

## Research Article

# Study on Fracturing and Diffusion Mechanism of Non-slab Fracturing Grouting

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The coupling effect of a slurry and the fractured rock layer controls a spatial attenuation of the fracture channel width and grouting pressure from a grouting hole to the slurry top of fracture diffusion. This paper comprehensively considers the influencing factors such as the mechanical properties of the injected rock mass and the time-varying characteristics of the serous viscosity and introduces the control equation of the fracture channel width to establish a single-fracture non-slab fracturing grouting model. Combining the motion law of the slurry with the extension form of fracture, the equation of slurry diffusion motion, considering the fracture geometry and the time-varying characteristics of the serous viscosity, is derived. Comparing this equation with the existing theories and experiments, the validity and reliability of the theory are verified. In this paper, the effects of rock elastic modulus, slurry viscosity, and grouting rate on the fracturing grouting diffusion law of rock mass are analyzed. It is pointed out that when fracturing grouting in deep rock layers, a larger initial grouting rate and grouting pressure should be selected in the early stages of grouting to generate or penetrate fractures in the rock layer. Also, when the grouting pressure is stable, it is appropriate to increase the viscosity so that the slurry can quickly gel in the fractures thus sealing the fractures.

## 1. Introduction

Since the depth of coal mining in China has gradually increased into kilometers, the requirements of grouting for stopping up water during the construction of vertical shafts have also become higher [1, 2]. Deep well construction disturbed rock formations have characteristics such as high geostress, poor microfracture connectivity, and high pore water pressure [3–6]. According to the conventional grouting scheme in shallow formations, it is difficult to effectively block bored well water. Studying the fluid-solid coupling mechanism between the slurry and the microfracture in the rock formation and analyzing the law of fracturing grouting and diffusion in the deep microfractured rock mass are of great significance for guiding the design of deep well grouting and water blocking in coal mines.

The fracturing grouting process is the result of the coupling of the slurry flow field and rock mass stress field. During the migration of the slurry, resistance from the two sides of the fracture channel and its viscosity causes the grouting pressure to decay along the diffusion radius within the fracture channel. At the same time, the attenuation of the fracture channel width in the direction of the diffusion radius results in different resistances of the channel sidewall to the diffusion of the slurry at different positions, thereby affecting the flow of the slurry. Therefore, the mechanical characteristics of the injected rock mass, the fracture geometry, and the time-varying characteristics of the serous viscosity are all important criteria for evaluating the effect of fracturing grouting and designing related grouting parameters. Although domestic and foreign scholars have carried out a lot of research on the mechanism of fracture grouting

[7–12], these studies mostly focus on the theory of fracturing grouting in soil, and due to the lack of comprehensive understanding of the fracture mechanism and material parameters, it is not yet possible to correctly predict or explain the fracture pressure of deeply buried rock strata.

Presently, domestic and foreign scholars have conducted a series of studies in the field of fracturing grouting. In abroad, Murdoch [13] obtained qualitative conclusions about fracture geometry through laboratory experiments; Bezuijen et al. [14] analyzed the influence of fracture length and thickness on fracture propagation based on a single fracturing grouting model; Gustafson and Claesson [15] established the grout migration equation for a single fracture under constant pressure grouting based on the Bingham fluid constitutive model; Mohammed [16] studied the grouting of soil grouting through model tests and observed the law of slurry diffusion distribution by CT scanning; Kishida et al. [17] used a numerical software to simulate the grouting process of a single fracture and studied the change of grouting pressure during the grouting process. In China, Huang et al. [18] proposed a method of induced fracturing grouting based on the principle of elastic mechanics; Wang and Li [19] studied the diffusion law of slurry in rock fractures, obtained the equation between grouting pressure and fracturing diffusion radius, and carried out verification and analysis in combination with fracturing grouting laboratory simulation experiments; Sun et al. [20] derived the diffusion law of the Bingham fluid slurry fracturing grouting and discussed the influence of slurry time-varying on grouting diffusion; Zhang et al. [21] considered the effect of interface stress coupling between the slurry and soil and studied the law of fracturing grouting of the Newtonian fluid; Zhang et al. [22, 23] also established a single-fracture slurry migration equation based on the predecessors under the time-varying slurry viscosity. The above studies help to better understand the mechanism of fracturing grouting. However, the existing grouting fracture models only study the slurry diffusion from the motion of the slurry in the fracture channel, and few studies have taken into account the time-varying viscosity characteristics of the slurry and the fracture propagation geometry. In fact, the motion of the slurry and the expansion of the fracturing cracks are performed simultaneously. On the one hand, the motion of the slurry should be followed, and on the other hand, the diffusion of the slurry should also be followed as well as the spread of the fracturing cracks.

In order to solve the above problems, a non-slab fracturing diffusion model was built based on the fracture mechanics theory and fluid mechanics in this paper. Combining the motion of the slurry with the propagation of the fracturing crack, an equation about the slurry diffusion motion in the fracture channel was derived, and the impacts of the fracture geometry and the time-varying characteristics of the slurry viscosity have been taken into consideration. And compared with the existing theories and measured results, the validity and reliability of the theory were verified. Based on the established theoretical model, the fracturing diffusion mechanism of the slurry in the rock layer was also studied, and the influencing factors such as elastic modulus, viscosity, and grouting rate on the rule of fracturing and diffusion of the

slurry were analyzed, which provided a theoretical basis for the design and optimization of grouting in the future.

## 2. Diffusion Model of Single-Fracture Non-slab Fracturing Grouting

Studies have shown that during fracturing grouting, the slurry in the grouting holes does not diffuse spherically or in a column but splits vertically along the sides of the grouting holes. It is assumed that the maximum and minimum principal stresses in the rock formation are horizontal and vertical, respectively, and the grouting fracturing direction is horizontal, as shown in Figure 1(a). During the grouting process, due to the resistance of the slurry from the upper and lower sides of the fracture channel and its own viscosity, the grouting pressure attenuates and unevenly distributes in the fracture channel. At the same time, the width of the fracture channel decreases from the grouting hole to the slurry top of fracturing diffusion, and the width of the fracturing crack is 0 at the slurry top of fracturing diffusion, as shown in Figure 1(b). Therefore, a single-fracture non-slab fracturing diffusion model for vertical fracturing along the side wall of a grouting hole was established.

### 2.1. Basic Assumptions

- (1) The slurry is a generalized Bingham fluid, and the flow pattern does not change during the movement of the slurry, only the viscosity changes with time
- (2) The injected rock mass is an isotropic elastomer
- (3) There is no slip at the boundary of the fracture channel
- (4) The slurry exists only inside the fracture channel and flows laminarily in the fracture channel
- (5) The force on the upper and lower side walls of the fracture channel is perpendicular to the axis of symmetry of the fracture channel
- (6) The flow at different locations in the fracture is constant

### 2.2. Fracture Expansion Criterion

**2.2.1. Fracturing Pressure.** The stress in the grouting hole is shown in Figure 1(a). The direction of the maximum principal stress ( $\sigma_1$ ) is horizontal and the direction of the minimum principal stress ( $\sigma_3$ ) is vertical. When the grouting pressure in the grouting section reaches a certain critical value, the grouting hole will produce horizontal fracturing in a direction parallel to the maximum principal stress, the grouting pressure when forming horizontal fracture is [24]

$$P_0 = \frac{\sigma_3 + \sigma_t^*}{0.94}, \quad (1)$$

where  $\sigma_t^*$  is the tensile strength of the rock under confining pressure conditions, its value is generally 2-3 times the pure

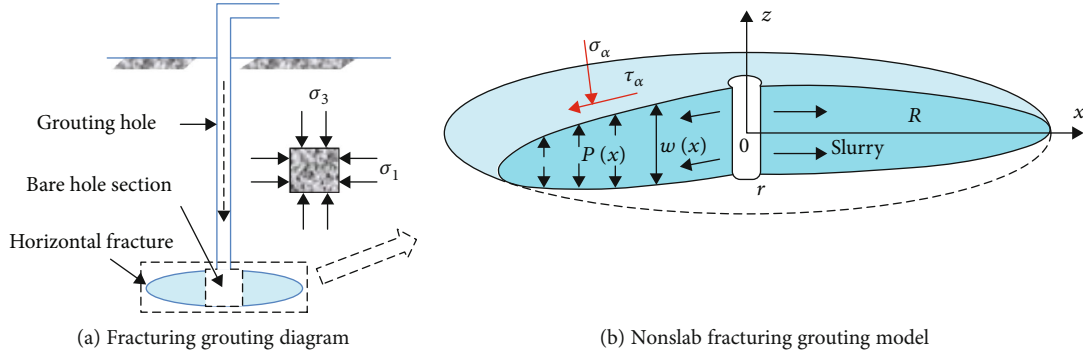


FIGURE 1: Analysis model of fracturing grouting process.

tensile strength value obtained by the uniaxial direct stretching method, and 0.94 is the correction factor.

**2.2.2. Channel Continues to Expand.** It can be known from geotechnical mechanics that under the stress conditions shown in Figure 1(a), the total normal stress  $\sigma_\alpha$  (MPa) acting on the outer wall of the microcrack is

$$\sigma_\alpha = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha, \quad (2)$$

where  $\sigma_3 = \sigma_{cz} + P_S$ ,  $\sigma_1 = k\sigma_{cz} + P_S$ ;  $P_S$  is the hydrostatic pressure (MPa),  $P_S = \gamma_w H_w$ ;  $\sigma_{cz}$  is the vertical effective stress; and  $k$  is the lateral pressure coefficient.

When the grouting pressure is nonuniformly distributed in the interior of the fracture channel, according to the hydraulic fracture expansion theory [25, 26], it can be derived that the stress intensity factor  $K_I$  is

$$K_I = \frac{2}{\sqrt{\pi R}} \int_r^R \frac{\Delta P(x)}{\sqrt{R^2 - x^2}} x dx, \quad (3)$$

where  $\Delta P(x) = P(x) - \sigma_\alpha$ ,  $P(x)$  is the grouting pressure distributed along the crack wall;  $r$  is the radius of the bare hole section, (because it is relatively small compared with the splitting radius, it is neglected in the calculation); and  $R$  is the disc-type crack radius.

According to the linear elastic fracture mechanics [25], the fracture extension standard is adopted as

$$K_I = K_{IC}, \quad (4)$$

where  $K_{IC}$  is the fracture toughness of the injected material.

**2.3. Spatiotemporal Distribution Equation of Slurry Viscosity.** Considering the slurry as the Bingham fluid, due to the existence of yield shear force, its viscosity changes directly affect the slurry diffusion range, and its viscosity increases with time [27]. As the slurry needs to overcome the shear force and the time-varying plastic viscosity, the slurry rheological equation is as follows:

$$\tau = \tau_0 + u(t) \dot{\gamma}, \quad (5)$$

where  $\tau$  is the shear stress of the slurry,  $\tau_0$  is the yield shear force,  $\dot{\gamma} = dv/dz$  is the shear rate, and  $t$  is the grouting time. Since the slurry viscosity time function is mostly obtained by fitting test data, its form is uncertain, so the general function form  $u(t)$  is used to represent the viscosity-time relationship.

If the slurry only flows in the radial direction, the split and diffusion distance of the slurry at time  $t$  is  $x$ , and according to the conservation of mass, the corresponding time at  $x$  is

$$t = \frac{2\pi\omega x^2}{q}. \quad (6)$$

It should be noted that, in the derivation below,  $w$  is sometimes represented as  $w(x)$ .

When the grouting time is  $t$ , the space-time distribution equation of viscosity in the slurry diffusion zone corresponds to  $x$ :

$$u(t, x) = u\left(\frac{2\pi\omega x^2}{q}\right). \quad (7)$$

In equation (7), the grouting time  $t$  is eliminated. This is because under the condition of constant grouting rate, the spatiotemporal distribution of the slurry viscosity is determined by the spatial position, and the grouting time affects the slurry diffusion radius.

**2.4. Governing Equation of Fracture Channel Width.** During the grouting process, as the slurry is continuously injected and the fractures are continuously expanding, the width of the fractures along the fracture channel changes and gradually decreases. Therefore, the calculation of fracture morphology is a coupling problem of fluid mechanics and fracture mechanics. According to the literature [28], if the center of the crack root is 0 and the  $x$ -axis is established along the crack direction, the width of the crack at the distance  $x$  from the origin can be defined as

$$w(x) = \frac{4}{E} K_{IC} \sqrt{\frac{R^2 - x^2}{\pi R}}. \quad (8)$$

It can be seen that the morphological equation at any time during the fracture propagation is constant. The

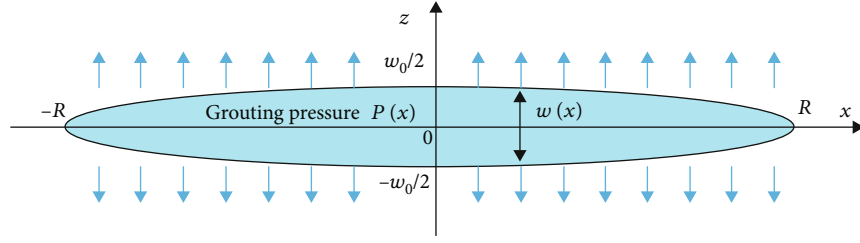


FIGURE 2: Fracture geometry model.

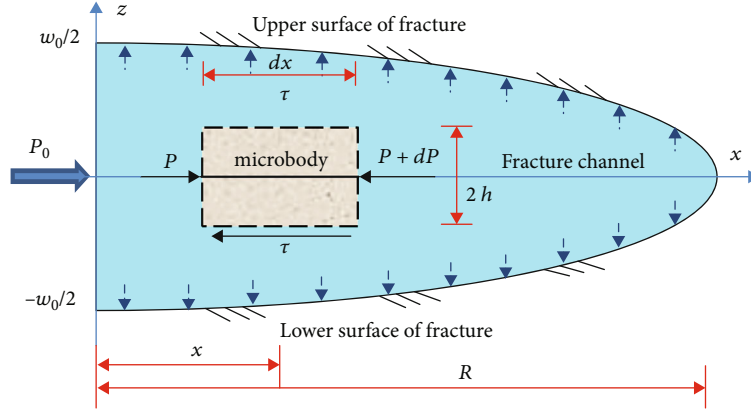


FIGURE 3: Microelement body balance analysis.

geometric model is shown in Figure 2. That is, there is a constant correspondence relationship between the fracture length and width, and the fracture width  $w_0$  at the grouting hole can be expressed as  $w_0 = 4K_{IC}/(E\sqrt{R/\pi})$ .

### 2.5. Governing Equation of Slurry Fracturing and Diffusion.

According to the basic assumption (5), a rectangular coordinate system as shown in Figure 3 is established with the vertical axis passing through the grouting hole and the symmetry center of the fracture channel as the coordinate axis.

Taking the serous vein center as the axis of symmetry to take the slurry microbody for force analysis, ignoring the self-weight of the slurry, from the equilibrium conditions, the shear stress distribution can be obtained as [29]

$$\tau = -z \left( \frac{dP}{dx} \right), \quad (9)$$

where  $dx$  is the length of the microbody,  $\tau$  is the shear stress,  $P$  is the slurry pressure, and  $dP$  is the slurry pressure volume.

The generalized Bingham body motion can be divided into two parts: the overall motion of the flow core area and the relative motion of the shear area. Through the force balance analysis of the unit body and substitution of the boundary conditions:  $z = \pm w/2$  and  $v = 0$ , the velocity distribution of the slurry in the direction of the fracture thickness can be obtained as

$$v = \begin{cases} -\frac{1}{u(2\pi\omega x^2/q)} \left[ \frac{(1/2)dP}{dx((w^2/4) - h^2) - \tau_0((w/2) - h)} \right], & (-h \leq z \leq h), \\ -\frac{1}{u(2\pi\omega x^2/q)} \left[ \frac{(1/2)dP}{dx((w^2/4) - z^2) - \tau_0((w/2) - z)} \right], & (|h| \leq |z| \leq |w/2|), \end{cases} \quad (10)$$

According to integral formula  $\bar{v} = \int_{-w/2}^{w/2} v dz$ , ignoring the higher order minor terms, the average velocity of the slurry on the fracture surface can be simplified as

$$\bar{v} = \frac{-w^2}{12u(2\pi\omega x^2/q)} \left( \frac{dP}{dx - (3\tau_0/w)} \right). \quad (11)$$

It can be known from the law of conservation of mass that during the grouting process, the unit flow rate of the slurry on any diffusion section inside the fracture channel is equal to the grouting rate  $q$  at the grouting hole, then

$$q = 2\pi x \int_{-w/2}^{w/2} v dz. \quad (12)$$

Simultaneously implementing (11) and (12), the pressure gradient of the slurry in the fracture channel is obtained:

$$\frac{dP}{dx} = -\frac{6u(2\pi\omega x^2/q)q}{\pi x w^3} + \frac{3\tau_0}{w}. \quad (13)$$

From the literature [22], the viscosity change of the slurry material can be fitted as the following function law:

$$u(t) = mt^2, \quad (14)$$

where  $m$  is a time-varying parameter of viscosity.

Simultaneously implementing (13) and (14),

$$\frac{dP}{dx} = -\frac{3 \times 2^3 \times \pi x^3}{qw} + \frac{3\tau_0}{w}. \quad (15)$$

Substitute (8) into (15) and bring in the boundary conditions:  $x \rightarrow 0, P = P_0$ , the spatial distribution equation of the slurry pressure inside the fracture channel can be obtained as

$$P(x) = P_0 - \frac{6\pi^{3/2}mE\sqrt{R}}{qK_{IC}} \left( \frac{2}{3}R^3 + \frac{1}{3}(R^2 - x^2)^{3/2} - R^2\sqrt{R^2 - x^2} \right) + \frac{3\sqrt{\pi}RE\tau_0}{4K_{IC}} \arcsin\left(\frac{x}{R}\right). \quad (16)$$

Substituting (2) and (16) into (3), the diffusion equation of time-varying grout fracturing grouting based on crack fracturing discrimination condition ( $K_I = K_{IC}$ ) is

$$P_0 = \frac{\sqrt{\pi}}{2\sqrt{R}}K_{IC} + \frac{3\pi^{3/2}mER^{7/2}}{2qK_{IC}} - \frac{3\sqrt{\pi}RE\tau_0}{4K_{IC}} + \sigma_\alpha. \quad (17)$$

### 3. Verify

Previously, when analyzing the mechanism of fracturing grouting, they often ignored the change in fracture width and assumed that the fracture width was a constant value, and when analyzing the influence of grouting pressure factors on the fracturing diffusion distance, the grouting pressure difference (the pressure at the grouting hole minus the rock fracture cracking pressure) was used as a variable. The relationship between the grouting pressure difference and the fracturing diffusion distance  $R$  is [29]:

$$\Delta P = P_0 - P_d = 3 \times 2^n \times \pi^{n-1} \frac{mw^{n-3}q^{1-n}}{n} (R^{2n} - r^{2n}) - \left( \frac{3\tau_0}{w} + \rho g \sin \alpha \cos \theta \right) (R - r). \quad (18)$$

However, during the field test, the grouting pressure is still the research object, so the determination of the fracturing pressure is particularly important. When Sun et al. [30] studied the fracturing grouting mechanism, they believed that the far-field stress could be eliminated and sustained development only when the grouting pressure inside the fracture channel was greater than the sum of the minimum principal stress  $\sigma_3$  and tensile strength  $\sigma_t^*$  of the injected rock mass.

$$P_d = \sigma_3 + \sigma_t^*. \quad (19)$$

Substituting equations (13) of the slurry viscosity and (19) into equation (18), the slurry fracturing grouting diffusion equation, which ignores the radius  $r$  of the grouting hole

TABLE 1: Comparison of two theoretical values of grouting pressure with field measured values.

Fracture extension length	Field measured value	Equation (17) theoretical value	Equation (20) theoretical value
0.4 m	2.1 MPa	2.48 MPa	5.37 MPa
1.8 m	1.2 MPa	1.39 MPa	5.42 MPa
2.6 m	0.8 MPa	0.86 MPa	5.56 MPa

and the time-varying viscosity obtained by self-weight of slurry is as follows:

$$P_0 = \frac{6\pi m}{qw} R^4 - \frac{3\tau_0 R}{w} + \sigma_3 + \sigma_t^* \quad (20)$$

In order to compare and analyze the fracturing diffusion laws of the two theories, the field test of Peili [31] was used to verify the theory in this paper.

Peili [31] selected three representative test points for grouting and fracturing tests in the grouting project of Nantiao Tower Coal Mine, the modulus of elasticity  $E$  in the test area is 4 GPa, the tensile strength  $\sigma_t$  is 4.56 MPa, the yield shear force  $\tau_0$  is 3.19 Pa, the grouting rate  $q = 500$  mL/s, the fracture toughness  $K_{IC}$  is  $1.2 \text{ MPa}\cdot\text{m}^{0.5}$ . The grouting slurry is a 1 : 1 cement slurry, the maximum principal stress in the grouting area is 1.8 MPa, and the minimum principal stress is 0.8 MPa. The fracture propagation lengths at each test point were 0.4 m, 1.8 m, and 2.6 m. The measured grouting pressures on site were 2.1 MPa, 1.2 MPa, and 0.8 MPa, respectively; equations (17) and (20) were used to calculate the grouting pressure in the three cases, as shown in Table 1.

As can be seen from Table 1,

- (1) The longer the fracture, the smaller the grouting pressure. Because the test uses a 1 : 1 cement slurry, the time-varying viscosity is not obvious, and the viscosity factor has not yet played a leading role. With reference to hydraulic fracturing theory, it can be known that the longer the fracture, the smaller the grouting pressure required
- (2) By comparison, the theoretical calculations in this paper show that the grouting pressure at the three test points is close to the actual measured value, but slightly higher than the measured value. This is because the theoretical derivation assumes that the slurry exists only inside the fracture channel and does not consider the influence of other factors such as the penetration of part of the slurry to both sides of the fracture on the fracturing diffusion, but the error is still within the allowable range of the project
- (3) Compared with the theoretical value of this paper, the theoretical value obtained from the traditional fracturing grouting theory has a large deviation from the measured value. This is because the strength of the rock is high. Judging whether the fractures are



TABLE 2: The relationship between the viscosity of different C-S slurries over time.

C/S	1 : 1	2 : 1	3 : 1
Relational	$u(t) = 0.00857t^2$	$u(t) = 0.01687t^2$	$u(t) = 0.02477t^2$
Fitting accuracy	0.996	0.972	0.999

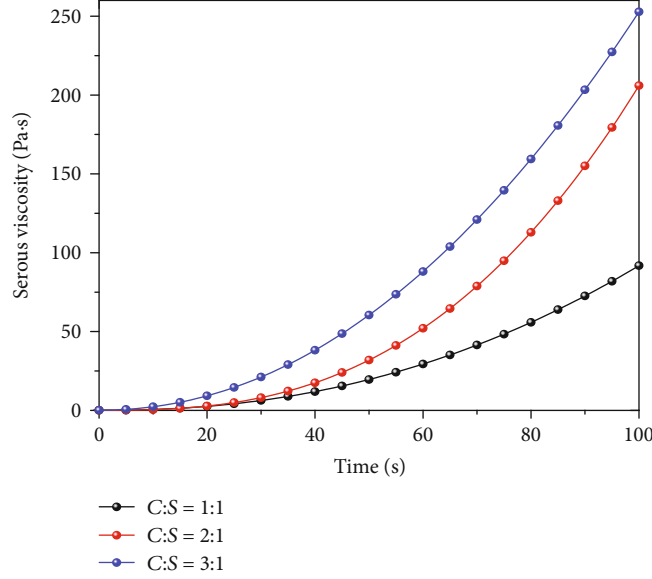


FIGURE 4: The curve of cement and sodium silicate slurry viscosity over time.

fracturing and expanding under the grouting pressure, the influence of the rock elastic modulus on the fracturing expansion and the uneven distribution of grouting pressure inside the fracture channel cannot be ignored, with the change of the fracture length, the fracturing pressure tend to be constantly changing instead of a fixed value. Therefore, the theory of fracturing grouting in this paper is more suitable for fracturing grouting in rock formations than the traditional fracturing grouting theory and can effectively guide the design and construction of fracturing grouting in the field

#### 4. Fracturing Grouting Diffusion Law of Rock Formation and Its Influencing Factors

Based on the foregoing theoretical model, this section analyzes the law of fracturing grouting and diffusion and its influencing factors. The size of the grout fracturing expansion radius depends on the grouting pressure. By substituting related parameters into the fracturing grouting control equation (17), we can get the variation curve of grouting pressure  $P_0$  with slurry diffusion radius  $R$ . The basic parameter values are as follows: effective stress  $\sigma_3 = 10.73$  MPa,  $\sigma_1 = 15.11$  MPa, side pressure coefficient  $k = 1.5$ , elastic modulus  $E = 40$  GPa, fracture toughness  $K_{IC} = 1.7$  MPa  $\cdot$  m<sup>0.5</sup>,  $\alpha = 30^\circ$ , the slurry is cement and sodium silicate slurry (C : S = 1 : 1), grouting rate  $q = 120$  L/min. According to the relationship between the viscosity of different cement slurry and sodium silicate slurry volume ratio slurry over time, the refitting relationship

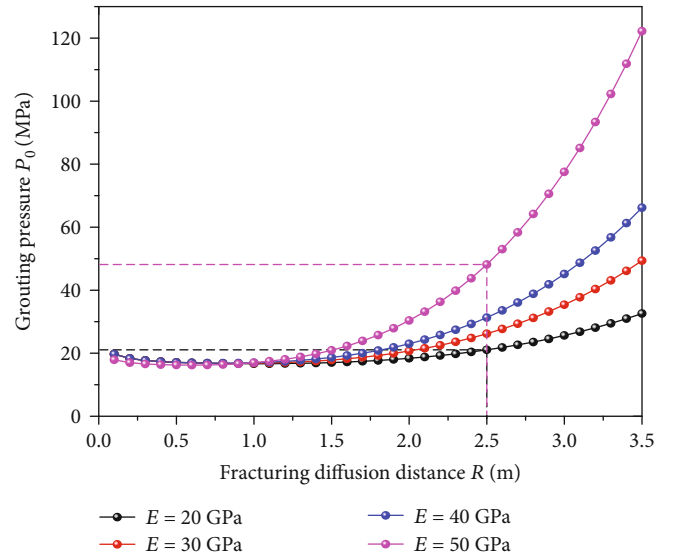


FIGURE 5: Effect of elastic modulus on slurry diffusion radius.

is shown in Table 2. The curve of cement and sodium silicate slurry viscosity over time was fitted, as shown in Figure 4.

The grouting pressure controls the size of the grout diffusion radius. When the relevant parameters are substituted into the time-varying slurry fracturing diffusion equation, the relationship curve  $P_0 - R$  under the influence of formation factors (Figure 5) and the relationship curve  $P_0 - R$

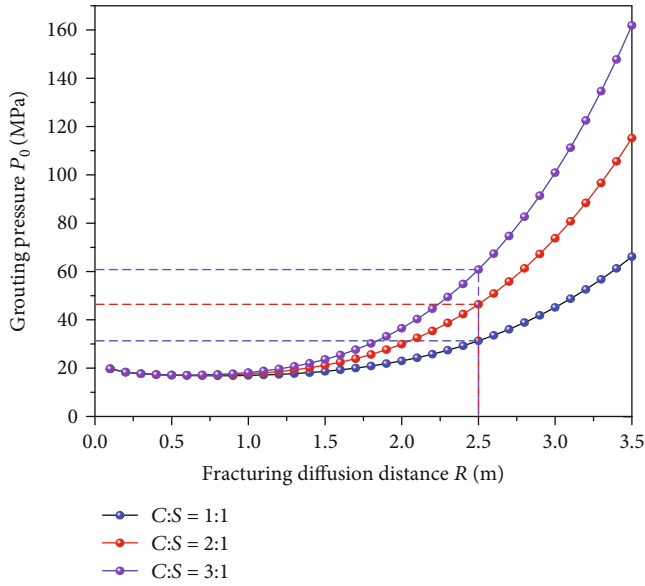


FIGURE 6: Effect of slurry viscosity on slurry diffusion radius.

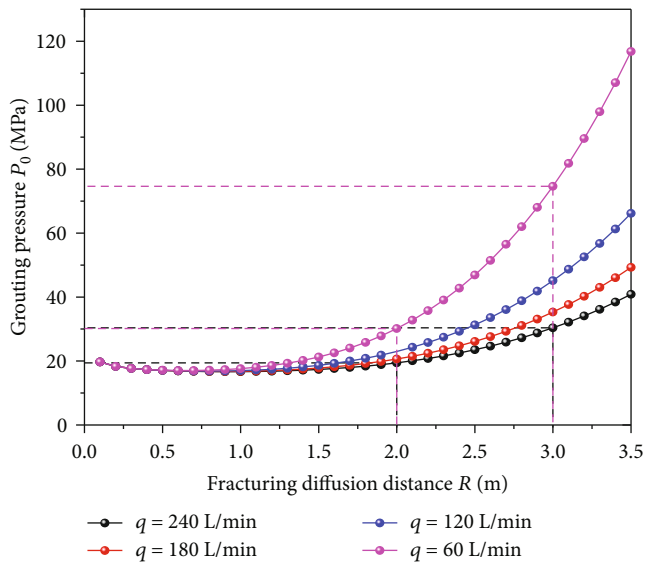


FIGURE 7: Effect of grouting rate on slurry diffusion radius.

under the influence of grouting parameter factors (Figures 6 and 7) can be obtained.

Analysis of Figures 5–7 shows the following:

- (1) Compared with the traditional infiltration grouting theory, the theoretical value of fracturing grouting pressure is very large. This is because split grouting must not only overcome the resistance caused by the viscosity of the slurry itself but also overcome the pressure required for rock initiation. However, in actual grouting projects, due to the large number of natural joints, fractures, bedding, and other structures distributed in the rock layer, the grouting pressure generally cannot reach the theoretical calculation value

- (2) In the initial stage of fracturing grouting, the plastic viscosity of the slurry with different proportions is small and the fracturing cracks are short. In order to continue the fracturing expansion, a larger grouting pressure must be accumulated. When the cleavage expands to 1 meter, the plastic viscosity of the slurry gradually increases with time, thus the required gradual pressure increases. It can also be seen from the theoretical formula that as the  $R$  increases, the  $(\sqrt{\pi}/2\sqrt{R})K_{IC}$  term decreases rapidly, and then, the viscosity control term  $3\pi^{3/2}mER^7/2qK_{IC}$  plays the main control role. Therefore, the required grouting pressure will decrease slightly and then increase as the fracture continues to expand

- (3) Under the same conditions of slurry diffusion radius  $R$ , the grouting pressure  $P_0$  is proportional to the rock mass elastic modulus  $E$  and the slurry viscosity. For example, when the grouting diffusion radius  $R = 2.5$  m, the elastic modulus of the injected rock mass increases from 20 GPa to 50 GPa and the corresponding grouting pressure  $P_0$  increases from 21.08 MPa to 48.15 MPa; Corresponding C:S is 3:1, 2:1, and 1:1 are 60.79 MPa, 46.42 MPa, and 31.32 MPa, respectively. It can be seen that the greater the elastic modulus of the injected rock mass, the higher the resistance encountered during fracturing grouting, and the more difficult the fracture propagation. Moreover, the greater the viscosity of the slurry, the greater the viscosity resistance of the slurry encounters during the flow process, and the greater the grouting pressure required to reach the predetermined fracturing diffusion radius

- (4) Under the same conditions of slurry diffusion radius  $R$ , the grouting pressure  $P_0$  is inversely proportional to the grouting rate  $q$ . When the fracturing diffusion radius is small, the required grouting pressure is not sensitive to changes in the grouting rate  $q$ . When the fracturing diffusion radius is larger, the grouting pressure required for the fracture continues to increase sharply, but the greater the grouting rate, the slower the grouting pressure increases

According to the above analysis, the elastic modulus of rock, time-varying characteristics of the serous viscosity, and grouting rate are the main influencing factors in controlling fracturing grouting. In the initial stage of grouting, the plastic viscosity of the slurry is relatively low. The grouting pressure and grouting rate are the main controlling factors of the grouting and spreading range of the slurry, increasing the grouting rate can significantly increase the grouting range. When the slurry viscosity exceeds a certain range, the viscosity becomes the main controlling factor of the slurry diffusion range. Therefore, in the design and selection of grouting parameters, stratum factors should be comprehensively considered, and a large initial grouting rate and grouting pressure should be selected in the early stage of

grouting, so that cracks can be generated or penetrated in the rock formation. When the grouting pressure is stable, while the slurry is sufficiently diffused in the fracture, the viscosity of the slurry is increased, the solidification reaction rate of the slurry is increased, and the slurry forms a blocking body in the fracture.

## 5. Conclusions

- (1) Combining the motion of the slurry with the expansion of the fracturing cracks, considering the various mechanical factors such as the mechanical properties of the rock formation and the time-varying characteristics of the serous viscosity, a theoretical model of fracturing grouting diffusion considering the spatial attenuation of the fracture channel width has been established. The fracturing grouting diffusion equation considering fluid-structure interaction was also derived and verified by experiments
- (2) Considering the time-varying characteristics of the serous viscosity, the main influencing factors on the effect of fracturing grouting and diffusion in rock formation are rock elastic modulus, slurry viscosity, and grouting rate. The larger the elastic modulus of the injected rock mass, the higher the resistance of the fracturing grouting and the more difficult the fracture extension. In the initial stage of grouting, the plastic viscosity of the slurry is low. The grouting pressure and grouting rate are the main controlling factors of the fracturing and spreading range of the slurry. When the viscosity of the grouting reaches a certain value, the viscosity becomes the main controlling factor of the slurry spreading range
- (3) Based on the fluid-solid coupling characteristics of grout and rock fractures, in order to meet the requirements of fracturing grouting in deep formations, a large initial grouting rate and grouting pressure should be selected in the early stage of grouting, so that fractures are generated or penetrated in the rock formation. When the grouting pressure is stable, while the slurry is sufficiently diffused in the fracture, the viscosity of the slurry increases, the solidification reaction rate of the slurry also increases, and the slurry forms a blocking body in the fracture

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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