YANSHUN ZHAO
PENG LI
QILEI YIN
and
TONG WANG

Application of sliding-block reverse-circulation drilling bit in multi-layer goaf detection

This paper researches specialized reverse-circulation drilling bit for multi-layer goaf detection based on the multi-layer goaf detection project of iron ore mine in Yuan Village and designs a sliding-block reverse-circulation drilling bit with innovation, which is designed with large-through hole central channel, double-row inner orifice and sliding block. The structure of sliding block is used on reverse-circulation drilling bit for the first time. The performance of sliding-block reverse-circulation drilling bit is observed in practical drilling test, indicating good effect of reverse circulation, and high drilling efficiency, with the average drilling efficiency of 33.75m/h on extremely cracked land and 10.17m/h on hard land. The sliding-block reverse-circulation drilling bit can effectively solve the problem of blocking central channel since the structure of sliding block can meet the requirement on drilling. The top plate of multi-layer goaf can be drilled through successfully. C-ALS three-dimensional laser scanner can be put down through the central channel to solve the difficulty of simultaneous scan and detection on multi-layer goaf.

Keywords: *Goaf; pass-through down-hole hammer reverse-circulation drilling technology; C-ALS three-dimensional laser scanner; sliding-block reverse-circulation drilling bit*

1. Introduction

Actually, as mentioned in the abstract section, it will be rather easy to follow these rules as long as you just replace the "content" here without modifying the "form". Goaf is underground cavity formed by human's underground excavation or geological movement. It is extremely elusive and has abnormal space distribution law. Besides, it is difficult to forecast the collapse of its top plate. Therefore, it is one of main danger sources of opencast mine working accident. Therefore, to guarantee the safety of opencast working, it is greatly significant to accurately detect underground unclear goaf [1-3].

At present, it is successful to apply the combination of three-dimensional laser scan and drilling in goaf detection. However, some problems of multi-layer goaf detection have not been solved. Pass-through down-hole hammer reverse-circulation drilling technology can be used to detect multi-layer goaf. C-ALS three-dimensional laser scanner is put down through the central channel of double-wall drill pipe to the internal position of goaf to achieve accurate detection [4]. In pass-through down-hole hammer reverse-circulation drilling system, reverse-circulation drilling bit is the key part for forming reverse circulation. It directly receives the impact of piston and transmits the stress wave to rock. Then the rock can be crushed. When the drilling bit reaches multi-layer space, the reverse-circulation drilling bit can take the clastic rocks at the bottom of hole into the central channel of double-wall drill pipe and up to the earth's surface relying on its specific fluid channel design. Therefore, interrupt of drilling hole does not influence the normal drilling. At the same time, while using reverse-circulation drilling bit for multi-layer goaf detection, C-ALS three-dimensional laser scanner shall be put down without blocking. Therefore, in multi-layer detection technology, the special reverse-circulation drilling bit shall have good reverse-circulation effect and good anti-impact ability. Besides, it shall meet technological requirements and functions. In this way, the reverse-circulation drilling bit will lay foundation for solving the difficulty of multi-layer goaf detection [5-7].

2. Engineering site

The iron ore mine of Yuan Village in Lan County is one of the iron ore mines of Taiyuan Iron & Steel (Group) Co., Ltd. Stratum structure of the iron ore mine is complex. As for the stratum in the opencast mine area, there are Pei Village group and Yuan Village group of Archaeozoic Lv Liang mountain group and Paleozoic Cambrian system and Ordovician. Because of long-term geological movement and mutual squeezing of stratums, irregular fold can be formed in close distribution and wide range. The fluctuation of fold is obvious at intersection. The folds existing in ore bed can cause zigzag structure and increase the thickness of ore bed. It is difficult to identify the fracture structure of mining area. There are normal fault and reverse fault. Complex change of geological

Messrs. Yanshun Zhao, College of Construction Engineering, Jilin University, Changchun 130026, Peng Li, Xian Research Institute of China Coal Research Institute, Xian 710043, Qilei Yin, College of Construction Engineering, Jilin University, Changchun 130026 and Tong Wang, Changchun Institute of Technology, Jilin University, Changchun 130021, China. Email: 1404363519@qq.com

structure makes the fissure of stratum abnormal. In addition, artificial exploiting activity further adds to the complexity of mining area. Rocks in the mining area are epidiabase, chlorite schist containing iron, grunerite schist containing iron and magnesium, quartzite and quartzite containing iron. They are hard with high density and large mine pressure strength. Because of tiny mine particles and backward mining technology in the past, scale exploitation was not achieved. Rich ore can be exploited along the trend of orebody in footrill mode. Deep primary orebody can be exploited through vertical shaft. In this way, underground orebody in the mining area has large quantity of intersectional exploitations in vertical and horizontal direction. Owing to disordered management, most goafs are not timely filled and not recorded in detail. Finally, a lot of unclear goafs exist in mining area and they connect mutually. Since 2011 that opencast working began, 4 collapse accidents have happened up to now. 26 unknown goafs have been detected. Some of them are overlapped multi-layer goafs. The goafs are constantly detected. However, distribution of goafs cannot be effectively forecast owing to large scale of goaf and limited detection means and materials.

Geophysical prospecting is the traditional means for goaf detection. Drilling method is used to verify drilling holes and rectify the data of geophysical prospecting. Radon measuring method and transient electromagnetic method are used to operate geophysical prospecting. Method of comparative analysis is used to rectify the detection data. Finally, drilling hole verification is operated on prospecting area using normal-circulation drilling technique. Through practical detection and drilling hole verification, the accuracy of geophysical prospecting for goaf detection is low [8]. In 2011, 5 goafs were detected in mining area. Only 1 goaf was detected by geophysical prospecting and other goafs were detected by drilling method. Regular drilling method cannot be used to drill unclear multi-layer goafs. The top plate of multi-layer goafs is thin. Secondary collapse of goaf can be easily caused while treating top goaf. Therefore, a practical and reliable method is urgently needed to detect multi-layer goaf and guarantee the safety of mining area [9,10].

Table 1 The performance parameters of SL-400A fully hydraulic crawler-type power-head drilling machine

Diameter of drill hole/m	110~273
Rotary torque/N·m	3300~4000
Axial pressure/T	4.5
Rotary speed/m/min	0~100
Hoisting force/T	8
Winding hoisting force/T	1
Speed of slow rise/m/min	2.5
Speed of fast rise/m/min	18
Speed of slowly going forward/m/min	0.5~5
Speed of fast going forward/m/min	35

3. Section headings

3.1 Key points of operation

Cooperatively use C-ALS three-dimensional laser scanner and pass-through down-hole hammer reverse-circulation drilling technology to accurately detect multi-layer goaf.

Design sliding-block reverse-circulation drilling bit with large-through hole central channel, double-row inner orifice and anti-blocking function aiming at complex stratum conditions in mining area.

3.2 Equipment and tools for field test

1. SL-400A fully hydraulic crawler-type power-head drilling machine is shown in Fig.1. The drilling machine is offered by mine. To meet the requirements of pass-through down-hole hammer reverse-circulation drilling technology, the drilling machine is transformed partially. Single channel of power head has been changed to be double channels (Fig.2). Channel 1 is the channel of air inlet; channel 2 is reverse-circulation slagging channel. Detailed work performance parameters of the drilling machine are listed in Table 1.

Fig.1 SL-400A fully hydraulic crawler-typewer-head drilling machine

Fig.2 Double-channel power head

TABLE 2 THE MAIN PERFORMANCE PARAMETERS OF XRVS 976 SCREW-TYPE AIR COMPRESSOR

Capacity flow (m^3/min)	27.6
Rated power (kW)	328
Discharge pressure (bar)	25
Weight (kg)	5700
Rated speed (rpm)	1600
Length×width×height (mm)	4910×2100×2500

2. Air compressor: XRVS 976 screw-type air compressor (Fig.3). The air compressor is manufactured by Swedish company Atlas Copco. Detailed parameters are listed in Table 2.
3. Orifice plate, movable fork and pad fork: To be applicable to the external diameter of new drilling tool, adjust the orifice plate, movable fork and pad fork of the original drilling machine to match the test drilling tool on the spot (Fig.4). In work, pad fork gets stuck with the lower part of double-wall drill pipe; movable fork is pushed by hydraulic cylinder to relax drill pipe. Drill pipe can be demounted through reversing power head. At the same time, orifice plate protects the center.
4. Pass-through down-hole hammer reverse-circulation drill: 2 sets of GQ-142 pass-through down-hole hammer and 2 specialized reverse-circulation drilling bits (one is large-through hole coring bit (Fig.5) and the other is sliding-block reverse-circulation bit (Fig.6) shall be prepared for this test. Through testing the coring bit of large-through hole central channel, the diameter of central channel and inner orifice in numerical value simulation optimization are verified. On the basis of observing work performance of sliding-block reverse-circulation drilling bit, the lifetime of sliding block is examined in test.

Fig.3 XRVS 976 screw-type air compressor

Fig.4 Orifice plate, movable fork and pad fork

Fig.5 Large-through hole coring drilling bit

Fig.6 Sliding-block reverse-circulation drilling bit

5. C-ALS three-dimensional laser scanner: C-ALS three-dimensional laser scanner is shown in Fig.7. Through putting down double-wall drill pipe to the bottom of hole, 360° three-dimensional scanning can be operated. In Fig.8, the scanner is put down to the bottom of hole by sliding-block drilling bit; the scanner pushes up sliding block and scanning probe reaches out. Cable, oriented rod and notebook are used to control the scanner and process data. Parameters of the scanner: external diameter 50mm, length 2m, scanning range 150m, precision 50mm, frequency 240 points and resolution ratio 10mm.

Apart from above main equipment, there are sludge discharge pipe and through hammer. Sludge discharge pipe can guide the discharge of rock sludge; through hammer can dredge the central channel of double-wall drill pipe.

3.3 FIELD TEST

Multi-layer goaf detection was started in November 2014. Three drilling tests are operated in total. Total drilling footage is 94.8m. Average hour efficiency is 12.77m/h.

Fig.7 C-ALS three-dimensional laser scanner

Fig.8 C-ALS scanner is put down by sliding-block drilling bit

Fig.9 Warning board of K 25-3 goaf

3.3.1 First-stage test

This test is operated in a multi-layer goaf (elevation level 1,695m) in the iron ore mine of Yuan Village (Fig.9). The goaf is located on No.2 orebody with code K 25-3. The goaf is multi-layer goaf. The height of top plate is 18m; net height of the cavity of the goaf is 11m. It mainly tests feasibility of the drilling technology.

GPS is used to position drilling point. After it is positioned, drilling machine moves, adjust the position of drilling machine to align the positioned point with the center of orifice plate of drilling machine, adjust drilling balance and guarantee verticality of drilling hole. Large through-hole coring drilling bit is used to drill the first hole (Fig.10). Through recording the drilling parameters in the drilling process of each drill pipe and recording reverse-circulation sludge discharge (Table 3), we can know that:

Reverse-circulation effect can form rapidly. There is reverse-circulation effect in the stage of drilling hole. It indicates strong suction of double-row inner orifice to bottom of drilling bit.

TABLE 3 DATA OF DRILLING TEST ON K 25-3 GOAF

Hole depth/m		Drilling footage /m	Pure drilling time/min	The number of drill pipes	Drilling efficiency/m/h	Speed/ rpm	Volume of air injected/m^3/min	Air injection pressure/bar
From	To							
0	0.6	0.6	0.4	0	90	20	27.6	22
0.6	3.6	3	5	1	36	20	27.6	22
3.6	6.6	3	5	2	36	20	27.6	22
6.6	9.6	3	5	3	36	20	27.6	23
9.6	12.6	3	7	4	25.7	20	27.6	23
12.6	15.6	3	15	5	12	20	27.6	23
15.6	17.6	2	13	6	9.23	20	27.6	23
17.6	28.6	—	—	10	—	—	—	—
28.6	30.6	2	24	10	5	20	27.6	19.3
30.6	33.6	3	33	11	5.45	20	27.6	19.3
33.6	36.6	3	36	12	5	20	27.6	19.4
36.6	39.6	3	43	13	4.19	20	27.6	19.4
39.6	42.6	3	31	14	5.81	20	27.6	18.8
42.6	44	1.4	10	15	8.4	20	27.6	18.9

Fig.10 Start of drilling

Steps are peeled by blasting, which causes a layer of virtual slag (thickness 12.6m) on surface of ground. It is fractured leakage stratum. In this working condition, down-hole hammer works normally and drilling efficiency is high; reverse-circulation slag discharge is unhindered. Through observing slag discharge pipe, the concentration of slags is large. The speed of drilling footage increases following the rise of concentration of slag discharge. Average drilling efficiency is 33.75m/h.

Drill to hard stratum and efficiency of drilling becomes low. Reverse circulation is normal and drilling efficiency is 10.17m/h.

While drilling to the 6th drilling pipe, top plate of the first-layer goaf is drilled through. Residual length at orifice is 1m. Total length of drilling tool is 18.6m; the thickness of top plate is 17.6m. They accord with the anticipative.

Drill the top plate of the second-layer goaf. The stratum is hard and complete; reverse circulation is normal. A large quantity of rock blocks are discharged. The largest diameter of rock blocks and the diameter of inlet at the bottom of drilling bit are almost same (Fig.11). There is no blocking phenomenon. This further indicates work performance of reverse-circulation drilling bit strengthens. In this stage, down-hole hammer does not work and debugging of bottom hole is non-effective. Pull up drill and dismount drilling tool to examine it. Owing to excessive air pressure given by air compressor, drilling machine cannot bear it. In this case, the

Fig.11 Rock blocks

Fig.12 Damaged end of drilling bit

end of drilling bit is damaged (Fig.12) and the work of down-hole hammer is influenced.

Change drilling bit and continue drilling. Drilling machine operators constantly give reaming operation to avoid loose slag collapsing and blocking drill. When drilling to the 15th drill pipe, reverse circulation of down-hole hammer suddenly strengthens and large quantity of dusts are discharged. At this time, the drilling pressure of drilling machine suddenly lowers and it can be put down easily. It indicates the second layer of goaf has been drilled through and proves the strong suction of inner orifice structure of reverse-circulation drilling bit to bottom hole. When drilling tool enters goaf, reverse circulation can still form. It indicates suction of drilling tool can continuously discharge large quantity of rock slags (Fig.13).

After the second layer is drilled through and drilling is continued, drilling tool and some drill pipes are lost into goaf owing to incorrect operation. Therefore, drilling stops and start goaf detection.

Fig.13 The slag discharge of discharge pipe when top plate of goaf is drilled through

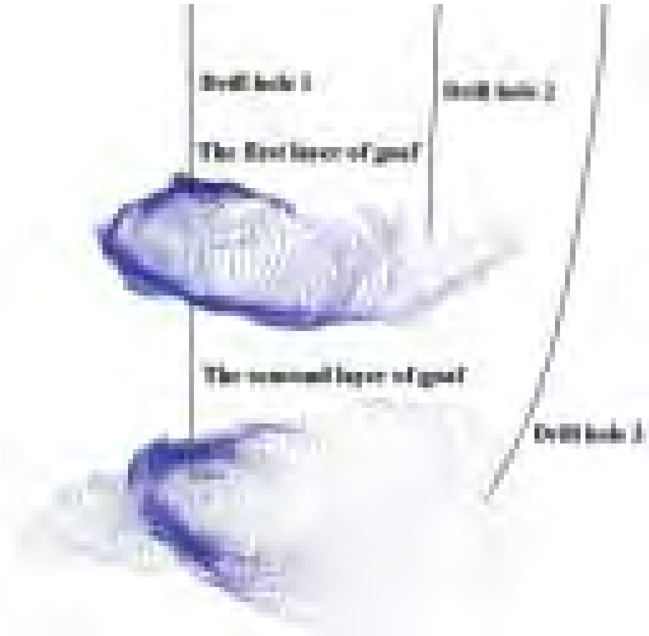

Fig.14 Three-dimensional laser scanning to goaf

Screw off drill pipe on orifice plate and put down C-ALS three-dimensional laser scanner to the internal of goaf using double-wall drill pipe. The workers on the ground scan bottom laser probe by oriented rod and cable, process scanning data by ground control unit, form dot matrix image (Fig.14), observe the internal goaf using LED camera at front end of probe and confirm existence of water.

In Fig.14, drill hole 1 is drilling track in this test; drill hole 2 and drill hole 3 are the drilling tracks when normal-circulation drilling technique is used. The comparison can well indicate that good verticality of drilling track can be got from using pass-through down-hole hammer reverse-circulation drilling technology. It can be used to drill multi-layer goaf, put down instrument and operate detection. It further proves the feasibility of the multi-layer goaf detection technology and verifies large through-hole central channel and the reverse-circulation drilling bit with double-row inner orifice can be used for complex stratum of multi-layer goaf. It meets rapid drilling and measurement requirements.

3.3.2 Second-stage test

In this test, vacant site is located on the platform at elevation level 1710m. The goaf was found in December 2013. Its no. is K27. At present, elevation of the platform is 1680m. In other words, the platform is peeled for two times and the elevation 15m is peeled every time. Comparing the first test, loose degree of the goaf is higher. It can be almost confirmed that some parts of the goaf have collapsed. In material, burial depth of top plate of the goaf is 23.5m; burial depth of bottom plate of the goaf is 29.64m; height of cavity is 6.14m.

GPS is used to position hole. Put drilling machine and tools at proper position and adjust the status of drilling machine. Sliding-block reverse-circulation drilling bit is selected in this test to drill hole. Table 4 lists drilling parameters.

In Table 4:

1. While using sliding-block reverse-circulation drilling bit, reverse-circulation effect can be formed when drilling to 0.4m.
2. Sliding-block reverse-circulation drilling bit used for very loose stratum can greatly decrease blocking. In addition, drilling efficiency is high and average drilling speed can be 12.4m/h.
3. In this test, pure drilling time of sliding-block reverse-circulation drilling bit is 109.73min; depth of drill hole is 30.6m. There is no blocking of central channel. When drilling to 18.6m, down-hole hammer works abnormally. Pull up drill and examine down-hole hammer and drilling bit. Problem is not found and a part of sliding-block reverse-circulation drilling bit is in abrasion. Sliding-block part works normally (Fig.15).
4. To compare with sliding-block reverse-circulation drilling

TABLE 4 DRILLING PARAMETERS OF K27 GOAF

Hole depth/m		Drilling footage /m	Pure drilling time/min	The number of drill pipes	Drilling efficiency/m/h	Speed/ rpm	Volume of air injected/m^3/min	Air injection pressure/bar
From	To							
0	0.6	0.6	3	0	12	20	27.6	18.78
0.6	3.6	3	12	1	15	20	27.6	18.76
3.6	6.6	3	18	2	10	20	27.6	18.67
6.6	9.6	3	24	3	7.5	20	27.6	18.71
9.6	12.6	3	22	4	8.18	20	27.6	18.63
12.6	15.6	3	11	5	16.36	20	27.6	18.67
15.6	18.6	3	11	6	16.36	20	27.6	18.93
18.6	21.6	3	6	7	30	20	27.6	18.84
21.6	24.6	3	2	8	90	20	27.6	18.80
24.6	27.6	3	0.4	9	450	20	27.6	18.84
27.6	30.6	3	0.33	10	540	20	27.6	18.83

Fig.15 Sliding-block reverse-circulation drilling bit

Fig.16 The rock blocks not crushed

bit, pull up drill, examine down-hole hammer and drilling bit, change coring drilling bit and drill when drilling to 18.6m. Reverse circulation is normal. Most slags discharged are large rock blocks which have not been crushed (Fig.16). They may block drill machine. This further indicates the necessity of designing sliding block.

5. When drilling to 21.6m, drilling accelerates obviously. In addition, the concentration of rock slags in discharge pipe increases obviously. It indicates partial collapse of the top plate of goaf is serious. Thickness of top plate is 21.6m. Continue the drilling, drilling speed reaches 197.56m/h between 21.6m and 30.6m. The drilling speed of the 10th drill pipe is especially striking. Its pure mechanical drilling speed can be 540m/h.
6. When drilling to 30.6m, large quantity of rock slags are discharged from hole bottom. In previous detection material, burial depth of top plate of the goaf was recorded to be 23.5m. Therefore, it can be concluded that collapse of top plate of the goaf is serious and cavity is filled.

3.3.3 Third-stage test

Middle part of K27 goaf is chosen in this test. Burial depth of top plate is 12.7m; thickness is 11.7m. Coring drilling bit is chosen in this test for drilling. Test parameters are listed in Table 5. In Table 5:

1. In the same test conditions as those of sliding-block reverse-circulation drilling bit, coring drilling bit is used to drill to 0.6m and form reverse circulation.
2. In drilling stage, there is obvious phenomenon of holding air pressure which reaches 19.15bar. When sliding-block reverse-circulation drilling bit is used, air pressure is 18.78bar. It indicates that large quantity of rock blocks in coring drilling bit block the bottom of central channel of drilling bit.
3. When drilling to 12.6m, central channel of double-wall drill pipe is blocked. Through using measuring rope to pull up hammer, impact and unblock it. Blocking point is confirmed to be at a distance of 5m from surface of ground. In preliminary analysis: coring drilling bit can effectively crush large rock blocks and double-row inner orifice has good reverse-circulation effect (Fig.17). The pushing force of drilling machine pushes large rock blocks enter central channel and return to surface of ground. With increase of height, backpressure gradually increases. When reaching surface of ground, slag discharge becomes slow.

Fig.17 Reverse-circulation slag discharge

TABLE 5 PARAMETERS IN THIRD-STAGE TEST

Hole depth/m		Drilling footage /m	Pure drilling time/min	The number of drill pipes	Drilling efficiency/m/h	Speed/ rpm	Volume of air injected/m^3/min	Air injection pressure/bar
From	To							
0	0.6	0.6	0.5	0	72	20	27.6	19.15
0.6	3.6	3	4	1	48	20	27.6	19.10
3.6	6.6	3	3	2	60	20	27.6	18.97
6.6	9.6	3	3	3	60	20	27.6	18.07
9.6	12.6	3	2	4	90	20	27.6	18.10

Comparing with small particles of rock, the speed of large rock blocks is lower. Mutual extrusion causes blocking. It also proves the necessity of sliding-block reverse-circulation drilling bit.

Middle part of K27 goaf is chosen in this test. Burial depth of top plate is 12.7m; thickness is 11.7m. Coring drilling bit is chosen in this test for drilling. Test parameters are listed in Table 5. In Table 5:

4. Conclusions

The test solves the problem of accurately detecting multi-layer goaf, expands the application field of pass-through down-hole hammer reverse-circulation drilling technology, explores a set of advanced detection technology, innovatively designs sliding-block reverse-circulation drilling bit and offers technical support to multi-layer goaf detection technology. In addition, large through-hole central channel and double-row inner orifice can greatly improve reverse-circulation effect.

From the test on application of sliding-block reverse-circulation drilling bit and coring reverse-circulation drilling bit, we can know that sliding-block reverse-circulation drilling bit performs well in this test and successfully solves the problem of contradiction between putting down instrument and preventing blocking. As for very loose stratum, sliding block can effectively crush large rock blocks. Through comparing with coring drilling bit, the advantages of sliding-block drilling bit can be obvious. Firstly, in drilling stage, sliding-block drilling bit can form reverse circulation earlier than coring drilling bit; air pressure is lower. It indicates the size of rock slags in central channel is small and they can be easily discharged. Secondly, there are large quantity of rock blocks not crushed when coring drilling bit is used (Figure 16). The rock slags discharged from using sliding-block drilling bit are small and have been crushed. The problem of blocking caused by the collision and extrusion between rock blocks and small rock slags is prevented.

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