A Grouts-Water Migration Model of Two-Phase Flow in a Single Fracture

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***Abstract* — Water hazard is one of the main natural disasters of coal mine, which is an outstanding problem in strict coal mine safety construction and development. Migration model of two-phase flow of grouts-water in a single fracture considers grout's viscosity time-varying characteristics to built up a relationship between model aperture and mechanical aperture. The roughness coefficient is also considered together with the effect of groundwater pressure on grouts diffusing range. The results show that the migration distance of two-phase flow of grouts-water decreases with dynamic water pressure's increasing, and decreases heavily compared to no-water conditions. The migration distance of two-phase flow of grouts-water becomes greater with larger mechanical aperture. By using this model, migration distance computation of two-phase flow of grouts-water of multi-factor can be programmed, which guides grouting design and construction properly.**

Keywords - two-phase of grouts-water, fracture, migration model, programming.

I. INTRODUCTION

Water hazard is one of the main natural disasters of coal mine, which is an outstanding problem to restrict coal mine safety construction and development. In recent years, water hazard has become a big problem to coal mine production and scientific research. present, the diffusion mechanism of the grouts in the coal rock mass is studied mainly stay the level of diffusion in no-water conditions. Before the perturbation of raw coal rock mass, groundwater is commonly still in a static state or slow flow state, the successful experience that water blocking curtain was formed by plugging water inrush point through grouting has been obtained; when the coal mass is disturbed by the disturbance, fracture become interconnected due to the change of the stress state of coal rock mass, the state of groundwater flow has been changed, upwelling along the connected fractures, and flow velocity, water quantity and water pressure are increasing, a large number of grouting materials are washed away, the grouting diffusion mechanism is different from diffusion under the anhydrous and still water. The grouting diffusion theory in no-water conditions has been unable to guide the design and construction of grouting scientifically and rationally, field grouting can cause a great waste of grouts. To better solve the above problem, the research on the migration mechanism of two-phase flow of grouts-water in fractures of coal rock mass and plugging mechanism under dynamic water, has important theoretical value and engineering application value.

M.Eriksson, H.Stille ac er[2] stood on variable distance fracture grout diffusion with the numerical calculation method, and considered the filtration effect in the process of grouts diffusion. Zhan Kai Yu[3,4] and others established grouting with dynamic water diffusion model in a single fracture by theoretical deduction, using computer to program and analyze the model, and developed test system of the model. Almir Draganovic and Hakan Stille[5] stood the flow law of cement-based grout with long plate, and considered the filtering effect of the grouts. Mohammed Hatem Mohamme, Roland Pusch and Sven Koetsson[6] stood the seepage law of the cement grouts in fractures under the condition of static and vibration. Through the combination of theoretical analysis and grouting simulation test method, investigated the generating mechanism of grouting pressure, researched the diffusion and plugging mechanism of grouts in pipe and fracture of rock mass with dynamic water, and respectively put forward the corresponding principle and condition of grouting plugging.

In conclusion, the grouts diffusion mechanism with dynamic water is still in the initial development stage, and the research results are mainly concentrated in the experimental stage. There is little research report on the grouts diffusion theory in the single fracture under the dynamic water condition, and most of the above grouting models with dynamic water have not clearly described the value of the fractures distance, which is an important factor to influence the grouts diffusion, the fracture distance is a function with the change of the space position. It is very difficult to measure the actual distance value, and need to find a reasonable distance value to replace the actual distance value; in addition, some diffusion theory neglects the influence of time-varying characteristics of the grouts viscosity. Therefore, it is urgent to find a reasonable and effective index to establish the migration model of two-phase flow of grouts-water in a single fracture of coal rock mass with dynamic water.

II. MIGRATION MODEL OF TWO-PHASE FLOW OF GROUTS-WATER IN A SINGLE FRACTURE

A. *Hypothetical condition*

(1) The grouts are an incompressible and homogeneous fluid, and the grouts are stable, and not precipitated;

(2) The flow of the grouts in the fracture is laminar, and the grouts-water phase interface is mixed status;

(3) The diffusion of the grouts in the pores is neglected;

(4) Grouts flow patterns and yield point don't change with time.

B. *The establishment of migration model of two-phase flow of grouts-water*

Rheological state equation of plastic fluid which Lee and Tsai provided is as follows:

$$\vec{\vec{T}} = -p\,\vec{\vec{I}} + \vec{\vec{\tau}} \qquad (1)$$

$$\vec{\vec{\tau}} = \vec{\vec{\tau}}_0 + 2\eta(t)\vec{\vec{D}} \qquad (2)$$

Where, $\vec{\vec{T}}$ Is the stress tensor, p is the static fluid pressure, $\vec{\vec{I}}$ is the unit tensor; $\vec{\vec{\tau}}$ is the additional stress tensor; $\vec{\vec{\tau}}_0$ is the yield stress tensor; $\eta(t)$ is the viscosity coefficient; $\vec{\vec{D}}$ is the deformation tensor

The dynamic equation of Incompressible plastic fluid transient flow between two parallel plates is:

$$\nabla\cdot\vec{\vec{T}} + \rho\vec{b} = \rho\frac{d\vec{V}}{dt} \qquad (3)$$

Where, $\vec{V}$ represents velocity vector; ρ represents the density of fluid; $\vec{b}$ represents physical field; ∇ represents discrete operator.

$$\vec{V} = u(y,i)\,\vec{i} \qquad (4)$$

$$\vec{\vec{\tau}} = \tau_{xy}\,\vec{i} \qquad (5)$$

Where, u is the velocity along x axis; τ_{xy} is the unit vector which has effect on the y plane along x axis.

The equation (4) is substituted into equation (2) and (3) to get:

$$\tau_{yx} = \tau_0 + \eta(t)\frac{\partial u}{\partial y} \qquad (6)$$

$$\frac{\partial p}{\partial x} = \frac{\partial \tau_{yx}}{\partial y} - \rho\frac{\partial u}{\partial t} \qquad (7)$$

Where, τ_0 is the initial shear strength for the fluid.

The equation (6) is substituted into equation (7) to get the following motion equation along x axis:

$$\rho\frac{\partial u}{\partial t} = \eta(t)\frac{\partial^2 u}{\partial y^2} - \frac{\partial p}{\partial x} \qquad (8)$$

Assume the flow of Bingaman grouts in rock mass fracture is steady, thus, equation (8) is changed to:

$$\eta(t)\frac{\partial^2 u}{\partial y^2} = \frac{\partial p}{\partial x} \qquad (9)$$

Where, p is grouting pressure.

The boundary conditions for the equation (9) are:

$$u\Big|_{y=\frac{h}{2}} = 0 \qquad (10)$$

$$\frac{\partial u}{\partial y}\Big|_{y=\frac{h_0}{2}} = 0 \qquad (11)$$

Where, h is fracture model distance, m, h_0 is the flow core height of the grout, m.

Equation (9) is substituted into the boundary conditions (10) and (11), then get the following mean flow rate of single plastic fluid:

$$\bar{u} = \frac{1}{4\eta(t)}\left(\frac{h_0 h}{2} - \frac{h_0^2}{6} - \frac{h^2}{3}\right)\frac{dp}{dx} \qquad (12)$$

Flow core height is $h_0 = 4\tau_0\dfrac{dx}{dp}$, which is substituted into equation (12),then get:

$$\bar{u} = \frac{1}{4\eta(t)}\left(2\tau_0\frac{dx}{dp}h - \frac{\left(4\tau_0\dfrac{dx}{dp}\right)^2}{6} - \frac{h^2}{3}\right)\frac{dp}{dx} \qquad (13)$$

Make $m = \dfrac{\tau_0}{h}\dfrac{dx}{dp}$, $m = \dfrac{\tau_0}{h}\cdot\dfrac{h_0}{4\tau_0} = \dfrac{h_0}{4h}$, and $\bar{u} = \dfrac{h^2}{12\eta(t)}\left(6m - 8m^2 - 1\right)\dfrac{dp}{dx}$, assuming that there is only one kind of fluid in the fracture path, and the pressure drop appears linear distribution:

$$\frac{dx}{dt} = \frac{\gamma_w h^2}{12\eta(t)}\left(1 - 6m + 8m^2\right)\cdot\frac{h_b - h_e}{l} \qquad (14)$$

where, γ_w Is the severe of water, N/m3; h_b is the grouting pressure of the fractures' starting point, m; h_e is the water pressure of the end of fracture, m; l is length of fracture, m.

Considering the dilution effect of flow of the fractured channel on prefrontal grouts, there is multiphase flow during fractured channel: pure grouts zone, grouts-water mixed zone and pure water zone(Figure 1), if the hydraulic gradient changes of the three regions are consistent with the linear changes, then the values of each region are constant, by $u = \dfrac{h_b - h_e}{\sum \dfrac{h_i - h_{i-1}}{u_i}}$, $\eta(t) = \eta_0 e^{kt}$ and $h = \dfrac{E^2}{JRC^{2.5}}$ to get:

$$\frac{dx}{dt} = \frac{\gamma_w E^4(h_b - h_e)}{12JRC^5\left[\dfrac{x_1\eta_{10}e^{k_1 t}}{1-6m_1+8m_1^2} + \dfrac{x_2\eta_{20}e^{k_2 t}}{1-6m_2+8m_2^2} + \dfrac{x_3\eta_{30}e^{k_3 t}}{1-6m_3+8m_3^2}\right]} \qquad (15)$$

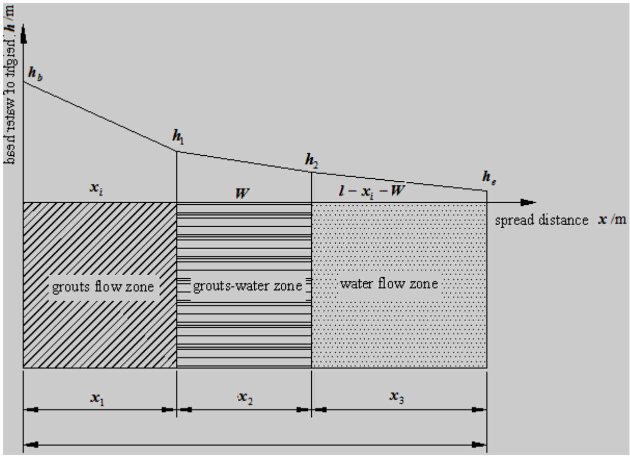


Figure 1. Graph of migration model of two-phase flow model

where, u is the average velocity of multiphase flow in fractured channel, m/s; u_i is the flow velocity of liquid in the i region, m/s; h_{i-1}, h_i is the water head height of the beginning and the end of the i area, m; η_0 is the initial viscosity coefficient, Pa.s; and k is the exponential coefficient refer to table I; t is the grouting time, s; E is fracture mechanics distance (obtained through field sampling mechanical test) , m; *JRC* is joint roughness coefficients; the η_{10} the initial viscosity coefficient of the pure pulp, Pa.s; η_{20} is the initial viscosity coefficient of the mixed zone, Pa.s; and η_{30} the initial viscosity coefficient of the water area is obtained, Pa.s.

Water has a small change of phase interfacewidth(W) tested through experiments in a condition of stable current. We assume that it is constant in (15) by substitution :

$$\begin{cases} \dfrac{dx}{dt} = \dfrac{\gamma_w E^4 (h_b - h_e)}{12JRC^5\left[\dfrac{x\eta_{20}e^{k_2 t}}{1-6m_2+8m_2^2} + (l-x)\eta_w\right]} (x \le W) \\ \dfrac{dx}{dt} = \dfrac{\gamma_w E^4 (h_b - h_e)}{12JRC^5\left[\dfrac{x\eta_{10}e^{k_1 t}}{1-6m_1+8m_1^2} + \dfrac{W\eta_{20}e^{k_2 t}}{1-6m_2+8m_2^2} + (l-x-W)\eta_w\right]} (x > W) \end{cases} \tag{16}$$

TABLE I VALUE OF η_0 AND K OF DIFFERENT GROUTS

Slurry name	/ Pa.s	Exponential coefficient k
grout（Water cement ratio 0.5）	70.2	0.00874
grout（Water cement ratio 0.8）	19.9	0.0233
grout（Water cement ratio 1.0）	11.37	0.0138
grout（Water cement ratio 2.0）	10.24	0.0178
Cement Clay Grouting Liquid	32.27	0.017
Silicate Sodium Grout	8.27	0.1256

Solve (16) by iterative method, that is:

$$\begin{cases} \dfrac{x_i - x_{i-1}}{t_i - t_{i-1}} = \dfrac{\gamma_w E^4 (h_b - h_e)}{12JRC^5\left[\dfrac{x_i\eta_{20}e^{k_2 t_i}}{1-6m_2+8m_2^2} + (l-x_i)\eta_w\right]} (x \le W) \\ \dfrac{x_i - x_{i-1}}{t_i - t_{i-1}} = \dfrac{\gamma_w E^4 (h_b - h_e)}{12JRC^5\left[\dfrac{x_i\eta_{10}e^{k_1 t_i}}{1-6m_1+8m_1^2} + \dfrac{W\eta_{20}e^{k_2 t_i}}{1-6m_2+8m_2^2} + (l-x_i-W)\eta_w\right]} (x > W) \end{cases} \tag{17}$$

The above-mentioned grouting model considers the rules of transport and dispersion of relative flow between slurry and water influenced by many factors(time-dependent behavior of viscosity of cement-based grouts, fissure mechanics aperture, fissure roughness, grouting time, ground water pressure, grouting pressure), the model we create can achieve the program of calculating the distance of transport and dispersion of relative flow between slurry and water under the circumstance of many factors, which is convenient for the design and construction of state grouting.

III. THE CALCULATION OF CALCULATION EXAMPLE

The model of transport and dispersion of relative flow between slurry and water based on theory, using Matlab to calculate the change regulation of the distance of transport and dispersion of relative flow between slurry and water with grouting time. Using 1:1 water cement ratio pure cement pulp as trial material, whose value is in table I. The initial viscosity of phase interface between slurry and water measured is approximate 10.62Pa.s in the test, the index coefficient η_{20} is about 0.0162, the length of fracture l is 5m, the phase interface between slurry and water, measured in this experiment, is about 1.5m with this serous ratio, the mechanics aperture of fracture is 1mm, the coefficient of rugosity is 0.063(the same coefficient of rugosity as glass), the grouting pressure is 2.0m water head height. The relation curve of time and distance of transport and dispersion of relative flow between slurry and water, under different hydrodynamic pressure is showed in picture 2(a), when other conditions are same, The relation curve of time and distance of transport and dispersion of relative flow between slurry and water, under different fracture mechanics aperture is showed in picture 2(b).

We can see that, in the same grouting time, the distance of transport and dispersion of relative flow between slurry and water is decreasing with the increasing of hydrodynamic pressure. When the hydrodynamic pressure is 1.0m and the grouting time is 60s, the distance of transport and dispersion of relative flow between slurry and water decreases about 30 percent, comparing with the case in the anhydrous state: picture 2(b) shows that the bigger the fracture mechanics aperture, the longer the distance of transport and dispersion of relative flow between slurry and water. When the fracture mechanics aperture is 4mm, the distance of transport and dispersion of relative flow between slurry and water can reach 6cm approximately in 60s.

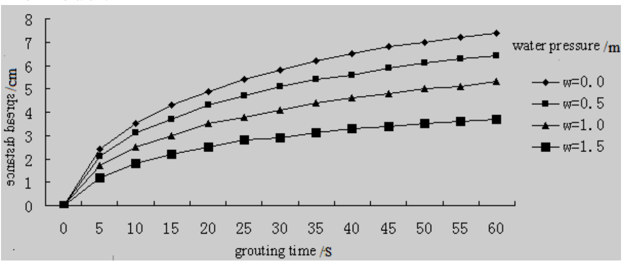
According to Poiseuill′s Planar fluid theory, in the anhydrous state, the grout diffusion radius in fractures is:

$$R = 0.178b\sqrt{\frac{bPT}{\eta h}} \qquad (18)$$

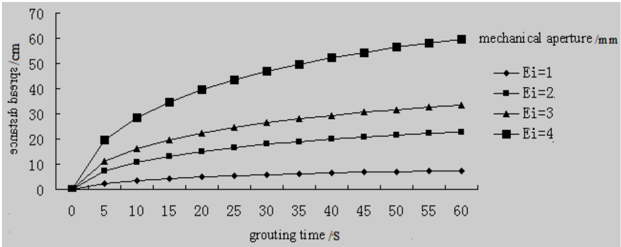
In this formula, R is the diffusion radius, m, b is the fracture aperture, m, P is the grouting hole pressure, Pa, T t is he grouting time, s, η is the grouting viscosity coefficient, Pa.s, h is the effective section of grouting, m.

The fracture aperture b is 1mm, the grouting pressure P is 2.0m water head height, the grouting viscosity coefficient is 11.7 Pa.s and the effective section of grouting is one unit length. Taking them into formula(18), we can get the radius of grouting spreading in 60s, which is 5.7cm. It can be seen that in picture2(a): When other conditions are same and the water pressure is, the radius of grouting spreading in 60s is 7.5cm.

We can see in the consequence of comparison that, there is little difference between the distance of transport and dispersion of relative flow model between slurry and water in the anhydrous state and Poiseuill′s planar fluid theory. Because they match each other, it can prove the rationality of this model.



（a）



（b）

Figure 2. Relationship between migration distance and time of two-phase flow of grouts- water

IV. CONCLUSION

Considering many factors, time-dependent behavior of viscosity of cement-based grouts, fissure mechanics aperture, fissure roughness, grouting time, ground water pressure, grouting pressure etc., the model is more close to construction surveying.

Using Matlab to achieve the calculating program of this model can be convenient for the design and construction of state grouting.

The distance of transport and dispersion of relative flow between slurry and water is decreasing with the increasing of hydrodynamic pressure. The distance of transport and dispersion of relative flow between slurry and water decreases much, comparing with the case in the anhydrous state.

There is little difference between the distance of transport and dispersion of relative flow model between slurry and water in the anhydrous state and Poiseuill′s planar fluid theory. Because they match each other, it can prove the rationality of this model.

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