Analysis and Study on the Effect of Exploration and Treatment on the Ground Area of Limestone Water Damage in Underground Roadway Floor

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Abstract. In recent years, the use of surface directional multi-branch near-horizontal boreholes for regional exploration and prevention of Ordovician limestone water hazards has emerged as a new technology in the Huainan mining area. This paper takes the example of the ground regional exploration and treatment project for the limestone water hazards in the floor of the system roadways in the West Fourth A coal mining area of Pan'er Mine to introduce the exploration and treatment techniques and methods. By utilizing geophysical data and underground verification, combined with construction and grouting data, the effectiveness of the exploration and treatment is analyzed, providing a reference for similar projects.

Keywords: Pan'er Mine; A coal group; exploration and treatment; effect analysis

1 Introduction

The ground regional exploration and treatment project for the limestone water hazards in the floor of the system roadways in the West Fourth A coal mining area of Pan'er Mine utilizes surface directional multi-branch horizontal boreholes. Drilling is conducted primarily through the Jiuhui layer at a depth of 80 meters below the 1st coal seam floor to investigate limestone voids, fractures, and potential vertical water-conducting structures. Grouting is applied to the detected voids, fractures, and vertical water-conducting channels between the Taiyuan Formation and the Ordovician limestone aquifers to ensure no catastrophic water hazards occur, thus achieving safe coal seam recovery.

2 Geological Overview

The geological structure of the No. A Coal Seam Mining Area in Pan'er Mine's West-Four is moderately to highly complex. Within the mine field, the karst fractures in the Ordovician and Cambrian limestone layers are unevenly developed, with some areas showing intense karstification. These layers exhibit varying degrees of water richness,

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ranging from weak to strong, with uneven distribution. The Ordovician limestone water can seep through water-conducting faults and geological anomalies like collapse columns, leading to the development of vertical fractures that recharge the Taiyuan limestone aquifer. This poses a water inrush risk to the mining of No. 1 coal seam and the construction of floor roadways. To mitigate this risk, near-horizontal directional drilling from the surface is employed to detect vertical water-conducting channels. Grouting is then performed in the Taiyuan Formation's ninth limestone layer to seal these channels, thereby controlling and preventing water from the Ordovician limestone.

3 Project Overview

3.1 Exploration Design

Boreholes were initially drilled to bedrock, then directionally drilled at large angles to near-horizontal entry into the target layer, followed by drilling along the Taiyuan Formation Jiuhui layer to expose aquifer fractures[1-4]. After the main borehole exploration and grouting, sub-layer directional branch boreholes were drilled from appropriate positions in the main borehole to maximize the exposure of water-bearing spaces and channels, providing favorable conditions for grouting reinforcement. The design included D2 and D3 borehole groups, comprising 2 main boreholes and 23 branch boreholes (31 after modification), with a designed workload of 14,749 meters (18,366 meters after modification) and a cement grouting volume of 21,000 tons(64,000 tons). The final layout is shown in Figures 1.

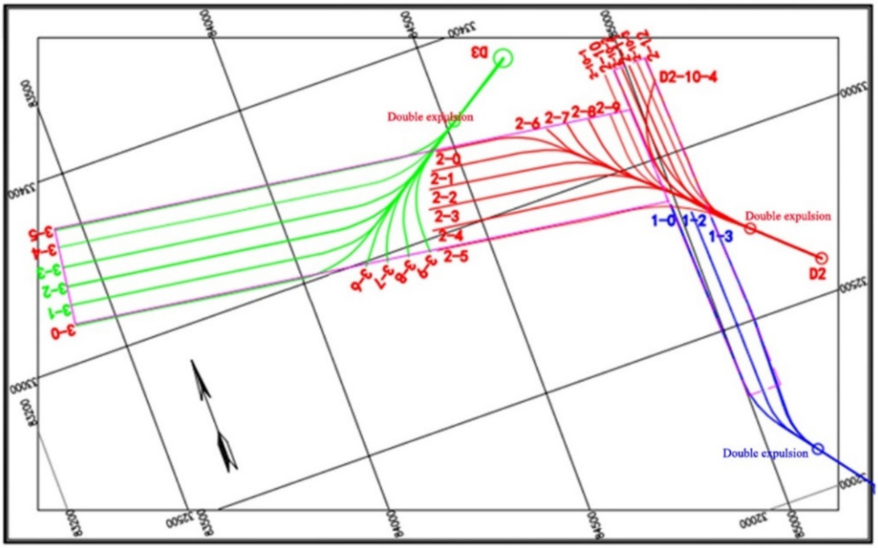


Fig. 1. Layout of drilling hole after the change of exploration and treatment project of limestone water damage in roadway floor of XISIA-Group coal system.

3.2 Grouting Design

The grouting project uses a segmented downhole method with closed wellhead static pressure grouting. The target grouting layer is the Jiuhui layer of the Taiyuan Formation[5-7]. In case of slurry leakage, the final pressure can be appropriately reduced. If fluid loss exceeds 3 m^3/h during drilling or if drilling encounters difficulties in broken zones, grouting is performed after pulling the drill. Each grouting segment is monitored by wellhead pressure, with a slurry density of 1.3 g/cm^3. Grouting is considered complete when the pressure reaches the design value, not less than 8 MPa, with a slurry absorption rate not exceeding 60 L/min, and sustained for no less than 30 minutes. After all branch holes are grouted, the main hole is sealed[8-11].

4 Construction Overview

4.1 Project Volume

The project involved drilling 3 main holes and 31 branch holes in 2 hole groups, achieving a total drilling footage of 19,891.01 meters, as shown in Table 1, with a total cement injection of 58,369 tons.

Table 1. List of exploration and treatment projects/drilling projects for limestone water damage ground area of the system roadway floor in the West Group A coal mining area of Pan 'er Mine

Hole number		Effective footage (m)	Starting hole depth (m)	Completion depth (m)	Spud time	Drilling completion time
D2 main hole	First section	336.20	0	1272.32	2020.3.09	2020.3.10
	Second section	368.27			2020.3.14	2020.3.21
	D2-11	567.85			2020.3.26	2020.3.30
					2020.4.04	2020.4.07
D2-12(1)		542.77	715.74	1258.51	2020.4.13	2020.4.24
D2-12(2)					2020.4.19	2020.4.24
D2-10		451.03	835.62	1286.65	2020.4.28	2020.5.03
D2-0		879.30	704.50	1583.80	2020.5.10	2020.5.20
D2-10-2(1)		569.79	704.50	1274.29	2020.5.28	2020.6.04
D2-10-2(2)				1274.29	2020.6.06	2020.7.01
D2-10-2(3)				1274.29	2020.7.03	2020.7.09
D2-10-2(4)				1274.29	2020.9.09	2020.9.14
D2-10-2(5)				1274.29	2020.9.17	2020.9.22
D2-5		733.38	816.52	1549.90	2020.7.24	2020.7.30
D2-9		288.12	916.88	1205.00	2020.8.03	2020.8.07
D2-10-3		556.56	704.50	1261.06	2020.8.15	2020.8.19
D2-10-1		594.80		1299.30	2020.8.25	2020.8.31

D2-6		207.96	1100.00	1307.96	2020.9.30	2020.10.06
D2-4		646.75	930.00	1576.75	2020.10.20	2020.10.29
D2-8(1)		335.85	995.00	1330.85	2020.11.08	2020.11.12
D2-8(2)					2020.12.07	2020.12.13
D2-3		569.02	1020.00	1589.02	2020.11.18	2020.11.25
D2-1		397.03	1195.00	1592.03	2020.12.19	2020.12.30
D2-7		317.92	1040.00	1357.92	2021.1.07	2021.1.12
D2-2		481.22	1110.00	1591.22	2021.1.18	2021.1.25
D2-10-4		542.35	704.50	1246.85	2021.2.16	2021.2.25
D2-10-7		423.50	704.50	1373.50	2021.3.13	2021.3.19
D2-10-5(1)		478.45	840.00	1318.45	2021.3.04	2021.3.11
D2-10-5(2)					2021.3.27	2021.4.07
D2-10-6		451.63	890.00	1341.63	2021.4.14	2021.5.02
D2-9-1		395.50	916.00	1311.50	2021.5.07	2021.5.13
D3 main hole	First section	348.00	0	1178.22	2020.3.23	2020.3.26
	Second section	441.24			2020.3.30	2020.4.08
	D3-9	284.42m	893.8		2020.4.12	2020.4.16
D3-8		242.21	953.47	1195.68	2020.4.23	2020.4.28
D3-7		203.26	1020.23	1223.49	2020.5.04	2020.5.08
D3-6		204.75	1047.13	1251.88	2020.5.17	2020.5.20
D3-0		1219.61	789.24	2008.85	2020.5.29	2020.7.04
D3-5		1113.15	794.35	1907.50	2020.8.01	2020.8.16
D3-4		1084.01	842.19	1926.20	2020.7.14	2020.7.25
					2020.8.21	2020.9.09
New D3 main hole	First section	330.56	0	787.44	2021.5.02	2021.5.07
	Second section	456.88			2021.5.11	2021.5.18
D3-1		854.53	1135.00	1989.53	2021.2.25	2021.3.22
D3-3		1053.26	890.00	1943.26	2021.7.03	2021.7.23
D3-2		919.88	1043.00	1962.88	2021.7.28	2021.8.24

4.2 Exploration Findings

4.2.1 Drilling Fluid Conditions

The project encountered strata primarily composed of limestone, mudstone, sandstone, and coal seams. High-quality, low-solid-phase polymer drilling fluid was used in the horizontal sections, with specifications: density 1.05–1.20, viscosity 24–28s, pH

8–10. Materials included high-quality sodium bentonite, caustic soda, sodium carboxymethyl cellulose (Na-CMC), potassium polyacrylate, viscosity modifier 141, anti-collapse water-reducing agent, sulfonated asphalt, and white oil.

4.2.2 Logging of Cuttings

Based on data analysis, the Jiuhui layer is about 80 meters from the 1st coal seam floor, with the top of Jiuhui composed of fine sandstone and sandy mudstone, locally containing coal lines. The floor consists of a thin coal line underlain by sandy mudstone, with a distance of 11.60 to 25.00 meters (average 16.62 meters) between the Jiuhui and the top of the Shiuhui. Comprehensive analysis of the actual drilling trajectory, drilling time logs, cuttings logs, and gamma data confirmed that the layer positioning is accurate at the Jiuhui target layer, with some branch holes showing cement cuttings after grouting.

4.2.3 Encountered Geological Structures

Within the treatment area of the limestone water hazard exploration and treatment project in the floor roadways of the West Fourth A mining area, based on surrounding roadway geological data and 3D seismic data analysis, the geological conditions are complex. The D2 hole group mainly revealed faults DF106 and DF14, while the D3 hole group revealed fault F251, with fractured lithology near the faults and well-developed subsidiary faults and fractures. The D3 hole group, located in the anticline axis, had extensive tensile fractures affecting construction significantly.

4.2.4 Drilling Abnormalities

1) Drilling Drag

Various degrees of drilling drag occurred at all well sites during directional drilling of horizontal wells. This was often caused by the well trajectory and various resistances, making it difficult for the drill pressure to transfer to the bit, resulting in no penetration despite increased drill pressure, with no rise in pump pressure or pump jamming. When torque suddenly increased, the turntable or top drive might jam. Careful adjustment of torque and multiple treatments were required to resume normal drilling. Dragging was analyzed to be caused mainly by poor well trajectory, the presence of cuttings beds, thick mud cake, and high mud friction coefficient. Well sites improved well trajectory control, adjusted drill string structure, enhanced mud purification with a solid control system, improved mud carrying capacity, increased mud lubrication, and improved mud cake quality to effectively reduce dragging.

2) Hole Abnormalities

During the project, 5 hole abnormalities occurred without geological anomalies causing loss, drill drop, etc. The analysis indicated that the strata affected by anticline structures and faults had developed vertical fractures, fractured rock, and water inflow affecting formation stability and mud performance, leading to stuck drill accidents. Abnormal situations were promptly addressed, meeting design requirements in subsequent drilling, but indicated that local strata had developed fractures[12-14].

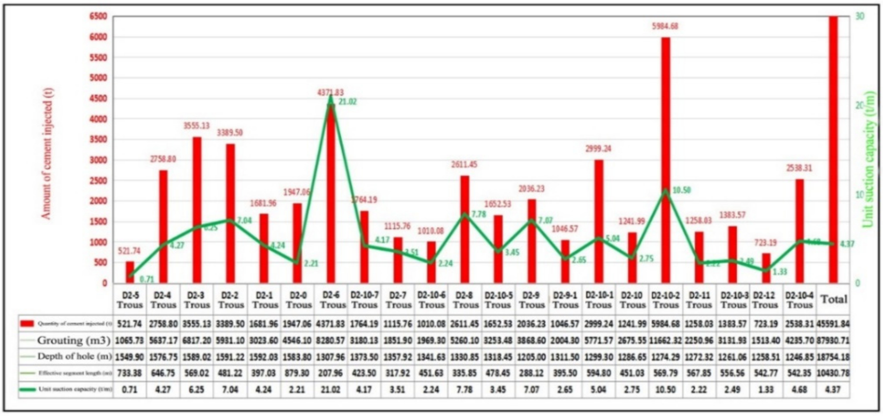
4.3 Grouting Situation

4.3.1 Pre-Grouting Water Pressure Test

According to the water pressure test results, slurry density was determined. Each grouting section in this project underwent required water pressure tests before grouting, with branch hole water absorption rates ranging from 0.01 to 0.00035 L/min·m². Analysis of the water pressure test and grouting volume indicated that the smaller the stable pressure before grouting, the greater the water absorption rate, and relatively higher grouting volume.

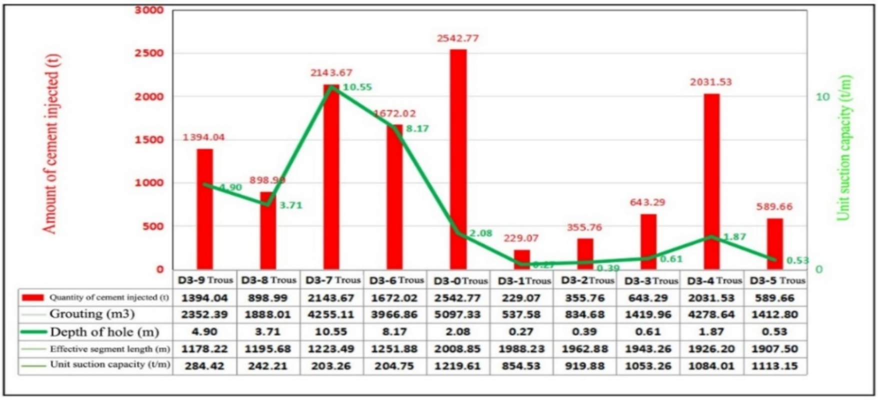
4.3.2 Grouting Volume and Pressure Variation

The project involved drilling and grouting in 31 branch holes across 2 hole groups, with an effective drilling length of 17,325.44 meters and 58,369 tons of cement injected, resulting in a unit grout consumption of 3.37 t/m. Details are shown in Figures 2 and Figures 3.



	D2-5 Trous	D2-4 Trous	D2-3 Trous	D2-2 Trous	D2-1 Trous	D2-0 Trous	D2-6 Trous	D2-10-7 Trous	D2-7 Trous	D2-10-6 Trous	D2-8 Trous	D2-10-5 Trous	D2-9 Trous	D2-9-1 Trous	D2-10-1 Trous	D2-10 Trous	D2-10-2 Trous	D2-11 Trous	D2-10-3 Trous	D2-12 Trous	D2-10-4 Trous	Total
Quantity of cement injected (t)	521.74	2758.80	3555.13	3389.50	1681.96	1947.06	4371.83	1764.19	1115.76	1010.08	2611.45	1652.53	2036.23	1046.57	2999.24	1241.99	5984.68	1258.03	1383.57	723.19	2538.31	45591.84
Grouting (m3)	1065.73	5637.17	6817.20	5931.10	3023.60	4546.10	8280.57	3180.13	1851.90	1969.30	5260.10	3253.48	3868.60	2004.30	5771.57	2675.55	11662.32	2250.96	3131.93	1513.40	4235.70	87930.71
Depth of hole (m)	1549.90	1576.75	1589.02	1591.22	1592.03	1583.80	1307.96	1373.50	1357.92	1341.63	1330.85	1318.45	1205.00	1311.50	1299.30	1286.65	1274.29	1272.32	1261.06	1258.51	1246.85	18754.18
Effective segment length (m)	733.38	646.75	569.02	481.22	397.03	879.30	207.96	423.50	317.92	451.63	335.85	478.45	288.12	395.50	594.80	451.03	569.79	567.85	556.56	542.77	542.35	10430.78
Unit suction capacity (t/m)	0.71	4.27	6.25	7.04	4.24	2.21	21.02	4.17	3.51	2.24	7.78	3.45	7.07	2.65	5.04	2.75	10.50	2.22	2.49	1.33	4.68	4.37

Fig. 2. Grouting quantity diagram of D2 hole grou



	D3-9 Trous	D3-8 Trous	D3-7 Trous	D3-6 Trous	D3-0 Trous	D3-1 Trous	D3-2 Trous	D3-3 Trous	D3-4 Trous	D3-5 Trous
Quantity of cement injected (t)	1394.04	898.99	2143.67	1672.02	2542.77	229.07	355.76	643.29	2031.53	589.66
Grouting (m3)	2352.39	1888.01	4255.11	3966.86	5097.33	537.58	834.68	1419.96	4278.64	1412.80
Depth of hole (m)	4.90	3.71	10.55	8.17	2.08	0.27	0.39	0.61	1.87	0.53
Effective segment length (m)	1178.22	1195.68	1223.49	1251.88	2008.85	1988.23	1962.88	1943.26	1926.20	1907.50
Unit suction capacity (t/m)	284.42	242.21	203.26	204.75	1219.61	854.53	919.88	1053.26	1084.01	1113.15

Fig. 3. Grouting quantity diagram of D3 hole group

5 Exploration Area Geophysical Data

On November 17, 2020, a dual-frequency advanced detection was conducted in the lower section of the gangue conveyor belt road of the West Fourth A coal mining area. The heading of the roadway showed a high polarization and low resistance anomaly zone, indicating strong water-bearing properties, as shown in Figure 4.

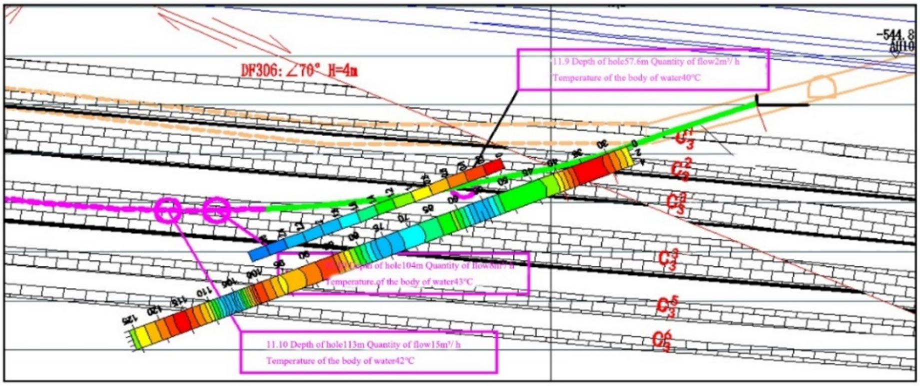


Fig. 4. Schematic diagram of dual-frequency advance detection

To address the vertically developed water-conducting fractures in the system roadway, combined ground and underground treatment measures were implemented. The ground exploration project extended the branches D2-6, D2-7, D2-8, and D2-9, adding three more branches to further explore and treat these vertically developed water-conducting fractures. Underground, five directional exploration and treatment holes (D1-2, Z1 to Z4) and one drainage hole (F1) were designed, all targeting the C33 lower limestone layer. Hole Z1 was positioned 8 meters east of the gangue conveyor belt road in the lower section, with holes Z2, Z3, and Z4 arranged at 15-meter intervals westward. Hole D1-2 was located 12 meters east of hole Z1, and hole F1 extended westward towards the working face for water interception and drainage. The vertical water-conducting fractures in the floor of the system roadway were further explored, treated, and verified along the three-gray layer. A total of 2238.5 meters of drilling was completed, with 616.59 cubic meters of grouting and 300.96 tons of cement injected, achieving final pressures of 8-15 MPa. High-pressure grouting effectively treated the three-gray layer. Post-treatment verification through holes Z2 showed an initial water inflow of 8.4 cubic meters per hour, gradually decreasing to 2.5 cubic meters per hour. According to the Anhui Economic and Information Commission's Coal Document [2017] No. 218, Article 48, "Verification borehole single-hole water inflow less than 3.0 cubic meters per hour" is required, and the underground exploration, treatment, and verification were qualified. Additionally, the F1 drainage hole's final water inflow was 10.8 cubic meters per hour, serving to intercept and drain water, reducing water pressure on the working face and further ensuring safe roadway excavation.

6 Analysis of Exploration and Treatment Effectiveness

6.1 Exploration Analysis

Based on geophysical data, exploration, and grouting treatment results, comprehensive analysis suggests that the fault zones in this area are highly reliable. The treatment area shows significant water-bearing anomalies, with some overlapping with fault fracture zones. Post-grouting drilling consumption was minimal, and some water inflow occurred, indicating that grouting filled the fractures, causing stress release in the revealed formations, with slurry water flowing into the boreholes. This suggests poor overall groundwater flow conditions, with groundwater in a relatively closed environment. Drilling fluid consumption and underground borehole and roadway slurry leakage indicate the presence of locally developed vertical fractures with strong water conductivity.

6.2 Grouting Effectiveness Analysis

Grout volume is a critical indicator of grouting effectiveness; higher grout volumes indicate better filling and treatment results. Some branch holes showed cement in the rock cuttings post-grouting, indicating good slurry diffusion in the fractured formations and some overlap in slurry diffusion between branch holes. Roadway slurry leakage indicates good water conductivity in locally developed vertical fractures, with significant slurry diffusion distances. Multiple sealing and re-grouting effectively addressed the anomalies, ensuring no further slurry leakage in the roadway, indicating effective treatment of the anomalies.

6.3 Treatment Evaluation

The range of slurry diffusion depends on grouting pressure, rock porosity, fracture fill, cement slurry density, pump rate, and fracture development direction. The treatment layer originally had poor water conductivity, but anomalous zones with developed vertical fractures showed significant heterogeneity and anisotropy. After primary pore and fracture filling and reinforcement, increased pressure causes slurry to fracture new paths perpendicular to the main stress plane, expanding the slurry diffusion range and reinforcing the formation's strength. Excessive pressure can cause slurry leakage in roadways, but intermittent grouting, multiple re-grouting, and densification effectively filled and reinforced the fracture zones, cutting off water-conducting channels.

7 Conclusions and Recommendations

7.1 Conclusions

1. All borehole placements, spacing, trajectories, and final depths were strictly in accordance with design and adjusted design specifications. Logging, simple hydrogeological observations, target layer tracking, and other parameters met design requirements, ensuring project quality.

2. Comprehensive analysis of drilling time, drilling fluid consumption, cuttings logging, natural gamma logging, simple hydrogeological observations, water pressure tests, single-hole grout volume, and grouting pressure variations, combined with geophysical data, further constrained the range of anomalies.

3. Multiple re-grouting and densification effectively filled and treated vertical water-conducting fractures, ensuring no further slurry leakage in roadways. The grouting successfully blocked hydraulic connections between the A coal group and Ordovician limestone, significantly reducing safety hazards.

4. Grouting volumes, final pressures, and post-grouting water pressure tests met design requirements, effectively blocking hydraulic connections between Taiyuan and Ordovician limestones. The exploration and treatment scheme proved reasonable, achieving clear exploration and effective treatment goals.

7.2 Recommendations

Further exploration, treatment, and verification of vertically developed water-conducting fractures in the floor of the system roadway along the three-gray layer are recommended. This should be integrated with ground-level exploration and treatment of the nine-gray layer and the water-blocking layer between Taiyuan and Ordovician limestones, forming a multi-layer barrier to further block hydraulic connections between Ordovician water and the working face.

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