time, s. The start times of contaminant propagation in three locations were 0.412 s, 0.456 s and 0.535 s, respectively.



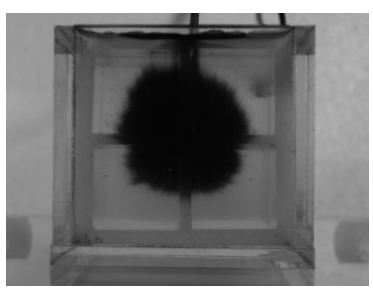
(a) 0.567 s (b) 2.567 s (c) 4.567 s



(d) 6.567 s (e) 8.567 s (f) 10.567 s



(g) 12.567 s (h) 14.567 s (i) 16.567 s



(j) 18.567 s

Figure 3 Contaminant propagation images captured by Camera 2 at different times

The border of the propagation for every image was approximately traced, and the propagation area was calculated. Fig. 5 shows the variation in the contaminant propagation area with time. The equations are as follows

$$A_N = -0.020t^2 + 0.892t - 0.758 \quad (4)$$

$$A_B = -0.006t^2 + 0.532t - 0.120 \quad (5)$$

$$A_L = -0.005t^2 + 0.550t - 0.199 \quad (6)$$

Where A_N = contaminant propagation area taken from underneath the model, cm^2; A_B = contaminant propagation area taken behind the model, cm^2; A_L = contaminant propagation area taken on the left side of the model, cm^2; and t = injection time, s. The start times are 0.332 s, 0.455 s and 0.590 s, respectively.

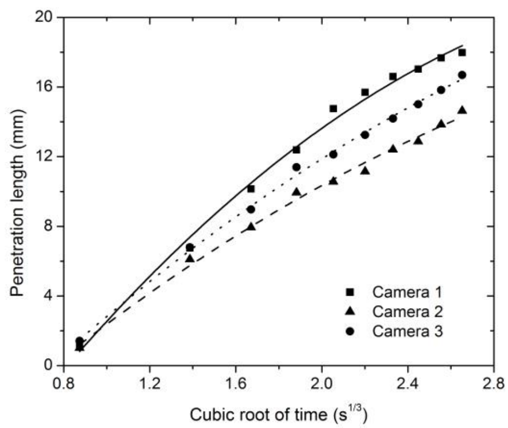


Figure 4 maximum penetration lengths with time

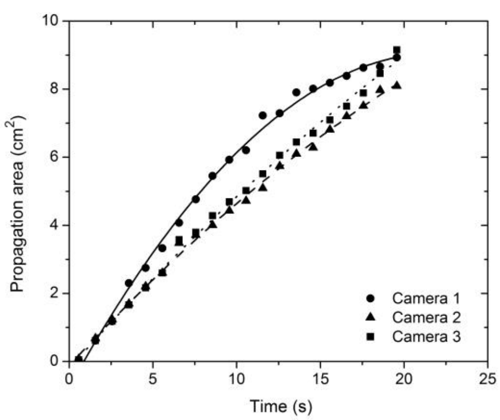


Figure 5 Contaminant propagation areas with time

CONCLUSIONS

This paper has presented an experimental investigation in which contaminant transportation phenomena were observed in a saturated transparent fracture replica filled with sand grains by using three CCD cameras. A series of images during contaminant transport have been captured and analyzed to identify the plume boundary, penetration length, and propagation area.

The results indicate that there is a square relationship between the maximum penetration length and the cubic root of injection time, and also a square relationship between the contaminant transport area and injection time when the pressure head is constant.

This paper is a very preliminary attempt to investigate the possibility of real-time observation of contaminant transport in a rock fracture replica. There are still many factors that need to be taken into consideration in further studies for more real and complicated geological conditions, such as different fracture shapes, dip angles, groundwater pressures. Furthermore, physical and chemical interactions should also be considered in future investigation.

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