Construction of Fluid-solids Coupling Model with Improved Richards-BP & Its Engineering Application

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Abstract. In order to study the slurry diffusion law during grouting, Richards unsaturated-saturated model was introduced, the definition of the grouting model is clear, the Richards model control equation was established, and the BP neural network was introduced, the improved fluid-solid coupling model was constructed. Through the use of saturated-unsaturated seepage flow model, as well as the overflow boundary iterative solution of the mixed boundary conditions, the free surface is calculated. Engineering practice for an example, with the aid of multi-field coupling analysis software, the diffusion law of slurry was simulated numerically. The results show that the slurry diffusion rule is affected by grouting material, initial pressure and other factors. When the slurry starts, it flows in the cracks along the upper side of the grouting hole, when the pressure gradient is reduced to the critical pressure, that is, to the lower side of the flow, when the slurry diffusion stability, and ultimately its shape like an 8. The slurry is spread evenly from the overall point of view, from the grouting mouth toward the surrounding evenly spread, it gradually reaches saturation by non-saturation, and it is not a purely saturated flow, when the slurry spread and reach a saturated state, the diffusion time is the engineering grouting time.

Keywords: Richards-BP model, fluid-solid coupling, diffusion law, model construction.

1. Introduction

The grouting technology improves the physical and mechanical properties of the goaf through the replacement, filling, extrusion, etc., thereby improving its safety. At present, the choice of grouting parameters was usually based on engineering experience, the grouting design and process not only by the geological environment, but also by the grouting works and its comprehensive impact of the object. There were still many problems in the grouting was not resolved. Such as the diffusion radius of the slurry, grouting time, grouting pressure and so on. When the site information was incomplete, or the promotion of new technology and materials cannot guarantee the grouting effect, this will be the safety of the project will be reduced. In this context, many scholars from the theoretical and experimental aspects of grouting design and technology were studied [1~5]. But this series of studies did not systematically carry out the analysis of the overall grouting effect of the corresponding model was presented [6].

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There were many factors that affect the effect of grouting. The research of theory and experiment cannot carry on the effective analysis to all aspects of grouting, the effective simulation of this study could be better applied to the engineering design. So the mathematical model had been used for reference, Through the appropriate improvement, and then the simulation of grouting effect was of great significance[7~8].

For the infiltration grouting process, grouting and anti-seepage and strengthening of the composition and structure of the individual and unpredictable were considered, The improved Richards-BP coupled model was constructed by numerical simulation of multi-field coupling. The Richards equation was introduced into the fluid flow model in the multi-field coupling software, The diffusion of the slurry, the main influencing factors and the diffusion effect were analyzed, Which provides an effective basis for grouting reinforcement design and grouting effect.

2. Improved Richards-BP model

2.1. Model building

The saturated - unsaturated seepage flow model of Richards equation was used to calculate the diffusion law of free surface. Richards equation could not only intuitively express the grouting effect, But also indirectly indicate the rationality of the various aspects of the grouting design [9].

Through the Richards equation control model was established, set the effective saturation and relative permeability expressed as a function of the matrix suction saturation zone for the positive pressure zone, the permeability coefficient was saturated permeability coefficient, the unsaturated region was a negative pressure zone, the infiltration coefficient was about zero [10]. The seepage field of grouting slurry was analyzed and studied, and then by means of multi-field coupling software for numerical simulation of effective slurry saturation - unsaturated simulation is obtained, to intuitively analyze the slurry diffusion law.

2.2. Richards grouting model control equation

Since the pressure in the seepage field was equal to the atmospheric pressure, the model control equation is set [11]

\[ [C + S_e S] \frac{\partial H_p}{\partial t} + \nabla [-K \nabla (H_p + D)] = 0 \]  

(1)

In the formula, pressure head \( H_p \) (m) as the dependent variable, \( C \) was the volume ratio of humidity (m-1), \( S_e \) was effective saturation, \( S \) was the pulp coefficient (m-1), \( t \) is time,\( K \) was the permeability coefficient m/s, \( D \) (such as x, y or z) represents the coordinates of the vertical direction (m). The equation does not show the volume fraction of water \( \theta \), But it was a value that depends on \( H_p \), because \( C \), \( S_e \) and \( K \) With changes in \( H_p \) and \( \theta \) changes.

Volume ratio timing could be expressed as

\[ C = \partial \theta / \partial H_p \]  

(2)

In the formula (2), the relationship between the slurry filling volume and the grouting pressure was described [12].

In order to simulate the slurry quality factor, it could be used more than the storage option.

\[ S = \rho_f g (\chi_p + \theta \chi_f) \]  

(3)

In the formula (3), \( \rho_f \) indicates fluid density kg/m3, \( g \) was gravity acceleration,\( \chi_p \) and\( \chi_f \) represents the compression rate of solid particles and fluid (m·s²/kg). Formula such as van Genuchtn, Brooks and
Corey, it could be described C, Se, K and \( \theta \) With \( H_p \) change in the relationship, the prerequisite were \( \theta_s \) and \( \theta_r \), as well as some other geomaterials \( \alpha, n, m \) and \( l \) as known. In the van Genuchten equation, assuming that when the pressure of the fluid was equal to atmospheric pressure, soil was saturated, which was \( H_p = 0 \), and according to the method of Brook and Corey, According to the intake air, Can distinguish the saturation of porous media (\( H_p > -1/\alpha \)) and unsaturation status (\( H_p < -1/\alpha \)), which was

\[
\theta = \begin{cases} 
\theta_s + S_e (\theta_s - \theta_r) & \text{if } H_p < -\frac{1}{\alpha} \\
\theta_r & \text{if } -\frac{1}{\alpha} \leq H_p 
\end{cases}
\]

(4)

\[
S_e = \begin{cases} 
\frac{1}{\alpha H_p} & \text{if } H_p < -\frac{1}{\alpha} \\
1 & \text{if } -\frac{1}{\alpha} \leq H_p 
\end{cases}
\]

(5)

\[
C = \begin{cases} 
\frac{-n}{H_p} (\theta_s - \theta_r) \frac{1}{\alpha H_p} & \text{if } H_p < -\frac{1}{\alpha} \\
0 & \text{if } -\frac{1}{\alpha} \leq H_p 
\end{cases}
\]

(6)

\[
K = \begin{cases} 
K_s S_e^{2s+2} & \text{if } H_p < -\frac{1}{\alpha} \\
K_s & \text{if } -\frac{1}{\alpha} \leq H_p 
\end{cases}
\]

(7)

2.3. Improved Richards-BP Neural Network

First, using the Richards model described above, the trend of slurry diffusion in the collapse zone was predicted. Then, the absolute error of the Richards model was processed by BP neural network model. That is, the absolute error predicted by the Richards model was taken as the input and output value of the BP neural network model, The BP neural network model was used to correct the prediction error, and the model prediction error of Richards-BP was obtained, to improve the prediction accuracy of the model[13].

2.4. Coupling calculation

Since there was an iterative coupling process in the above calculation, the number of unsaturation layers \( N \) and the layer thickness \( \Delta z_N \) were constantly changing, and therefore need to use the saturated band calculation of the head results, so that the mesh of the non-saturated band was updated. On the other hand, when running the groundwater module [14], the upper boundary condition was the bottom flux \( q_N, N + 1 \), to ensure the overall water balance, the water level should be equal to the free porosity in the unsaturated zone during the period, which was

\[
\mu = \theta_s N - \theta_N \]

(8)

In the formula, \( \theta_s N \) and \( \theta_N \) are the saturated volume water content and volume water content of the last layer of the unsaturated zone, respectively.
In order to get the answer to this question, initial conditions and boundary conditions could be set. Initially, the sample had the same pressure on the head HP0. The boundary condition was \((n)\) was the unit vector perpendicular to the boundary

| Boundary conditions | \(\boldsymbol{n}[-K\nabla(H_p + D)]\) | \(\boldsymbol{n}[-K\nabla(H_p + D)]\) | \(H_p = H_p0\) | \(H_p = H_p0\) |
|---------------------|---------------------------------|---------------------------------|-------------|-------------|
| Initial value       | \(\partial\Omega\text{Sides}\) | \(\partial\Omega\text{Rings}\) | \(\partial\Omega\text{Base}\) | \(\partial\Omega\text{Surface}\) |

2.5. Model build process and calculation parameters

In order to study the law of slurry diffusion, combined with multi-field coupling software, and the numerical model of the calculation parameters in Table 1. As the diffusion law by many factors, under certain environmental conditions set, the effect of the subsequent slurry material and the initial pressure on the diffusion law was studied. Based on experience, respectively, the slurry water-cement ratio was set to 0.8:1 and 1:1, the grouting pressure was set to 0.5 to 1 MPa [15].

**Table 1** Numerical simulation calculation parameters

| Slurry properties | Model parameter setting |
|-------------------|-------------------------|
| Total drilling volume(m) | Grouting volume(m³) | Use cement(t) | Water glass(kg) | Grouting pressure(Mpa) | Water-cement ratio | Saturated slurry volume fraction | Residual liquid volume fraction | Constitutive constants |
| 440.5m | 72 | 41.5 | 20 | 0.5-1 | 0.8:1,1:1 | 0.43 | 0.045 | 14.5 |

In the saturated stream, the permeability will change as the fluid flows through the porous medium which was filling the voids. Using the Richards equation to simulate flow, the sloughness of the voids could be considered by using the van Genuchten and Brooks-Corey formulas.

3. Engineering Applications

3.1. Engineering examples

A lead-zinc mine in a stope, due to the mine was not timely and mined-out area exposure time was too long, resulting in two groups of filling body collapse and the top ore body fall, in the mining process, due to the mined-out area and the surrounding rock of the plastic zone to expand and extend to the adjacent stope lead to through and a large range of crust damage. Combined with on-site investigation, the surrounding rock was very unstable, the collapse area must be filled with grouting. According to engineering practice, cement slurry grouting method was selected to fill the collapse area to fill grouting. The grouting process must involve the slurry in the filling body voids and cracks in the flow problem, it was possible to simulate the flow of the slurry in the filling body by means of numerical analysis.

3.2. Hole Mesh Model for Rectangular Grouting

Select a section of the collapse area to set the grouting hole, In the Richards model, the pressure head was uniform, and all the vertical slices were the same, it can select a 2D cross section, the establishment of the direction of the direction of \(Y = 636m, 100m\) to 220m down hole collapse model. In order to reduce the amount of computation, the free-split triangular mesh was selected, set the maximum unit size to 0.025, the results were shown in Fig1, a total of four grouting holes were arranged.
3.3. Analysis of Basic Seepage Regularity of Grouting

The parameters of the material are converted into variable parameters in the Richards model. The results of the diffusion calculation of the four grouting holes are simulated, the distribution of effective saturation, pressure head (contour) and flow rate (arrow) is shown. The diffusion saturation in the filling body is in the order of blue, yellow and red, respectively, from low to high, it can be seen that the flow around the slurry hole has undergone significant changes. While in other parts of the change is basically uniform, as shown in picture 2, slurry diffusion is not spread evenly around, But the degree of slurry saturation will continue to change with the continuous injection of the slurry.

Figure 2 for the different time points out of the pulp around the slurry of the effective saturation of the one-dimensional map, X is the distance to the grouting hole, and y represents the effective saturation of the position. The angular coordinates (+180°, 0°) and (-180°, 0°) correspond to the upper and lower parts of the boundary, it shows the upper and lower sides of the pulp on the effective saturation, the effective saturation is 0s, 50s, 100s, 300s, 600s, 900s, respectively, from the middle to the sides (in the order of dark blue, green, red, light blue, rose). From Figure 2, ① the initial value of the effective saturation is a horizontal line, ② the influence of the initial pressure on the upper rock mass is larger than that of the lower part of the region also began to increase, the final out of the mouth will be fully saturated. ③ the saturation of the slurry increases with time. ④ slurry diffusion is along a certain path, it constitutes an irregular closure curve, and it can be calculated by calculating the trajectory path perimeter to the theoretical diffusion radius, it can be seen that when other grouting conditions are constant, a certain initial pressure of the grouting directly affects the effect of grouting diffusion is set so that the grouting spread evenly.

3.4. With the law of time spread

On the basis of the above model, set the relevant parameters in the grouting design, change the time step, Set the time step are 0s, 50s, 100s, 150s, Thus, the slurry diffusion is studied in chronological order. Through the multi-field coupling software to simulate as shown in Figure 3.
Fig.3 The law of the diffusion of the slurry over time

By comparing the diffusion maps of different times, ① the upper and lower sides of the slurry spread the same degree of beginning, but as time changes, when the slurry away from the grouting hole, which is affected by gravity, the pressure gradient is reduced to the critical pressure, the initial pressure is weakened and the diffusion on the upper side of the slurry is not uniformly diffused, that is, the initial pressure of grouting needs to be adjusted. ② Slurry in a certain grouting pressure gradient, it will flow along the chamber or fissure diffusion, Slurry density, viscosity increases, low flow rate, this may cause it to not spread completely, and the slurry may stop flowing.

Through the above verification, according to the demand for grouting numerical simulation, Such as the progress of the project tight, the material water-cement ratio that changes the material density and viscosity in the model is adjusted, the best water-cement ratio in the same area is obtained, this can effectively shorten the duration, but also to make the slurry will not premature condensation and spread in place.

4. Conclusion
(1) Richards unsaturated-saturated model is introduced, the definition of the grouting model is defined, and the Richards model control equation is established, introduced into the BP neural network, and the improved fluid-solid coupling model is constructed. Taking the engineering practice as an example, the numerical simulation of the slurry diffusion process is carried out on the basis of setting the grouting parameters.

(2) Through the slurry diffusion analysis can be obtained, the slurry began to flow along the upper part of the grouting hole flow diffusion, when it is away from the grouting hole, the pressure gradient will be reduced to critical pressure, this time, the slurry by gravity, It will flow to the bottom, and ultimately it gradually reached a uniform state, when the slurry tends to stabilize the diffusion, the shape of the class "8" shape.

(3) Slurry diffusion from the whole to be evenly dispersed, from the grouting port to its saturation around the uniform diffusion, and gradually from the saturation to saturation, it is not purely saturated flow. When the slurry time to promote the map did not show significant changes, That is, the diffusion of the slurry reaches saturation, and the diffusion time at this time is the grouting time of the project.

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