Experimental Investigation on Permeability Evolution of Granite Samples Containing a Grout Infilled Fracture under Triaxial Compression

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Abstract. Grouting has been widely used in rock engineering to improve the stability and strength of fractured rock mass, as well as to decrease the permeability of fractured rock mass. Fractures infilled with grout may endure different in-situ stress conditions during the construction and operation life of tunnels and other underground spaces in fractured rocks. To study the stress induced changes in permeability of fractures infilled with grout, we carried out triaxial compression tests on the fractured rock samples infilled with grout, during which the permeability of fractured rock samples was measured. Both planar and rough fractures with different apertures were tested. The results showed that the permeability of infilled fracture samples increases with increasing grout width, but the strength of infilled fracture samples decreases with increasing grout width. The evolution of permeability is highly related with the volumetric strain. The permeability decreases slightly with increasing deviatoric stress from 0 to crack damage stress, followed by drastic enhancement in permeability with further increasing deviatoric stress. The sample’s permeability is enhanced by about 5~10 times at the peak deviatoric stress compared with the initial value at 5MPa deviatoric stress.

1. Introduction
Grouting is an effective method to reduce the permeability of fractured rock mass and to enhance the stability of tunnels and wellbores (Zhang 2014, Li et al. 2016). During the construction and operation life of different underground engineering in fractured rock mass, engineering or naturally caused changes in in-situ stresses may influence the mechanical response of grout infilled fractures in terms of crack initiation, propagation and coalescence, which can induce significant improvements in the permeability of grout infilled fractures (Zhao and Zhou 2016). This is one of the main reasons that trigger inflow disasters in tunnels, storage caverns, or many other underground engineering.

Considering the importance of practical rock permeability, many previous studies focused on the permeability of rocks in triaxial compression (Li et al. 1997, Yu 2019). Li et al. (1997) firstly studied the permeability of sandstone during full stress-strain process, summarizing the relationship between permeability coefficient and permeability curve. Seven permeability characteristic points (minimum permeability, elastic section permeability, elastic-plastic section permeability, peak stress permeability, strain softening section permeability, plastic flow section permeability and maximum permeability)
were proposed, which could describe the permeability process more clearly. Yu et al. (2016) tested the permeability of sandstone samples containing a single joint filled with gypsum under triaxial compression, and found that the fracture inclination angles have a great influence on the specimen’s permeability. With the development of subsea tunnels and deep underground engineering, the permeability of fractured granites becomes a hot topic (Brace et al. 1968, Liu et al. 2016). The permeability of rock fractures infilled with granular materials is mainly determined by the porosity and its granulometric composition of the granular materials, so fractures infilled with fine-grained gouge show lower permeabilities than those infilled with medium- or coarse-grained gouge (Wang et al. 2016). Although the permeability of rock fractures infilled with granular materials (e.g., fault gouge, quartz sands) has been studied in the past, the experimental studies on the permeability of grout infilled rock fractures is rare. So far, the evolution process of permeability of rock fractures infilled with grout during the complete stress-strain process under triaxial compression has not been investigated to the authors’ best knowledge.

The main objective of this experimental study is to investigate the changes in the permeability of granite fractures infilled with grout during the complete stress-strain process under triaxial compression of a confining pressure of 5 MPa. Excavation always disturbs the original in-situ stress field in the preliminary grouted zone of subsea tunnel, which leads to stress redistribution around the excavation face, and the fractured rocks infilled with grout may be subjected to different stress conditions on the complete stress-strain curves (Figure 1). Therefore, a clear understanding of the evolution process of permeability of grout infilled fractures with different stress is critical. In this study, we considered two types of grout infilled granite fractures with planar or rough surfaces, the permeability of which was tested using a MTS 815 rock mechanics testing system.

![Figure 1. Stress state on the grout infilled fractures in the vicinity of a subsea tunnel. (left) Schematic diagram of the position of grout infilled fractures with different stress conditions, (right) Photos of grout infilled fractures taken in Kiaochow Bay subsea tunnel, Qingdao, China.](image)

2. Method

2.1. Sample preparation

To study the influence of infilled grout on fluid flow through rock fractures, it is important to avoid the effect of the matrix permeability as much as possible (Gao et al. 2019). Jinan granite from Shandong, China, was therefore selected in this study because of its low matrix permeability of $1.4 \times 10^{-20}$ m². Ordinary Portland cement (OPC), grade P.O. 42.5, is selected as the infilling material, with an average
The density of 1744 kg/m$^3$. The permeability of grout sample under triaxial compression is suggested as 7.9×10$^{-17}$ m$^2$.

Two types of infilled fractures with planar and rough surfaces are considered in this experiment, and one unfilled fracture sample with planar surfaces is also included as the reference. Planar fractures were manufactured by cutting along the middle plane of the cuboid granite blocks and polishing them using an ultrafine sandpaper with 23 μm particle size. Rough fractures were generated by axially splitting the granite blocks along the middle planes. Grout with water-to-cement ratio of 0.6 was adopted to provide high workability during grouting and ensure the fracture infilling strength.

Planar fractures were manufactured by cutting along the middle plane of the cuboid granite blocks and polishing them using an ultrafine sandpaper with 23 μm particle size. Rough fractures were generated by axially splitting the granite blocks along the middle planes. Grout with water-to-cement ratio of 0.6 was adopted to provide high workability during grouting and ensure the fracture infilling strength. To prepare “sandwich” samples including grout with a designed width, steel sheets with thickness of 2, 5, and 8 mm were inserted to the both lateral sides of the fractured rocks. The grouted fracture samples were then cured in the environment at a temperature of 20 ± 2 °C and relative humidity of 95% for 28 days. Lastly, Core plugs were saw cut to a diameter of 50 mm and a height of 100 mm (Figure 2). The samples were numbered as “unfilled”, “P2, P5, and P8”, and “R2 and R8”, where “P” and “R” represent planar and rough fracture surfaces, and numbers “2, 5, 8” represent grout thickness respectively.

2.2. Experiment procedure

In this study, the following test procedure was designed. Before test, fracture samples were saturated within deionized water for 24 h. The fracture samples were jacketed by a 0.5 mm-thick Teflon heat shrinkage tube, and then binded by five stainless steel wires. The jacketed sample assembly was placed inside the pressure vessel, and the hydrostatic pressure of 5 MPa was applied on the fractured rock samples. In the succedent steps, a constant confining stress ($P_c$) of 5 MPa was applied, and the axial stress increased in the displacement-controlled mode with the strain rate of 0.005 mm/s. From this stage, the sample permeability was measured until the peak stress was reached. For each permeability test, the hydraulic pressure of 2.2 MPa was applied on both upper and bottom ends. The hydraulic pressure at top end surface was descended to 0.2 MPa, in order to generate a pressure gradient between the two end surfaces. The deionized water at the bottom end of the sample flowed toward the top end, passing through inside of the rock sample. Using the recorded $\Delta P$–$t$ curve (Figure 3), the value of rock sample permeability was calculated according to Eq. (1). Note that the load was kept constant when performing the permeability measurement. It took about 3 mins to 30 mins for each permeability measurement.

$$k = \frac{c_f B H \mu}{2tA} \ln \frac{\Delta P_r}{\Delta P_f}$$

where $k$ is the permeability of sample, $c_f$ is the compressibility of deionized water, $B$ is the reference volumes, $H$ is the specimen length, $\mu$ is the viscosity of deionized water, $t$ is the duration time of the test,

Figure 2. the unfilled sample (left), and grout infilled sample (right)

Figure 3. the hydraulic pressure difference varied with time are recorded with test time, and the fitting curve is used to calculate rock permeability.
A is the cross sectional area of sample, \(\Delta P_f\) is the steady hydraulic pressure difference between the top and bottom ends of the fractured rock specimen. During permeability measurements, the \(\Delta P-t\) curve was automatically recorded by the computer, e.g., the example showed in Figure 3. The sample permeability is calculated through curve fitting based on Eq. (1), and the parameters \(c_f = 453 - 12\ \text{Pa}\), \(B = 175 \text{cm}^3\), \(H = 100 \text{ mm}\), \(\mu = 1 - 3\ \text{Pa} \cdot \text{s}\), \(A = 19.625 \text{ cm}^2\), \(\Delta P_0 = 2.0 \text{ MPa}\), and \(\Delta P_f = 0.5\text{MPa}\).

3. Results

3.1 Volumetric strain and permeability

All the rock samples infilled fractures exhibited a similar volumetric strain variation in Figure 4, except for the unfilled one in which case volumetric strain was failed to measure. The crack damage stress is generally defined as the point where volumetric strain reversal occurs and unstable crack growth begins (Cai et al. 2004). The crack initiation stress values were determined for each of the five specimens using the LSR method (Nicksiar and Martin 2012), and the calculation process of crack initiation stress of P5 sample were showed in Figure 4 in detail. First, determine the crack damage stress point by the volumetric strain showed in Figure 5. Second, determine the linear lateral strain reference line. Third, find the horizontal distance \(\Delta x\) between lateral strain and linear reference line. Then, plot the \(\Delta x\) versus the deviatoric stress. Finally, determine the maximum horizontal distance \(\Delta x\) and the associated deviatoric stress. All the five crack initiation stresses and crack damage stresses were summarized in Table 1.

![Figure 4. Example of the methodology used to calculate the crack initiation stress of sample P5 using the lateral strain response (LSR). Orange ball is the crack damage stress. (left) Illustration of the LSR methodology and (right) the LSR result of sample P5.](image)

| Different thickness | Unfilled | P2 | P5 | P8 | R2 | R8 |
|--------------------|---------|----|----|----|----|----|
| Peak deviatoric stress/MPa | 210.32 | 195.6 | 181.2 | 163.1 | 193.3 | 164.3 |
| Crack initiation stress/MPa | / | 60.5 | 68.8 | 76 | 73 | 80 |
| Crack damage stress/MPa | / | 148.2 | 135.4 | 120.0 | 145.1 | 119.3 |
| Crack damage stress/Peak | / | 0.75 | 0.74 | 0.74 | 0.75 | 0.74 |
| Sample permeability/10^{-18}\text{m}^2 | 78.56 | 1.82 | 3.03 | 17.37 | 1.52 | 4.38 |

It was also clear that the variation of volumetric strain of the infilled fracture was highly related with the variation of the sample permeability. The volumetric strain of infilled sample can be considered as a macroscopic index of the microscopic cracks process, and the changes of microscopic cracks cause the sample’s permeability varied, so the volumetric strain can be adopted to predict the permeability change under different deviatoric stress approximately.
3.2 Mechanical behavior and permeability

Initial permeability measurements were made on unfilled (no grout) fractured samples at effective pressures of 5 MPa as a baseline. Measurements were then repeated on the same samples but filled with different thick layers of grout. Table 1 lists the permeabilities of six samples under deviatoric stress of 5 MPa. Compared with grout infilled fractures, the unfilled one showed the highest compressive strength of 210.32 MPa and the highest permeability of $7.86 \times 10^{-17}$ m$^2$. With the grout thickness increasing, the compressive strength of the infilled fissures decreased, while the permeability of rock samples increased. For example, in planar group, P8 showed the lowest stress 161.9 MPa and highest permeability $1.74 \times 10^{-17}$ m$^2$. Because of the weakness of grout, the increased thickness of grout decreased the strength of the sample. Under the same grout thickness, both the planar and rough infilled fractures exhibited the similar strength, however the permeability of the former was larger than that of the latter.

![Figure 5](image_url)

**Figure. 5.** Evolution of deviatoric stress, volumetric strain and sample permeability as a function of axial strain. (Orange circles and blue stars on the stress-strain curves represent the crack initiation stress and crack damage stress respectively.)
The curves of axial deviatoric stress, volumetric strain and permeability versus axial strain for six samples were plotted in Figure 5. It’s clear that the deviatoric stress increased almost linearly with axial strain before reaching the peak, and declined steeply after the peak showing the softening. A nonlinear relationship between permeability and axial pressure was observed. For grouted samples, as the deviatoric stress increased, the permeability would decrease at first, then it changed a little over the pressure range from 25 MPa to crack damage stress showed in Table 1 and Figure 5. When the pressure was less than 60 MPa, the sample’s permeability was in the permeability of elastic region; and the sample’s permeability began to improve which was in the elasto-plastic region; then the pressure was near peak, the sample’s permeability increased drastically (about five times of the initial value). The results of the permeability evolution were similar to other authors’ work (Li et al., 1997; Zhang et al., 2000). However, the permeability of unfilled rock showed randomly fluctuated with the increasing stress. When the pressure exceeded the peak, the loading capacity of crisp granite descend rapidly, and the permeability was hardly to test, so the permeability of strain-softening region was not shown.

The normalized permeability $K_n$ was defined as the ratio of measured permeability $k$ with that at the deviatoric stress of 5 MPa, and the change of $K_n$ with the deviatoric stress was presented in Figure 6. It showed that $K_n$ of the unfilled fracture fluctuated in a narrow scope varied between 0.7 and 1.2, which was not sensitive to the deviatoric stress. The changes in $K_n$ of infilled fractures with the deviatoric stress can be divided into two stages: fluctuant stage and rapidly increased stage. The stage I was dominated below the crack damage stress showed as the blue stars in Figure 4 and $K_n$ varied between 0.2 and 2.0. In this stage, the sample became more closed with the increasing deviatoric stress (before the crack initiation stress) and the sample’s permeability decreased as the seepage channel narrowed. When the deviatoric stress was between the crack initiation stress and the crack damage stress, minor cracks appeared but didn’t connected together which only caused some slight improvement in the permeability. The stage II occurred above the the crack damage stress, and $K_n$ increased to about 10 at the peak deviatoric stress. In this stage, much cracks came into being and connected together which triggered drastic increase in the permeability.

4. Conclusions
In this experiment, we studied the permeability evolution of both unfilled and grout infilled fractures under triaxial compression of 5 MPa confining pressure, some conclusions are drawn below.
1) With the grout thickness increasing, the compressive strength of the infilled fracture decreases, while the permeability of rock sample increases, and the permeability of the planar group is lower than the rough group under the same grout thickness.
2) The volumetric strain of infilled sample can be considered as a macroscopic index of the microscopic

Figure 6. Evolution of normalized permeability ($K_n$) with the increasing deviatoric stress.
cracks process, and the changes of microscopic cracks cause the sample’s permeability varied. the variation of volumetric strain is similar with the evolution of permeability.

3) The permeability of grout infilled sample shows the lowest permeability around the crack initiation stress and changes in a narrow band below the crack damage stress, but it increases drastically when the deviatoric stress is over crack damage stress showing 5–10 times at the peak deviatoric stress.

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