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TECHNICAL ARTICLE

Data Analysis and Key Parameters of Typical Water Hazard Control Engineering in Coal Mines of China

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Abstract

Large-scale efforts to control water hazards require knowledge of relevant grouting theories and recognition of their shortcomings. Relationships between key engineering technical specifications and conventional hydrogeological parameters were defined to guide engineering designs. For regional control of working face projects, the main influential parameters and relationships were obtained by gray correlation and regression analysis. The results showed that fluid loss and water absorption of boreholes are the main determinants of grout volume. When the grouting pressure reaches 2–4 times the hydrostatic pressure, the grout volume can be effectively increased by up to 40%. For water pathway cut-off projects, the general relationship between water inrush and grout quantity was obtained by the theoretical derivation and regression analysis. It was shown that there is a quadratic polynomial relationship between the quantity of grout and the volume of water inrush. These results can be used to plan and optimize large-scale water disaster prevention and control projects and estimate the required investments.

Keywords Regional control of floor water hazards · Tunnel cut-off technology by grouting · Water hazards data analysis · Grouting optimization

Introduction

In China, coal mining can be hydrologically complicated, with serious water hazard threats. With ever-increasing mining depths, conventional water control techniques are unable to meet the demand for intrinsically safe mining. Water control in these deep coal mines requires comprehensive water control measures, including exploration, prevention, blockage, dewatering, drainage, interception, and monitoring (SAWS 2018).

The common grouting technologies used in the fields of water prevention and control in coal mines can be roughly divided into two categories (Wu et al. 2013; Zhang et al. 2012; Zhao 2008): emergency cut-off of water inrush pathways and floor grouting of the working faces. There are significant differences between these two engineering control categories in terms of the construction technology and equipment, grouting materials, quality evaluation methods, and economic indicators used. The grouting theory and control factors are also different.

Grouting in coal mines is often characterized by concealment, complexity, flexible technical schemes, large investments, and difficulty in predicting the engineering scale. At present, there are no industry-accepted technical specifications and cost documents for these grouting projects. Thus, the investment estimates of coal mine production and construction often have greater uncertainty due to water prevention and control problems, which can cause considerable uncertainties and investment risk. Therefore, it is necessary to focus on large-scale water hazard prevention and control projects, perform reverse analysis on the data and information obtained from a large number of typical projects, and discuss cost control factors and key technical problems of large-scale grouting projects in coal mines. These analyses can be very useful in establishing relevant industry-wide

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technical specifications and quota standards and in optimizing similar projects.

Grouting in Coal Mines

Grouting theory is based on solid mechanics, fluid mechanics, material mechanics, hydraulics, and other disciplines. A theoretical model of grout volume, grouting pressure, radius of influence, time, and other variables has been established (Hu and Lu 2012; Li et al. 2010), though a large number of grouting-related engineering and technical problems are still being researched.

Classification of Common Grouting Theories

Grouting can be categorized into seepage (Funehag and Gustafson 2008; Almer and Stoel 2003), hydrofracturing (Grotenhuis 2004; Vliet 2002), compaction (Miller and Roycrof 2004; Albert et al. 2011; Adel et al. 2012), fractured rock mass (Zhang et al. 2010, 2011), jet (Wong and Poh 2000; Nikbakhtan and Ahangari 2010), and electro-osmotic chemical grouting (Hideki et al. 2012; Lohrasb et al. 2016). The grouting technology used in coal seam floors mainly belongs to the fractured rock and hydrofracturing grouting types. Water pathway cut-off grouting, in addition to seepage, compaction, and hydrofracturing grouting, is closely related to aggregate construction theory (Wang 2012; Geng et al. 2017), in which, at present, there are large gaps.

Grouting Technology for Water Inrush Pathways

To mitigate coal mine water disasters, the object of treatment changes from the traditional grouting environment with static water and fissures (or pores) to an environment with dynamic water flowing in large open cross-section migration channels. The first step is to pour fill material into the water-flowing pathway to form an artificial accumulation body. Then, grouting reinforcement is carried out. Since traditional grouting theory cannot objectively describe this combined approach, the quantitative indicators needed for economic and technical evaluation are missing (Wang 2012).

Internal Relationship of Grouting Parameters

Traditional grouting theory has been used to establish theoretical models to analyze the flow pattern of grout, while grout volume cannot be described by a single model. However, there must be an optimal combination of parameters that can be used to define the minimum grout volume (effective grouting entity), the shortest grouting time, and the optimal technical effect that can be achieved. Generally, the parameters related to the grout volume used in rock and soil include the effective grouting pressure P, permeability of the rock mass k, changing grouting viscosity η(t), effective grouting time t, fissure opening b, and geomechanical parameters. Because these parameters change during the construction process, they cannot be obtained directly, but based on mechanical analysis, are closely related.

1) The effective grouting pressure P overcomes propagation resistance and the energy loss of secondary hydrofracturing due to the grout in the pores or fissures, and is related to permeability and rock mechanics parameters.
2) The permeability parameter k is determined by the pores' structure and morphology and the crack opening and its morphology, which indirectly affect the pressure required for the slurry to flow.
3) The grout viscosity η(t) determines the grouting energy loss as well as the grouting efficiency.
4) The effective grouting time t is related to grouting pressure, permeability of rock or soil, and time-varying viscosity of grout.
5) The grout quantity is affected by the permeability parameter k of the rock or soil, grout properties, effective grouting pressure, effective grouting time, and whether secondary hydrofracturing is carried out.

The correlation between key parameters such as grout volume, grouting pressure, and common hydrogeological parameters allow the scale and cost of grouting engineering to be quickly estimated using existing exploration data. This approach is particularly effective for floor grouting projects.

For pathway closure and cut-off, the main parameters determining the scale of the project are the area of the pathway section and the flow velocity, whose product is the water inrush volumetric flow rate. These data can be determined, and the relationship between the actual grout quantity and cross-sectional area and flow velocity can be established, which can provide a reference for project budget planning.

Grouting of Coal Floors: Key Technologies and Engineering Analysis

Mechanical Meaning and Mathematical Formulation of the Grouting Process

The grouting flow q(t) of a single grouting hole is a function of the effective grouting pressure, grout viscosity, and permeability parameters of the rock and soil and can be written in the following form (Zhang and Cui 2015):

$$\mathrm{qt} = \lambda \frac{\Delta \mathrm{P(t)Ft}}{\eta(\mathrm{t})} + \mathrm{C} \quad (1)$$

where $\triangle P(t)$ is the effective grouting pressure required to overcome the resistance of the grout in the crack or pore (MPa); $\eta(t)$ is the viscosity parameter used to describe the time-varying characteristics of the grout (N s/m^2); F(t) is the permeability parameter that changes with the filling of the cracks or secondary hydrofracturing during grouting (m^2); λ is the magnification factor; and C is the filling grout volume in the no-pressure stage (L/s). Equation 1 is an empirical formula for describing complex processes and is used to gain a better understanding of the grouting process. To obtain the exact empirical parameters, more statistical data is needed.

For a specific project type, the selected grout material and proportions are relatively fixed, and the single-hole grouting flow rate is positively correlated with the effective grouting pressure $\triangle P(t)$ and fracture permeability parameter F(t), and negatively correlated with the slurry viscosity parameter $\eta(t)$. With the continuous filling of cracks, the degree of crack opening and connectivity gradually decreases, and the permeability decreases. At this time, the effective grouting pressure $\triangle P(t)$ must be increased so that the original cracks can be further opened or new cracks can form to continue the grouting process. When the increasing rate of $\triangle P(t)$ does not match the decreasing rate of F(t), the grouting flow q(t) decreases and the grouting pressure increases rapidly to the equipment's limit; then, the grouting process stops. By integrating Eq. 1 along the time axis, the relationship between grout volume and parameters is obtained. Through analysis, it is found that both the influence range of the grout and the resistance to be overcome increases rapidly. Only the energy provided by the grouting-induced hydraulic pressure is sufficient to maintain certain fracture permeability so that the grouting process can continue, which shows the importance of grouting pressure to the grouting process.

In northern China coalfields, it is common to control water-induced damage in limestone by directional drilling. Figure 1 shows the typical directional borehole layout and the total grouting pressure. The total pressure P1 is the sum of the grouting column pressure P2 and pump pressure P3. The borehole numbering scheme is as follows: D1 is the main hole, D1–1 is the primary branch hole, D1–1–1 is the secondary branch hole, and the other holes follow a similar numbering pattern.

The grouting data from treatment boreholes of the thin-bedded Taiyuan limestone aquifer in the floor of the 3634 working face of the Zhuzhuang Mine are presented in Fig. 2. The horizontal axis is the amount of grout, and the vertical axis is the grouting pressure at the orifice.

In the past, the total grouting pressure has generally been recommended to be 1.5–2 times the hydrostatic pressure, which generally works well in environments that require limited grouting, where the pressure mainly drives the grout to replace the water in aquifers, assuming that the fracture network is connected (Zhang and Dong 2013). However, fully open cracks are uncommon in rock, and mining activities often change the fracture network connectivity. In these environments, if the slurry-induced hydraulic pressure is insufficient, it is impossible to ensure that all potential water-conducting cracks are completely filled. It is necessary to increase the grouting pressure to enhance the connectivity between cracks.

According to Song (2016), the grouting process is actually a process of energy transmission and dissipation. The slurry flow needs to overcome pipeline loss, crack and hydraulic resistance, rock mass deformation and crack propagation energy loss. When the grouting pressure is sufficient, the stress and tensile strength of a weak surface can be effectively overcome to form a secondary hydrofracturing surface. Traditional theory holds that rock hydrofracturing must satisfy the following requirements:

$$p > 3\sigma_3 - \sigma_2 + \sigma_t - p_0 \tag{2}$$

$$p > \sigma_1 + \sigma_t - p_0 \tag{3}$$

where p is the hydrofracturing-inducing grouting pressure, σ_1 is the vertical principal stress, σ_2 is the horizontal maximum principal stress, σ_3 is the horizontal minimum principal stress, σ_t is the rock tensile strength and p_0 is the pore water pressure.

For example, the hydrostatic pressure of the Taiyuan Formation limestone is 5 MPa, and the grouting column pressure is ≈6 MPa. Based on the residual water after mining, the engineering effect was the best when the output pressure of the grouting pump on the ground was 12 MPa and the total grouting pressure was 18 MPa. The total grouting pressure is the sum of the ground pump pressure and the grouting column pressure from the ground to the grouting layer. In this project, the total grouting pressure was 2–4 times the hydrostatic pressure (5 MPa), which is much greater than what would have been used in the past. According to the pressure distribution of the grouting pump on the ground, the grouting process can be divided into four stages.

1) No-pressure stage: Grouting mainly filled and reinforced the natural fissures in the aquifers; the grout volume injected during this stage accounted for 25% of the total grout volume.
2) Low-pressure stage (pump pressure < 4 MPa): With increasing pressure, the penetration distance of the slurry gradually increased, and the natural cracks become relatively dense with the filling of the slurry. The grout volume injected during this stage accounted for 33% of the total grout volume.
3) Medium-pressure stage (pump pressure 4–8 MPa): With the continuous increase in pressure, the stress and tensile strengths of the weakest part of the aquifer were over-

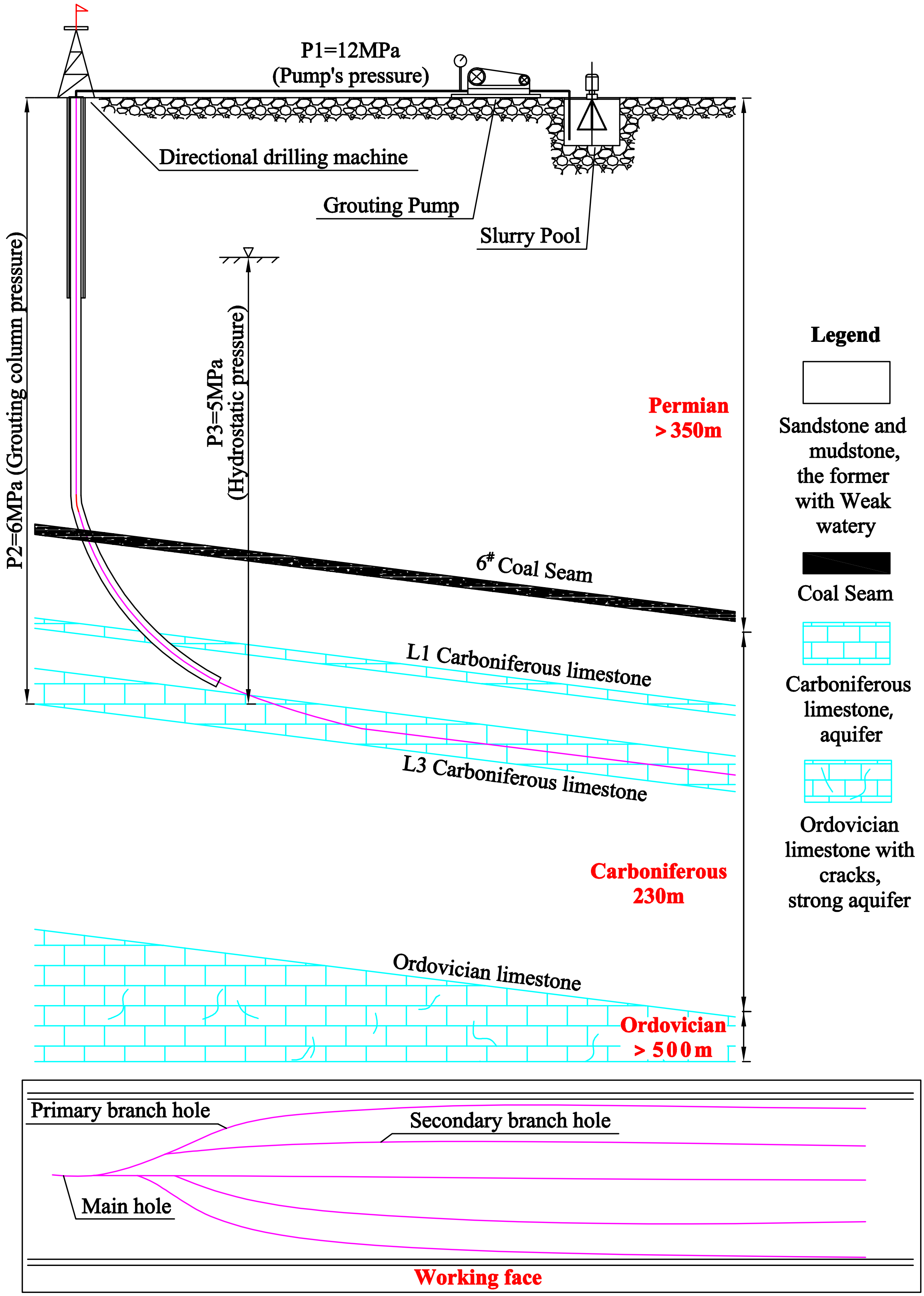


Fig. 1 Schematic diagram of directional borehole grouting for floor water hazard control

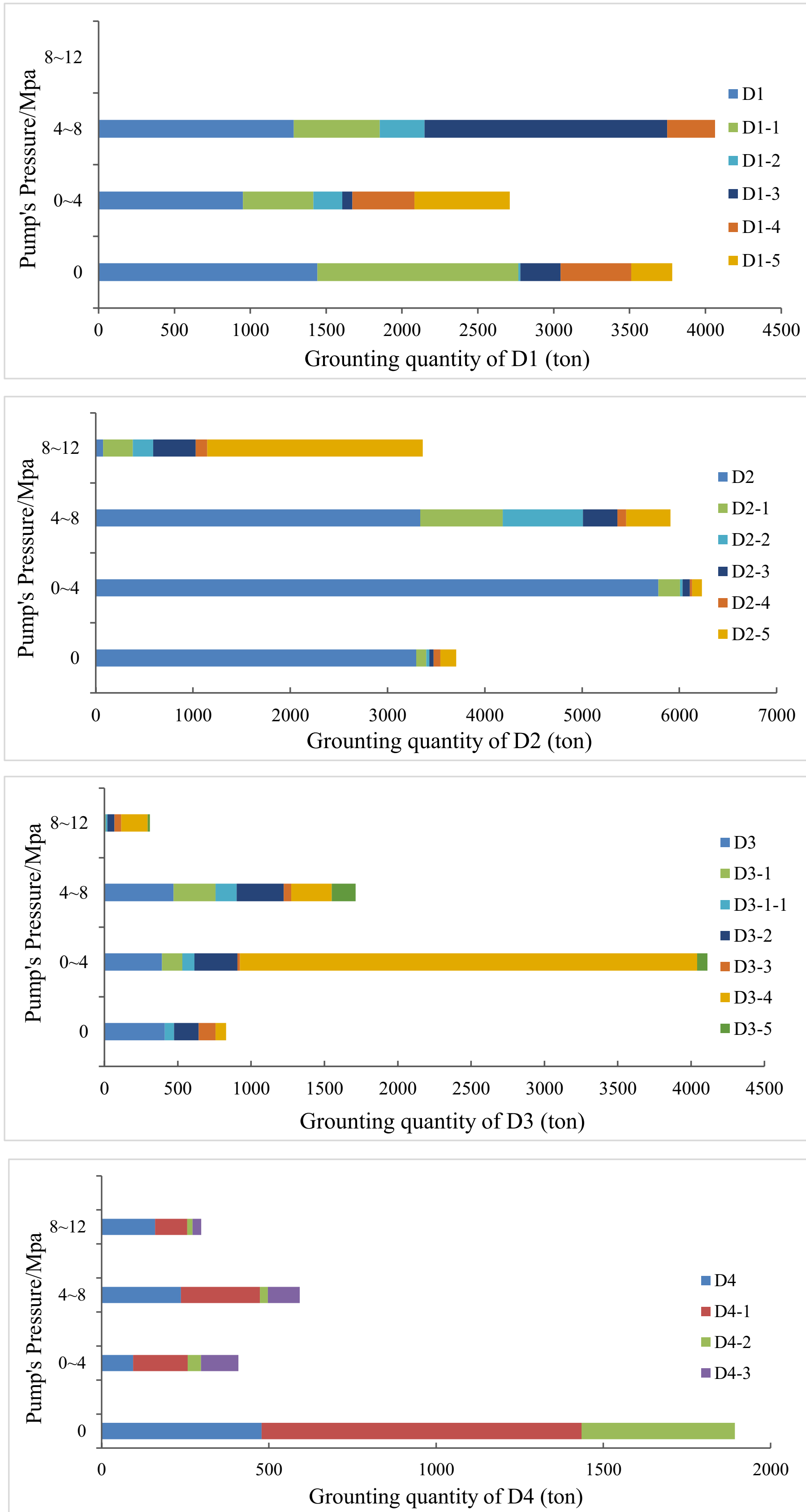


Fig. 2 Statistics of grout volume of boreholes at different pressure stages: **a** D1 hole, **b** D2 hole, **c** D3 hole, **d** D4 hole

come. The hydrofracturing-induced cracks that formed perpendicular to the plane of the maximum principal stress filled with grout, and the mechanical strength of the aquifer was strengthened. The grout volume in this stage accounted for 30% of the total grout volume.

4) High-pressure stage (pump pressure 8–12 MPa): With the increase in pressure, the original cracks and the cracks formed by hydrofracturing were filled with grout; this stage accounted for 12% of the total grout volume.

The total grouting pressure was 6–10 MPa (pump pressure 0–4 MPa) in the no-pressure and low-pressure stages, which is 1.2–2 times the hydrostatic pressure, accounting for 58% of the total grout volume. In the medium- and high-pressure stages, the total grouting pressure reaches 10–18 MPa (pump pressure 4–12 MPa), which is 2–4 times the hydrostatic pressure, accounting for 42% of the total grout volume.

In a fractured rock mass, the skeleton effect formed by the overlapping and embedment of block structures between intact rock blocks bears most of the effective stresses in the formation. The stress state of the intact rock blocks cannot simply be used to describe the weak areas or fracture surfaces. Therefore, the effective pressure of hydrofracturing-induced grouting in these areas is theoretically less than that calculated by Eqs. 2 and 3. When grouting in deep coal-bearing strata, aquifers and aquifuges are very commonly interbedded. The existence of a mudstone aquifuge can effectively reduce grouting overflow in aquifers. Appropriately increasing the grouting pressure can increase the horizontal penetration distance and reduce the amount of drilling. At the same time, an effective hydrofracturing effect can be guaranteed for the fissures, and the discontinuous fissures can be interconnected, which minimizes missing areas during engineering treatment.

In summary, the grouting transformation in a limestone stratum begins at the stage of fissure filling, during which the grouting pressure is low and the grouting fluid fills the interconnected fissures near the borehole. The fracturing stage requires a higher grouting pressure. Hydrofracturing connects the previously disconnected fissures around the area, thus improving grouting effect of a single hole.

Relationship Between Grout Volume and Hydrogeological Parameters

For a coal seam floor in a specific area, a key parameter to determine the grout quantity is the effective fracture rate. Closely related parameters include drilling fluid loss, unit absorption rate, formation depth, rock tensile strength, unit water inflow of the pores and core recovery rate through an aquifer section. We analyzed the relationship between grout quantity and the relevant parameters using relevant data from floor grouting in working faces II 632 and II 633 of the Hengyuan coal mine. The relationship between grout quantity and the relevant parameters was established using the gray relational analysis method (Li et al. 2017; Zhang et al. 2015).

1) To establish a gray relational analysis sequence:

$$X_i = \left(x_i(1), x_i(2), \ldots, x_i(n)\right), \quad i = 1, 2, \ldots, m \tag{4}$$

where $x_1(n)$ is the grout volume (ton), and $x_2(m)$ to $x_5(m)$ are the key related hydrogeological parameters, Table 1 lists the grout volume used in the 24 branch holes and the hydrogeological parameters of each hole.

2) Normalize raw data:

$$X'_i = \frac{X_i}{\bar{X}} = \left(x'_i(1), x'_i(2), \ldots, x'_i(n)\right), \quad i = 1, 2, \ldots, m \tag{5}$$

In this step, data normalization is performed by dividing X_i by $\bar{X}$, where $\bar{X}$ is the average value of this line.

Normalization is used to determine the relative change between the specific value and the average value.

3) Sequence of difference:

$$\Delta_i(k) = \left|x'_1(k) - x'_i(k)\right|, \quad i = 2, \ldots, m \; k = 1, 2, \ldots, n \tag{6}$$

After normalization, the dimensionless unification between relevant hydrogeological parameters and grout volume is realized. Its internal correlation is expressed by the difference $\Delta_i(k)$, where $x'_1(k)$ is the dimensionless grout volume and $x'_i(k)$ is a dimensionless hydrogeological parameter.

4) Calculate correlation coefficient:

$$\gamma_i(k) = \frac{m + \xi M}{\Delta_i(k) + \xi M}, \quad \xi \in (0, 1), \; i = 1, 2, \ldots, m \; k = 1, 2, \ldots, n \tag{7}$$

In this step, the correlation coefficients are calculated (Table 2), where M is the maximum of $\Delta_i(k)$; m is the minimum of $\Delta_i(k)$; and ξ is the resolution coefficient (generally, 0.5 is chosen).

5) Relevance analysis and comparison:

$$\bar{\gamma}_i = \frac{1}{n}\sum_{k=1}^{n} \gamma_i(k), \quad i = 1, 2, \ldots, m \tag{8}$$

The average value of the correlation coefficients $\bar{\gamma}_i$ is used to analyze which hydrogeological parameters have the greatest impact on the grout quantity. The correlation coefficients are the highest between the grout quantity and the drilling fluid loss and the unit absorption rate for

Table 1 Borehole grout volume and related hydrogeological parameters

Grouting boreholes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Cement usage (ton)	1270	1510	160	160	80	260	410	24	26	165	115	35	1123	300	290	200	80	40	50	55	75	30	60	94
Grouting depth (m)	951	1210	1107	1273	1092	1268	1246	1271	1321	1227	1316	1289	1217	1353	1405	1394	1404	1357	1280	1280	1385	1374	1353	1305
Grouting length (m)	105	364	270	436	252	428	414	443	493	392	486	453	244	380	410	404	417	354	304	304	413	408	388	348
Drilling fluid loss (m^3/h)	78.0	20.0	6.5	2.0	2.0	3.0	2.0	2.5	2.5	2.0	4.0	2.0	7.0	2.0	2.0	8.0	2.0	2.0	2.0	1.5	2.0	2.0	2.0	2.0
Unit water absorption [L/(m MPa min)]	91.6	23.0	34.0	11.0	19.0	19.0	11.0	9.7	4.4	12.0	5.6	8.0	36.0	11.0	12.0	21.0	7.1	11.0	15.0	14.0	5.5	4.1	5.0	4.8

Table 2 Gray correlation coefficient between the borehole grout quantity and related hydrogeological parameters

Grouting boreholes	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22	23	24	25	Avg
Grouting depth (m)	0.37	0.33	0.89	0.85	0.80	0.98	0.82	0.71	0.71	0.86	0.79	0.72	0.42	0.99	0.98	0.86	0.74	0.71	0.73	0.74	0.74	0.70	0.73	0.77	0.75
Grouting length (m)	0.34	0.34	0.94	0.79	0.85	0.92	0.86	0.67	0.65	0.83	0.72	0.67	0.40	0.97	0.98	0.86	0.73	0.74	0.78	0.79	0.73	0.70	0.73	0.79	0.74
Drilling fluid loss (m^3/h)	0.24	0.48	0.85	0.89	1.00	0.82	0.66	0.89	0.89	0.88	0.93	0.93	0.43	0.74	0.75	0.83	1.00	0.94	0.95	0.99	0.99	0.92	0.97	0.98	0.83
Unit water absorption [L/(m MPa min)]	0.70	0.36	0.60	0.96	0.72	0.91	0.73	0.82	0.93	0.95	0.97	0.86	0.55	0.84	0.88	0.80	0.94	0.81	0.76	0.78	0.97	0.94	0.96	0.98	0.82

a single hole (0.83 and 0.82, respectively), while the correlation coefficients between the grout quantity and the depth of the hole and the length of the grouting section are lower (0.75 and 0.74, respectively). Overall, the correlation coefficients of these four factors all exceed 0.7, indicating a high degree of influence.

The relationship between the grout quantity at the surface and drilling fluid loss and unit water absorption for a single hole in the Hengyuan Mine was obtained by multivariant linear regression:

$$y = 62.78 + 7.152x_1 + 10.014x_2 \quad (9)$$

where x_1 is the drilling fluid loss, m^3/h; x_2 is the unit water absorption, L/(m MPa min); and y is the single hole grout quantity, in metric tons.

The regression equation of the grout volume per unit area can also be obtained by dividing the number of boreholes on the right side of Eq. 9 by the grouting area. In addition, the relationship between the grout quantity of a single hole and the water inflow per unit of hole length, core recovery rate, and other factors can be established for an area with sufficient supplementary hydrogeological exploration data. It is preferable to use Eq. 9 if sufficient data is available for prediction.

The above analysis shows that drilling fluid loss and water absorption in Eq. 9 are the key indicators in determining grout volume. These indicators describe the natural state of the fissures before grouting, which is intrinsically related to the F(t) and P(t), as described in Eq. 1. F(t) emphasizes the dynamic change in the fissure state in the grouting process. P(t) is the dynamic response of the grouting process to fissure state F(t). Loss and water absorption represent the initial fissure state. Therefore, the mathematical model described in Eq. 1 is consistent with the results of the gray relational analysis in this section.

Key Technology of Aggregate Closure and Engineering Case Analysis

Construction Process

As shown in Fig. 3, the construction of aggregate accumulation can be divided into three stages:

1) Fine aggregate bedding stage: The velocity of flow is relatively slow. Lighter, fine aggregate particles (5–10 mm) are transported in flowing water and accumulate downstream to form a natural sand slope. In this stage, we strive to increase the particle transport distance to ensure that the length of the water-blocking section after further aggregate accumulation and reinforcement meets the safety requirements of interception.
2) Medium aggregate accumulation stage: The accumulation cross-section increases, and the flow rate increases gradually. Fine aggregates deposit less frequently; thus, it is necessary to increase the particle size to fill the remaining cross-section. In this stage, small or medium aggregates (10–30 mm) usually accumulate.
3) Coarse aggregate interception stage: There is a narrow zone at the top of the aggregate accumulation body with high velocity and pressure. It is necessary to utilize multiple boreholes and multiple coarse aggregate (30–50 mm) batches to achieve a successful water interception effect. This stage is the key in determining the success or failure of water interception.

Length of the Water Blockage

The strength of the water-blocking body consists of two parts: the strength of the aggregate and the shear strength calculation of the contact zone between the pathway and rock strata. Dong et al. (2018) provided general guidance on the length design: under a uniaxial compressive state, the required strength should not be less than the water pressure

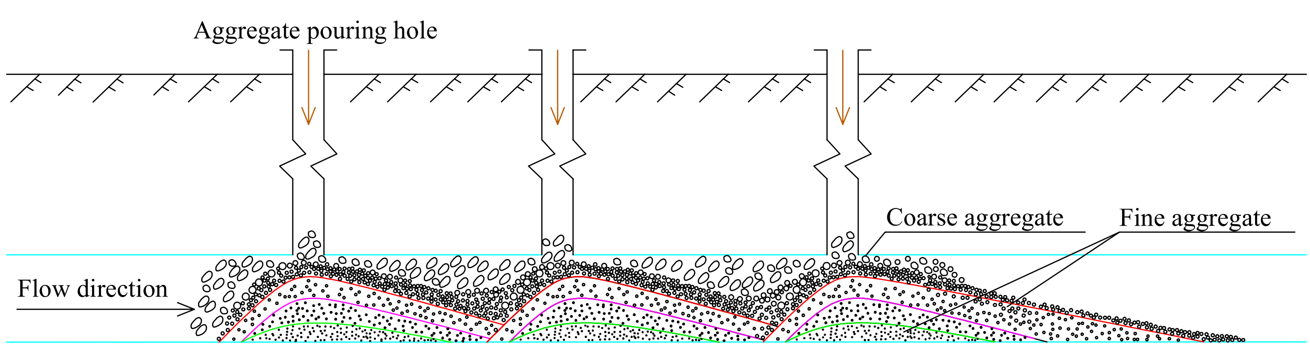


Fig. 3 Cross-sectional sketch of the aggregate accumulation body in the tunnel closure project

in the direction of water flow. According to the Mohr–Coulomb failure criterion, the strength (f_s) can be calculated using Eq. 10 (Cai 2002):

$$f_s = \sigma_1 - 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}} \quad (10)$$

where σ_1 is the maximum principal stress ($\sigma_2 = \sigma_3 = 0$) and c and φ are the cohesive force and friction angle of the stone body, respectively. When $f_s > 0$, fracturing failure will occur in the water-blocking section.

When calculating the shear strength of the interface between the pathway wall and the grouted area, the length of the water blockage must be long enough to resist the water pressure, as expressed in Eq. 11:

$$PAK > \tau LS \quad (11)$$

where P is the water pressure, A is the sectional area, K is the safety factor (2–3), τ is the shear strength, L is the length of the water resistant section, and S is the perimeter of the pathway.

Analysis of the Main Factors Controlling Grout Quantity

We analyzed the relevant data from typical water inrush accidents in nine coal mines in China from 2010 to 2017 (Fig. 4 and Table 3) in which water inrushes caused the mine tunnel system or mining area to be submerged rapidly. The first step to recover the mine was to close the roadway.

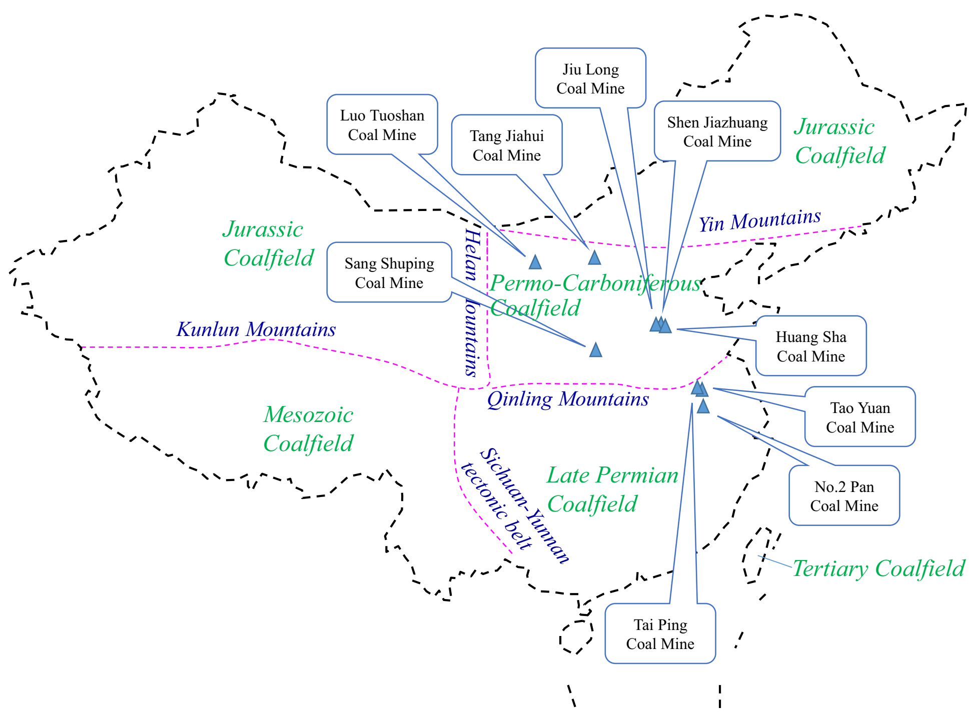


Fig. 4 Coal age distribution and location of mines that have experienced water inrush in China (2010–2017)

Table 3 Related factors for the scale of the water inrush tunnel closure project

Mine	Sectional area (m^2)	Sectional velocity (m/s)	Water bursting volume Q (m^3/h)	Aggregate used (m^3)	Cement used (ton)	Remarks
Tao Yuan	15	0.556	30,000	–	115,000	Hydrostatic, tunnel
Huang Sha	14	0.214	10,800	63,000	28,250	Hydrodynamic, tunnel
No. 2 Pan	18.9	0.107	7250	18,300	11,100	Hydrodynamic, tunnel
Jiu Long	10	0.2	7200	11,300	12,000	Hydrodynamic, karst column
Sang Shuping	60	0.03	6580	25,700	18,550	Hydrodynamic, tunnel
Luo Tuoshan	17.5	0.061	3850	75	6500	Hydrodynamic, tunnel
Shen Jiazhuang	–	–	750	400	92,000	Hydrostatic, goaf
Tang Jiahui	15	0.01	500	2060	10,000	Hydrostatic, tunnel
Tai Ping	16.7	0.005	300	4500	1600	Hydrodynamic, tunnel

These conditions are usually divided into hydrostatic and hydrodynamic conditions, with hydrodynamic water conditions being more common. In static water, aggregate filling is difficult to control and does not spread effectively. Grouting is the main method of plugging, and a water-blocking accumulation is formed by the free flow of grout.

Under hydrodynamic conditions, aggregate particles are carried downstream a certain distance to form a sand slope deposit. Grout is injected into the interior of the deposit to reinforce it. The process is repeated until the water-blocking effect is achieved. Equation 11 shows that when the post-grouting aggregate meets the strength requirement (Eq. 10), the effective length L of the water-blocking body is positively correlated with the product of P and A when other parameters are assumed to remain constant. According to the Bernoulli equation, potential energy P and velocity V are related:

$$L = \frac{PAK}{\tau S} \tag{12}$$

$$P = \varphi v^2 \tag{13}$$

where $\boldsymbol{\varphi}$ is the coefficient related to the shape and roughness of the pathway. Combining Eqs. 12 and 13 results in the following:

$$LA = \frac{\varphi K}{\tau S}(vA)^2 \tag{14}$$

The left side of Eq. 14 is the volume V of the effective water-blocking section. The right side of Eq. (14) includes the cross-section flow Q. Equation 14 can then be rewritten as follows:

$$V = \frac{\varphi K}{\tau S}Q^2 \tag{15}$$

In Eq. 15, the parameters $\boldsymbol{\varphi}$, K, τ, and S are all independent of Q. For pathways in a specific engineering geological environment, their values are specified. In addition, the material loss should also be accounted for in blocking water pathways, which is expressed by the flow-related quantity C_1Q. The extreme case of zero water inrush should also be considered with the minimum engineering quantity C_2. A quadratic polynomial relationship exists between the volume V of an effective water-blocking section and a stable water inrush flow:

$$V = \frac{\varphi K}{\tau S}Q^2 + C_1Q + C_2 \tag{16}$$

Figure 5 shows that the relationship between water inrush and volume V is as follows:

$$V = 0.0007x^2 - 2.6284x + 7106.3 \tag{17}$$

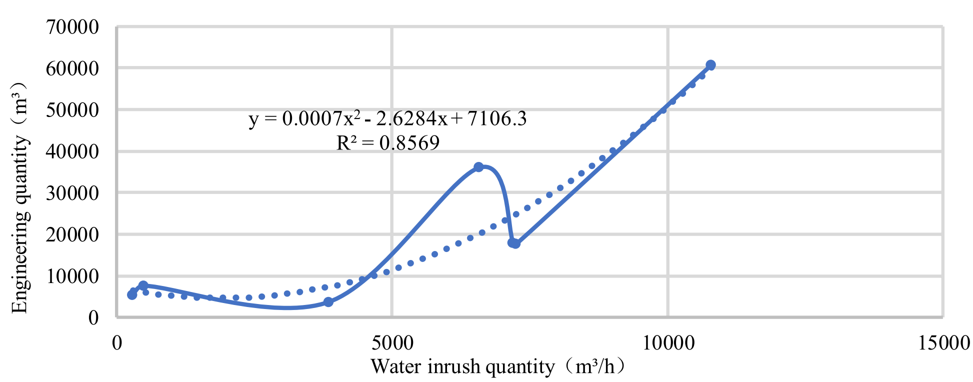
where x is the water inrush quantity, m^3/h and V is the engineering quantity, m^3. In Eq. (16), the effective accumulation section described in the first term is only a part of the total amount of work, and the second term often plays a dominant role. This equation also explains that when the pathway cut-off project is completed and excavated, except for the effective section, the remaining part can generally be described as a "trailing" phenomenon formed by the flow of aggregate or slurry along the pathway. The trailing section can be greater than two-thirds of the total amount of materials used in the project.

Equation 17 is similar to Eq. 16. However, the second term in Eq. 17 is negative, which is mainly related to the amount of data and unique differences in the cases studied. In practice, exponential interpolation can be used:

$$V = 4400e^{0.0002x} \tag{18}$$

Figures 6 and 7 show the correlations between water inrush and aggregate and cement content, respectively, without considering the case of grouting alone. The amount of aggregate and cement used for the old kiln roadway in the Sangshuping Mine was relatively large due to cross-sectional erosion, but the data from the other mines are in good agreement with the trend line. Figure 8 shows that the ratio of aggregate consumption to cement consumption is ≈ 1.7:1. In theory, cement consumption is determined by the

Fig. 5 Relationship between water inrush and grout quantity



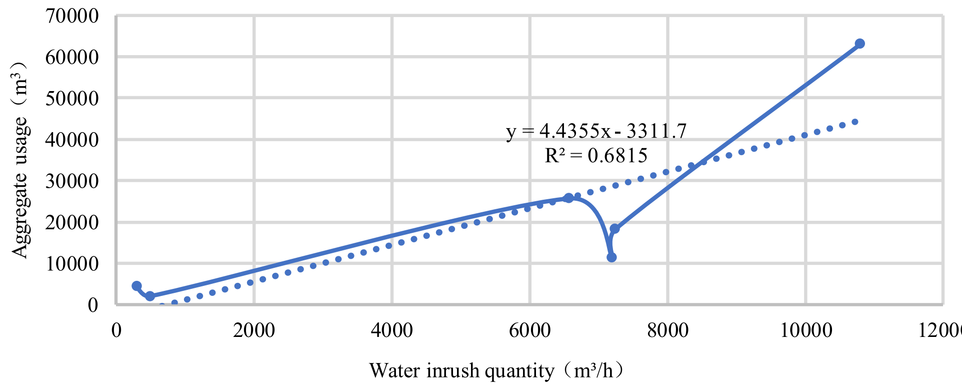


Fig. 6 Relationship between water inrush and aggregate dosage

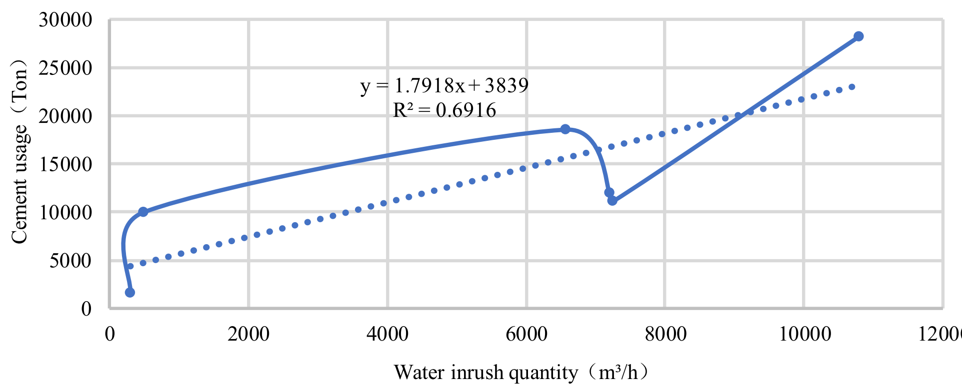


Fig. 7 Relationship between water inrush and cement dosage

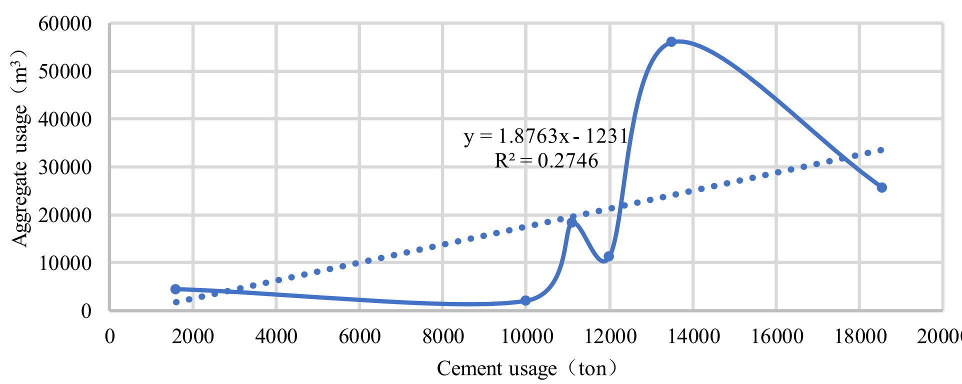


Fig. 8 Relationship between cement dosage and aggregate dosage

porosity of the accumulation body and should be relatively small. However, its proportion is considerable in practical applications due to the inevitable slurry running factor. In addition, the permeability of the surrounding rock is four times greater after excavation and water erosion than before excavation (Zaidel et al. 2010), which also provides storage space for slurry flow.

The size of the roadway in a coal mine system is usually fixed. The main controlling factor affecting the scale of the investment in closure projects is the magnitude of the water inrush. The larger inrushes tend to carry more aggregate and slurry, making construction of an effective water-blocking section more difficult and more expensive due to the greater amount of lost material.

Construction Cost Composition and Engineering Technology Optimization

Cost Composition Analysis

Costs of large-scale water disaster control projects are mainly determined by directional drilling footage and grout volume. The relevant statistics are shown in Table 4. For grouting in coal seam floors, the spacing of directional drilling is determined by the hydrogeological conditions and is generally between 30 and 60 m, so the amount of drilling work required per unit area is relatively fixed. Generally, it can be controlled between 0.025 and

Table 4 Cost components of large-scale water disaster control projects in coal mines

	Zhu Zhuang Mine			Heng Yuan Mine			Tao Yuan Mine		
Grouting transformation in coal seam floor									
Project	Quantity	Grouting area	Avg	Quantity	Grouting area	Avg	Quantity	Grouting area	Avg
Drilling	16570 m	599,500 m^2	0.0276 m/m^2	10360 m	250,000 m^2	0.0414 m/m^2	45,800 m	927,400 m^2	0.0493 m/m^2
Cement	42750 ton		0.0713 ton/m^2	75590 ton		0.3024 ton/m^2	266,700 ton		0.2878 ton/m^2

Project	Tao Yuan	Huang Sha	Pan no. 2	Jiu Long	Sang Shup-ing	Luo Tuoshan	Shen Jiazhuang	Tang Jiahui	Tai Ping
Water cut-off in tunnel									
Drilling (m)	2740	11,600	1950	12,950	2000	3370	10,230	2800	2770
Aggregate (ton)	–	56,000	18,300	11,300	25,700	75	400	2060	4500
Cement (ton)	115,000	13,500	11,100	12,000	18,550	6500	92,000	10,000	1600
Cost (10^4*Yuan)	6216	3767	1253	3028	1782	899	6347	1017	641

Drilling unit price is 1700 yuan/m, aggregate perfusion 200 yuan/ton (including materials), grouting 500 yuan/ton (including materials)

0.05 m/m^2, equivalent to a unit price of 42.5–85 Chinese yuan/m^2. The grout volume required is controlled by karst fissure density, and its cement consumption obviously fluctuates. For example, the Zhuzhuang Mine used 0.0713 ton/m^2, while the Hengyuan and Taoyuan Mines used 0.2878–0.3024 ton/m^2, equivalent to a unit price of 35–150 Chinese yuan/m^2. With drilling costs added to the grouting, the costs ranged from 70 to 235 Chinese yuan/m^2. Generally, drilling accounts for 40% and grouting accounts for 60% of the total cost.

For water cut-off in tunnels, the number of boreholes required for adding material or reinforcement is generally 4–8, according to the size of the water inrush; the amount of work is relatively fixed. If the grouting target is a karst collapse column, a goaf, a double tunnel, or multiple tunnels, the amount of drilling will increase and the grout volume will be greatly affected by water inrush, hydrostatic or hydrodynamic water conditions, open boundaries, and other factors. Table 4 shows that when the abovementioned special conditions exist, the amount of drilling increases to 3–4 times the amount needed to plug a single-headed pathway, and the aggregate and cement amounts rapidly increase with more water inrush. When more aggregate is used, the proportion of cement decreases. Overall, the drilling, aggregate injection, and cement injection account for 35%, 10% and 55% of the total cost, respectively.

Engineering Technology Optimization

Grouting in coal seam floors

Our analysis showed that the main factors affecting the cost of grouting reinforcement in coal seam floors are drilling footage and grout quantity. Drilling costs account for ≈ 40% and grouting costs account for ≈ 60% of the total cost. To maximize economic benefits, grouting engineering can be optimized by the following (Zheng 2018; Zhao et al. 2016; Nan 2010; Zhao and Zhao 2015).

1) Select reasonable grouting layers, and drill in relatively water-poor limestone strata that are sufficiently thick after reinforcement.
2) When the grouting horizon depth is sufficient, the distance between boreholes can be appropriately increased according to field tests and the radius of influence can be increased using high-pressure hydrofracturing-inducing grouting.
3) Optimize the slurry ratio, adopt a strategy of slow slurry penetration, and increase density incrementally to increase the total volume of slurry injected into a single hole.
4) By using information design, the spacing of boreholes can be adjusted dynamically in areas where the fluid loss is obviously reduced or sharply increased.
5) Optimize the construction technology to inject the grouting down as far as possible, reinforcing layer by layer, which can reduce the area that is not effectively reinforced due to grout entering a highly fractured area.
6) Use a high-powered directional drilling rig to increase the drilling penetration rate and borehole diameter and thereby reduce the unnecessary vertical drilling footage.
7) Establish an automated slurry system at the surface to avoid the drawbacks of low slurry production efficiency and low equipment power, thereby improving construction efficiency.

Water Cut-Off Engineering in Tunnels

For a tunnel closure project, the drilling length is usually fixed, and the optimization space is small, while the grout quantity can be optimized in a larger space. Research on improving this technology can be carried out in the following aspects.

1) Preferential pouring of aggregate can reduce ineffective loss caused by late grouting, and high-pressure anti-blowout aggregate pouring devices can be installed to improve the pouring efficiency.
2) Controllable grouting and rapid plugging are realized with grouting bag technology, which can be implemented in boreholes (Zhu 2015; Yang and Dong 2018). This technology has been successfully used to close small water inrush pathways.
3) As mining progresses, a remotely controlled waterproof sluice wall can be installed in the pathway section and opened automatically if a water inrush occurs. The pre-embedded aggregate and cement fills and solidifies quickly to form a closure skeleton, which can quickly be reinforced by grouting to achieve closure and water shutoff.

Conclusion

Large-scale water hazard control projects in coal mines have a great impact on mine production and construction. Limited by the complexity of the basic conditions of concealed projects, their investment estimation and key technical parameter setting mostly depend on empirical judgment. We conducted data analysis on typical cases of water hazard control projects. The main conclusions are:

1) For a coal seam floor, the grout quantity for a single hole correlates the best with drilling fluid loss and unit absorption rate. An expression between grout quantity and common hydrogeological parameters was established to predict the required grout quantity.
2) An expression of instantaneous grout quantity is proposed based on the mechanical response of the grouting process in the coal seam floor. The engineering significance of hydrofracturing-inducing grouting in deep coal seam floors is discussed with data. To achieve the best grouting, it is suggested that the total pressure in the grouting layer be 3–4 times the hydrostatic pressure.
3) A quadratic polynomial relationship between the quantity of grout needed and the water inrush flow was found based on the Bernoulli equation. The relationship between aggregate and cement dosage and the key technical problems causing the numerous related engineering issues were analyzed.
4) Drilling footage and grout volume are the main factors affecting the scale of floor grouting projects, accounting for ≈ 40% and 60% of the total cost, respectively. For pathway cut-off engineering projects, the drilling length is relatively fixed, while the volume of water-blocking section varies greatly, and its optimization space is large. The paper proposes an engineering technology optimization scheme and ideas for further development.

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