Research on the Formation Mechanism of Seepage Channels in Broken Rock Mass under the effects of Particle Migration

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Abstract. Seepage within broken rock mass widely exists in geotechnical engineerings, such as railways, slopes, dam foundations and mining. Seepage is often accompanied by particle migration, which usually cause structural instability and water inrush disasters. In order to study the formation mechanism of seepage channels in the broken rock mass under the effects of particle migration, a series of seepage tests were designed on broken red sandstone. The effects of pore pressure and particle size distribution (PSD) on particle migration and porosity evolution were studied. The main conclusions are as follows: 1) By observing the particles collected during the see page process, particles with size range of 0-2 mm, 2-5 mm and 5-8 mm appear in sequence, which means that with the formation of seepage channels, large size of rock particles can pass through the broken rock mass. 2) The cumulative mass of migrating particle increases with the increase of pore pressure and decrease of PSD; with the increasing duration of migration process, the pore pressure and PSD decrease. 3) The peak value of porosity increases with the increase of pore pressure and decrease of PSD. According to above results, the seepage channels of the samples with smaller PSD and larger pore pressure are wider. Besides, the formation speed of seepage channels is larger in sample under higher pore perssure. These can explain the higher risk of geological disasters (i.e., water inrush and structural instability) in broken rock mass within higher pore pressure and smaller PSD.

1. Introduction
Broken rock mass is usually a porous medium consist of different sizes particles packing naturally or randomly after destruction. It is often used as a filling materials or as a carrier for liquid or gas migration. Seepage is one of the most remarkable mechanical behaviors. The phenomenon of seepage with in broken rock masses widely exists in railways, slopes, dam foundations and other projects. Railway surrounding rocks often crackle under the action of weathering, which in turn is prone to induce water inrush and mud outburst accidents. Surface seepage caused by rainfall often cause slope areas unstable and damaged. Larger concrete dams are usually built on high-capacity consolidated sediments or volcanic rocks. In these places, water may leak out of fissures or cracks, which will erode the dam foundation. In addition, the seepage of broken rock mass also exists in mining engineering. When a water inrush occurs, a large amount of groundwater bursts into the mine suddenly. When the maximum water inflow is greater than the total drainage capacity of the underground drainage equipment, flooding roadways, working faces, mining areas, wells, or other casualties will happen [1]. According to statistics,
from 2012 to 2016, there were 35 coal mine flood accidents in China, with 233 deaths [2]. Roof, floor, fault zone, karst collapse column area and surrounding rock fracture zone became the high incidence of water inrush.

Under the action of pressure, water flow rushes into broken rock mass such as dam foundations, faults, roof and floors, which will cause the particles filling in the pore of broken rock mass to move and flow out with water. As a result, the structure in the broken rock mass become looser and the seepage channels are formed gradually (a schematic diagram of the particles migration is shown in Figure 1), which greatly increases the risk of accidents such as water inrush and structural instability [3-6].

Therefore, in order to explore the mechanism of the formation of seepage channels in the fracture zone, a series of seepage tests of the broken red sandstone under the condition of particle migration were designed, and the amount of particle migration and pore characteristics of the broken red sandstone under different water pressures and particle size distributions (PSDs) were studied. In the following, the details of the research are interpreted.

![Figure 1. Particles transferred by confined water.](image1)

2. Testing schemes

2.1. Testing system

The testing system shown as Figure 2 mainly composed of five parts: (i) self-made permeameter, (ii) axial loading system, (iii) water pressure supply system, (iv) solid-liquid mixture collection device and (v) data acquisition system.

![Figure 2. Testing system.](image2)

(i) The self-made permeameter mainly includes a piston, a pair of permeation plates, a cylinder and a pedestal. Initially, the water flow enters the water inlet, flows through the upper permeable plate, the sample sequentially and carries particles. During the seepage process, a solid-liquid mixture is formed, which next through the lower permeable plate and flows out from the water outlet eventually.
(ii) The axial loading system mainly refers to the DDL600 material testing machine. The function of the machine is mainly to preload the sample, in order to ensure that the surface of the sample remains flat and the height of samples keep uniformly before the start of the experiments.

(iii) The water pressure supply system, supply power for seepage processing, is composed of water pump, oil pump, double-acting hydraulic cylinder and control valves.

(iv) The solid-liquid mixture collection device is used for filtering out particles from the mixtures.

(v) The data acquisition system mainly includes a computer and a paperless recorder. In addition, the paperless recorder is connected with a water pressure gauge, which can monitor the change of pore pressure in real time.

2.2. Sample preparation

The density of red sandstone used for testing is 2267 kg/m$^3$. The red sandstones were crushed first to obtain gravel particles of different sizes. And then use sieving devices with pore size of 20 mm, 15 mm, 10 mm and 5 mm to sieve out particles which sizes ranging from 0-5 mm, 5-10 mm, 10-15 mm and 15-20 mm. In order to describe PSD, Talbot index is adopted and define that PSD increases as Talbot index increases. The particle migration mass of each particle size range can be calculated by equation (1). Finally, the particles ranging in different size are mixed uniformly. The total mass of the mixed rock sample is all 1200 g. The particle gradation curves of different samples are shown in Figure 3.

\[ \frac{M}{M'} = \left(\frac{d}{D}\right)^n \]  

(1)

Where $M_i$ is the total mass (1200 g), and $M$ is the mass of particles with a particle size smaller than $d$, $D$ is the maximum size of the sample, $n$ is the Talbot index.

![Figure 3. Curve of particle size distribution.](image)

2.3. Testing design and procedures

2.3.1. Testing design. In order to study the mechanism of the formation of seepage channels in the broken rock mass, a seepage experiment of broken red sandstone under the condition of particle migration was designed and two independent variables, pore water pressure and PSD, were considered. The testing design is shown in Table 1.
Table 1. Testing design.

| Test No | Pore pressure (Mpa) | Talbot index | Weight of each particle size (g) |
|---------|---------------------|--------------|----------------------------------|
|         |                     |              | 0-5 mm | 5-10 mm | 10-15 mm | 15-20 mm |
| T1      | 0.1                 |              |        |         |          |
| T2      | 0.3                 | 0.6          | 522.33 | 269.37  | 218.06   | 190.24   |
| T3, T8  | 0.5                 |              |        |         |          |
| T4      | 0.7                 |              |        |         |          |
| T5      | 0.9                 |              |        |         |          |
| T6      |                     | 0.2          | 909.43 | 135.23  | 88.24    | 67.10    |
| T7      |                     | 0.4          | 689.22 | 220.21  | 218.06   | 190.24   |
| T9      |                     | 1.0          | 300.00 | 300.00  | 300.00   | 300.00   |
| T10     |                     | 1.4          | 172.30 | 282.41  | 347.46   | 397.83   |

2.3.2. Testing procedures. Before the tests, the assembly of the equipment should be checked, and ensure that there won't be leakage under the maximum water pressure of 0.9 MPa. The procedures of the tests are as follows:

Step 1: Sample loading. Put the broken rocks into the cylinder, turn on the switch of the axial loading system, and the sample is pre-compacted to the set height. The initial height of the sample is measured and recorded.

Step 2: Fill the sample with water for saturation. Turn on switch of the water pump and keep the valve I and valve II close, valve III open for water flowing into the sample.

Step 3: Set the water pressure according to Table 1 and start seepage.

Step 4: The solid-liquid mixture was collected every 10 s for the first 30 s, every 20 s for the next 40 s, and then every 30 s until no particles are washed out. The test meets the ending, when no particle rushed out.

Step 5: Filter the solid-liquid mixture collected in each time period, then dry, weigh, and record the particles filtered.

In order to reduce the discreteness of tests and improve the accuracy of the test, each test was repeated three times, and the average value of the three tests was taken as the final results.

2.4. Calculation principles

During the seepage process, the water flow will cause the particles to migrate and flow out with the it. The weight (after air-drying) of the particles collected at each time interval is $\Delta m_i$. During the $i$th time interval and before this interval, all cumulative mass of migrating particle $m_i$ is:

$$m_i = \sum_{i=1}^{n} \Delta m_i$$  \hspace{1cm} (2)

Initial porosity of the sample can be calculated by equation (3):

$$\phi_0 = 1 - \frac{m}{\rho_g \pi r^2 h_s}$$  \hspace{1cm} (3)

In the process of the seepage tests, the porosity at each moment changes constantly which can be calculated by equation (4):

$$\phi = 1 - \frac{m - m_n}{\rho_g \pi r^2 h_s}$$  \hspace{1cm} (4)

Where $h_s$ is the height of the sample, $\rho_g$ is the density of the red sandstone, $m$ is the total mass of the sample, and $r$ is the radius of the cylinder.
3. Results analysis

3.1. Particle migration
After being filtered and drying, three sizes of particles were obtained from solid-liquid mixtures. As shown in Figure 4, there are sizes of 0-2 mm, 2-5 mm, and 5-8 mm respectively. The amount of particle migration under different test conditions is shown in Table 2. By observing the collected particles, it is found that in the first 30 s of the particle migration process, most of them are within size of 0-2 mm. As the migration process continues, particles of size 2-5 mm even a very small amount of size 5-8 mm began to appear. Ultimately, the particle migration process is over. Therefore, it can also be seen that the ability that the seepage channels allow the particles to pass is stronger with seepage proceeding.

![Figure 4. Particles collected during tests.](image)

**Table 2.** Amount of particles transfer during each test (g).

| Test No. | Time (s)       | 0 | 10  | 20  | 30  | 50  | 70  | 100 | 130 | 160 | 190 | 220 |
|----------|----------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| T 1      | 0              | 43.80 | 19.34 | 5.85 | 9.76 | 7.75 | 7.08 | 7.16 | 7.04 | 6.85 | 0   |
| T 2      | 0              | 53.40 | 21.70 | 13.90 | 9.71 | 7.71 | 6.71 | 6.77 | 6.44 | 5.64 | 0   |
| T 3      | 0              | 81.11 | 14.52 | 8.13 | 6.93 | 12.57 | 17.39 | 0   | 0   | 0   | 0   |
| T 4      | 0              | 91.98 | 10.17 | 6.47 | 16.81 | 7.04 | 12.25 | 3.70 | 0   | 0   | 0   |
| T 5      | 0              | 94.72 | 15.91 | 4.90 | 13.21 | 5.84 | 15.49 | 4.10 | 0   | 0   | 0   |
| T 6      | 0              | 114.96 | 54.62 | 44.64 | 53.94 | 39.29 | 63.73 | 36.43 | 0   | 0   | 0   |
| T 7      | 0              | 116.17 | 6.72 | 9.66 | 9.95 | 7.34 | 7.34 | 12.60 | 0   | 0   | 0   |
| T 8      | 0              | 81.11 | 14.52 | 8.13 | 6.93 | 12.57 | 17.39 | 0   | 0   | 0   | 0   |
| T 9      | 0              | 28.82 | 5.80 | 0   | 0   | 0   | 9.90 | 0   | 0   | 0   | 0   |
| T 10     | 0              | 8.70 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |

The cumulative mass of migrating particle can be calculated by equation (2). The curves of particle migration are shown in Figure 5. It can be seen that the processes of particle migration are fast and then slow, and finally tend to be stable. From the Figure 5(a), we can find that as the pore pressure increases, the amount of particle migration increases, and the earlier the particle migration ends. The reason for these phenomena is that the greater the pore pressure, the stronger the kinetic energy of the water flow and more particles will migrate out with it. In fact, under the action of pore pressure, water flow rushes rapidly into the pores of the broken rock sample, causing the particles to rotate or dislocate. At the same time, particles that are easier to move in the sample are carried away by the water flow, and the migration process is expressed more rapidly as the pore pressure increases. From Figure 5(b), a law that as the PSD decreases, the amount of particle migration increases, and the later the particle migration process ends is obtained. This is because the smaller the PSD, the more the content of small particles in the
sample, in which the pore distribution is more uniform. The more uniform pore distribution means the smoother the passage, so that the more fine particles are taken away. Moreover, as the migration process continues, particle migration channels will be further formed, so that the particle migration process will take place more violently. When the Talbot index is 0.2, the cumulative mass of migrating particle is nearly 10 times than that of Talbot index is 1.4. Therefore, the smaller the PSD, the greater the amount of migration and the longer the duration of the samples.

![Graph](image)

**Figure 5.** Amount of particles migration during different tests.

3.2. Porosity evolution

Equation (4) is used to calculate the porosity at different moments. The variation of porosity is shown in Figure 6. It can be seen that the porosity increases with the increase of pore pressure and decrease of the PSD. The porosity of the sample in T6 has the most obvious variation, and its final value is about twice that of the sample in T10. The evolution of porosity can be divided into three stages: rapid growth stage, slow growth stage and stable stage. Combining with the Figure 5, it can be found that the rapid growth of porosity is also the stage where large-scale particle migration occurs in the sample. At this stage, the seepage channels are initially formed. In the slow porosity growth stage, a small amount of particles continue to migrate and gradually form a stable seepage channels. Until the third stage, with the particle migration ending, stable channels are formed and the porosity reaches a constant value. The migration of particles directly affects the evolution of porosity.

![Graph](image)

**Figure 6.** Evolution of porosity during different tests.
In a word, the greater the water pressure of the broken rock mass, the faster the formation of seepage channels. The greater the water pressure and the smaller the PSD of the broken rock mass, the greater the variation in their internal porosity, meaning that the smoother the seepage channels formed. Under such circumstances, the easier it is to induce geological disasters such as water inrush and structural instability.

4. Conclusion
In order to explore the mechanism of the formation of seepage channels in broken rock mass, a series of seepage tests under the condition of particle migration were designed. The test results were analyzed. Conclusions are obtained as follows:

(1) By observing the particles collected during the seepage process, it is found that particles with a particle size range of 0-2 mm, 2-5 mm, and 5-8 mm appear in sequence. It can be seen that the formation of the seepage ability of seepage channels is stronger.

(2) With the increase of pore pressure, the cumulative mass of migrating particle increases, but the process is more short; with the decrease of PSD, the cumulative mass of migrating particle increases and that process duration also increases.

(3) Samples with more pore pressure and PSD own a more peak value of porosity, the seepage channels with in them are more wide, correspondingly. The evolution of the porosity can be divided into three stages: rapid growth stage, slow growth stage and stable stage. The particle migration process is consistent with the porosity change process. The more the pore pressure and the smaller the PSD, the more rapidly the porosity peak value reach. Therefore, the broken rock mass with larger pore pressure and smaller PSD more likely to induce water inrush, structural instability and other geological disasters.

This article focus on the porosity, for sake of porosity is closely related to the formation of seepage channels. However, it is still not thorough enough to reveal the laws of seepage in the broken rock mass. In the next study, we will further explore the variation of permeability, a parameter characterize the water inrush process directly.

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References
[1] Li, Lin, Study of Intelligence Algorithm for Rapid Identification of Mine Water Inrush Source, D, 2018.
[2] Gong, Houjian, Statistical analysis on water accidents of coal mines in China from 2012 to 2016, J. Inner Mongolia Coal Economy, 2017, 23, 107-108.
[3] Huang, Xianwu, et al., Testing study on seepage properties of broken sandstone, J. Rock and Soil Mechanics, 2005, 2(9), 1385-1388.
[4] Ma, Dan, et al., Variations of hydraulic properties of granular sandstones during water inrush: Effect of small particle migration, J. Engineering geology, 2017, 217, 61-67.
[5] The Feng, M., J. Wu and Ma. D, Talbol index-Experimental investigation on the seepage property of saturated broken red sandstone of continuous gradation. Bull Eng Geol Environ, 2018, 23, 1167-1178.
[6] Ma, Dan, et al., Effects of seepage-induced erosion on nonlinear hydraulic properties of broken red sandstones, J. Tunnelling and Underground Space Technology, 2019, 102993.