Research and microscopic analysis of seepage characteristics of sandstone under low-frequency cyclic loading

Ma Chunde1*, Long Shan1, Li Xibing1, Liu Zelin1, Xie Weibin1

1Central South University, School of Resources and Safety Engineering, Changsha, 410083, Hunan Province, China

*Corresponding author: cd.ma@163.com

Abstract. The change of rock permeability properties under cyclic load is of great significance to the safety of underground engineering. However, there are few studies on triaxial seepage tests under different cyclic loads, and most of them have not carried out microscopic mechanism analysis. Therefore, in this paper, the seepage test of intact sandstone under different cyclic loads was carried out under low confining pressure. The test used sine waves to simulate low-frequency seismic waves, highlighting the permeability of underground water-bearing engineering rock mass with vibration frequency and amplitude under low-frequency source disturbance. Variations and test results show that in the sandstone triaxial stress-strain curve, from the compacted section, the elastic section to the expansion section, the permeability of the rock gradually increases, and the sensitivity to cyclic load also increases. At the same time, the damage threshold of the rock gradually decreases, and the rock will break even in the elastic section. Under low confining pressure, the loading amplitude has a greater impact on rock permeability than the loading frequency under low-frequency cyclic loading. The loading frequency and loading amplitude can be comprehensively characterized by the average loading rate. Then, using nuclear magnetic imaging technology to change the microstructure of the rock sample before and after the test, the analysis shows that the effect of different cyclic load parameters on the permeability of the rock sample is actually obtained through the effect of force on pores and cracks. For dense rocks, the increase in permeability caused by cracks is even greater.

Key words: Red sandstone; Cyclic loading; Nuclear magnetic resonance; Seepage characteristics
1. Introduction

Engineering rock masses are generally in the environment of in-situ stress and underground fluid interaction, and are often affected by external disturbance loads (such as earthquakes, blasting, drilling vibration, vehicle vibration and groundwater pressure changes, etc.), causing changes in rock stress. This in turn will affect the permeability characteristics of the rock. The disturbance generated by blasting is the most commonly encountered disturbance in actual engineering. As the distance from the blasting source increases, the shock wave gradually attenuates into a seismic wave with a smaller stress amplitude. Engineering rock masses at low-frequency sources are usually subject to repeated disturbances. If the engineering rock masses under critical stress conditions are subject to external dynamic interference in the direction of maximum stress, even weak disturbances can cause instability or even sudden destruction. This kind of rock rupture is likely to occur at seemingly random locations and times. It is not only difficult to predict, but also easy to cause water inrush disasters, which poses a serious threat to the safety of underground structures. Therefore, the seepage properties of rocks under low-frequency cyclic loading are required research.

In 1968, Brace [1] first conducted an experimental study on the variation of granite permeability under the effect of hydraulic coupling, so that the interaction between rock deformation and failure and its permeability change was known; rock permeability and pores The rate is closely related, Farquharson [2] et al. proposed that the power law describing the relationship between permeability and porosity can be divided into two forms: namely, in a dense state (<14% (volume) pore), the permeability of rock The connectivity of the fractures is controlled, while in the porous state (> 14% (volume) pores), the fluid is controlled by the pores; Yang Feng et al. [3] used CT scanning technology to scan the tight sandstone samples, and used COMSOL to simulate Seepage characteristics of fluids in the pores of rocks, studied the seepage characteristics and stress sensitivity of tight sandstones; Zhang LF [4] et al. studied the permeability changes of intact limestones under erosive fluid penetration, and used nuclear magnetic resonance technology (NMR) was observed; in 1963, Burdine [5] first studied the fatigue characteristics of rocks under cyclic loading. He conducted uniaxial cyclic tests and triaxial compression tests on Berea sandstone; so far, many scholars have The mechanical properties of rocks under cyclic loading are studied [6-9], but there are relatively few studies on the seepage properties of rocks under cyclic loading. The research results of rock fluid-structure coupling test under cyclic loading were initially mainly reflected in the study of sand materials. T. Wichtmann et al. [10-11] conducted a triaxial drainage test on sand under dynamic disturbance, analyzed the main influencing factors of sand polarization under high-frequency cyclic loading and unloading conditions, and established a related prediction model; Bagde [12] et al. conducted uniaxial compression tests on intact sandstones under normal and saturated conditions under cyclic loading. The experimental results showed that with increasing loading frequency and loading amplitude, the uniaxial strength and axis of sandstone rock samples under cyclic loading The stiffness gradually decreases, and the dynamic modulus decreases with amplitude as the loading frequency increases. Xu Jiang [13-14] et al. carried out fatigue tests on sandstones with different water contents by changing the loading rate and initial axial pressure of the periodic load, and obtained the hysteretic loop deformation law and acoustic emission of the sandstone with the periodic load (AE) characteristics; Rhett and Teufel [15] have found through a large number of experiments that the dynamic-static combined loading method
has a greater influence on the permeability of sandstone and the permeability is more sensitive to changes; nowadays, the research on the permeability of rock under cyclic loading is mainly focusing on rocks with large porosity and even fissures, and few studies on low-frequency cyclic loading, few people have studied the permeability properties of rocks under cyclic loading at different stress stages.

In order to fill the above-mentioned gap, this paper uses sine waves to simulate low-frequency seismic waves. At different stress stages, triaxial seepage tests under low-frequency periodic loads were carried out on red sandstone to study the effects of cyclic loading parameters such as loading frequency and loading amplitude on permeability. At the same time, based on the nuclear magnetic resonance technology, the pore changes before and after the rock sample test are obtained. The experimental results are analyzed from the micro level to obtain the mechanism of the coupling effect of rock and pore water under cyclic loading. It can provide an important reference for disaster prediction and safety assessment of underground engineering in the rock mass when an earthquake occurs or when it is subjected to blasting vibration, such as tunnel excavation, coal mining, and other underground rock engineering.

2. Seepage experiment under cyclic load

2.1. Materials

In order to ensure the consistency of the test rock samples, samples were taken from the same core and polished into rock samples with a size of 50 mm×50 mm. The height, diameter, porosity, longitudinal wave velocity and density of the rock samples were tested to exclude the rocks with larger dispersion, and then the selected rocks were numbered. In addition, SEM was also used to scan the rock sample, and it can be seen that the particle size of the red sandstone rock sample is small and evenly distributed, which belongs to dense fine sandstone. Most of the cemented material is filled in the pores between the rock particles and firmly adheres to the rock sample particles, and there is basically no gap between the particles, so the structure of the red sandstone is the type of pore cementation. X-ray diffraction (XRD) was used to detect the composition of the rock sample, and the minerals in the test red sandstone material were feldspar, quartz, montmorillonite, calcite and a little mud. The detailed composition is as follows: feldspar content is 50%, quartz is 20%, montmorillonite is 15%, calcite is 10%, and mud is 5%.

![Red sandstone and SEM image for research](image)

Figure 1. Red sandstone and SEM image for research

The tests in this paper are all conducted on the MTS815 rock mechanics test system. The equipment is equipped with the MTS 286.31 transient permeability system for rock seepage test. The system will measure the attenuation of the pressure difference across the rock sample with time. For the experimental study of the rock's permeability properties, it is also possible to design different test schemes and loading methods for triaxial static and dynamic compression tests on rock samples through software applications. The transient permeability
equation is as follows:

$$K = \mu \beta V \left( \ln\left( \frac{\frac{\Delta P_f}{2\Delta P_t}}{\frac{\Delta P_f}{2\Delta P_t}} \right) \right)$$  \hspace{1cm} (1)

\(V\) = reference volumes, \(\text{cm}^3\), \((V = V_1 = V_2)\);
\(\Delta P_f/\Delta P_t\) = ratio of initial pressure differential to final pressure differential;
\(\Delta t\) = the duration of the test, \(\text{s}\);
\(L_s\) = specimen length, \(\text{cm}\);
\(D_s\) = specimen diameter, \(\text{cm}\);
\(A_s\) = specimen cross sectional area, \(\text{cm}^2\);
\(\mu\) = viscosity of pore fluid, \(\text{Pa} \cdot \text{sec}\);
\(\beta\) = compressibility of pore fluid, \(\text{Pa}^{-1}\)

**Figure 2.** MTS 815 mechanical test system real shot diagram

In order to obtain the triaxial compressive strength to guide the definition of the maximum stress level of the cyclic load, the conventional triaxial compression test at 10MPa confining pressure was carried out on the saturated red sandstone sample on MTS815, and the axial and lateral deformation of the rock sample was adopted by the LVDT displacement sensor. Through monitoring, detailed data such as stress and strain of the rock were obtained, and the data obtained from the triaxial compression test was processed to obtain the triaxial mechanical parameters of red sandstone as follows:

**Table 1.** Mechanical parameters of triaxial compression of red sandstone under 10MPa confining pressure

| Confining pressure (MPa) | Triaxial compressive strength \(\sigma_c\) (MPa) | Elastic Modulus \(E_c\) (GPa) | Axial peak strain \(\varepsilon_{\text{max}}\) \(\times 10^{-3}\) | Hoop peak strain \(\varepsilon_{\text{ymax}}\) \(\times 10^{-3}\) |
|--------------------------|---------------------------------|-----------------|---------------------|---------------------|
| 10MPa                    | 109.87261                       | 10.44           | 8.24                | -1.04               |

2.2. Methodology

There are many factors that affect the fatigue failure of rocks, such as the frequency and amplitude of cyclic loading, upper (lower) limit stress, loading waveform, loading time, number of cycles and so on. In this test, only one type of loading waveform is used to focus on the influence of the frequency and amplitude of the periodic load on the permeability of the red sandstone at different characteristic stress stages. In this test, sinusoidal waves were used to
simulate seismic waves, highlighting the change of permeability of underground water-bearing engineering rock masses under low-frequency source disturbance. During the test, the confining pressure $\sigma_1 = 10 \text{ MPa}$, the seepage pressure was $1 \text{ MPa}$, and the number of cycles was 100. The compressive strength of the sample is 15%, 45% and 75%, and the initial axial compression is equivalent to that the rock sample is in different stress stages.

Figure 3 shows the curve of the actual load with time in the cyclic load test for the entire period. The loading process of axial stress is divided into two stages: quasi-static loading stage and cyclic loading stage. In the quasi-static loading stage, axial stress is applied at a rate of 0.02 mm /min in the axial displacement control mode to reach the target set point, which is 15%, 45% of the compressive strength of the rock sample under a confining pressure of 10 MPa % And 75%. In the period of cyclic loading, the average stress $\sigma$ is kept constant at the target set point $\sigma_m$. The rod used for disturbance loading applies a small preload, and the required disturbance load with a certain frequency and amplitude level is accurately controlled by servo control. Ground is applied to the bottom of the sample, and a closed loop is used to disturb the load, “fixing” the loading force on the rock sample. Set 5 sets of loading frequencies, from 0.5Hz-1.5Hz increments to 0.3Hz, and set the loading amplitude to 5KN, 10KN, 30KN and 50KN respectively, and measure the permeability of the rock sample at each point in sequence.

![Figure 3. The curve of actual load with time](image)

2.3. Permeability under different cyclic loads

It can be seen from Fig. 4 that under 10MPa confining pressure, the effect of loading frequency and amplitude on the permeability of red sandstone is obvious. In the compaction section, the loading frequency dominates. As the frequency increases, the permeability exhibits a nearly linear rapid decline stage. The permeability decreases by at most an order of magnitude, but the permeability decreases more rapidly at low frequencies. As the frequency increases, the decrease in penetration slows. This may be due to the shorter time required to reach the same number of cycles under the action of high-frequency cyclic loading, the shorter time the force acts on the rock sample, and the lesser the effect on permeability. In the elastic section, when the loading amplitude exceeds 30KN, the permeability first decreases with frequency and increases at $f=0.6\text{Hz}$. When the loading amplitude $\sigma_a=50\text{KN}$ and $f=1.5\text{Hz}$, the rock sample breaks down. In the expansion section, the permeability decreases first and then increases with the increase of frequency. When the inflection point is $f=0.6\text{Hz}$, and the loading amplitude...
It can be seen from the test results that in the compaction section, with the increase of frequency and amplitude, the rock permeability generally shows a downward trend. When the other conditions are the same, the greater the loading frequency, the shorter the contact time between the cyclic stress and the rock sample, the smaller the effect on the rock sample, the more difficult the rock sample deformation, the more the number of cycles required for the rock sample to reach the failure standard, and the permeability change is slower, and the points appear closer on the graph. Compared with the cyclic loading and unloading at high frequency, the lower the loading frequency, the faster the pore pressure in saturated water samples develops, resulting in the reduction of finite stress in the rock samples, the ability to resist external cyclic loads becomes weaker, and the dynamic strength becomes lower. The permeability changes faster. It can be deduced that in the compaction section, the increase of the loading frequency under cyclic loading will increase the strength of the rock sample to a certain extent. When the loading
amplitude is the same, the higher the loading frequency, the more the number of cycles the rock can stand. This is in common with the conclusion of Ma [17] et al. They concluded in the triaxial cyclic compression test that after a certain number of cyclic loads, the strength of sandstone can be increased by 171%. As also discussed by Singh [18], if the stress level under cyclic load is much lower than the monotonic peak strength, then the rock will not break under cyclic load and will even become stronger.

Since the loading frequency and loading amplitude have a certain degree of influence on the permeability of the rock sample, the larger the loading frequency and loading amplitude, the faster the average loading rate, which will affect the distribution, deformation and development of the microstructure inside the rock. The greater the impact, the greater the impact on rock permeability. In summary, the loading rate of the cyclic load also indirectly affects the mechanical and seepage properties of the rock. From an average point of view, the two can be characterized by the average loading rate of each cycle, making the permeability and loading rate single. The factors are directly related. The main test in this paper is carried out under different load amplitude and load frequency under cyclic load, so that the load rate also changes continuously during the cycle test, and the load rate in each cycle is regarded as the average load rate, you can get:

\[
\bar{\sigma} = \frac{d\sigma}{dt} \approx \frac{\sigma_a}{\tau} = 4 \frac{\sigma_a}{f} \tau
\]

(b), (c), and (d) in Figure 5 below are pictures of rock samples damaged under different stress stages and different cyclic loading parameters under 10MPa confining pressure. Compared with the sandstone damaged under the conventional triaxial compression test (Figure 6-a), more local cracks were observed under the cyclic load, the rock sample was broken to a large extent and the fragments were more detached, and the fragments could not aggregate together. It can be seen that the periodic load increases the degree of rock fragmentation. The rock samples are all in the form of complex failure. The failure starts from the contact surface of the cyclic load. This end is the most severely broken. The main failure slope and the direction of the periodic load are at an oblique angle, and there are also a few diagonal fractures. The higher the initial axial pressure and the larger the loading amplitude, the more severe the rock sample failure, and the larger the failure angle between the horizontal plane applying the maximum principal stress and the shear fracture plane. In the expansion section, the sample expands more in the lateral direction, and a small network of shear cracks appears. The surface of the rock sample will show more spalling and spalling locally, the degree of fragmentation increases, and the brittleness of the failure weakens. Because the red sandstone used in this experiment is a muddy cement structure, due to the effect of pore water and the mud component in the rock sample, with the increase of loading frequency and loading amplitude, the coupling effect of high-amplitude periodic load and pore water The lower rock sample disintegrates and breaks into pieces quickly, and even muds (see Figure 6-d). However, on the whole, the failure mode of
rock samples under periodic loading is still brittle ductility enhancement to a certain extent, especially under the coupling condition of higher frequency and higher amplitude.  

$$\sigma_a=0\text{KN}, \quad f=0\text{Hz} \quad \sigma_a=50\text{KN}, \quad f=1.5\text{Hz} \quad \sigma_a=30\text{KN}, \quad f=1.2\text{Hz} \quad \sigma_a=50\text{KN}, \quad f=1.5\text{Hz}$$  

**Figure 5.** Destruction diagram of red sandstone samples

### 3. Analysis of results A based on NMR

Nuclear magnetic resonance test (NMR) can not only quantitatively analyze the microscopic failure process of rock through the change of porosity, but also obtain the two-dimensional distribution of the internal pore structure of the rock by MRI system of the NMR system, thereby directly revealing the microscopic characteristics of the rock, and the evolution process of rock permeability. The rock samples were damaged under the conditions of loading amplitude of 30KN and 50KN, and nuclear magnetic resonance could not be carried out. Therefore, the developed Niupai AiniMK-150/60 nuclear magnetic resonance analyzer was used to carry out the test before and after the test when the loading amplitude was 10KN. NMR test, obtain the porosity and T2 relaxation time spectrum of the rock sample before and after the test, and the NMR imaging of the rock sample on the X-Y plane, and explore the mechanism of permeability change under periodic loading from the microscopic level.

### Table 2. Porosity before and after some rock samples

| Confining pressure (MPa) | Amplitude (KN) | Sample number | Before the test | After the test |
|--------------------------|----------------|---------------|----------------|---------------|
|                          |                |               | Porosity (%)   | Permeability (10^{-15}) | Porosity (%) | Permeability (10^{-15}) |
| 10                       | 10             | A-1-1         | 3.75           | 10.14          | 2.89          | 1.22                      |
|                          |                | A-2-1         | 3.59           | 9.84           | 2.36          | 2.92                      |
|                          |                | A-3-1         | 4.11           | 11.29          | 3.92          | 12.89                     |

**Figure 6.** Scanning rock sample location by MRI
3.1. $T_2$ Spectrum Variation

Figure 7 shows the $T_2$ spectrum of the red sandstone before and after the periodic load seepage test under 10MPa confining pressure. The blue curve represents the $T_2$ spectral distribution of the initial rock, and the black curve represents the $T_2$ of the pores after the seepage test under a 10KN periodic load. Spectral distribution. The $T_2$ spectrum is continuously distributed from 0.01ms to 10000ms, indicating that the red sandstone has a complete pore spectrum, a large pore span, and a certain degree of connectivity between pores. Before and after the test, the $T_2$ spectra of the rock sample in the elastic section and the expansion section have three peaks, reflecting the three pore size distributions. The first peak is all small pores with a span greater than 1ms and a span not exceeding 100, and the first peak occupies the largest ratio indicates that small pores account for most of the red sandstone samples. Looking at the figures (a) and (b) first, the peak distribution in the initial state of the compacted section and the elastic section is similar. The first peak ranges from 1ms to 10ms, and the second peak ranges from 10ms to 100ms, which are all small pores. The third peak occupies the widest $T_2$ range of more than 1000ms, which indicates that the original rock sample has almost no large holes, microcracks or small holes. After the test, the area of the first peak increased, and the third peak decreased significantly and moved to the left. The large pore diameter decreased while the small pore diameter increased, indicating that the cyclic load reduced the number of large pores, resulting in a rapid decrease in permeability. The first compaction section The peak value is obviously increased, and the elastic section only slightly increases, indicating that the permeability of the compacted section will decrease more, which is consistent with the test results. In the expansion section, the test results show that as the loading frequency increases, the permeability first decreases and then increases. Under the initial periodic load, the large pores will be compacted while the small pores will increase. As the loading frequency increases, the cumulative load causes irreversible internal rock formation. Damage and the generation of micro-cracks lead to an increase in permeability. From the figure (c), the $T_2$ spectrum of the expansion section shows that in the rock sample before and after the test, both large and small pores have increased, and the number of small pores has increased significantly, which is basically consistent with the experimental results.

The low frequency cyclic load cannot have any effect on the micropores and microcracks of a certain size that are too small, which means that in the cyclic load test, there will be no new micropores beyond the initial size range. The $T_2$ value before and after the test can be seen from Figure 7. Basically remain unchanged before and after the cyclic load. However, the dynamic effects of cyclic loading have changed the existing pores in the red sandstone, turning the micropores into small pores to large pores. The size and number of macropores increase, and the macropores gradually develop into microcracks, and microcracks gradually accumulate. And expand into larger cracks. Therefore, cyclic loading will cause the formation of micro-pores, micro-cracks and micro-structure degradation in red sandstone, which is a kind of fatigue damage.
3.2. MRI Analysis

Since nuclear magnetic resonance detects the pore structure of the rock through the hydrogen atoms of the water in the rock, by detecting the distribution of water in the saturated rock sample and forming a two-dimensional image, the distribution of the microstructure can be visually displayed. The blue dot in the rock sample represents the water molecules in the hole, and the brightness of the blue dot pixel represents the signal strength inside the rock sample. For these small and scattered spots on the image, even those that look blurry to the naked eye, it indicates that there are few water molecules in this part, which means that the size of the holes in this part is very small and the connectivity between the holes is very weak. Therefore, for these large and bright spots, it indicates that the water molecules are abundant and concentrated in this part, which means that the size of the pores is larger and the connectivity between the pores is stronger. Some spots are connected into pieces to represent the generation of microcracks, and the permeability is greater.

According to the MRI image shown in Figure 8, it can be found that the initial sample has small or even fuzzy spots on the MRI image slices at different stress stages. This is because the original microcracks in the rock sample are few, and the small holes account for the largest proportion. The connectivity between them is weak. At a confining pressure of 10MPa, the spots in the figure are reduced before and after the compaction section and the expansion section test, indicating that the original pores are compacted under cyclic loading. The increase of small pores is shown in the figure as the increase in the black part. Since the pores are mostly arched, the cyclic loading and unloading makes the physical structure more prone to deformation, making the large pores become small pores, and the permeability is affected by the pore size.
Affected by the size, the reduction of the pore size and airtightness will lead to the reduction of rock porosity, and the permeability reduction is observed in the test. In the expansion section, large and scattered bright spots gradually appeared in the rock samples after the test, the number of large pores increased, and the permeability of the rock gradually increased. At the same time, there was a significant increase in local brightness in the lower right corner, indicating that the pore connectivity was further enhanced, and the micropores began to coalesce, and the cyclic loading caused irreversible damage to the rock sample. The generation of microcracks and damage to the internal structure of the rock lead to an increase in porosity. However, the upper left corner becomes darker, indicating that the pores increase, but at this time the fracture dominates the permeability, and the permeability increases accordingly, which corresponds to the T_2 spectrum and the test results.

![Figure 8. SEM images before and after rock sample test](image)

Combined with the T_2 spectrum of the rock sample under the same conditions shown (Figure 7), it can be found that the maximum T_2 value has no significant change compared with the previous state. This phenomenon shows that although the application of cyclic loading will cause the micropores in the rock sample to coalesce and form microcracks, the size of these largest microcracks does not show a significant increase (Figure 8). Because the stress triggered by the cyclic load has not yet reached the stress threshold for maximum microcrack growth, if the cyclic load continues to be applied to the rock sample, the pore structure will be further damaged and degraded, and the density of micro-cracks in the middle part will increase to a certain extent and begin to connect with each other, which will eventually lead to the failure of the rock sample. From the MRI image, it can be seen more intuitively than the T_2 spectrum that the significant increase in the permeability of the rock sample is mainly due to the increase in the density of microcracks in the rock. The trends shown in MRI images are consistent with the trends in porosity, free fluid porosity, pore size development, and permeability. In general, through MRI images, we can further understand the failure process of red sandstone microstructure under cyclic loading, so as to explain the changes in permeability of red sandstone.
sandstone under cyclic loading.

4. Conclusions
The microstructure of red sandstone under cyclic loading will change with the loading amplitude, loading frequency, and stress stage, and its permeability properties will also change accordingly. In order to correctly understand the seepage properties of red sandstone under low-frequency cyclic loading, this paper has conducted seepage experiments on red sandstone under different cyclic loading conditions, and obtained the following conclusions, which are also certain for engineering practice and future research on rock fluid-solid coupling meaningful.

(1) Under the action of cyclic loading, the permeability characteristics of red sandstone show different laws under different stress stages. From the compaction section, the elastic section to the expansion section, the permeability of the rock gradually increases, and the sensitivity to cyclic loading also increases. In the compaction section, the loading frequency has a greater impact on the permeability change of the rock sample. The permeability of the rock sample gradually decreases with the increase of the loading frequency. When the loading amplitude increases from 5KN to 50KN, the permeability of the rock sample does not change significantly. The frequency is increased from 0Hz to 1.5Hz, and the permeability of the rock sample is reduced by at most an order of magnitude; In the expansion section, the permeability of the rock sample first decreases and then increases with the increase of the loading frequency. The loading amplitude has a greater impact on the red sandstone seepage rate, and the loading frequency remains unchanged. As the loading amplitude increases, the rock permeability increases Faster and faster, the destruction process will get faster and faster.

(2) Under the action of cyclic loading, the rock permeability is affected by the loading frequency and the loading amplitude. According to the test results and with reference to the existing research results on the influence of loading rate on seepage characteristics, from the perspective of the average concept, the average loading rate is used to characterize the loading frequency and loading amplitude, so that the single factor of permeability and loading rate is directly Related. For example, in the compaction section, the loading rate becomes faster as the loading frequency and loading amplitude increase, which restricts the recovery of strain and pores and the play of creep effects, so the permeability will be smaller.

(3) Based on nuclear magnetic resonance technology, the T2 relaxation time spectrum before and after the rock sample test and the two-dimensional distribution map of the internal pore structure of the rock (MRI image) are obtained. The mechanism of the red sandstone seepage change under periodic load is analyzed from the microscopic level, and the MRI image shows the trend is consistent with the trend of porosity, pore size development and permeability, And from the MRI image, it can be seen more intuitively than the T2 spectrum that the significant increase in the permeability of the rock sample is mainly due to the increase in the density of microcracks in the rock.

(4) According to the experimental results and nuclear magnetic resonance technology, comprehensively considering the movement of microscopic particles and macroscopic solid skeletons, the coupling mechanism of rock and pore water under different stress-strain stages and periodic loads is obtained. The mechanical response of the rock mass to the increase of porosity or the formation of cracks when the permeability changes. The influence of different periodic load parameters on the permeability of the rock sample is actually obtained by the influence of cyclic loads on the cracks and aperture.
References

[1] Brace WF, Walsh JB, Frangos WT. Permeability of granite under high pressure. *Geophys Res*. 1968, 73:2225-2236.

[2] Farquharson J, Heap M J, Varley, N R, Baud, P & Reusclé T. Permeability and porosity relationships of edifice-forming andesites: A combined eld and laboratory study. *Journal of Volcanology and Geothermal Research*, 1997, 52-68.

[3] Yang Feng, Wang Hao, Huang Bo, et al. Research on seepage characteristics and stress sensitivity of tight sandstone based on CT scan. *Journal of Geomechanics*, 2019, 3 (4): 475-482. (In China)

[4] Zhang LF, Zhou F J, Zhang S C, et al. Evaluation of permeability damage caused by drilling and fracturing fluids in tight low permeability sandstone reservoirs. *Journal Petroleum Science and Engineering*, 2019 (173): 1122-1135.

[5] Burdine, N. T. Rock failure under dynamic loading conditions. *Soc. Petr. Eng*. 1963, J. 3, 1-8.

[6] Yu Jin, Li Hong, Chen Xu, et al. Experimental study on permeability and acoustic emission of sandstone during unloading confining pressure deformation. *Journal of Rock Mechanics and Engineering*, 2014, 33 (1): 69-81. (In China)

[7] Cai Guojun, Feng Weiqiang, Zhao Daan, et al. Experimental study on deformation and damage mechanics of sandstone under triaxial cyclic loading. *Hydropower*, 2019, 22 (6): 1-6. (In China)

[8] Zheng Yi, Cao Junxing, He Xiaoyan. Research on time evolution law of fractal permeability of underground rock stratum after earthquake. *Journal of Geophysics*, 2018, 61(10): 244-253. (In China)

[9] Feng Chunlin, Wu Xianqiang, Ding Dexin, et al. Fatigue characteristics of white sandstone under cyclic loading. *Journal of Rock Mechanics and Engineering*, 2009, 28 (S1): 166-171. (In China)

[10] T. Wichtmann, A. Niemunis, T. Triantafyllidis. Strain accumulation in sand due to cyclic loading: drained triaxial tests. *Soil Dynamics and Earthquake Engineering*, 2005, 25 (12), 967-979.

[11] T. Wichtmann, A. Niemunis, T. Triantafyllidis. Improved simplified calibration procedure for a high-cycle accumulation model. *Soil Dynamics and Earthquake Engineering*, 2015, 70:118-132.

[12] Bagde M. N., Petrov V. Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading. *Elsevier Ltd*. 2004, 42 (2): 237-250.

[13] Xu Jiang, Wang Weizhong, Yang Xiugui, et al. Deformation test of fine-grained sandstone under cyclic loading. *Journal of Chongqing University (Natural Science Edition)*, 2004, 27 (12): 60-62. (In China)

[14] Xu Jiang, Xian Xuefu, Wang Hong, et al. Experimental study on deformation characteristics of rock materials under cyclic loading and unloading conditions. *Journal of Rock Mechanics and Engineering*, 2006, 25 (1): 3040-3045. (In China)

[15] Rhee D W, Teufel L W. Stress path dependence of matrix permeability of North Sea sandstone reservoir rock. *Proc. U.S. Rock Mech. Symp*. 1992, 33: 345-354.

[16] Ma L, Liu X, Wang M, Xu H, Hua R, Fan P, Jiang S, Wang G, YiQ. Experimental investigation of the mechanical properties of rock salt under triaxial cyclic loading. *Int J Rock
[17] Singh SK. Fatigue and strain hardening behaviour of Graywacke from the Flagstaff formation. *Eng Geol*, 26:171–179.