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Comprehensive Study and Simulation of the Full-Area Fine Grouting Method in Directional Drilling

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Abstract: Grouting technology serves as a prevalent method for preventing and controlling mine water damage, with directional grouting emerging as a notable approach in recent years. This study introduces an optimized whole-area fine grouting method aimed at enhancing the layout of directional drilling, reducing grouting blind zones, and cutting costs. Theoretical foundations and simulation analyses validate this method. A simplified mathematical model demonstrates that positioning branch holes at a 60 ° angle to the main holes optimizes cost-effectiveness while eliminating grouting blind zones. Furthermore, numerical simulations of slurry diffusion in 45 °, 60 °, and 75 ° configurations using COMSOL software reveal that the 60 ° arrangement significantly reduces grouting time for a given reformed area.

1. Introduction

Extensive engineering applications have been implemented, particularly in managing the water in thick gray rock layers beneath coal seams and in handling similar challenges in the thin gray rock layers of Eastern China [1-3].

Numerous factors influence the efficacy of grouting in karst aquifers, including hydrogeological conditions, grouting technology, and materials. Crucially, the selection of grouting layers and the arrangement of grouting drill holes play a pivotal role in determining the success of the grouting process. Significant research has focused on directional grouting for horizontal branch holes. For instance, Liu applied this technique to the Austrian ash water damage at Qipanjing coal mine, enhancing the water isolation capabilities of the aquifer's top layer [4]. Additionally, Meng utilized numerical simulations to establish that the radius of slurry diffusion correlates with porosity and grouting pressure, providing a theoretical basis for designing the spacing of grouting boreholes in horizontal branch sections under deep burial conditions [5]. Despite these advancements, a gap remains in research regarding the optimization of horizontal hole layouts to eliminate grouting blind zones and reduce costs.

Consequently, this study aims to eradicate grouting blind zones by proposing an optimized grouting hole placement strategy. The efficacy of this strategy is substantiated through mathematical modeling and numerical simulations, thereby offering a scientific foundation for the enhanced application of directional drilling grouting technology.

2. Engineering overview

Located in Dezhou City, Shandong Province, Qiuji Coal Mine boasts an annual production capacity of 750,000 t. This mine is characterized by its intricate hydrogeological conditions. Particularly, the 11 coal seams currently being exploited face a significant threat from the underlying limestone aquifers. The top and bottom plate of the 11 coal seam in Qiuji Mine has a limestone aquifer with strong water-richness.

Since 2016, Qiuji Coal Mine has implemented directional drilling technology for the grouting and transformation of aquifers. This process involves the strategic placement of drill holes in parallel branch formations. Empirical evidence from this practice indicates a significant reduction in the permeability of the limestone aquifer post-grouting. This transformation has yielded considerable economic benefits for Qiuji Coal Mine.

3. Comprehensive Fine Grouting Method for Area-Wide Application

Prior studies have established that under hydrostatic conditions, the diffusion pattern of slurry tends to be approximately circular [6]. Directional grouting techniques allow for the advance prediction of the slurry's spread radius. This prediction is facilitated by parameters such as aquifer water pressure, rock permeability characteristics, grouting pressure, and grouting duration. These predictive insights are instrumental in optimizing the spatial arrangement of grouting boreholes [7].

Therefore, the drill holes can be arranged as follows: the main holes are at a specific angle to the branch holes, and the individual branch holes are selected from each other. A diffusion circle is used as a standard, a positive hexagon is made inside it and another identical hexagon is made with one of the sides, and the distance between the centers of the two hexagons is the distance D between the branch holes. At this time, the spread of the slurry is shown in Figure. 1. This method maximizes the use of slurry, smaller grouting blind zones, and cost savings.

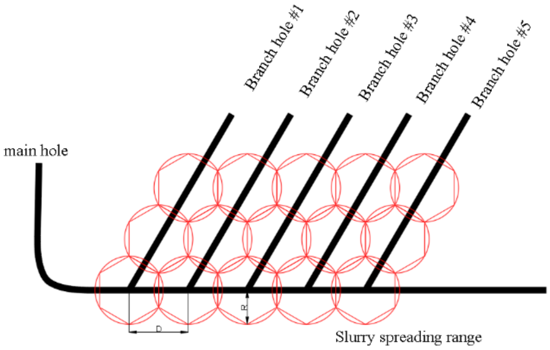

Figure 1: Spreading of slurry in parallel branch holes

4. Optimal Angle Analysis for Branch Hole Arrangement in Directional Grouting

This study initiates with the verification of the optimal angle, aimed primarily at conserving grouting materials, minimizing grouting costs, and maximizing material utilization while ensuring comprehensive area coverage. However, given the substantial variation in grouting volume across different geological conditions, this paper introduces the following assumptions:It is posited that the slurry density remains uniform throughout the diffusion circle.

Hence, in ideal scenarios, the diffusion circle's area may serve as a proxy for grouting volume, necessitating the development of a mathematical model that links this area to the alignment angles of both branch and main holes.In line with these considerations, we establish an analytical geometry and coordinate system, as depicted in Figure 2(a)(b), to delineate the functional relationship between the shaded area S and the angle α.

Given that the radius R of the diffusion circle is a fixed value and the spacing D of the branch holes is determined based on R, both R and D are known quantities. For ease of subsequent calculations, this study assumes R to be 1m and D to be √3m. It is important to note that these specific values are chosen for analytical convenience and do not alter the underlying relationship between the shaded area S and the angle α.

(a) (b)

Figure 2: Schematic of the Analytical Geometry Coordinate System

Thus, the problem is reduced to a configuration involving two circles intersecting the X-axis, with a fixed distance D between them. The center of a third circle is designated as (a, b), which must intersect with at least one intersection point, labeled A, of the first two circles. The trajectory of this third circle's center forms a circular path with A as its center and R as its radius. To achieve comprehensive grouting without leaving any unattended areas, the shaded regions formed by all three circles must overlap. The limiting condition for this configuration occurs when the center of the third circle is at (a, b) and the latter two circles are tangent to each other. This sets the constraints for the range of values for angle α.

At this juncture, the coordinates (a, b) of the third circle's center must fulfill the following criteria:

$$\begin{cases} \left(\dfrac{\sqrt{3}}{2}-a\right)^2+\left(\dfrac{1}{2}-b\right)^2=1 \\ \mathrm{b}=\mathrm{a}\tan\alpha=\left(\sqrt{3}-\mathrm{a}\right)\tan\beta \end{cases} \tag{1}$$

Calculation of the Area for the Shaded Region in the Graph:

$$\mathrm{S}=S_5+S_6+S_7 \tag{2}$$

Here, S represents the total area of the shaded region; S5 denotes the area of the shaded segment on the left; S6 refers to the area of the shaded segment on the right; and S7 signifies the area of the centrally located shaded segment.

Calculation of the Area for the Left Shaded Region:

$$S_5=2S_1-S_3 \tag{3}$$

Here, S1 denotes the area of the sector located on the left side, while S3 represents the area of the quadrilateral on the left.

Calculation of the Area for the Right Shaded Region:

$$S_6=2S_2-S_4 \tag{4}$$

Here, S2 represents the area of the sector on the right side, while S4 denotes the area of the quadrilateral also located on the right.

The correlation between the area S and the angle α can be deduced by integrating equations (1) through (4) as follows:

$$S = \frac{-\left(\begin{array}{l} 24\alpha - 8\pi + 3\sqrt{3} - 18\sin 2\alpha + 4\sqrt{3}\sin 2\alpha - 12\sqrt{3}\alpha\sin 2\alpha \\ -4\pi\cos 2\alpha + 6\sqrt{3}\cos 2\alpha - 6\sqrt{3}\cos 4\alpha - 12\alpha\cos 2\alpha \\ +12\cos 2\alpha \arctan\dfrac{\sin\alpha + \sqrt{3}\cos\alpha}{2\cos(\alpha + \frac{\pi}{3})} + 12\sqrt{3}\sin 2\alpha \arctan\dfrac{\sin\alpha + \sqrt{3}\cos\alpha}{2\cos(\alpha + \frac{\pi}{3})} \\ +24\arctan\dfrac{\sin\alpha + \sqrt{3}\cos\alpha}{2\cos(\alpha + \frac{\pi}{3})} \end{array}\right)}{12\cos\left(2\alpha - \frac{\pi}{3}\right) - 12} \tag{5}$$

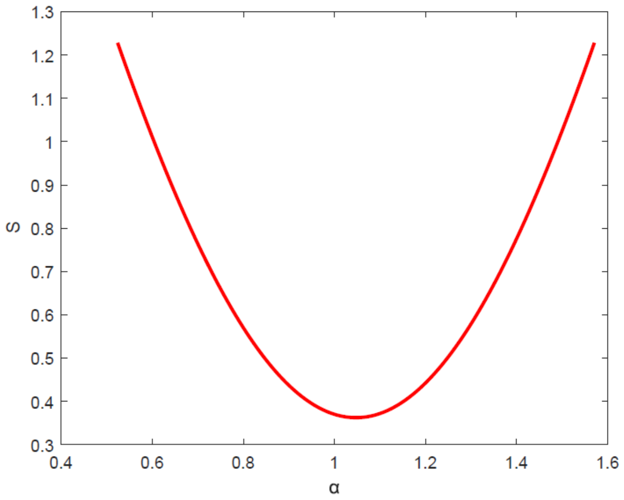

Figure 3: Graph Illustrating the Relationship between Area S and Angle α

The variation of area S as a function of angle α is illustrated in Figure 3, generated via Matlab. The plot reveals that at α = 1.046, the value of S reaches its minimum, corresponding to the smallest shaded area. This observation substantiates that setting the angle between the branch hole and the main hole at 60° minimizes the repetitive grouting area, thereby optimizing material usage for enhanced economic efficiency.

5. Numerical Simulation of Grouting Processes with Varied Branch Hole Angles

The diffusion of slurry in various configurations, specifically differing angles between branch and main holes, was simulated using COMSOL Multiphysics software. Numerical simulations suggest that the most economically beneficial angle between branch and main holes is 60 degrees. Consequently, we established models to analyze the grouting hole arrangements at various angles, facilitating comparative analyses to validate this finding.

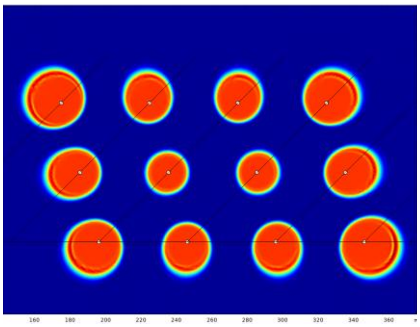

Figure 4: Grouting Process Using a 45 °Layout Method for a Duration of 10 Minutes

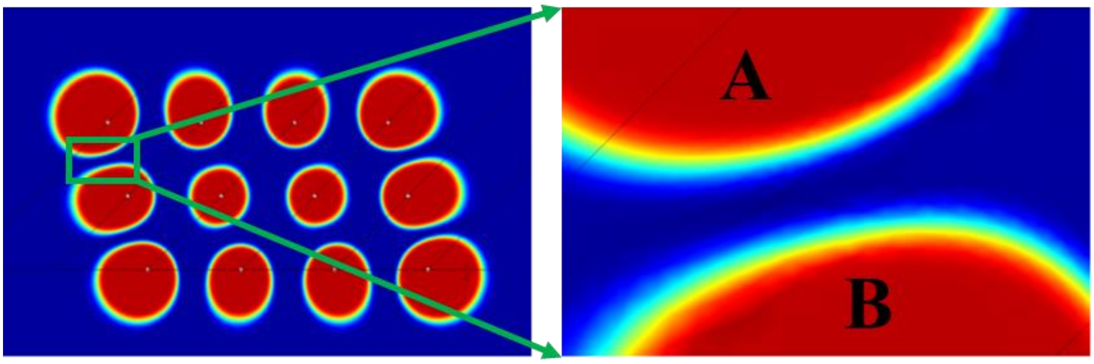

Figure 5: Grouting Process Employing a 45 °Layout Strategy for a Duration of 30 Minutes.

Illustrating with the example of a 45 °branched hole configuration, Figure 4 demonstrates that with 10 minutes of continuous grouting, the ingress of grout into the borehole induces localized pressure variations within the aquifer. Centering on the grouting borehole, a pressure gradient is established, diminishing outwards. During this phase, the grout primarily maintains a circular spread. However, due to the influence of adjacent grouting boreholes, some of the grout dispersion circles undergo deformation, indicating a propensity to extend farther. At the 30-minute mark of continuous grouting, the grout dispersion from certain boreholes starts impacting the dispersion patterns of neighboring boreholes. As depicted in Figure 5, the dispersion of grout from Borehole A notably interacts with the grout dispersion in Region B. The morphology of grout dispersion undergoes deformation at the juncture of these two regions. Assuming Region A represents an area where grouting has been completed, this suggests that at this specific time, it is challenging for the grout in Region B to fully permeate to the periphery of the grouted zone in Region A, necessitating an extended duration of grouting for complete dispersion.

Upon extending the grouting process to a duration of one hour, as illustrated in Figure 6, the interactive dynamics among different grouting zones, initially observed at the 30-minute mark, continue to evolve under the applied grouting pressure. Concurrently, the grout progressively saturates the previously challenging-to-permeate edge regions. This leads to an intensified interplay among the various grout diffusion zones.

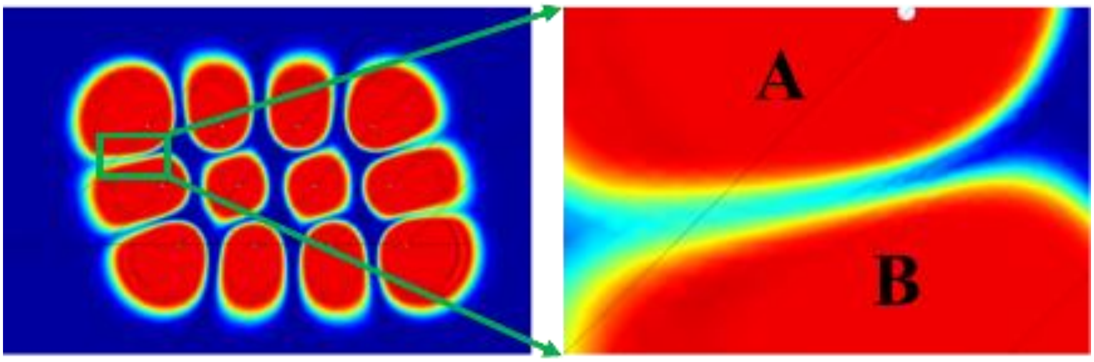

Figure 6: Grouting Process Utilizing a 45 °Layout Approach for a Duration of 1 Hour.

Upon extending the grouting process to three hours, the zones subjected to repeated grouting exhibit enhanced solidification. Consequently, the grouting zones from all boreholes start interlinking with their neighboring regions, leading to substantial alterations in the grout dispersion pattern. As a result, the entire grouted area begins to be uniformly enveloped by the grout. Driven by the applied grouting pressure, the grout from various sectors starts to amalgamate, progressively evolving into a unified mass, as depicted in Figure 7.

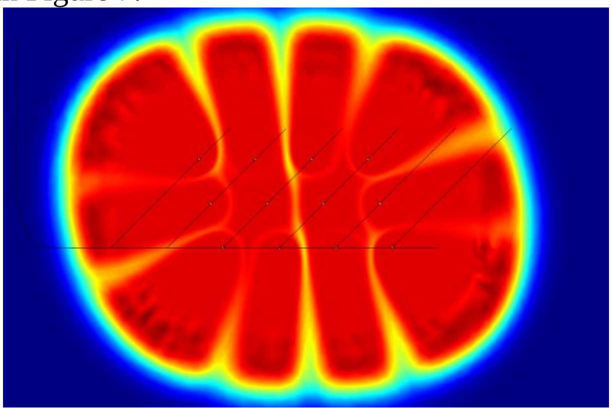

Figure 7: Grouting Process Employing a 45 °Layout Approach for a Duration of 3 Hours.

Comparative analysis of the grouting times required for modifying a similar area using 45 °, 60 °, and 75 °configurations (refer to Table 1) reveals that the 60 °layout necessitates the shortest duration compared to the other two methods. This suggests that the volume of grout required for area modification using the 60 °layout is lower than that required for the 45 °and 75 °configurations.

Table 1: Grouting time Comparison

Configuration Approach	Duration of Grouting.
45 °	140
60 °	130
75 °	150

6. Conclusion

(1) The comprehensive precision grouting technique introduced in this study effectively eradicates blind spots in the grouting process. Additionally, it facilitates the conservation of grouting materials and enhances economic efficiency.

(2) By streamlining the borehole configuration and developing both geometric and mathematical

models of the drilling process, the study confirms that, while ensuring the absence of grouting blind spots, positioning branch holes at a 60° angle relative to the main holes minimizes the usage of grouting materials.

(3) Utilizing the COMSOL Multiphysics simulation tool, the study performed comparative analyses across various borehole configurations. The findings indicate that a 60° separation between branch and main holes yields the most efficient grouting process for a given area, characterized by the shortest grouting duration and minimal material usage.

References

[1] Zhao Qingbiao. Technology of regional advance water prevention and control applied to pressurized coal mining zone above Ordovician limestone karst water[J]. Coal Science and Technology, 2014, 42(8):1−4.

[2] Zheng Shitian. Advanced exploration and control technology of limestone water hazard in coal seam floor in Huainan and Huaibei coalfields [J]. Coal Geology & Exploration, 2018, 46(4):142−146

[3] Zheng Shitian, Ma Hewen, Ji Yadong. Optimization of region-al advanced coal floor water hazard prevention and control technology and its application [J]. Coal Geology & Exploration, 2021, 49(5):167−173.

[4] Liu Zhongquan, Zhang Baoyou, Guo Yonghong. Regional advance treatment technology of Ordovician limestone water for using directional drilling and grouting in Qipanjing Coal Mine [J]. Coal Engineering, 2023, 55(03):52-57.

[5] Meng Fanding, Xu Guangquan, Sun Gui, et al. Grouting Simulation With Horizontal Branch Drilling Under Deep Buried Condition[J]. Journal of Green Science and Technology, 2021, 23(14):194-198+213. DOI:10.16663/j. cnki.lskj. 2021.14.065

[6] Liu Jian, Liu Rentai, Zhang Xiao, et al. Diffusion law model test and numerical simulation of cement fracture grouting [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(12):2445-2452.

[7] Chen Juntao, Zhang Yi, Wu Shanyuan, et al. Key technology of directional grouting in roof and floor ofcoal field in the north of the Yellow River[J].Safety in Coal Mines, 2021, 52(5):104-111.