

DIFFUSION CHARACTERISTICS OF GROUT IN LAYERED FAULT MEDIUM

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ABSTRACT

The grouting method has been widely adopted to improve the soft and broken ground properties in tunnelling engineering. This paper carries out numerical and experimental investigation to study the diffusion characteristics of grout in layered fault, considering the influence of flowing water and multiple injections. The fault is simplified to consist of (1) fault gouge, (2) fault breccia and (3) mixed area. It can be concluded that the grout shows significantly different diffusion characteristics in fault breccia and mixed area, moreover, due to the scouring effect of flowing water, grout has greater diffusion tendency in the direction of the water. In the case of single injection, the grout diffusion distance in mixed area was between 75.86 % and 88.10 % of that in fault breccia, while it was 59.8 % when multiple injections were carried out. It appeared that, the higher the injection pressure, the grout diffusion priority in fault breccia is greater. It can be also concluded that the pressure dissipated gradually from the injection hole to periphery, and the pressure dissipation in mixed area is faster than that in fault breccia. The results of experiment match reasonably well with numerical simulation, furthermore, the grouting reinforcement mode for layered fault medium are proposed. These conclusions can be used to better understand grouting theory.

KEYWORDS

Grouting, Layered fault medium, Grout diffusion characteristics, Reinforcement mode

INTRODUCTION

With the rapid development of tunnelling and underground engineering in China, weak rock masses such as fault which tends to have complex lithology, rich groundwater and low strength, are commonly encountered by excavation, resulting in susceptibility to groundwater and mud inrush [1,2].

For safety purposes, the grouting method [3,4] has been one of the most popular methods that used to improve the permeability and strength resistance of fault, and to avoid associated negative effects. However, due to its high complexity, our current understanding of grout diffusion theory [5] especially for fault is still limited and therefore, there is a lack of an effective theoretical framework for grouting scheme design.

To our knowledge, by using theoretical, numerical and experimental approaches, current studies on grout diffusion theory have focused on the interaction between grout and medium, description of diffusion mode as well as calculation of diffusion radius, and also the influence of key

factors including injection pressure, injection rate and grout properties on them. For example, Houlsby [6] presented a model to describe the propagation of grout in a single fracture. Gothäll and Stille [7], Eisa [8], and Tirupati [9] investigated the grout diffusion characteristics in porous media by adopting model experiment. Silas and Deborah [10], Adam [11,12] proposed theoretical models for compensation grouting in sand, which can be used to calculate the width-to-length ratio of the fracture induced in the grout injection.

Various researchers and engineers have contributed to further increase our understanding of grout diffusion theory. However, little is known about grout diffusion characteristics in layered fault medium, especially taking into consideration the influence of flowing water and interaction between multiple injections.

This study aims to obtain knowledge on the propagation of grout in layered fault medium, under the influence of flowing water and multiple injections. With the purpose of simplifying complicated geological conditions in engineering, a simplified model for layered fault medium is proposed and adopted in this investigation.

SIMPLIFIED GROUTING MODEL

Engineering situation

Yonglian tunnel [13, 14] with a length of more than 2500 m is located at Lian’hua City, in Jiangxi Province, China, with a lot of faults and secondary faults such as fault-2. With rich groundwater, strong weathered sandstone and shale, the fault-2 tends to have low strength and has induced a large number of groundwater and mud inrush during excavation, seriously threatening the safety of tunnel construction. Therefore, it is very necessary to reinforce weak rock masses by grouting method to meet the requirements of tunnel excavation.

After carrying out geological prospecting by boreholes, it was found that the fault medium was mainly composed of fault breccia and fault gouge, with significant stratification phenomenon. To simplify the complicated geological conditions of fault-2, a simplified model consisting of fault gouge, fault breccia and mixed area, named as the grouting model for layered fault medium, is proposed, as shown in Figure 1. In addition, the conditions including flowing water, single grouting as well as multiple grouting (three holes), are taken into consideration.

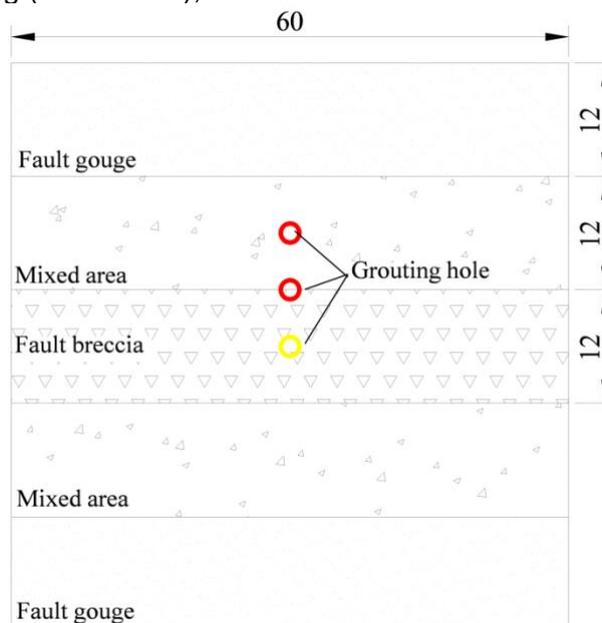


Fig. 1 – Schematic diagram of the grouting model for layered fault medium (unit: cm)

By performing in-situ sampling and laboratory tests, the properties of layered fault medium were measured and are therefore summarized in Table 1.

Tab.1 – Properties of layered fault medium

Medium type	Porosity	Permeability (m ²)	Density (kg/m ³)
Fault breccia	0.5	1e-10	2.2e3
Fault gouge	0.3	2.89e-13	1.85e3
Mixed area	0.4	1e-11	1.95e3

Software selection and control equation

On the basis of finite element method, the COMSOL Multiphysics [15], has been one of the most popular software that used to better calculate, describe and simulate various physical phenomena, by solving partial differential equations under the conditions of multi-physics coupling. This paper selected the porous media and groundwater flow Darcy's law, which belongs to the fluid flow module, to carry out related numerical analysis.

The basic assumptions of two-phase seepage Darcy's law are as follows.

- (1) The injected medium is homogeneous and isotropic, which cannot be compressed.
- (2) The groundwater flow and grout, which are taken as incompressible Newtonian fluid, are assumed to follow the Darcy's law in the seepage process.
- (3) The influence of gravity and capillary water pressure are not taken into consideration.

Equation 1 and Equation 2 [16] show the control equations of two-phase seepage Darcy's law under two-dimensional conditions.

$$-\frac{K_0}{\mu_0} \left[\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right] = \phi \frac{\partial (S_0)}{\partial t} \quad (1)$$

$$-\frac{K_w}{\mu_w} \left[\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right] = \phi \frac{\partial (S_w)}{\partial t} \quad (2)$$

Where K_0 = permeability coefficient of grout; K_w = permeability coefficient of water; μ_0 = viscosity coefficient of grout; μ_w = viscosity coefficient of water; p = pressure tensor; S_0 = saturation of grout; S_w = saturation of water, and $S_0 + S_w = 1$; ϕ = porosity of injected medium.

Calculation model and boundary conditions

Generally, the fault in actual engineering tends to have a large size. However, in order to verify the rationality and correctness of numerical simulation results, model experiment should be performed and therefore, the sizes of models that adopted in numerical simulation and model experiment should be consistent.

Taking into account the feasibility of the model experiment, the two-dimensional square calculation model with the dimensions of 60 cm × 60 cm was adopted, as shown in Figure 1 and

Figure 2. The calculation model was equally divided into five parts: (1) fault gouge; (2) mixed area; (3) fault breccia; (4) mixed area and (5) fault gouge.

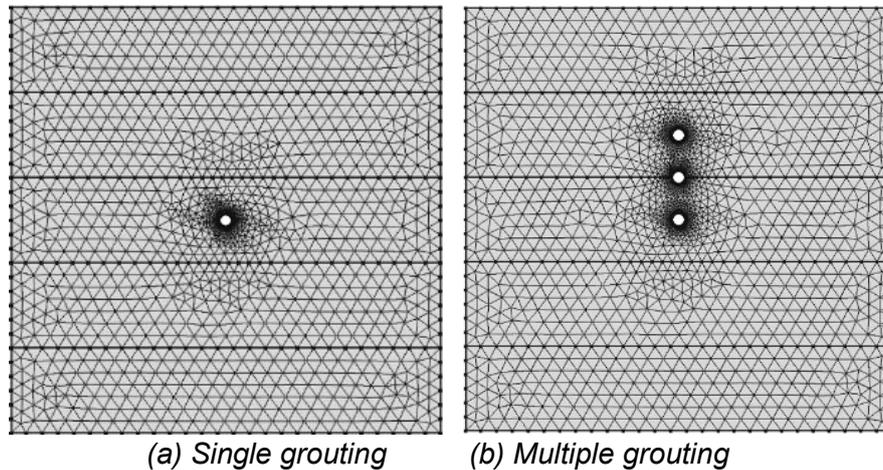


Fig. 2 – Calculation model

In the case of single grouting, the grouting hole with a radius of 1 cm was located at a depth of 30 cm from the upper boundary, and when multiple grouting was performed, the other two grouting holes were located at a depth of 18 cm and 24 cm from the upper boundary, respectively.

The freedom triangular grid was applied, moreover, the grid around the grouting holes was densified to improve calculation accuracy.

Based on the actual conditions of both engineering and experiment, the upper boundary was set for a stable water head with a height of 2 m, and the lower boundary was the exit boundary. In addition, the left and right boundary were impermeable.

Grouting parameters selection

The cement and sodium silicate grout (abbreviated as C-S grout), which is one of the most common grout in engineering, was selected for both numerical simulation and experiment, ignoring the influence of the time-varying characteristics of viscosity. Table 2 shows the properties of water and C-S grout.

Tab.2 – Properties of water and C-S grout

Materials	Density (kg/m ³)	Viscosity (Pa·s)
C-S grout	1500	0.06
Water	1000	0.001

According to the actual engineering conditions and equipment performance, the simulation of grout diffusion characteristics in layered fault medium was carried out at a total of four injection pressure levels ($p = 0.6$ MPa, 0.8 MPa, 1 MPa and 1.2 MPa).

Numerical simulation results and analyses

Results of single grouting

Diffusion mode of grout

By using the volume fraction method to describe the distribution of grout, when $t = 10$ s, 30 s, 50 s, 90 s, 130 s and 200 s, respectively, the diffusion mode of grout is shown in Figure 3.

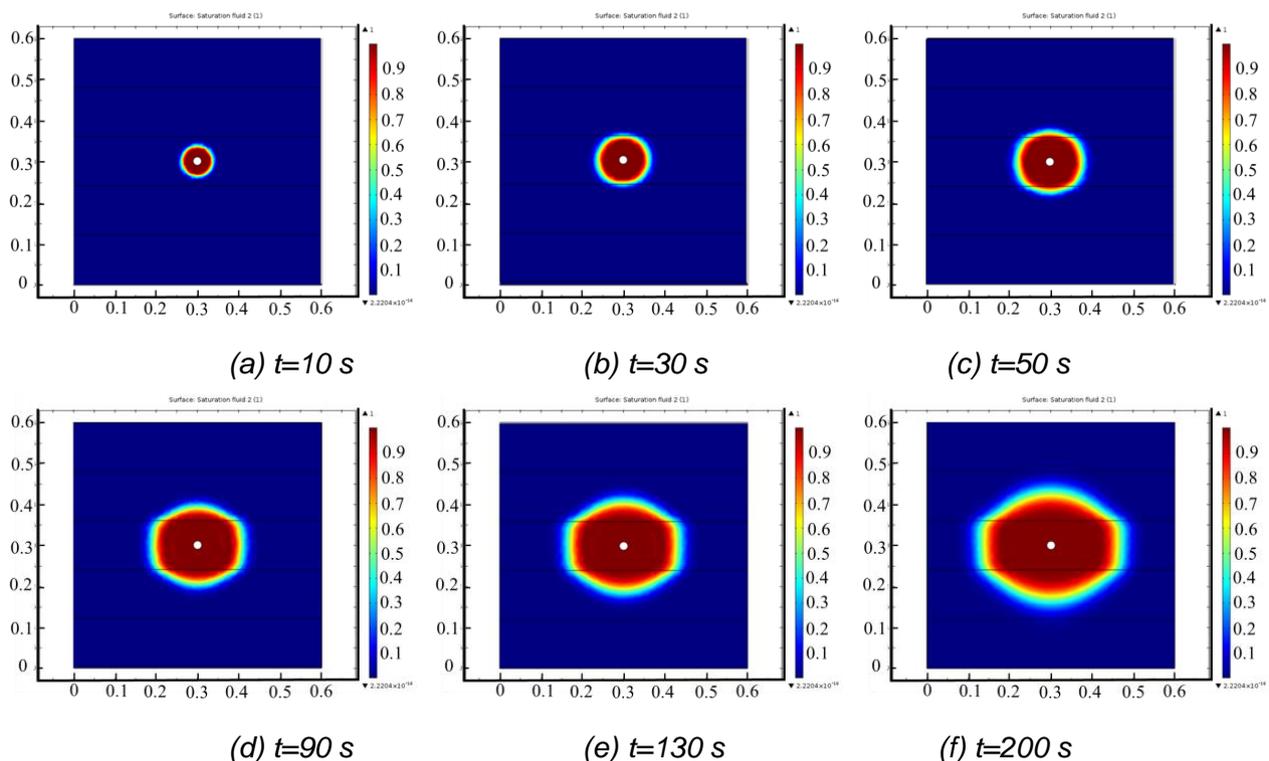


Fig. 3 – Diffusion mode of grout at different times

The grout diffusion characteristics in fault breccia and mixed area is summarized as follows. In the initial stage, the grout propagates in fault breccia with an approximately circular shape and a high velocity (Figure 3a). The boundaries between the fault breccia and mixed area start to play a controlling role for the propagation of grout from 30 s (Figure 3b), resulting in a lower propagation velocity in mixed area. Therefore, due to different propagation tendency and velocity, the grout shows significantly different diffusion characteristics in fault breccia and mixed area from 30 s to 200 s.

The influence of injection pressure on final diffusion mode of grout

Figure 4 shows the final diffusion mode of grout under the conditions of four injection pressure levels ($p = 0.6$ MPa, 0.8 MPa, 1 MPa and 1.2 MPa).

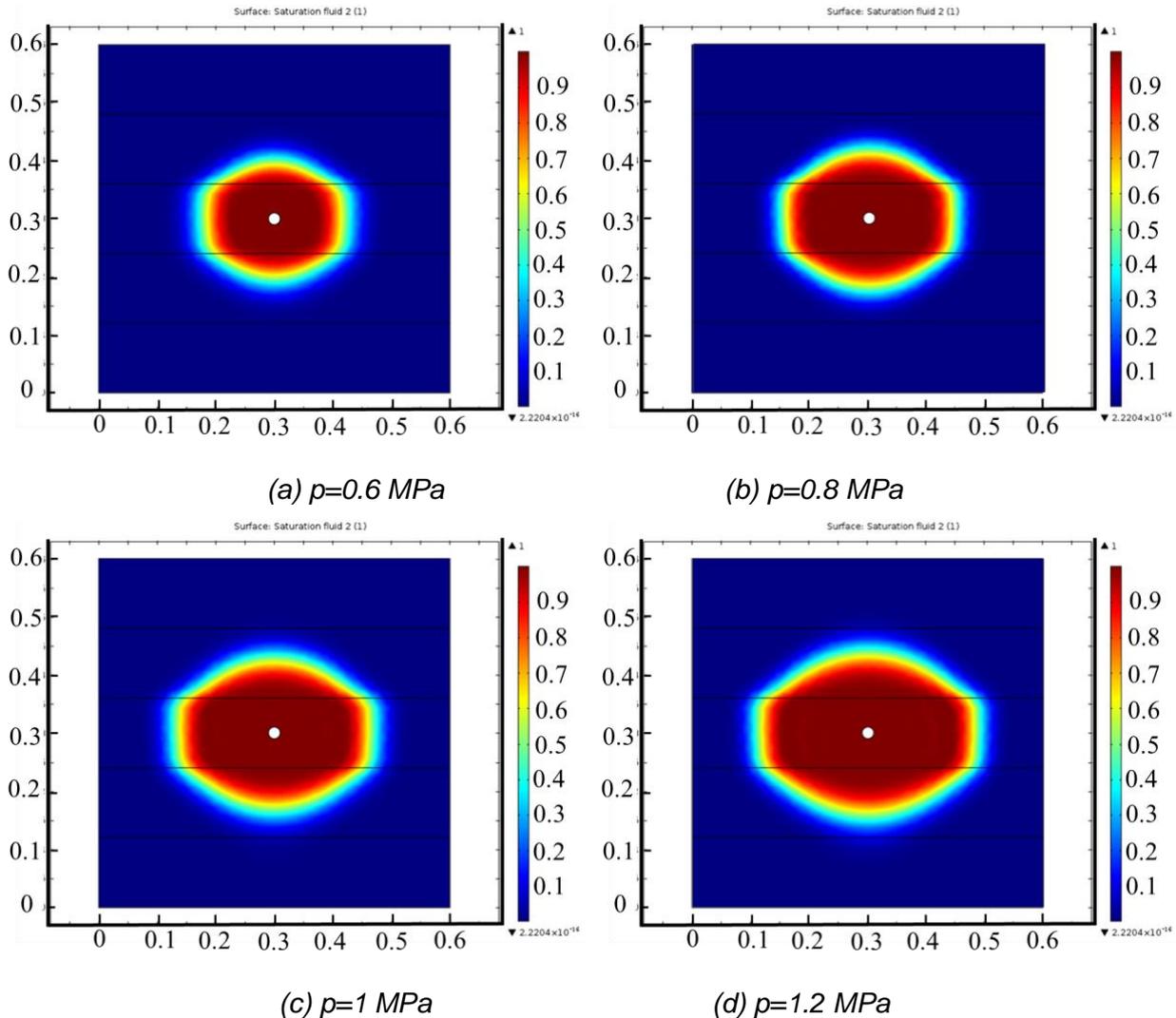


Fig. 4 – Final diffusion mode of grout under four injection pressure levels

It can be concluded from Figure 4 that the grout preferentially propagate in fault breccia, followed by the mixed area. In addition, due to low porosity and injection pressure, as well as far from the grouting hole, the propagation tendency of grout in fault gouge is not obvious. Therefore, in order to characterize this kind of difference of grout propagation, the concepts of (1) diffusion distance in fault breccia (S_b), (2) diffusion distance in mixed area in the reverse direction of the water (S_{m1}), (3) diffusion distance in mixed area in the direction of the water (S_{m2}) and (4) diffusion distance difference (S_d) are proposed, respectively, whose schematic diagram are shown in Figure 5. Moreover, it is noted that S_d refers to the difference between diffusion distance in fault breccia and diffusion distance in mixed area.

The values of S_b , S_{m1} , S_{m2} and S_d versus injection pressure are also shown in Figure 5.

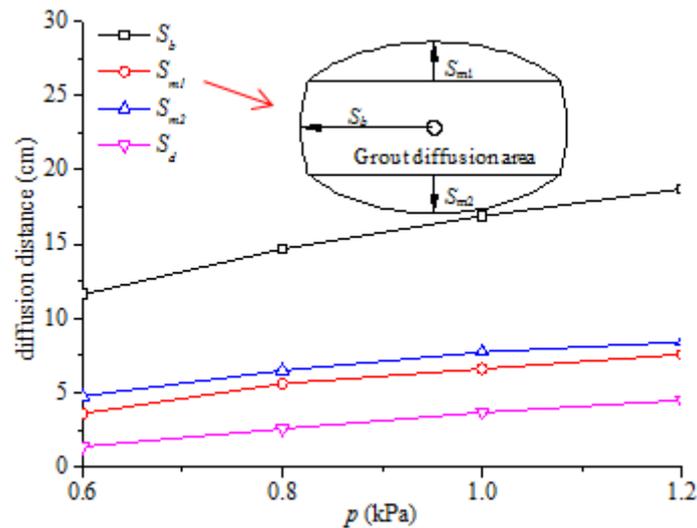


Fig. 5 – The values of S_b , S_{m1} , S_{m2} and S_d with injection pressure varying

It can be found that the values of S_b , S_{m1} and S_{m2} increase gradually with injection pressure increasing. For example, as the injection pressure increases from 0.6 MPa to 1.2 MPa, the values of S_b , S_{m1} and S_{m2} increased by 109.82 %, 76.22 % and 60.98 %, respectively, which is because increasing injection pressure provides greater driving force for grout propagation.

The values of S_b and S_d vary between 11.63 and 18.71 cm, 1.38 and 4.52 cm, respectively, indicating that the higher the injection pressure, the grout diffusion priority in fault breccia is greater. In general, the grout diffusion distance in mixed area is between 75.86 % and 88.10 % of that in fault breccia, and this is because the fault breccia tends to have better inject ability, with higher porosity and permeability.

Besides, under same injection pressure conditions, the value of S_{m1} is less than that of S_{m2} , for example, they are 6.62 cm and 7.75 cm respectively when the injection pressure is taken as 1 MPa, i.e. grout has greater diffusion tendency in the direction of the water, which is caused by the scouring effect of flowing water.

Pressure dissipation in layered fault medium

Figure 6 shows the pressure contours in layered fault medium under the conditions of four injection pressure levels. It is found that the pressure dissipates gradually from the injection hole to periphery, and this is because the grout need to overcome the influence of pore water pressure, viscous resistance, frictional resistance and other factors in the process of propagation. Moreover, in comparison with fault breccia, the pressure contours in mixed area are denser, indicating that the pressure dissipation velocity in mixed area is higher, which is caused by greater resistance.

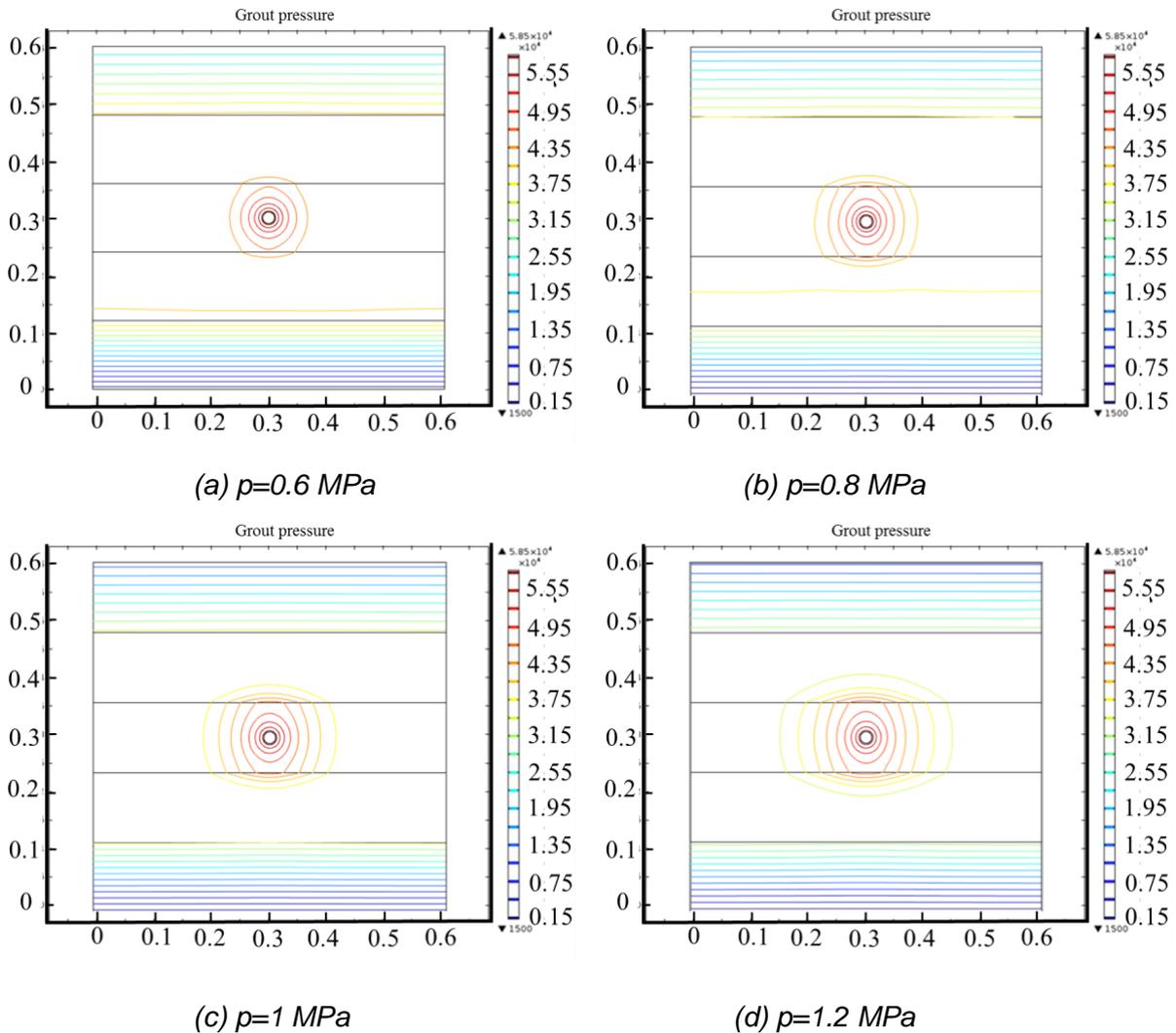


Fig. 6 – The pressure contours in layered fault medium

Results of multiple grouting

In actual engineering, multiple grouting is commonly carried out to get greater reinforcement range and better reinforcement effect. Due to different locations of grouting holes and geological conditions, the grout tends to show different diffusion characteristics. Therefore, simulation is performed to investigate the diffusion characteristics of grout in multiple grouting.

Multiple grouting is carried out synchronously, with the injection pressure set as 1 MPa, also taking into the consideration the effect of flowing water. Figure 7 shows the diffusion mode of grout at different times. It can be found that the grout still showed significantly different diffusion characteristics in fault breccia and mixed area, which is summarized as follows.

Both in fault breccia and mixed area, the grout propagates with an approximately circular shape, whereas the former has a larger diffusion range, e.g. when $t=10 \text{ s}$, their diffusion ranges are 311 cm and 2.29 cm, respectively. The grout from three grouting holes begins to intersect and interact with each other from 50 s, and the grout from boundary hole reaches the range that other two holes cannot cover. Finally, the effective diffusion distance of grout in fault breccia is 13.89 cm, whereas it is 8.31 cm in mixed area.

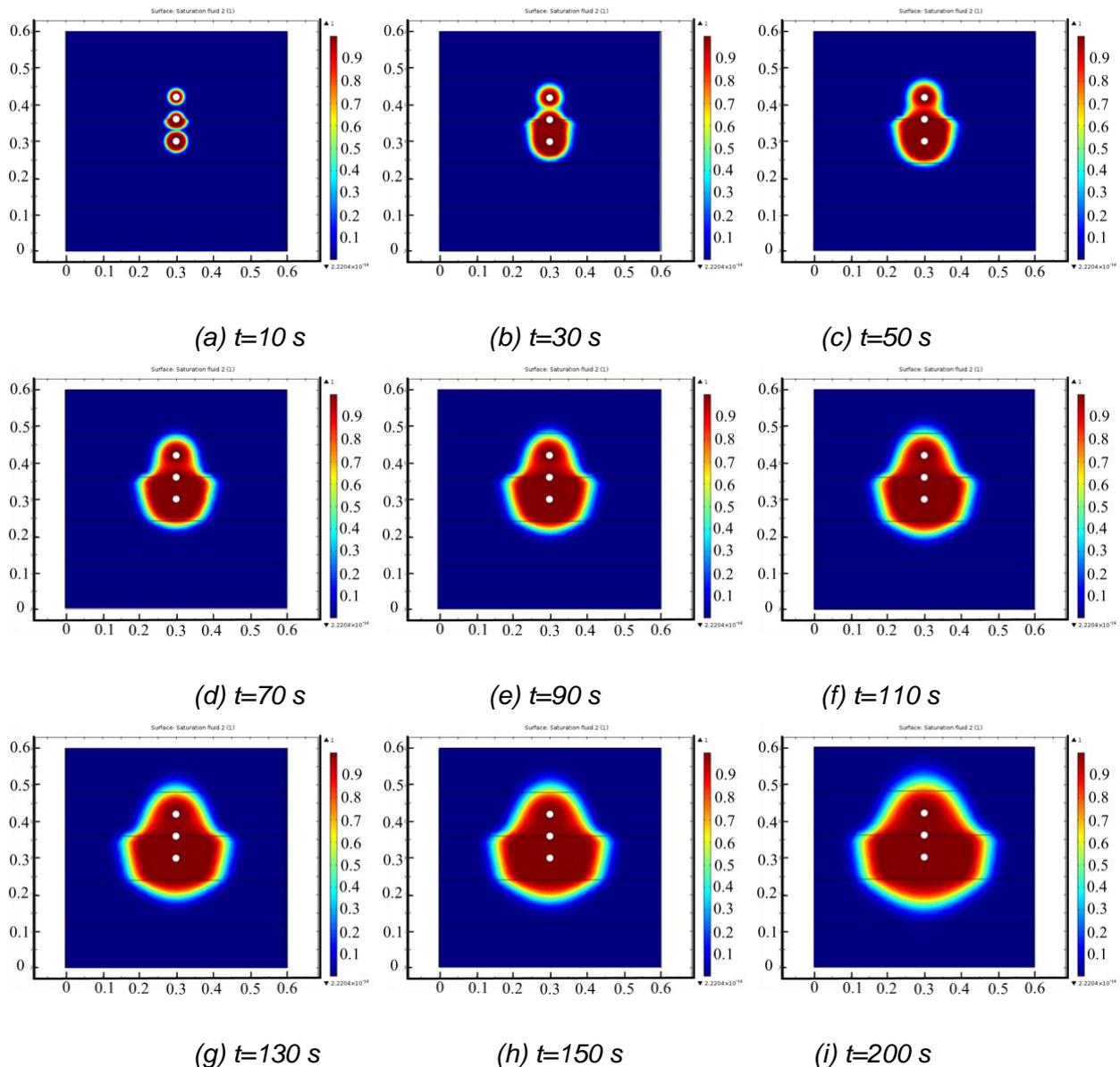


Fig. 7 – Diffusion mode of grout at different times in multiple grouting

EXPERIMENTAL INVESTIGATION

Experimental set-up

Figure 8 shows a picture of the experimental set-up, which is composed by (1) grouting equipment, (2) data acquisition system, (3) layered medium simulation device and (4) water supply device. A manual pump was used to carry out grouting with small velocity and high pressure. Data acquisition system consists of soil pressure transducers, pore pressure transducers and matched data acquisition equipment.



Fig. 8 – Picture of the experimental set-up

For the sake of convenience for assembling, filling medium and excavation after grouting, the layered medium simulation device is composed of three cells (inside dimensions: 60 cm × 60 cm × 20 cm), which is made up of steel plate with a thickness of 1 cm. In addition, to meet the requirements of bearing high pressure, the cells were fixed by high strength bolts and sealed by sealant.

Two reservoirs with a volume of 15 L were positioned above the layered medium simulation device at a height of 2 m, providing stable flowing water conditions.

Experimental design and materials

Materials including fault breccia and fault gouge used to simulate the layered fault medium were obtained from Yonglian tunnel, whose grain composition and properties are shown in Table 3 and Table 4, respectively. The mixed area was made up of fault breccia and fault gouge with a ratio of 1:1.

Tab.3 – Properties of fault gouge [17,18]

Optimum moisture content (%)	Maximum dry density (g · cm ⁻³)	Liquid limit (%)	Plastic limit (%)	Plasticity index
23.1	1.7	48.3	25.6	22.7

Tab.4 – Grain composition of fault breccia

Grain size (mm)	2.5 ~ 5	1.25 ~ 2.5	0.63 ~ 1.25	0.315 ~ 0.63	0.16 ~ 0.315	0.08 ~ 0.16	< 0.08
Content (%)	74.03	69.41	54.70	33.36	13.18	9.03	1.43

The fault gouge, mixed area and fault breccia were filled into the layered medium simulation device in sequence, ranging from (1) 0 ~12 cm, (2) 48~60 cm and 24 ~ 36 cm, (3) 12~24 cm and 36~48 cm.

Consistent with the numerical simulation, C-S grout (1:1) was selected for experimental investigation, which was injected into the container through single grouting hole, with an injection pressure of 1 MPa, as shown in Figure 9.



Fig. 9 – Picture of grouting process

Experimental results

Diffusion mode of grout

Excavation was carried out after curing of 24 hours and therefore, the diffusion mode of grout is shown in Figure 10.



Fig. 10 – Picture of grout diffusion mode

With an injection pressure of 1 MPa, the values of S_b , S_{m1} and S_{m2} are shown in Table 5.

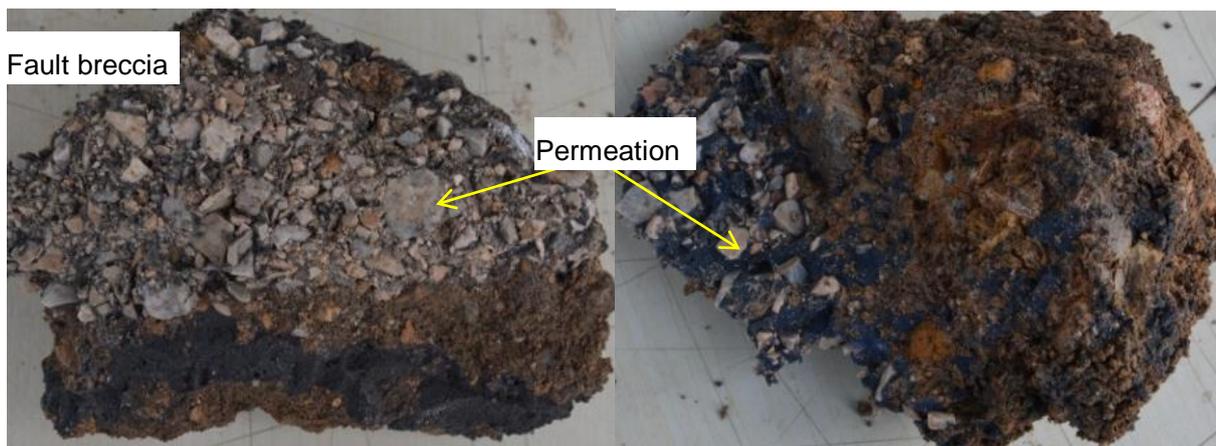
Tab.5 – Comparison of numerical and experimental results

Type	S_b (cm)	S_{m1} (cm)	S_{m2} (cm)
Numerical results	16.89	6.62	7.75
Experimental results	30	7.85	8.38

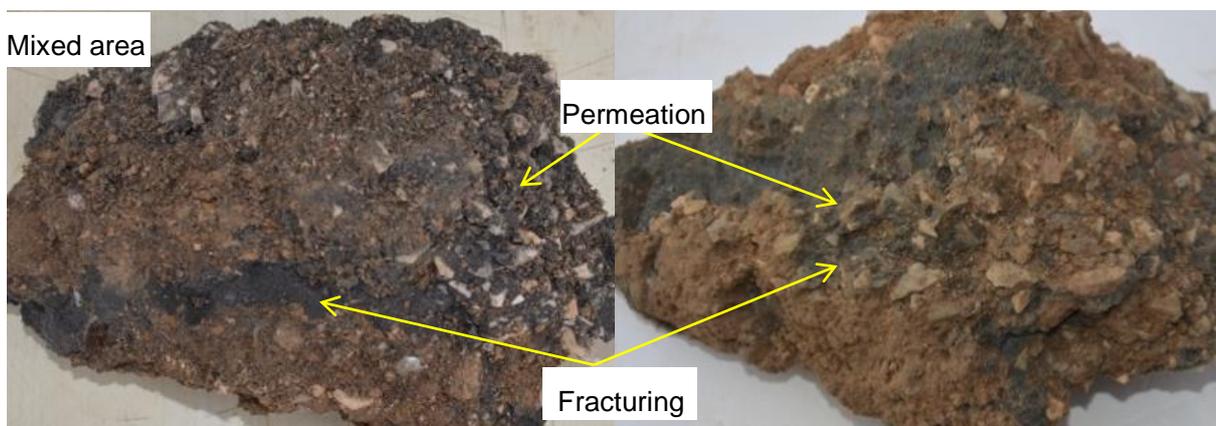
It can be concluded from Table 5 and Figure 10 as follows. In the longitudinal direction, the experimental and numerical results are approximate, with the former 15.7 % and 7.6 % larger than the latter. However, there was an obvious boundary effect in the transverse direction (S_b), with the experimental results significantly larger than the numerical results. This is because it is difficult to ensure the uniformity of materials when filling into the container, resulting in possible weak interface in which grout will preferentially propagate. However, as a whole, the experimental results agree with the numerical results well, i.e. the grout preferentially propagate in fault breccia, followed by the mixed area.

Reinforcement mode of grout

By excavation, it can be also found that grout has different reinforcement mode for fault breccia and mixed area, which has been classified into two types as follows. Due to large porosity, grout penetrates into the fault breccia to cement particles (Figure 11a), whereas the mixed area has small porosity, therefore, in addition to permeation effect, grout tends to fracture the medium and form veins to play a supporting role (Figure 11b).



(a) Permeation effect



(b) Permeation and fracturing effect Fig. 11 – Picture of grout reinforcement mode

CONCLUSION

On basis of the current investigation, conclusions can be drawn as follows.

A simplified grouting model for layered fault medium is proposed, composed of (1) fault gouge, (2) fault breccia and (3) mixed area.

In the case of single grouting, the grout diffusion distance in mixed area was between 75.86 % and 88.10 % of that in fault breccia, while it was 59.8 % for multiple grouting. The concepts of S_b , S_{m1} , S_{m2} and S_d are proposed to characterize propagation difference of grout in layered fault medium, whose relationship with injection pressure is also analysed.

The pressure dissipated gradually from the injection hole to periphery, and the pressure dissipation in mixed area is faster than that in fault breccia.

Experimental investigation was performed, whose results correspond well with what was found in numerical simulation.

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