Experimental Study on the Evolution Characteristics of Pore Structure in Soil-Rock Mixtures under Stress-Permeation Conditions

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Abstract. Within soil-rock mixtures, there exist numerous pores, and under the action of seepage, particles migrate along internal pore channels, leading to structural damage and disasters such as dam collapses and landslides. In practical situations, pore development under seepage often occurs under complex stress conditions, influenced by factors such as confining pressure and water pressure. To address research needs, triaxial permeability tests and Nuclear Magnetic Resonance (NMR) experiments were conducted on cohesive soil-rock mixtures to investigate the influence of confining pressure and water pressure-induced changes in internal porosity and pore structure on permeability. The results indicate that: the greater the water pressure, the larger the permeability coefficient, while the greater the confining pressure, the smaller the permeability coefficient; the action of water pressure promotes the development of pores under seepage, whereas the action of confining pressure inhibits pore development; pores of different sizes exhibit different sensitivities to confining pressure and water pressure; the relationship between pores and permeability coefficient is complex, influenced by multiple factors.

Keywords: Soil-rock mixtures; Seepage erosion; Nuclear Magnetic Resonance; Pore evolution.

1 Introduction

Soil-rock mixtures, serving as materials for slope protection, embankments, and fillings in projects like dams, levees, and waterways, find extensive application in various fields such as geotechnical and hydraulic engineering. They are also the primary geological and soil medium constituting natural slopes and disasters like landslides[1]. Due to the inherent differences in composition between "soil" and "rock" components and their mechanical properties, soil-rock mixtures exhibit non-uniformity, heterogeneity, and discontinuity, harboring numerous internal pores[2]. Under the influence of external seepage, fine particles migrate along existing pore channels, leading to significant alterations in the internal structure and irreversible infiltration erosion damage. Dam and

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levee structures are susceptible to cavities, potentially resulting in dam breaches[3], while slopes may experience severe landslide disasters[4].

Based on this, numerous scholars have conducted multi-faceted experimental studies on the seepage of soil-rock mixtures. Triaxial permeability testing, compared to conventional permeability tests[5], can reflect the permeability characteristics under complex stress conditions, making it more suitable for practical engineering applications. Researchers have investigated the variations in permeability induced by different confining pressures through loading and unloading artificial powdery clay and fault zone mud and gravel mixtures, and provided insights into the relationship between isotropic effective stress, internal fluid pressure gradient, gravel content, confining pressure, and permeability coefficient[6]. Furthermore, Nuclear Magnetic Resonance (NMR) technology[7] based on pore structure and transverse relaxation time (T2) has been employed to study changes in pore size distribution and porosity during the seepage process in porous media[8].

It can be seen that the limitations of previous studies failed to comprehensively analyze the seepage laws and internal pore evolution under the pressure of soil-rock mixtures. Therefore, building upon the foundation laid by previous research, this study selects clay and gravel as research subjects and conducts triaxial permeability tests on remolded soil-rock mixture specimens. Permeability coefficients under different confining pressures and hydraulic head conditions are measured. Subsequently, NMR testing and analysis are performed on the specimens before and after the permeability tests to explore the influence of changes in internal porosity and pore structure induced by confining pressure and hydraulic pressure on the permeability of soil-rock mixtures. This study aims to reflect the pore evolution characteristics during the seepage erosion process inside the soil-rock mixture at the micro level, and provide experimental data support for engineering design and disaster prevention.

2 Sample preparation and test methods

Through X-ray diffraction (XRD) analysis, the main mineral components of the clay were determined to be montmorillonite (57.8%), kaolinite (38.1%), and quartz (4.1%). Additionally, basic physical properties of the clay were measured through indoor compaction tests and other methods, as presented in Table 1.

Table 1. Basic physical indexes of clay

Liquid limit (%)	Plastic limit (%)	Plasticity indicators	Maximum dry density (g/cm^3)	Optimum water content (%)
35.0	17.4	17.6	2.02	12.9

The specimens are remolded samples consisting of clay and gravel mixture. The diameter of the specimens is 50mm, and the height is 100mm. Prior to specimen preparation, it is necessary to determine the threshold value of soil/rock and the maximum particle size of the gravel. According to the definitions provided by Medley et al.[9] and Xu Wenjie et al.[10]The threshold for soil/rock was determined to be 2.5 mm, and according to standard, the maximum particle size of the rocks should be 1/6 of the sample diameter. Past experiences have shown that the ideal ratio between sample size and the maximum particle size is 8. Based on these considerations, the particle size range of the rocks in this experiment is determined to be 2.5 to 6.3 mm. Using the optimal water content for clay, cylindrical samples with a 40% rock content were prepared using the wet mixing and layering compaction method, with a compaction degree of 0.9. At this point, the soil-rock mixture is considered to be in its optimal compacted state. Fig. 1 shows the particle size distribution curve of the soil-rock mixture with a 35% rock content.

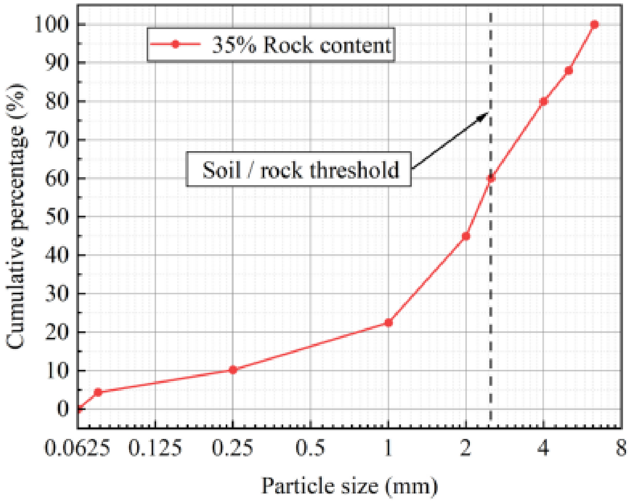

Fig. 1. Particle gradation curve of soil-rock mixtures with 35% rock content

3 Test instruments and principles

3.1 Triaxial seepage test

Considering the actual pressures exerted on soil in engineering applications, and the variation of pressures at different locations within the soil, the use of conventional permeability tests may overlook these complexities. Therefore, triaxial permeability tests are more suitable as they can reflect the permeability characteristics under complex stress conditions, which align better with engineering realities. The instrument used in this permeability test is a GDS triaxial permeability meter. During the experiment, the computer can control the experimental process through the dedicated GDSLAB software. After data collection, it will be automatically recorded and the permeability coefficient will be calculated in real time, as shown in Fig. 2.

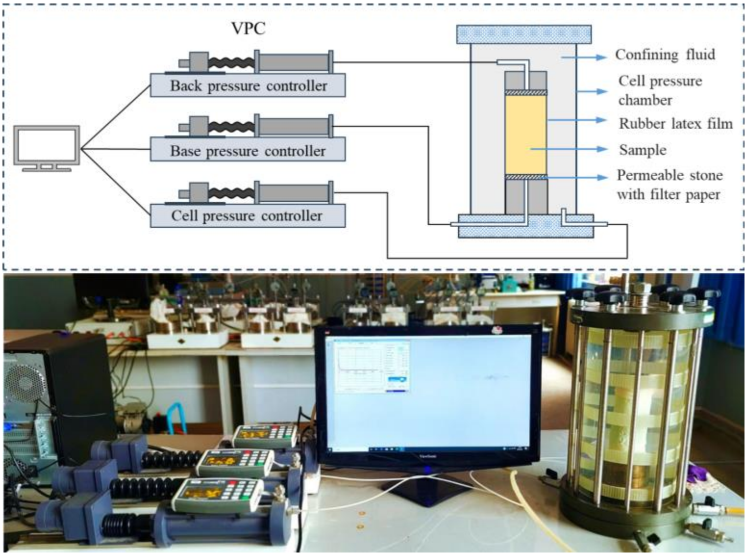

Fig. 2. The GDS triaxial test system and the structural diagram

3.2 NMR test

In order to explore the change of pore structure distribution of soil-rock mixture before and after seepage from the microscopic level, NMR analysis and test were carried out on the cylindrical samples of soil-rock mixture before and after GDS test.

NMR analysis technology is based on the fact that the peak area of NMR signal is proportional to the number of hydrogen protons, which can be used for quantitative testing of water content. The speed of signal attenuation (characterized by relaxation time) can reflect the environment of pore water, and then inverse the pore size and distribution of porous media. The speed of signal attenuation (characterized by T2) can reflect the environment in which the pore water is located, and then inverse the pore size and distribution of the soil-rock mixture.

3.3 Specific test plan

This experiment focuses on the effects of confining pressure and hydraulic head on permeability coefficient in soil-rock mixtures. Prior research indicates that a rock content of around 40% is optimal for both permeability and mechanical properties. Therefore, all samples in this study contained 40% rock. The samples were initially saturated under vacuum before being placed in a triaxial cell with confining fluid. Two sets of conditions were tested: fixed confining pressure with varying hydraulic head (C series) and fixed hydraulic head with varying confining pressure (S series). The resulting permeability coefficients are presented in Fig. 3.

Fig. 3. Sample, test conditions description and NMR instrument

4 Test results and analysis

4.1 Triaxial seepage test results and analysis

Fig. 4 displays the relationship between the permeability coefficient of soil-rock mixtures and confining pressure (black line, 100-300 kPa) or water pressure (red line, 20-60 kPa). As confining pressure rises, the sample's permeability coefficient decreases gradually due to pore compression and narrowed pore connections. The attenuation amplitude decreases with increasing pressure, with the permeability coefficient ranging at 10-7 cm/s. Conversely, when confining pressure is fixed, a higher water pressure results in a larger permeability coefficient, though staying within the 10-7 cm/s range. The complexity of internal pore conditions, influenced by factors like soil and rock particle arrangement, particle contact force, and soil-rock interface seepage, makes the relationship between water pressure and permeability coefficient nonlinear.

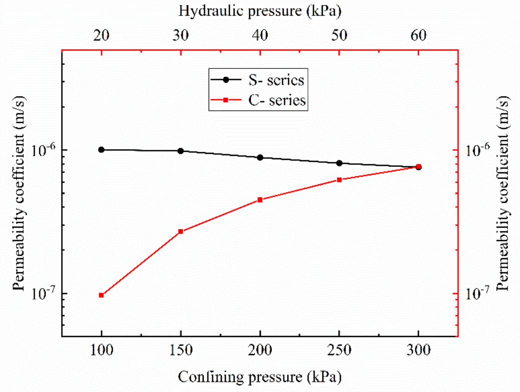

Fig. 4. Changes in permeability coefficient of soil-rock mixture with confining pressure and water pressure

4.2 NMR test results and analysis

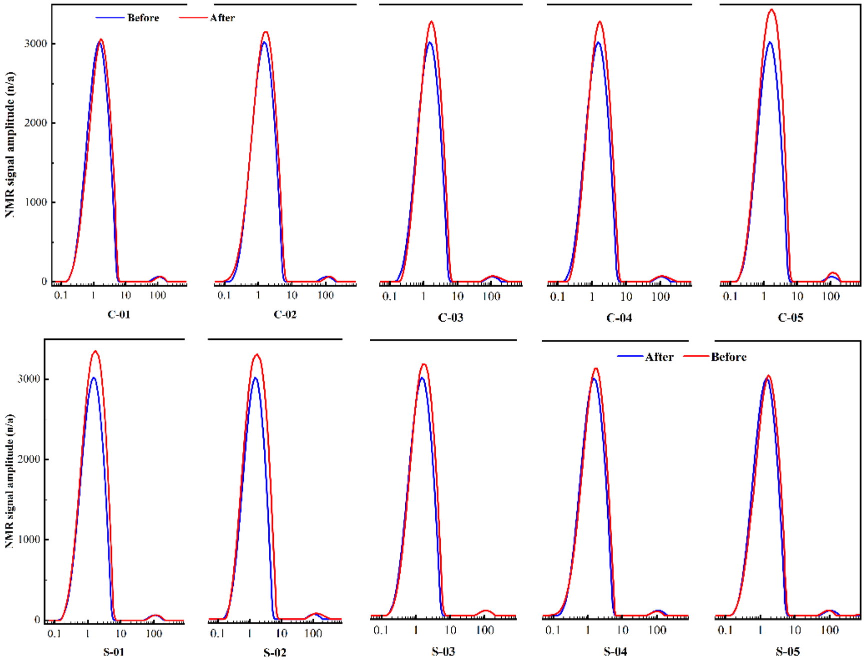

Fig. 5. T2 spectrum before and after seepage obtained by NMR

Fig. 5 presents T2 curves from nuclear magnetic resonance (NMR) testing, reflecting pore size distributions in soil-rock mixtures after infiltration under various conditions. The T2 spectrum exhibits two peaks: the left representing smaller pores (T2 ≤ 10 ms, r ≤ 2 μm) and the right larger pores (T2 > 10 ms, r > 2 μm).

Infiltration leads to internal pore development. Water pressure promotes pore expansion, while confining pressure suppresses it. Higher confining pressure has a more significant inhibitory effect, especially on larger pores.

Without confining pressure, pore rates increase after infiltration, with the T2 curves shifting right and the left peak magnitude increasing. Higher water pressure causes the right peak to shift right and increase in magnitude, indicating small pore expansion and quantity increase. Water pressure plays a dominant role in pore rate development in these tests.

When water pressure is fixed at 80 kPa, pore rates still increase after infiltration, but the right peak region remains unchanged or slightly shifts left under high confining pressure. This suggests that while small pores expand and increase in quantity, confining pressure compresses large pores, inhibiting pore development.

5 Conclusion

This study employed triaxial permeability tests on reconstituted cohesive soil-rock mixtures and nuclear magnetic resonance (NMR) testing to investigate how confining pressure and hydraulic pressure influence the internal porosity, pore structure, and permeability of these porous media. The findings reveal that an increase in hydraulic pressure enhances the permeability coefficient, while an elevation in confining pressure diminishes it. These effects are attributed to pore deformation caused by confining pressure and changes in the permeation flow driving force induced by hydraulic pressure. Additionally, infiltration was found to promote pore development, with hydraulic pressure acting as a stimulant and confining pressure as an inhibitor. Notably, pores of different sizes respond differently to these pressures, with smaller pores being more sensitive to hydraulic pressure and larger pores to confining pressure. These research results help to enrich the theory of pore evolution during the internal erosion process of porous media, and at the same time provide scientific basis for the design of underground engineering with soil-rock mixture as the main body, and help predict and prevent the occurrence of geological disasters.

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