Practice and Challenge of in-seam Directional Borehole over 2000 m in Coal Mines in China

Chao Xu, Xian Wang, Fei Liu, Quanxin Li, Jun Fang
CCTEG Xi’an Research Institute, Xi’an 710077, China
*Corresponding author’s e-mail: xuchao@cctegxian.com

Abstract. The gas in the coal seam is an important disaster-causing factor that affects and restricts the safe and efficient mining in coal mines. The use of directional drilling in the coal seam is the preferred method to reduce the gas content and pressure of the coal seam. In the past two decades, the directional drilling technology and equipment have been widely used in high -gas coal mine in China, and remarkable gas control effects have been achieved. In view of the need for gas control in super-long working face in China, it is proposed to use ZDY12000LD directional drill rig, BLY460/13 pump, survey system and supporting drilling tools to carry out directional drilling of in-seam over 2,000m, and to summarize and form the matching technology of directional drilling over 2,000m. It provides a new way to improve the construction capability of directional borehole in coal mines and explore a new mode for gas control in long working face.

1. Introduction
The geological conditions of coal seam in most coal mines in China are complex. With the increase of mining scale, mining intensity and mining depth, the threats of gas explosion and outburst and other disasters are becoming more and more serious, and the cost of gas control is rising[1-3]. The use of directional drilling in the coal seam for gas drainage is an effective measure for the prevention and control of gas disaster accidents. It has become the main means of efficient gas drainage in coal mines in China[4-6]. Compared with the rotary drilling, directional drilling have the advantages of precise and controllable trajectory, large drilling depth and high gas drainage efficiency, and can significantly reduce coal seam gas content and gas pressure. At the beginning of the 21st century, some coal mines successively introduced foreign directional drilling technology and equipment in China, and successfully applied to the directional drilling construction for gas drainage in medium-hard coal seams. The directional borehole depth for gas drainage has exceeded 1,000 m, and regional gas drainage in coal mine has been preliminarily realized[7]. In 2007, the first set of directional drilling equipment with independent intellectual property rights came out in China. After years of practice and development, the in-seam directional drilling technology have been continuously improved in China, forming matching drilling technology and equipment for in-seam drilling with a depth of over 1,000m. In 2008, the in-seam directional borehole depth in the coal seam reached 1,046 m in Tingnan Coal Mine. In 2012, the in-seam directional borehole depth rose to 1,212m in Dafosi Coal Mine. In 2014, the depth of 1,811m in-seam directional borehole was completed in Sihe Coal Mine[8]. In order to solve the problem of advanced treatment of gas in the super long working face of coal mines in China, the contradiction between mining and excavation is alleviated and the cost of gas control is reduced, many new requirements and challenges are brought for in-seam directional drilling with a depth of over 2000m.
2. In-seam directional drilling equipment over 2000m

2.1. Drill rig

The drill rig is used to provide thrust, pull and rotary power, clamp and unscrew drilling tools in borehole, overcome reverse torque of screw motor, etc, and this is the foundation and guarantee for drilling over 2,000 m in-seam directional borehole[9]. ZDY12000LD directional drill rig with high-power is developed independently by Chinese company, and it integrates main engine, pump station, operation table, explosion-proof computer, flow meter and tracked vehicle, can walk independently, as shown in Fig1. The drill rig have the maximum output torque of 12,000 Nm, the thrust capacity of 250 kN, the rated braking torque of 2,000 Nm, and can be matched with a variety of specifications of drilling tools. The rotary system and the push system of ZDY12000LD directional drill rig is designed to operate in fast and slow stages, which can meet the requirements of rotary drilling, sliding directional drilling and compound drilling, the performance parameters of the drill rig are shown in Table 1.

| index                      | unit    | parameter       |
|----------------------------|---------|-----------------|
| Rated torque               | Nm      | 12,000~3,000    |
| Rated speed                | r·min⁻¹ | 50~150          |
| Rated pressure             | MPa     | 28              |
| Maximum push/pull-out force| kN      | 250             |
| Push/pull-out distance     | mm      | 1 200           |
| Diameter of spindle through hole | mm    | 135             |
| Spindle inclination angle  | (º)     | -10~20          |
| Motor power                | kW      | 132             |
| Outline size               | m       | 4.2×1.6×1.9     |
| Whole machine quality      | kg      | 9,000           |

2.2. Pump

The function of pump is to convert hydrostatic water into high-pressure water for driving DHM to cut coal seam, and then cool the bit and carry drilling cuttings so as to ensure drilling smoothly[10]. BLY460/13 pump integrates hydraulic pump station, electromagnetic starter, locomotive lamp assembly, methane sensor, control platform, tracked car body, etc. can walk independently, as shown in Fig.2. The pump is driven by hydraulic pressure, which can realize continuously adjust of pump volume in the range of 0~460L/min. The output pressure can reach 13 MPa and can still ensure stable output of large flow. The BLY460/13 pump can drive DHM with diameter Φ89 mm and meet the requirement of slag discharge of in-seam directional borehole with Φ120 mm diameter. The performance parameters of the pump are shown in Table 2.

Fig. 1 ZDY12000LD drill rig

Fig. 2 BLY460/13 pump
Table 2 Performance parameters of BLY460/13

| index                | unit    | parameter |
|----------------------|---------|-----------|
| rated discharge      | L·min⁻¹ | 390       |
| rated pressure       | MPa     | 13        |
| motor power          | kW      | 110       |
| outline size         | m       | 3.25×1.30×1.76 |
| whole machine quality| kg      | 5 500     |

2.3. The survey system

2.3.1. YHD2-1000 (A) wired MWD system

The system consists of measuring device, measuring data line, explosion-proof computer, explosion-proof keyboard, explosion-proof memory. The signal measurement strength is expressed by measured voltage, the explosion-proof computer supply power to the measuring device in the bottom of borehole resulted in the working time is not limited, and the signal transmission speed is fast, but the special cable drill pipe must be used for signal transmission.

2.3.2. YHD3-1500 mud pulse wireless MWD system

Compared to YHD2-1000 (A) wired MWD system, YHD3-1500 mud pulse wireless MWD system consists of the mud pulse measuring device, the pressure transmitter and other device, the main performance parameters of the MWD system are shown in Table 3. It can generate stable pulse signals in the small displacement and meet the requirements of coal mine under explosive gas environment. The system breaks away from the dependence on the cable drill pipe and adapts to various types of drilling tools. However, it has a limited use time and the signal transmission speed is slower than that of the YHD2-1000 (A) wired MWD system.

Table 3 Main performance parameters of MWD system

| measurement system | design transmission distance /m | measurement performance |
|--------------------|--------------------------------|-------------------------|
| YHD2-1000(A)       | > 2,000                        | Dip angle: .90°~+.90°, Azimuth: 0°~360°, Tool Angle Oriented: 0°~360°, Allowable Error: ±0.2°, ±1.5° |
| YHD3-1500          | > 2,000                        | Dip angle: .90°~+.90°, Azimuth: 0°~360°, Tool Angle Oriented: 0°~360°, Allowable Error: ±0.2°, ±1.5° |

3. In-seam directional drilling technology over 2000m

3.1. Compound directional drilling technology

Compound directional drilling technology is developed on the basis of sliding directional drilling technology. By combining sliding directional drilling with compound drilling, and making use of the bending law of borehole trajectory of compound drilling as far as possible, the drilling technology of sliding inclination generation and compound inclination stabilization is formed[12]. Because the problems caused by sliding directional drilling are poor drilling smoothness, high friction resistance between drilling tools and borehole wall, poor effect of slag removal and insufficient deep borehole drilling ability. Compound directional drilling technology includes two meanings: 1) two drilling modes of sliding drilling and rotary drilling; 2) two rock breaking force of drilling tools rotary and DHM operation. The drilling trajectory formed by compound directional drilling is smoother, the transmission efficiency of drilling pressure is higher, and the drilling slag removal effect is better, which is conducive to the realization of deep borehole drilling.
3.2. Inclination control technology of compound drilling

Compound directional drilling technology has obvious advantages over sliding directional drilling technology. The essence of compound drilling is compound drilling with superimposed rotary power at the bottom of the borehole. The amount of drilling cuttings and the particle size is larger when at a higher drilling speed and lower rotational speed. It is easy to form cuttings wedge at the lower edge of the drilling tool, which enhances the upward inclination tendency of the drilling tool and weakens the downward cutting ability, and generally causes upward deflection of the borehole. The amount of drilling cuttings and the particle size is smaller when at a lower drilling speed and high rotational speed. Under the action of drilling tool agitation and water circulation, the effect of cuttings wedge is weakened and caused the borehole deflect downward. Similarly, inclination stabilization drilling can also be achieved by matching the appropriate drilling speed and rotational speed.

3.3. In-seam directional drilling technology

In-seam directional drilling technology are required to periodically intersect the roof and floor. The geological structure and fluctuation of coal seam are explored by branch borehole to guide directional drilling, which ensure the main borehole trajectory extend effectively in the coal seam[12]. The following two points need to be noted:

- Selection principle of branch borehole point
  The following principles should be followed: (1) selecting the rising inclination angle of borehole trajectory in coal seam to improve thesuccess rate and efficiency of drilling branch borehole; (2) selecting the upper part of coal seam to reserve enough space for adjusting the trajectory after drilling branch borehole; (3) the deviation between the inclination of trajectory of branch borehole and the inclination of coal seam should not exceed 5 degrees.

- Drilling profile trajectory control
  In order to avoid deviation of drilling trajectory caused by coal seam fluctuation, the distance between the two branch points should be set between 60~80 m. Borehole trajectory control should be based on compound drilling and sliding drilling, which is not only conducive to the setting of branch points, but also conducive to the realization of long-distance in-seam directional drilling.

4. Project Practice

4.1. Coal mine geology

The Baode coal mine is located in Shangxi Province, China. The drilling area belongs to the unexploited area, and the No.8 coal seam with a thickness of 8 m. According to the in-situ sample test of the working face, the original gas content is 4.87~8.96 m$^3$/t, and the original gas content of the working face where the drilling is located is 8.48 m$^3$/t. The length of the working face is about 3400 m, the length of the fully mechanized mining face is 240 m. So super-long in-seam directional borehole with a depth of over 2000 m is designed in the working face.

4.2. Drilling construction

Table 4 is the drilling information of in-seam directional borehole over 2,000m. The average daily footage is over 150 m and the coal seam drilling rate is over 97% under normal drilling conditions, which meets the need for accurate control of borehole trajectory. It also have the advantages of smooth borehole trajectory, small bending curvature and high slag discharging efficiency. The depth of the three boreholes is over 2,000 m, of which the largest borehole depth is 2,570 m, and creating a new record of in-seam directional borehole depth in the world. Fig. 3 is borehole trajectory profile of No. 2.
Table 4 Drilling information

| number | depth /m  | footage /m | diameter /mm | in-seam drilling rate /% | survey system | daily average footage /m |
|--------|-----------|------------|--------------|--------------------------|---------------|--------------------------|
| 1      | 2,311     | 3,094      | 120          | 100                      | YHD2-1000(A)  | 172                      |
| 1-2    | 2,008     | 2,110      | 120          | 100                      | YHD2-1000(A)  | 151                      |
| 2      | 2,570     | 3,164      | 120          | 97                       | YHD2-1000(A)  | 198                      |
|        |           |            |              |                          | YHD3-1500     |                          |

4.3. Analysis of drilling effect

Compound directional drilling technology provides continuous drilling power for drilling tools, which can greatly reduce friction in the borehole and increase borehole depth. The proportion of compound drilling in No. 1 and No. 2 borehole is 65% and 76%, respectively. The thrust on the drilling tools of No. 1 borehole is close to the limit value when the borehole depth is 2,000 m, while No. 2 borehole prolongs the depth to 2,300 m. Borehole inclination can be adjusted by controlling drilling speed and penetration rate in compound drilling. When the compound drilling rate is higher than 60 rpm and the penetration rate is lower than 0.25 m/min, the dip angle decreases. When the compound drilling rate is lower than 40 rpm and the penetration rate is lower than 0.4 m/min, the dip angle increases. When the compound drilling rate is about 40 rpm and the penetration rate is about 0.3 m/min, the dip angle basically remains unchanged. The inclination rate of compound drilling reach 0.15 degree/m, which can meet the need of in-seam directional borehole trajectory control.

Taking the in-seam directional borehole of 2,570 m as an example to analyze the adaptability of drilling equipment.

- ZDY12000LD drill rig

ZDY12000LD drill rig has superior performance and stable operation and can provide enough thrust to offset the friction of drilling tools. As shown in Fig. 4, with the sliding directional drilling, when the borehole depth is less than 1,000 m, the rig penetration pressure is less than 10 MPa; when the drilling depth exceeds 1,000 m, the rig penetration pressure increases with the borehole depth gradually increases and show a linear increase, but less than 20 MPa, and lower than the rated penetration pressure; when the borehole depth exceeds 2,000 m, the penetration pressure of the drill rig suddenly increases, and approaches the rate penetration pressure. With the compound directional drilling, the penetration pressure of the drill rig is always maintained at about 5 MPa, which can only reach about 25% of the rate penetration pressure. At the same time, the rotary pressure of the drill rig increases with the increase of the borehole depth, but the increase is small. It indicates that the rig system pressure is kept at a low level, and the reserve is surplus, which can meet the needs of drilling over 2,000 m.

![Fig.3 The trajectory profile of in-seam directional borehole drilling of No. 2](image)

![Fig.4 The relationship between pressure of drilling system and borehole depth](image)
BLY460/13 pump

BLY460/13 pump can realize output of large flow and high pressure, and the flow rate changes linearly and can be adjusted continuously. As shown in Fig.5, in order to maintain high drilling efficiency, the driller set the pump output flow to 300 L/min before the depth reached 1 500m. Due to the resistance along the path, the pump pressure increases linearly with the borehole depth by 0.5 MPa/hm. As the depth of the borehole increases, the pump pressure is close to the rated pressure of 13 MPa. For avoid damage to the pump for a long time, the flow rate is reduced to 250~280 L/min, which can meet the needs of DHM starting and normal operation. However, the reduction in flow rate has an adverse effect on the power output of DHM and slag discharge in the borehole. Therefore, pump pressure is one of the main limiting factors for implementing ultra-long in-seam directional drilling.

Survey system

The measurement process shows that the YHD2-1000(A) system has high stability, accurate measurement data, fast signal transmission speed and low maintenance cost. Both the No. 1 and No. 1-1 boreholes are drilled using the YHD2-1000(A) system, and the maximum actual transmission distance is 2311m. The measured voltage has been maintained above 9.7V during drilling, which is higher than the requirement of critical voltage value of 7V. However, it is difficult to meet the need of signal transmission in deep borehole drilling with the extension of service life of directional drill pipe. As shown in fig. 6, the measurement signal cannot be stably transmitted when the depth reached 1,824m in No. 2 borehole. Then we replaced the YHD3-1500 system and it successfully measured to 2,570m, but in the application process, we also found that the signal transmission stability decreases with the pump pressure gradually approaches the rated pressure.

Situation of gas drainage

Fig.7 is a statistical analysis of the gas drainage in No. 1 borehole. The total volume of single-hole drainage gas exceeds 1.1 million m³ after 300 days. It can be seen that the maximum gas extraction concentrating amount reaches 4.26m³/min, and the maximum gas drainage concentration reaches 80.6%. In the early stage of the extraction, the main branch hole of the No. 1 borehole was not constructed, the pure volume of the drilled gas drainage was kept at about 1.7m³/min, and the gas drainage concentration was kept at about 58%. When the main branch borehole of No. 1-1 was completed, the gas extraction purity and extraction concentration showed a jumping increase. The stable and efficient gas extraction from boreholes has been
realized, which further verifies the technical advantages of super-long in-seam directional boreholes in gas drainage.

![Fig.7 The curve of borehole gas drainage](image)

5. Conclusion
- The ultra-long directional drilling technology and high-power directional drilling equipment in the coal seam layer have well met the needs of ultra-long directional drilling construction of the coal seam above 2,000 m, and the maximum drilling depth reached 2,570 m, which created a new world record of in-seam directional borehole depth.
- The compound directional drilling technology effectively overcomes the limitation of the bending strength of the pure sliding directional borehole trajectory and the low efficiency of drilling power transmission, which realize the precise manual control of the super long directional borehole trajectory in the coal seam.
- ZDY12000LD directional drill rig provides enough thrust for deep borehole drilling while providing rotary power for compound drilling; the BLY460/13 pump has strong pressure resistance, by controlling the pressure and flow of the mud pump, the compound drilling can make better use of its advantages; YHD2-1000(A) system and YHD3-1500 system have the advantage of stability of signal transmission, which lays a solid foundation for in-seam directional drilling of over 2,000 m, but is greatly disturbed by external factors.
- In order to further improve the construction capability of in-seam directional borehole, it is necessary to continue to improve the working capacity of existing equipment, develop supporting equipment, and carry out research on new drilling technology and equipment. In this way to promote the upgrading and development of directional drilling technology and equipment to ensure safe and efficient production of coal mines.

Acknowledgments
This work is supported by National Science and Technology Major Special Funding Project in China (2016ZX05045-003-001)

References
[1] Cheng YP, Wang L, Zhang XL.(2011)Environmental impact of coal mine methane emissions and responding strategies in China. Int J Greenh Gas Control ,5:157-166.
[2] Li HY. (2011)Major and minor structural features of a bedding shear zone along a coal seam and related gasoutburst, Pingdingshan coalfield, northern China. Int J Coal Geol,47:101-113.
[3] Lin XY, Su XB, Guo HY. (2010)An evaluation study on the sealing mechanisms of Sitou fault to coalbed methane reservoirs in the Southeast Qinshui Basin. Nat Gas Ind ,4:20-23.
[4] Wang F, Ren T, Tu S, et al.(2012) Implementation of underground longhole directional drilling technology for greenhouse gas mitigation in Chinese coal mines[J]. International Journal of Greenhouse Gas Control, 11:290-303.
[5] SHI Zhi-jun, LI Quan-xin, YAO Ke. (2015)Latest Developments of Horizontal Directional
Drilling Technology and the Equipments for Underground Coal Mine. Exploration Engineering (Rock & Soil Drilling and Tunneling), 42(1): 12-16.

[6] DOGN Chang-le. (2015) Directional drilling technology and development tendency in underground mine[J]. Coal Science and Technology, 43(05):106-110.

[7] SHI Zhi-jun, LIU Jian-lin, LI Quan-xin. (2018) Development and application of drilling technique and equipment in coal mining area of China[J]. Coal Science and Technology, 46(4): 1-6.

[8] SHI Zhi-jun, LI Quan-xin, YAO Ke. (2015) Underground mine 1800 m horizontal directional drilling technology and equipment[J]. Coal Science and Technology, 43(2):109-113.

[9] Frank Hungerford, Wayne Green. (2016) Inseam Boreholes to and Beyond 2000 m with a Combination of Slide and Rotary Drilling[J]. Coal Operators' Conference, 223-235.

[10] YAO Ke, Zhang Zhan-qiang, LI Dong, et al. (2016) Development of series of crawler mud pumps for drilling in underground coal mine[J]. Coal Geology & Exploration, 44(04):153-156+160.

[11] Frank H, Ting R, Naj A. (2013) Evolution and application of in-seam drilling for gas drainage[J]. International Journal of Mining Science and Technology, 23(4):543-553.

[12] Lu S, Cheng Y, Ma J, et al. (2014) Application of in-seam directional drilling technology for gas drainage with benefits to gas outburst control and greenhouse gas reductions in Daning coal mine, China[J]. Natural Hazards, 73(3):1419-1437.

[13] Hu G, Xu J, Ren T, et al. (2016) Field investigation of using water injection through inseam gas drainage boreholes to control coal dust from the longwall face during the influence of abutment pressure[J]. International Journal of Surface Mining, Reclamation and Environment, 30(1):16.