ORIGINAL ARTICLE

Study on control water of Ordovician aquifer: a coal mine of Feicheng mining area, China

Weifu Gao[1,2] · Longqing Shi[2] · Jin Han[3] · Peihe Zhai[2]

Abstract

Water-inrush accidents often occur when coal seams are mined with thin water-resisting layer and high confined water. To prevent water-inrush from coal seam floor, based on the analysis of the characteristics of Ordovician limestone (OLS) karst in Feicheng mining area, a series of key technologies or methods for OLS aquifer were studied in this paper. First, the grouting area of the working face floor was determined by the water-inrush coefficient. According to the given formula of water bursting coefficient, the formula for calculating the thickness of reinforced aquifers by grouting was deduced. Second, the 'three-stage casing' drilling with small angle was designed for fully grouting in the OLS. Finally, the 3D DC mine resistivity method was used to check the effect of grouting for the working face to ensure the grouting quality of the floor. Through the case study, it shows that the technology elaborated has better practicability and popularization.

Keywords Water inrush from floor · Grouting of ordovician limestone · Drilling of grouting · Evaluation of grouting · 3D DC resistivity method

Introduction

With the rapid development of China's economy, most of the shallow buried coal deposits have been mined, to meet the national energy demands for domestic using, there is great need to mine the deep coal seams. In the geological evolution history of China, the main coal seam of North China type coalfield is Carboniferous Permian coal seam. Most of the coal seams are directly deposited on the Ordovician limestone (OLS), lacking the Silurian and Devonian strata.

Because the Silurian and Devonian strata have been denuded, the OLS exposed to the earth surface for 0.9 million years, not only suffered weathering, erosion and the development of karst, but also laid the foundation for the development of underground karst (Shi and Singh 2001). The floor of aquifer (NO.5 Limestone) is connected with the OLS aquifer due to faults, which makes the floor of aquifer and the OLS aquifer form the same groundwater system. The OLS aquifer is characterized by high water pressure, strong recharge, and large water volume. The coal seam floor is threatened by the OLS aquifer, and water inrush from the floor often occurs.

At present, research on water control technology mainly includes the following aspects: The water bursting was sealed by combining surface and underground, which was implemented by Xing and Fu (2014), achieving an efficient and fast grouting effect. Yao (2014) successfully achieved the grouting for OLS aquifer based on the combination of geophysical exploration and drilling. Pan and Zhang (2014) believes that the comprehensive influence of various factors should be considered in the pre-grouting of the working face. Lu and Hu (2010) applied curtain grouting technology to the Ordovician aquifer in metallurgical mines. The influence factors of water-inrush from grouting face are summarized by Xu et al. (2011, 2012), and water disaster prevention measures are put forward. The idea of 'regional advance management' was put forward by Zhao (2013, 2014) for water-inrush from OLS aquifer, and it was pretreated. Wang

✉ Weifu Gao
  gaoweifu-2006@163.com

1 College of Natural Resources, Shandong University of Science and Technology, Tai'an 271019, People's Republic of China

2 College of Earth Sciences and Engineering, Shandong University of Science and Technology, Qingdao 266590, People's Republic of China

3 College of Information Sciences and Engineering, Shandong University of Science and Technology, Qingdao 266590, People's Republic of China

(2017) employed physical exploration, inspection hole, and the permeability coefficient, to evaluate the grouting effects of floor. After grouting, the safe production of the working face is guaranteed. Li et al. (2017) proposed an improved grouting method, which is useful to ensure the safe production of coal mine. Qian et al. (2017) proposed ground surface pre-grouting implemented for reinforcing the regional engineering rock mass through large fault zones, and concluded the effect of blocking water-bearing faults and eliminating groundwater inrush risk.

The above literature studies mainly focused on the actual situation of different study areas. Although these can solve practical problems, there is no systematic research on OLS of grouting technology. Based on feasibility analysis of grouting for the OLS aquifers, 'small angle' drilling and 'three pole' casing technology are adopted to ensure accurate grouting in the OLS aquifers. At the same time, the

working face is grouted in sequence to ensure the quality of grouting, thus ensuring the safe mining of the working face.

Study area

The location of working face

The study area is located in the Feicheng Coal Field, Shandong Province, as shown in Fig. 1a. The Feicheng Coal Field, shown in Fig. 1b, includes the Caozhuang coal mine (CM), the Baizhuang CM, the Yangzhuang CM, and the Taoyang CM. The Baizhuang CM in the Western part of Feicheng Coal Field is bounded by Fault F_{21} in the east, artificially drawn technical boundary in the west, Fault F_1 in the north, and No. 11CS outcrop in the south. Wells were first installed in April 1963, and official production began
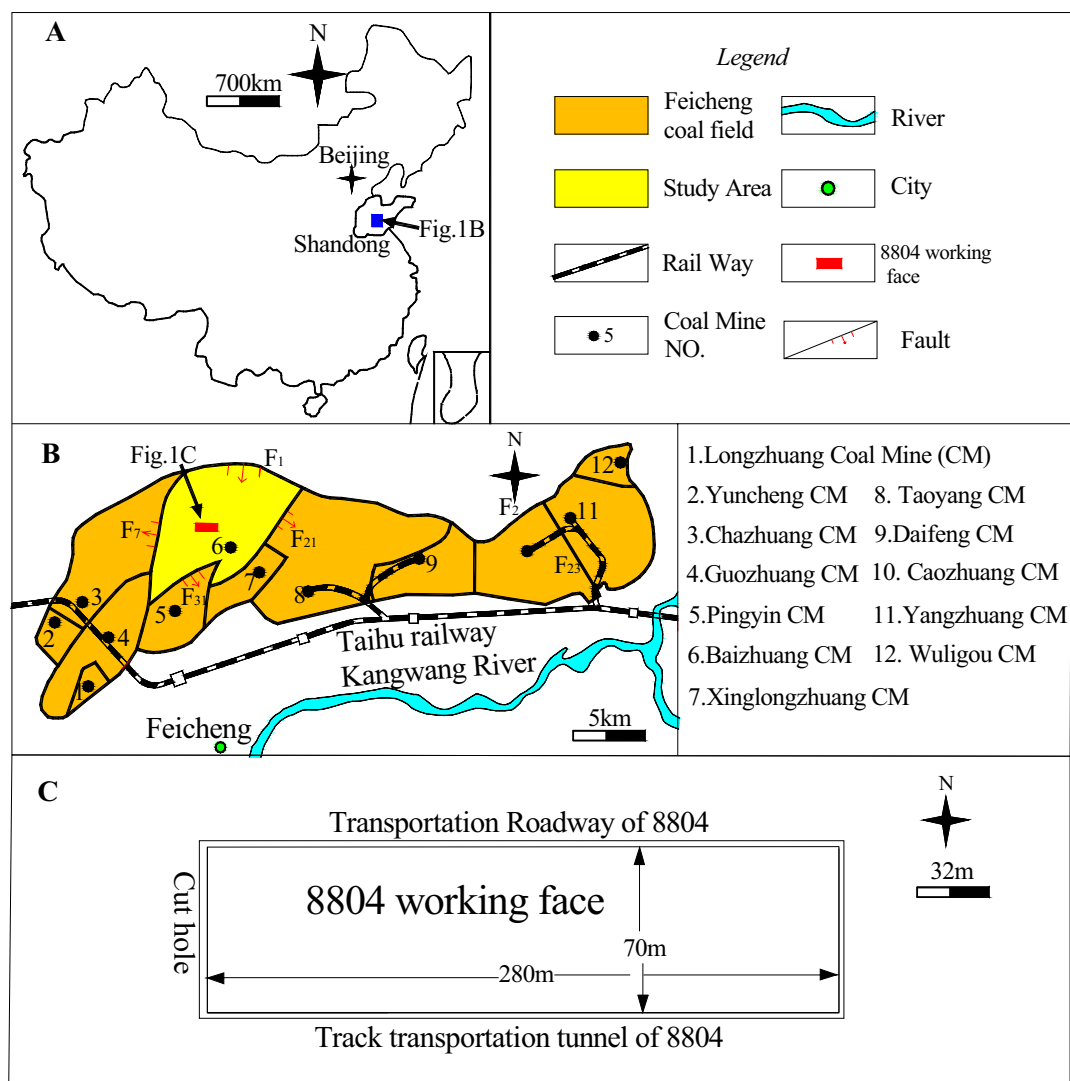

Fig. 1 Location of the study area in China including (**a**), the Feicheng coal field within China (**b**), schematic diagram of 8804 working face (**c**)

in December 1964. The current main minable CS is of Carboniferous and Permian age.

Taking the 8804 working face of the BaiZhuang CM as an example, grouting in the OLS practical application is illustrated. As shown in Fig. 1c, 8804 working face is the second working face in the 8th mining area of No. 8 CM. The left side of the working face is 8802 working face that has been mined, and the right side is 8806 working face that has not been mined. The span of 8804 working face is 70 m, and the mining distance is 280 m.

At present, the main coal seam (CS) in Baizhuang CM is No. 8 (CS). From the comprehensive columnar, No. 8 CS (Fig. 2), the main aquifers of the working face, respectively, are No. 4 LS, No. 5 LS, and the OLS. No. 4 LS is the roof of No. 8 CS, and the water of No. 4 LS has been dried up in the process of mining No. 7 CS, which will not threaten No.

Fig. 2 The comprehensive columnar of 8804 working face

8 CS. The water pressure of OLS is 3.2–3.8 MPa, and that of NO.5LS is 1.2–2.1 MPa.

The distances from No. 8 CS to No. 5 LS and OLS, respectively, are 37 m and 47.6 m. Therefore, the thickness of floor water-resisting layer is very thin, and water inrush from the floor often occurs. The aquifer of the floor is grouted, which can ensure the safe mining of the working face.

Feasibility analysis of the top grouting for OLS

To study the lithological characteristics of OLS, data from 123 OLS boreholes of Feicheng mining area were collected. According to the degree of fracture development, water inflow, and the number of drilling drops, the characteristics of OLS karst development were analyzed in the unit of 20-m interval. The horizon characteristics of OLS in boreholes are shown in Table 1.

When the borehole entered the OLS layer 0–20 m (Fig. 3a), the rock fissures are developed poorly, and most of the fissures were filled with calcite, the water inflow of stratum is 0.5–8 m^3/h which indicates that the water richness of layer is moderate. When the OLS reached 20–40 m (Fig. 3b), the core is broken seriously, the karst fissures developed well, and no calcite is filled, the water inflow of borehole is 8–10 m^3 /h, which indicate that the water richness of layer is strong. In the OLS section of 40–60 m (Fig. 3c), the fissures of the stratum were basically filled by calcite dikes, and the water inflow of stratum is 0.5–3 m^3/h, which indicate that the water richness of stratum is weak. In the OLS section below 60 m (Fig. 3d), the core was intact, the fissures developed poorly and the water inflow of stratum is less than 0.5 m^3/h, which indicate the water richness of stratum is poor.

The part of the OLS (0–20 m) is aquitard, which forms the 'cover' required for the OLS grouting with the range from 0 to 10 m as the relatively impermeable layer. The section of OLS (20–40 m) is a relatively strong aquifer, which is the best target layer for grouting in OLS. The section of the OLS (40–60 m)is a poor aquifer with 20 m thickness, which is the 'bottom' needed for grouting target layer of OLS. The grouting fluid are protected by 'cover' and 'bottom' to
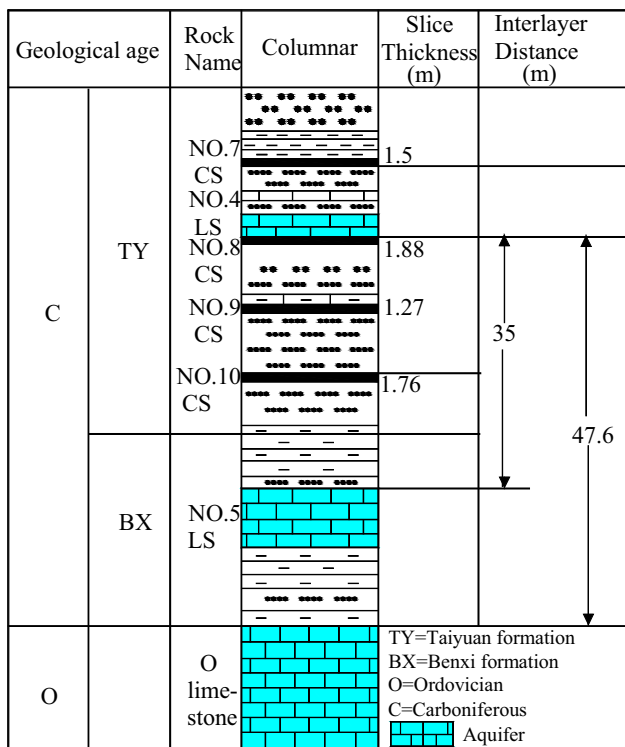
Table 1 The horizon characteristics of OLS

Depth of drilling OLS (m)	Fracture development(strip %)	Water inflow(m^3/h)	The times of drilling drops	Characteristics of fracture
0 ~ 20	15	0.5–8	1	Most fissures are filled with calcite(Fig. 3a)
20 ~ 40	90	8–10	8	Core broken, good connectivity, cracks not filled(Fig. 3b)
40 ~ 60	20	3–0.5	3	A few fissures have not been filled(Fig. 3c)
below 60	10	< 0.5	0	Fracture is not developed(Fig. 3d)

Fig. 3 Characteristics of OLS fractures, the borehole enters the OLS layer 0–20 m (**a**), the OLS layer 20–40 m (**b**), the OLS section of 40–60 m (**c**), the OLS section below 60 m (**d**)

A   **B**   **C**   **D**
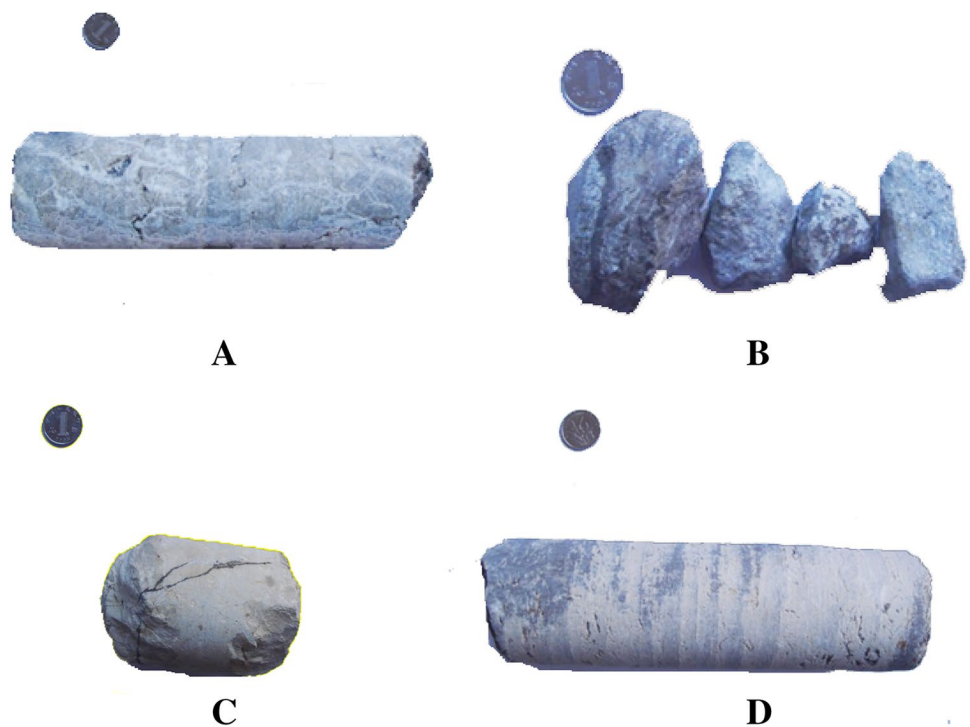
prevent slurry running and ensure that the 'middle layer' grouting is carried out normally.

Method or technology of grouting

Grouting area of 8804 working face

According to 'Coal Mine Water Prevention and Control Regulation (State Coal Mine Safety Supervision Bureau 2018)', it can be seen the water inrush coefficient (Shi 2012; Shi et al. 2017, 2019a, b) is less than 0.1 MPa/m, which is the safe working face, and the water inrush coefficient that abnormal structure or complex hydrogeological of working face must be less than 0.06 MPa/m. The water inrush coefficient is calculated through the OLS observation holes and construction holes, and the water inrush coefficient map of the OLS is obtained using SUFER. The software only needs to know the drilling coordinates and the water inrush coefficient of the working face, and the contour of the water inrush coefficient of the whole working face is drawn (Fig. 4). According to Fig. 4, the maximum water inrush coefficient is less than 0.1, and the working face belongs to the safe area. However, the water unit-inflow of OLS aquifer is 1.43 L/s m, the hydrogeological belongs to complex types. Therefore, it is necessary to grout the OLS aquifer in the working face.
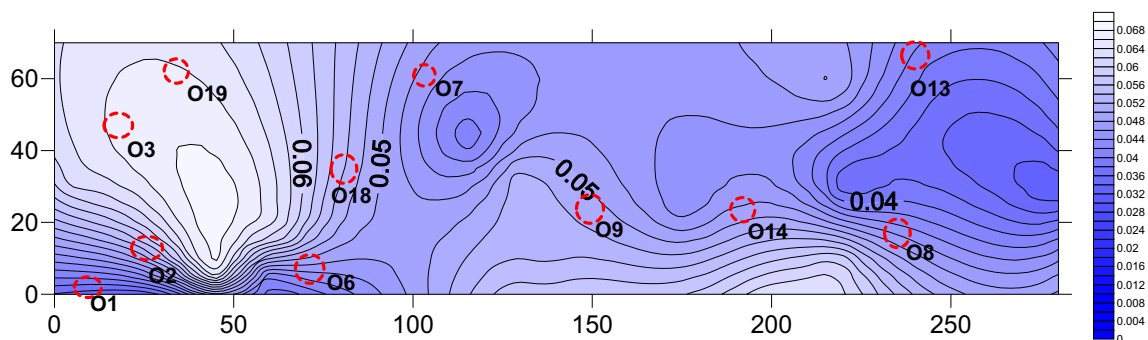

Fig. 4 The water inrush coefficient map of OLS; the red circle is the location of the borehole

Grouting depth of 8804 working face

Before grouting, it is necessary to calculate the grouting thickness ensure that there is enough resisting-water layers in the process of mining. The pressure intensities of the water head before and after the grouting are p_1 and p_2, respectively. The formulas are as follows:

$$p_1 = \frac{H + h + M_1}{100}, \tag{1}$$

$$p_2 = \frac{H + h + M_1 + M_{mod}}{100}, \tag{2}$$

where H is the working face elevation, m; h is the OLS water-level elevation, m; M_1 is the thickness of floor resisting-water layers before grouting, m; M_{mod} is the grouting depth of OLS, m; and h is the increased depth of resisting-water layer, m. Formulas 4 and 5 are derived from formulas 1 and 2 carried into formula 3.

$$T = \frac{P}{M}, \tag{3}$$

$$T_1 = \frac{H + h + M_1}{100M}, \tag{4}$$

$$T_2 = \frac{H + h + M_1 + M_{mod}}{100M}, \tag{5}$$

where T is the coefficient of bursting water, Mpa/m; P is the pressure of OLS water, Mpa; and M is the thickness of the resisting-water layer, m.

Solving the equations of formulas 4 and 5, formula 6 is obtained.

$$M_{mod} = \frac{100M_1(T_1 - T_2)}{100T_2 - 1}, \tag{6}$$

where T_1 is the coefficient of water inrush before grouting, MPa/m; T_2 is the coefficient of water inrush after grouting, MPa/m. Formula 6 is the calculation for depth of grouting of OLS, m.

This paper takes O_3 as an example to illustrate the depth of grouting of OLS. Before grouting: $T_s = P/M = 0.804$ MPa/m (according to Ordovician three hole), it is necessary to carry out grouting reinforcement on the floor of the working face. The coefficient of water inrush is 0.06 after grouting and the thickness of the grouting is calculated by formula 6: $M_{mod} = 27.50$ m. The actual grouting thickness is 50 m and $Ts = P/M = 0.051$ MPa/m after grouting, which can meet the requirements of safe mining.

Design of grouting hole

The design requirements of the grouting hole (Fig. 5) were as follows: this hole may detect the water richness of the rock, and can pass through the aquifer with more OLS to achieve the purpose of grouting reinforcement. Therefore, the design of the grouting hole should be as small as possible and the general angle between the grouting hole and the rock face is between 25°and 35°.

Grouting holes of OLS trepanning began at Φ146 mm(Φ is the diameter of the borehole), the next-level casing (Φ127 mm) 20 m, second-level casing (Φ108 mm) down to 8–10 m of the hard and complete rock strata of below the floor form No. 10 CS, and the third-level casing (Φ89 mm) down to the hard and complete rock strata of 1 m below of No. 5 LS. The finished drilling hole diameter was Φ73 mm.

Using three tubes of grouting hole has the following advantages compared with a traditional grouting hole: it can not only be used for grouting but also to check water inflow of the hole, and pass through as much of the grouting layer as possible to seal the fractures of the rock layer and to improve the working efficiency of grouting. It can not only save grouting materials but also ensure grouting quality.

There are 31 OLS grouting holes and the total length is 3513 m (Fig. 6). The OLS grouting hole of working face grouting was divided into two sequences. Included in the first sequence were Ordovician 1, 3, 5, 6, 7, 8, 12, 14, 21, and 23. The second sequence was Ordovician 2, 4, 9, 10, 12, 15, 17, 19, 20, and 22. The inspection holes were in 11 and 18. The drainage holes are in 13 and 16. When the distance between boreholes was less than 50 m, the two boreholes cannot expose to the OLS rock at the same time. The dewatering test will be performed when the OLS boreholes are fully completed to make a successive grouting.

Results and discussion

Water flow in the borehole comparison before and after grouting was as follows: when water flow in the borehole reaches the following specifications, the working face can be explored. Water flow inspection hole more than − 300 m should be no more than 20m³/h. Water flow inspection hole less than − 300 m should be no more than 10m³/h.

Before grouting (Fig. 7), it can be seen that the abnormal area of the working face floor mainly concentrates on the right side of the working face. Therefore, the key grouting is carried out on the right side of the working face. After complete grouting, the 3D DC mine resistivity (Gao et al. 2019; Shi et al. 2019b) is carried out. After grouting (Fig. 8), the abnormal area is still on the right side of the working face. Comparing before grouting (Fig. 7) and after grouting (Fig. 8), the right side of the section area decreases

Fig. 5 The profile map of drilling

Horizontal scale 1:1000

Orientation：128¡ã   Dip angle of hole：-34¡ã   Drilling depth:121m

NO.4 Limestone(LS)
NO.8 Coal seam(CS)
NO.9 CS
NO.10 CS
Unknown LS
NO.11 CS
NO.5 LS
Ordovician LS

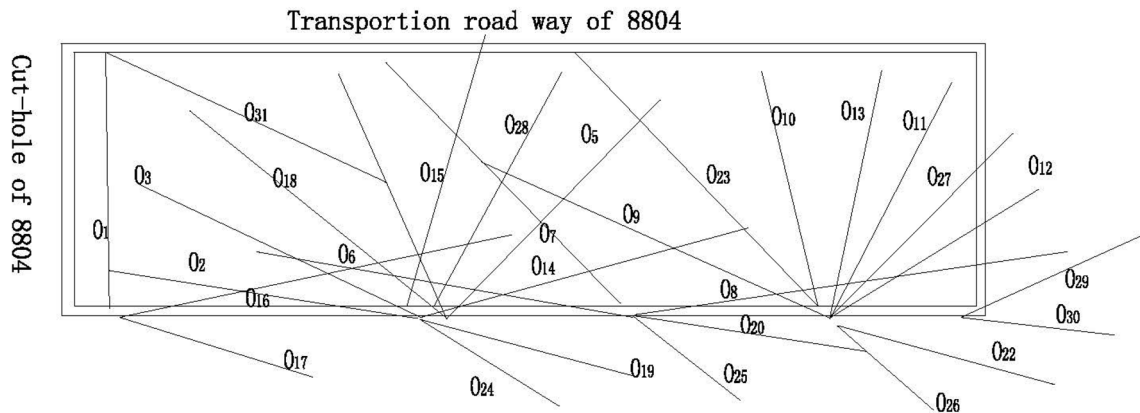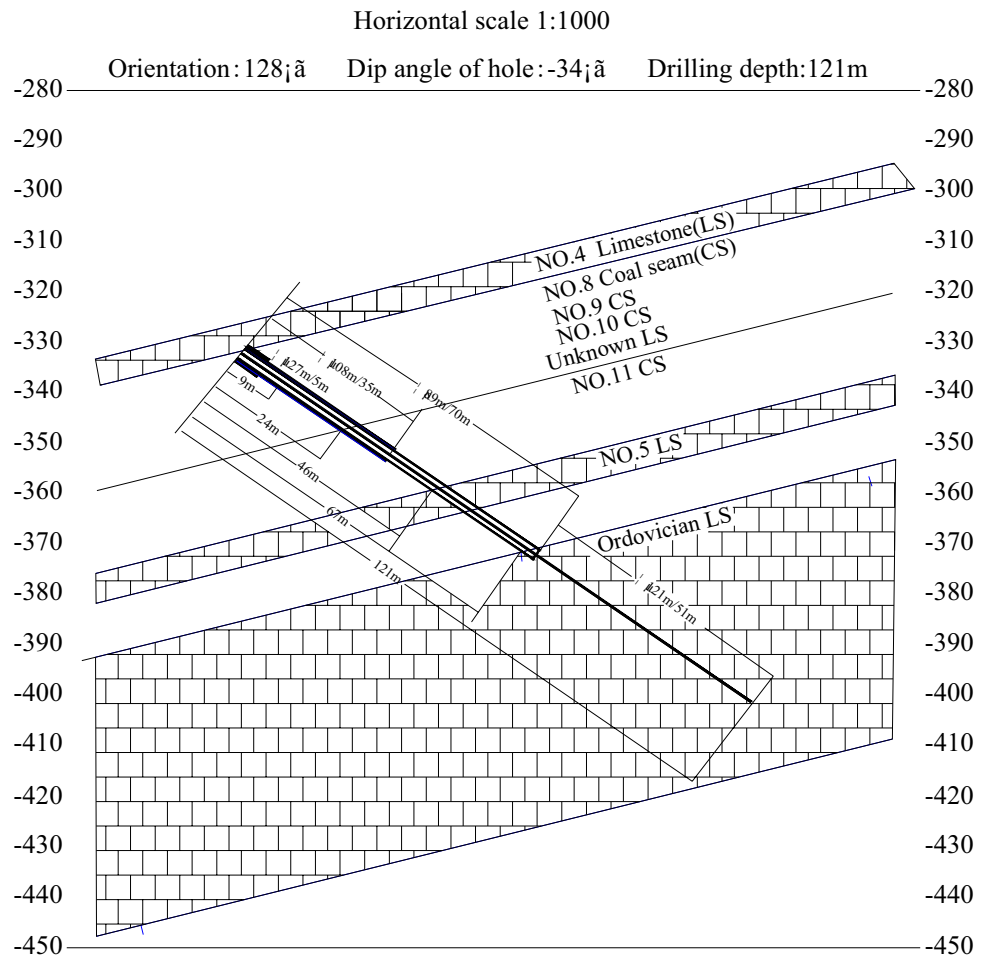Transportion road way of 8804

Cut-hole of 8804

Fig. 6 Drilling design plane graph of 8804 working face

significantly and the resistivity value is larger. The left side of the high-resistivity region is relatively small compared with that before grouting, which illustrates the layer-specific resistivity value is changed after the related grouting. Although the resistivity changes of the whole formation are large, the local formation resistivity value changes are small,

which should be noted. After grouting, the water inflow of observation holes 11 is less than $15m^3$/h. According to the change of water inflow, grouting has met the needs of safe mining.

At present, the working face of 8804 has been realized safe as mining and there is no water-inrush event, which
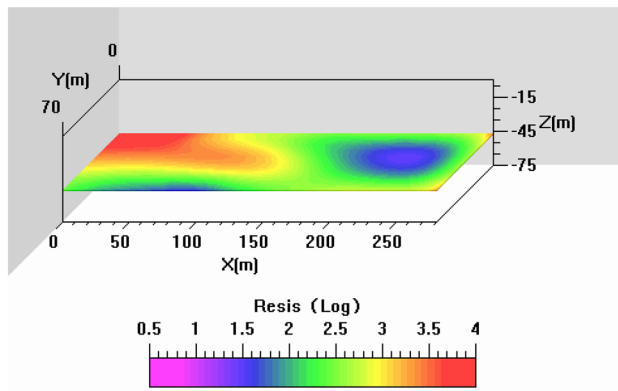
Fig. 7 The horizontal slice resistivity of Ordovician 8804 face floor before grouting
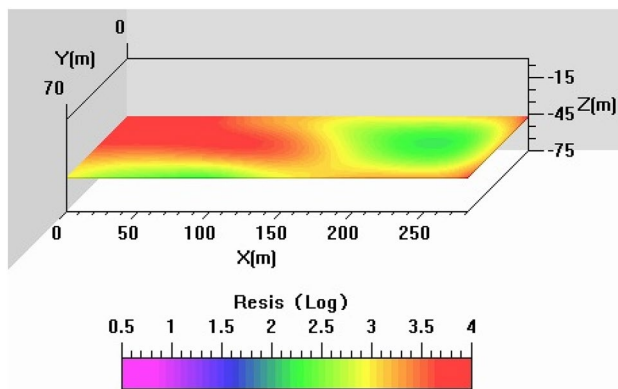

Fig. 8 The horizontal slice resistivity map Ordovician 8804 face floor after grouting

shows that the technology of grouting in the OLS has a strong practicality and adaptability.

Conclusion

The OLS is not rich in water from 0 to 20 m, which provides the 'cover' for the Ordovician limestone grouting. The aquifer thickness from 20 to 40 m provides 'injection layer' for slurry. The water of 40 m to approximately 60 m provides the 'bottom layer' for the grouting work. Ordovician limestone stratum has a good geological environment, which provides the necessary conditions for grouting.

Using the formula of water inrush coefficient, the formula of grouting for reinforcement thickness of water-resisting layer is deduced, which provides a theoretical basis for the floor of grouting face. From the design of grouting holes to the detection holes, 3D DC mine resistivity method is used to detect the grouting effect and a series of key grouting technologies are used to ensure the grouting quality.

The example proves that a working face of large mining depth, high confined groundwater, and thin water-resisting layer is able to be safely mined after reinforcing thickness of floor by grouting, which shows the technology has a strong practicality and adaptability. The disadvantage of this method is that grouting protects the water and the hydraulic pressure does not change, which is still a threat to the mining of the deep coal seam.

References

Gao W, Shi L, Zhai P (2019) Water detection within the working face of an underground coal mine using 3D Electric Resistivity Tomography (ERT). J Environ Eng Geophys 24(3):497–505. https://doi.org/10.2113/JEEG24.3.497

Li H, Bai H, Wu J, Wang C, Ma Z, Du Y, Ma K (2017) Mechanism of water inrush driven by grouting and control measures-a case study of Chensilou mine China. Arab J Geosci. https://doi.org/10.1007/s12517-017-3258-8

Lu P, Hou K (2010) Current application status and development trend of curtain grouting in water-rich mine. Mod Min 3:21–24 **(in Chinese)**

Pan R, Zhang B (2014) Study on the influencing factors of grouting face about high pressure water in the main mine. Ener Tech Mang 2:103–105

Qian D, Zhang N, Zhang M, Shimada H, Cao P, Chen Y, Zhang N (2017) Application and evaluation of ground surface pre-grouting reinforcement for 800-m-deep underground opening through large fault zones. Arab J Geosci. https://doi.org/10.1007/s12517-017-3052-7

Shi L (2012) Analysis of the origin of water inrush coefficient and its applicability. J Shandong Univ Sci Technol 31(6):6–9 **(in Chinese)**

Shi L, Gao W, Han J, Tan X (2017) A nonlinear risk evaluation method for water inrush through the seam floor. Mine Water Environ 36(4):597–605

Shi L, Xu D, Wang Y, Qiu M, Hao J (2019a) A novel conceptual model of fracture evolution patterns in the overlying strata during horizontal coal seam mining. Arab J Geosci 12(10):326. https://doi.org/10.1007/s12517-019-4486-x

Shi L, Wang Y, Qiu M, Gao W, Zhai P (2019b) Application of three-dimensional high-density resistivity method in roof water advanced detection during working stope mining. Arab J Geosci. https://doi.org/10.1007/s12517-019-4586-7

Shi L, Singh RN (2001) Study of mine water inrush from floor strata through faults. Mine Water Environ 20(3):140–147. https://doi.org/10.1007/s10230-001-8095-y

State Coal Mine Safety Supervision Bureau (2018) Coal Mine Water Prevention and Control Regulation Coal Industry Press. State Coal Mine Safety Supervision Bureau, Beijing, p p32

Wang X, Qin Q, Fan C (2017) Research on comprehensive evaluation for grouting effect of broken and soft floor. Arab J Geosci. https://doi.org/10.1007/s12517-017-3198-3

Xing W, Fu S (2014) Technology of efficient and rapid sealing water bursting point at up and down mine. Saf Coal Mine 2:47–49 **(in Chinese)**

Xu Y, Chen X, Yao Y (2012) Key technology of water prevention and control for coal mining face with high water pressure water inrush dangers. Coal Sci Technol 9:99–103 **(in Chinese)**

Xu Y, Li J, Liu B (2011) Reason and prevention of floor grouting reinforcement working face water inrush in Jiaozuo mining area. Coal field Geolo Explo 4:50–54 **(in Chinese)**

Yao Z (2014) Grouting and water blocking technology under complex conditions of water inrush in coal mine. Explor Eng 41(5):61–65

Zhao Q (2013) Technology of regional advance water prevention and control applied to pressurized coal mining zone above Ordovician Limestone Karst Water. Coal Sci Technol 9:83–86 **(in Chinese)**

Zhao Q (2014) Ordovician limestone karst water disaster regional advanced governance technology study and application. J Chin coal Soc 6:1112–1117 **(in Chinese)**

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.