A Numerical Simulation of the Interaction of Aggregate and Rockfill in a Gangue Fluidized Filling Method

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Abstract: To solve the problem of gangue discharge in coal mining, fluidized gangue filling technology was developed. The key scientific problem of this technology is the diffusion characteristics of the gangue in the goaf. Therefore, a discrete element fluidized gangue model was established based on the ARR contact model. Based on the Rblock module, a goaf model with a certain void ratio was created, and the meso-parameters of fluidized gangue were calibrated. The fluidized gangue diffusion and rock displacement laws were explored under different grouting speeds, void ratios, and gangue particle sizes. The research results show that with the increase in the grouting speed and void ratio, and the decrease in the gangue particle size, the diffusion radius gradually increases, and the rock displacement in the goaf also gradually increases. Under given geological conditions, the total grouting mass of a single hole can reach $5.63 \times 10^4$ kg.

Keywords: fluidized gangue; goaf; PFC3D; Rblock; slurry diffusion; rockfill

1. Introduction

China is a major coal country and the world’s largest coal market. According to statistics, coal production capacity will remain at $3.9 \times 10^9$ t in 2020 [1–3]. The level of coal development in China will further increase in the future. According to the prediction of the Chinese Academy of Engineering, in 2030 and 2050, China’s coal will account for 55% and 50% of the primary energy structure [4–6]. This large-scale coal development brings about a large amount of gangue discharge, and the cumulative amount of gangue piled up in the country has exceeded $6 \times 10^9$ t [7–9]. These gangues will cause a large area of land to be occupied, a large amount of smoke and dust, and the emission of toxic and harmful gases. Therefore, the large-scale treatment of mine gangue is imperative.

Many scholars have researched gangue treatment technology and proposed a variety of gangue treatment and disposal methods. Conventional gangue treatment methods mainly include gangue power generation, gangue bricks, and gangue cement [10–12]. Traditional gangue disposal methods mainly include solid filling methods and cemented filling forms [13–15]. The solid filling method was proposed in 2008. Based on comprehensive mechanized mining, key filling equipment was added that can realize the parallel operation of coal mining and filling under cover of the same hydraulic support and safely and efficiently transport ground filling materials to underground filling [16–18]. The cemented filling method uses cement as the cementing material and gangue as the aggregate to make a certain concentration of slurry, filled into the goaf using the filling pipeline [19–21].

The above method can dispose of the gangue. For the movement characteristics of gangue in goaf, relevant scholars’ research shows that in the process of solid filling, gangue particles are compacted under the action of compaction mechanism, and the overall strength and natural rest angle of the gangue pile are improved [22–24]. During the filling process of cemented filling material, the slump of slurry decreases with the increase of...
gangue concentration, and the strength of the filling body increases with the growth of cement content \[25-27\].

For the above research results, the investment of solid and cemented filling methods is high, the process is complex, and the treatment capacity is low. The goaf of these two methods is well supported in advance, and the movement of gangue in it is essentially accumulation, so the study of its flow characteristics is meaningless. Summarizing the research results at home and abroad, some foreign scholars have studied the formation process and volume distribution of goaf cavities \[28\]. The effect of the particle size ratio and additives ratio on the slurry flow characteristics has also been further studied \[29,30\]. However, there has been little research on the interaction between crushed stone blocks and the slurry in the goaf. Therefore, this paper proposes a fluidized gangue filling method that can treat gangue on a large scale, has a simple process, and low investment cost. The discrete element model of fluidized gangue and the rock block model of goaf is established to explore gangue aggregate’s diffusion law under different working conditions, such as void ratio in goaf, grouting pressure, gangue particle size, and concentration. The diffusion range and grouting scale of fluidized gangue are calculated based on the actual geological conditions.

2. Test Background

2.1. Fluidized Gangue Filling Method

Fluidized gangue filling is proposed here. The filling material is gangue and water, the filling method is pipeline transportation, and the filling power is the pump. Coal mining will destroy the original stress balance of the overlying rock, resulting in the damage and deformation of the rock mass such as stretching, shearing, bending, caving, and fissures. During the mining process, the roof collapsed rock will fill part of the goaf, forming an underground void. These voids will provide space for filling. Firstly, the coal gangue is sorted underground, and then the large-size gangue is broken and mixed with water to prepare fluidized gangue, which is pumped to the gap of goaf through the filling pump and filling the pipeline. The gangue fluidization filling system includes the gangue crushing system, slurry preparation system, and slurry transportation system, respectively responsible for the preparation, transportation, and filling of fluidized gangue, as shown in Figure 1. The process of gangue from separation to filling is shown in Figure 2.

![Figure 1. Fluidized gangue filling method.](image1)

![Figure 2. Preparation, transportation, and filling process of fluidized gangue.](image2)
2.2. Key Scientific Issues

As the main filling space of fluidized gangue, goaf is characterized by uneven void quantity and diameter distribution. Therefore, the diffusion radius of fluidized gangue in goaf can only be used as the evaluation standard of filling effect. From the point of view of filling material, the particle size and aggregate concentration are the influencing factors of the filling effect. In terms of filling space, the void ratio of goaf is the influencing factor of the filling effect. In terms of filling power, pump pressure is an influencing factor affecting the filling effect. The numerical model of the interaction between fluidized gangue and goaf is established to explore the diffusion law of fluidized gangue and lay a theoretical foundation for popularizing the fluidized gangue filling method.

3. Test Principle and Scheme

3.1. Simulation Method of Fluidized Gangue and Goaf

1. Simulation method of fluidized gangue

There are three main simulation methods for wet aggregate: single-phase fluid, discrete particle population, and suspension. The discrete particle group has great advantages. The discrete element unit can reconstruct the microstructure of fluidized gangue, and the calculation results can feedback the law of aggregate interaction in fluidized gangue. Therefore, when used to treat fluidized gangue, gangue aggregate is generally described by the discrete element [31–33]. In contrast, the ARR (adhesive rolling resistance) linear model describes water and mud, as shown in Figure 3.

\[ F^a = \begin{cases} 
F_0 & \text{if } g_s \leq 0 \\
F_0(1 - \frac{g_s}{D_0}) & \text{if } 0 < g_s < D_0 \\
0 & \text{if } g_s \geq D_0 
\end{cases} \]  

(1)

Figure 3. Simplified model of fluidized gangue.

The ARR model can represent the adhesion between particles caused by argillaceous material. The main parameters representing rolling are friction coefficient \( \mu \) and rolling friction coefficient \( \mu_r \). The main viscosity parameters are the maximum attraction \( F_0 \) and the attraction range \( D_0 \). The above parameters are the parameters to be calibrated. The attraction \( F^a \) between argillaceous and gangue aggregate represents the cementation. It is calculated by the formula (1), where \( g_s \) is the surface clearance.
2. Simulation method of goaf

There are two construction methods for the rocks in the goaf: One is to construct the cluster unit based on the spherical particles and rock block template, and the other is to build the Rblock unit based on the rock block template. Using the Rblock element to make rock blocks can improve the balance speed of the software and reduce the probability of broken sphere particles flying out of the domain during a collision. The full name of Rblock is the rigid block, and it is a closed convex rigid block. The inertia tensor is updated in real-time by using the rotating dynamic equation. The contact information among Rblock-facet, Rblock-Rblock, and Rblock-ball is detected and calculated in real-time. Therefore, the interaction information between gangue aggregate and goaf rock can be obtained more accurately using the Rblock module.

3.2. Test Scheme

The experimental scheme is designed to study the effects of grouting speed, void ratio, and gangue particle size on the fluidization grouting effect. The single factor rotation method is used to calculate and analyze the influence of the above factors on the grouting diffusion range and the rock displacement in the goaf. A total of 13 groups of tests were carried out. The gangue selected for the test comes from the Pingdingshan coal mine in Henan province, and the lithology is mudstone with a density of 2.6 kg/m$^3$. The test scheme is shown in Table 1. The third group was the basic experiment.

Table 1. General test scheme.

| Serial Number | Influence Factor | Grouting Speed m/s | Void Ratio | Particle Size /m |
|---------------|-----------------|-------------------|------------|-----------------|
| 1             | Grouting speed  | 10                | 0.35       | 0.005           |
| 2             |                 | 30                |            |                 |
| 3 (Basic experiment) |            | 50                | 0.35       | 0.005           |
| 4             |                 | 70                |            |                 |
| 5             |                 | 90                |            |                 |
| 6             | Void ratio      | 50                | 0.15       | 0.005           |
| 7             |                 |                   | 0.25       |                 |
| 8             |                 |                   | 0.45       |                 |
| 9             |                 |                   | 0.55       |                 |
| 10            | Particle size   | 50                | 0.35       | 0.001           |
| 11            |                 |                   |            | 0.003           |
| 12            |                 |                   | 0.35       | 0.007           |
| 13            |                 |                   |            | 0.009           |

4. Model Parameter Calibration

4.1. Parameter Calibration Method

Because PFC is a discrete element simulation software, it is necessary to calibrate the parameters of fluidized gangue before simulation, to establish a correspondence between micro parameters and macrophysical parameters [34–36]. For the calibration process, as long as the macro-physical parameters exhibited by the interaction between particles are the same as the actual parameters of the fluidized gangue filling material, the adopted parameters can be used to simulate the fluidized gangue. Therefore, the stacking and L box tests were used to calibrate the parameters. The design parameter calibration scheme is shown in Table 2. Design a four-factor three-level orthogonal experiment scheme, a total of 9 groups of experiments. The levels of friction resistance $F_{ric}$ are 0, 0.15, and 0.75 respectively, the levels of rolling resistance coefficient $R_{fic}$ are 0, 0.1, and 0.5 respectively, the levels of maximum attraction $F_0$ are 0, $2.2 \times 10^{-3}$, and $1.1 \times 10^{-2}$ respectively, and the levels of attraction range $D_0$ are $0$, $1.5 \times 10^{-4}$ and $7.5 \times 10^{-4}$ respectively.
Table 2. Parameter calibration scheme.

| Factor         | Fric | Rfric | Fy/N          | Dy/m |
|----------------|------|-------|---------------|------|
| Test 1         | 0    | 0     | 0             | 0    |
| Test 2         | 0    | 0.1   | 2.2 × 10^{-3} | 1.5 × 10^{-4} |
| Test 3         | 0    | 0.5   | 1.1 × 10^{-2} | 7.5 × 10^{-4} |
| Test 4         | 0.15 | 0     | 2.2 × 10^{-3} | 7.5 × 10^{-4} |
| Test 5         | 0.15 | 0.1   | 1.1 × 10^{-2} | 7.5 × 10^{-4} |
| Test 6         | 0.15 | 0.5   | 0             | 1.5 × 10^{-4} |
| Test 7         | 0.75 | 0     | 1.1 × 10^{-2} | 7.5 × 10^{-4} |
| Test 8         | 0.75 | 0.1   | 0             | 7.5 × 10^{-4} |
| Test 9         | 0.75 | 0.5   | 2.2 × 10^{-3} | 0    |
| Correction test| 0.75 | 0.1   | 2.2 × 10^{-3} | 7.5 × 10^{-4} |

The model for designing the stacking test is shown in Figure 4. The test process is to slowly lift the drum, measure the slump of fluidized gangue after stabilization, and observe whether it is consistent with the laboratory test. The design of the l-box test model is shown in Figure 5. The test process is to open the door inside the L box and observe the flow trace of fluidized gangue.

![Figure 4. Stacking test model.](image)

![Figure 5. L-box test model.](image)

4.2. Calibration Results of Atacking Test

The slump results of each scheme are shown in Table 3, and some results are shown in Figure 6. When the particle size of gangue is 5–10 mm, the actual slump measured in the laboratory is 172 mm, similar to test 5. Therefore, based on test 5, we continued to fine-tune the parameters for the correction test. The adjusted friction coefficient is 0.75, the maximum

| Factor | Fric | Rfric | Fy/N | Dy/m |
|--------|------|-------|------|------|
| Test 9 | 0.75 | 0.5   | 2.2 × 10^{-3} | 0 |
| Correction test | 0.75 | 0.1   | 2.2 × 10^{-3} | 7.5 × 10^{-4} |
attraction is $2.2 \times 10^{-3}$, the attraction range is $7.5 \times 10^{-4}$, and the rolling friction coefficient is 0.1. The slump is 172 mm, which is in line with the physical test results, as shown in Figure 6f.

Table 3. Test results.

| Test    | Slump/mm | Test    | Slump/mm |
|---------|----------|---------|----------|
| Test 1  | 292      | Test 6  | 250      |
| Test 2  | 292      | Test 7  | 120      |
| Test 3  | 232      | Test 8  | 180      |
| Test 4  | 223      | Test 9  | 150      |
| Test 5  | 168      | Correction test | 172 |

It can be seen from Figure 7 that when the friction coefficient is 0.75, the maximum attraction is $2.2 \times 10^{-3}$, the attraction range is $7.5 \times 10^{-4}$, and the rolling friction coefficient
is 0.1, the obtained flow trace is closest to the laboratory results, that is, the correction test, as shown in Figure 7f.

5. Model Establishment and Test
5.1. Model Establishment and Process
5.1.1. Goaf Construction

After obtaining the appropriate meso-parameters, the interaction model between the fluidized gangue and the rock in the mined-out area is designed. A box with a length, width, and height of 15 m × 20 m × 15 m is intended to indicate a certain range of goaf. There are stones with a certain void ratio inside to simulate a certain void ratio. And build a grouting pipeline outside with an inner diameter of 300 mm, the length of the outer pipeline in the goaf is 5.0 m, and the size of the internal pipeline is also 5.0 m. Extract the binary image of the rock in the mined-out area, calculate its length, width and height, and reconstruct the Rblock template in PFC3D. Finally, Rblock is filled with the entire goaf with a void ratio of 35%, and the goaf is obtained, as shown in Figure 8.

![Overall construction of goaf.](image)

5.1.2. Construction of Fluid Gangue

The representative gangue particles taken from the site were measured and photographed in the laboratory [37–39]. The captured gangue particles were analyzed in Matlab software, and the color image was transformed into a gray image by the rgb2gray command. Then, the gray was processed by threshold binarization to generate a digital image. In CAD, multiple groups of closed curves were stacked and connected into a closed surface, and finally, the shape of gangue particles was obtained as shown in Figure 9.

![Particle morphology of gangue.](image)

5.2. Slurry Diffusion Law

The numerical simulation process first generates the rock pile in the goaf, with a range of 15 m × 20 m × 15 m, rock with a certain void ratio is generated inside. Then, slurry
particles with a particle size of 3–8 mm are generated in the grouting pipe, and a certain initial velocity is given outside the pipe. After the slurry leaves the grouting pipe, it will continue to advance a certain distance by relying on inertia and collide with the rocks in the goaf. Numerical simulation was carried out based on the conditions set in Table 1 to analyze the slurry diffusion range under different influencing factors, as shown in Figure 10. See Table 4 for test results.

Figure 10. Partial results of the slurry diffusion test: (a) Test3; (b) Test 5; (c) Test 9; (d) Test 13.
Table 4. Slurry diffusion range.

| Number | Factor          | Slurry Diffusion Range (Width × Deep × High = m × m × m) |
|--------|-----------------|--------------------------------------------------------|
| 1      |                 | 7.62 × 7.63 × 2.85                                     |
| 2      |                 | 7.95 × 8.21 × 2.90                                     |
| 3      | Grouting speed  | 8.18 × 8.54 × 3.52                                     |
| 4      |                 | 8.22 × 9.86 × 3.63                                     |
| 5      |                 | 8.29 × 10.49 × 4.84                                    |
| 6      |                 | 7.65 × 6.82 × 3.18                                     |
| 7      |                 | 8.16 × 7.78 × 3.50                                     |
| 8      |                 | 9.50 × 8.81 × 3.54                                     |
| 9      |                 | 11.82 × 8.90 × 3.86                                    |
| 10     |                 | 8.81 × 9.05 × 3.86                                     |
| 11     |                 | 8.74 × 8.58 × 3.77                                     |
| 12     |                 | 7.41 × 8.50 × 3.48                                     |
| 13     |                 | 7.02 × 8.38 × 3.20                                     |

It can be seen from Table 4 that the influence of grouting speed on slurry diffusion radius was analyzed in test 1, test 2, test 3, test 4, and test 5. When the grouting speeds were 10, 30, 50, 70, and 90 m/s, the diffusion ranges of slurry were 7.62 m × 7.63 m × 2.85 m, 7.95 m × 8.21 m × 2.90 m, 8.18 m × 8.54 m × 3.52 m, 8.22 m × 9.86 m × 3.63 m, and 8.29 m × 10.49 m × 4.84 m, respectively. With the increase of grouting speed, the slurry diffusion range increases gradually.

Test 6, test 7, test 3, test 8, and test 9 analyzed the effect of void ratio on slurry diffusion radius. When the voids were 0.15, 0.25, 0.35, 0.45 and 0.55, the diffusion ranges of slurry were 7.65 m × 6.82 m × 3.18 m, 8.16 m × 7.78 m × 3.50 m, 8.18 m × 8.54 m × 3.52 m, 9.50 m × 8.81 m × 3.54 m, and 11.82 m × 8.90 m × 3.86 m, respectively. With the increase of void fraction, the slurry diffusion range increases gradually, and the width direction rises obviously.

Test 10, test 11, test 3, test 12, and test 13 analyzed the influence of gangue particle size on slurry diffusion radius. When the particle sizes were 0.01, 0.03, 0.05, 0.07, and 0.09, the diffusion ranges of slurry were 8.81 m × 9.05 m × 3.86 m, 8.74 m × 8.58 m × 3.77 m, 8.18 m × 8.54 m × 3.52 m, 7.41 m × 8.50 m × 3.48 m, and 7.02 m × 8.38 m × 3.20 m, respectively. With the increase of particle size, the diffusion range of slurry decreases gradually.

5.3. Law of Rock Movement in Goaf

A numerical simulation was conducted based on Table 1 to analyze the influence range of rock movement in goaf under different influencing factors, as shown in Figure 11. See Table 5 for test results.

It can be seen from Table 5 that test 1, test 2, test 3, test 4, and test 5 analyzed the influence of grouting speed on rock displacement in goaf. When the grouting speeds were 10, 30, 50, 70, and 90 m/s, the influence ranges of rock displacement were 7.45 m × 2.38 m × 4.54 m, 7.60 m × 2.50 m × 4.68 m, 7.81 m × 5.52 m × 7.26 m, 7.84 m × 9.34 m × 7.29 m, and 9.50 m × 9.35 m × 7.35 m, respectively. With the increase of grouting speed, the influence range of rock displacement increases gradually. The maximum rock displacements were 1.086 m, 1.206 m, 1.210 m, 1.231 m, and 1.307 m, respectively.

Test 6, test 7, test 3, test 8, and test 9 analyzed the influence of void ratio on rock displacement. When the voids were 0.15, 0.25, 0.35, 0.45, and 0.55, the influence ranges of rock displacement were 6.05 m × 3.35 m × 1.49 m, 7.72 m × 5.26 m × 3.01 m, 7.81 m × 5.52 m × 7.26 m, 8.62 m × 7.44 m × 10.10 m, and 16.85 m × 8.29 m × 15.0 m, respectively. With the increase in grouting speed, the influence range of rock displacement increased gradually and was significantly affected in the width, depth, and height direction. The maximum rock displacements were 0.988 m, 1.237 m, 1.210 m, 1.728 m, and 2.182 m, respectively.
Figure 11. Partial results of influence range of rock movement: (a) Test 3; (b) Test 5; (c) Test 9; (d) Test 13.

The influence of particle size on rock displacement was analyzed in test 10, test 11, test 3, test 12, and test 13. When the particle sizes were 0.01, 0.03, 0.05, 0.07, and 0.09 m, the influence ranges of rock displacement were $7.34 \times 4.34 \times 5.34$ m, $7.42 \times 4.56 \times 6.42$ m, $7.81 \times 5.52 \times 7.26$ m, $8.91 \times 8.96 \times 9.73$ m, and $9.02 \times 9.44 \times 10.72$ m, respectively. With the increase of particle size, the influence range of rock displacement increases gradually and is significantly affected by in-depth direction and height direction. This is because at the same grouting speed, the larger the gangue particle size, the greater the kinetic energy, and the greater the rock displacement in the goaf under the impact of gangue particles. The maximum rock displacements were 1.205 m, 1.208 m, 1.210 m, 1.243 m, and 1.364 m, respectively.
Table 5. Influence range of rock movement in goaf.

| Number | Factor         | Influence Range of Rock Movement (Width × Deep × High) | The Maximum Displacement of Rock |
|--------|----------------|--------------------------------------------------------|----------------------------------|
| 1      |                | 7.45 × 3.38 × 4.54                                      | 1.086                            |
| 2      | Grouting speed | 7.60 × 3.50 × 4.68                                      | 1.206                            |
| 3      |                | 7.81 × 5.52 × 7.26                                      | 1.210                            |
| 4      |                | 7.84 × 9.54 × 7.29                                      | 1.231                            |
| 5      |                | 9.50 × 9.35 × 7.35                                      | 1.307                            |
| 6      | Void ratio     | 6.05 × 3.35 × 1.49                                      | 0.988                            |
| 7      |                | 7.72 × 5.26 × 3.01                                      | 1.237                            |
| 8      |                | 8.62 × 7.44 × 10.10                                     | 1.728                            |
| 9      |                | 16.85 × 8.29 × 15.0                                     | 2.182                            |
| 10     |                | 7.34 × 4.34 × 5.34                                      | 1.205                            |
| 11     |                | 7.42 × 4.56 × 6.42                                      | 1.208                            |
| 12     | Particle size  | 8.91 × 8.96 × 9.73                                      | 1.243                            |
| 13     |                | 9.02 × 9.44 × 10.72                                     | 1.364                            |

6. Results Analysis and Discussion

6.1. Grouting Scale under Specific Conditions

Based on the actual grouting conditions, the grouting time is set as 0.5 h, and the grouting speed is 5 m/s. When the void ratio of goaf is 35%, its diffusion width is 8.36 m, diffusion height is 3.18 m, and diffusion depth is 7.90 m. The influence radius of grouting on goaf rock is 7.61 m wide, 8.01 m deep, and 8.97 m high. The design function is used to calculate the total mass of fluidized gangue, and the PFC3D built-in fish function is used to write the code. Finally, the mass of fluidized gangue in goaf is $5.63 \times 10^4$ kg. In the actual filling operation, the grouting quality of a single grouting mouth can reach $5.63 \times 10^4$ kg. Slurry diffusion and rock displacement in goaf are shown in Figure 12.

(a) Slurry diffusion; (b) Influence range of rock movement in goaf.
6.2. Optimization and Adjustment of Grouting Technology

The range analysis method analyzes the influence of grouting speed, porosity, and particle size on slurry diffusion range, rock movement range, and maximum rock displacement. The range analysis table is shown in Table 6.

Table 6. Range analysis.

| Factors             | Range of Slurry Diffusion | Range of Influence of Rock Movement | Range Value of Maximum Displacement of Rock |
|---------------------|---------------------------|------------------------------------|-------------------------------------------|
|                     | Width  | Depth  | Height | Range Sum | Width  | Depth  | Height | Range Sum |                     |
| Grouting speed       | 0.67   | 2.86   | 1.99   | 5.52      | 2.05   | 5.97   | 2.81   | 10.83      | 0.221                |
| Void ratio           | 4.17   | 2.08   | 0.68   | 6.93      | 10.80  | 4.94   | 13.51  | 29.25      | 1.194                |
| Particle size        | 1.79   | 0.67   | 0.66   | 3.12      | 1.68   | 5.10   | 5.38   | 12.16      | 0.159                |

It can be seen from Table 6 that the porosity is the main factor affecting the diffusion range of slurry, the influence range of rock movement, and the maximum displacement of rock, followed by the grouting speed. The slurry diffusion width and rock movement width are seriously affected by porosity. Grout diffusion depth and rock movement depth are seriously affected by grouting speed. The grouting speed seriously affects the slurry diffusion height, and the height of the influence range of rock movement is seriously affected by the porosity. Therefore, the grouting speed should be improved to facilitate grouting, improve grouting depth, further improve grouting volume, and increase gangue treatment capacity.

7. Conclusions

Gangue fluidization filling is a large-scale method of treating gangue. The discrete element model of fluidized gangue and goaf rock is established to explore the interaction law between fluidized gangue and goaf rock. And the diffusion law of gangue aggregate and the influence range of goaf rock displacement under different working conditions are explored. The main conclusions are as follows:

1. The fluidization filling technology of gangue is developed. The interaction model between filling aggregate and goaf rock is constructed. The discrete element simulation method of Fluidized gangue is proposed, and the appropriate meso parameters of gangue are selected through a calibration test. The rock model of goaf based on Rblock structure is constructed.

2. The diffusion range of fluidized gangue under the influence of different grouting speeds, porosity, and gangue particle sizes are analyzed. With the increase of porosity, the diffusion width increases significantly. Diffusion depth and diffusion height are greatly affected by grouting speed. With the rise of grouting speed, diffusion depth and diffusion height increase significantly.

3. The influence range of rock displacement in goaf under the influence of different grouting speeds, porosity, and gangue particle size is analyzed. Porosity affects the maximum displacement of rock, and the range value is 1.194. The width and height of rock displacement are greatly affected by porosity, and the range values are 10.80 and 13.51. The influence depth of rock displacement is greatly affected by grouting speed, and the range value reaches 5.97.

4. To facilitate grouting, improve grouting depth, increase grouting volume, and increase gangue treatment capacity, grouting speed should be increased. When the grouting time is 0.5 h, and the grouting speed is 5 m/s, the single hole grouting amount reaches $5.63 \times 10^4$ kg.
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