System for Prevention and Control of Old Goaf Water during Coal Mine Re-mining

Shuning Dong
Xi'an University of Science and Technology
Xiaolong Li (Lxlxust@163.com)
Xi'an University of Science and Technology
Liuzhu Ma
CCTEG: China Coal Technology and Engineering Group Corp

Case study

Keywords: Old goaf water, Coal mine, Technology system, Mining, Borehole

Posted Date: May 13th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-515336/v1

Abstract

One integrated mine was currently threatened with an old goaf water disaster, therefore, the development of an advanced detection-guarantee system for roadway excavation with no blind area was imperative. Further, multiple geophysical exploration in combination with two types of boreholes were used to explore and drain water technology, with the anomalous geophysical area as the target area, The conventional borehole with the largest water outflow was taken as the target spot, at a low elevation of the mining area, and a remote directional borehole was used to drill into the old goaf along the stable rock strata below the coal seam floor to intercept the dynamic recharge water, which increased the efficiency of roadway excavation 4–9 times. The 'isolated island' old goaf water in the mining face was controlled through multiple geophysical exploration combined with the full-coverage exploration technology by conventional boreholes, and the water-rich anomalous area and geological anomalous area were determined, thus ensuring the safety of the mining face in terms of old goaf water. The technology for advanced short-distance exploration, advanced estimate, roadway exploration, and dynamic old goaf water with drainage was used to comprehensively guarantee real-time, safe mining. This system for the prevention and control of old goaf water was applied to a control project for the old goaf water disaster in the 101 mining face. At present, 1.37 Mt of coal has been safely mined from this mining face. The technical system has improved *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018), and improved the technology for the prevention and control of old goaf water under conditions where the upper portion in the same coal seam was destroyed by a small-scale coal mine and re-mining.

Introduction

Coal mining in China is often affected by five major types of disasters: water inrush, fires, gas outbursts, coal-dust explosions, and roof collapses. In 2020, seven serious water accidents occurred in China's coal mines, including three old goaf water inrush accidents, causing 19 deaths. It is clear that goaf water disasters still threaten the safety of production, especially in the re-mining areas in Shanxi, Sichuan, and Guizhou (Cui et al. 2014, 2018 a, b; Dong et al. 2020; Li et al. 2018; Li et al. 2021; Sun et al. 2016).

In recent years, researchers have studied techniques to control old goaf water, and considered that the formation of the old goaf water requires three elements: water resources, channels, and space. Several prevention and control measures have been put forward, such no exploration, no drain absolutely, and no mining. The main methods included a comprehensive exploration using a variety of means of geophysical and geochemical exploration, combined with borehole and auxiliary roadway analysis, etc (Liu et al. 2015; Mou et al. 2020; Vutukuri et al. 1995). The geophysical exploration techniques that were used to detect the scope and water in goaf mainly included the 3-D seismic, GPR, radio-wave, channel-wave seismic, Rayleigh-wave, TEM, DC, AMT, audio-frequency electrical penetration, laser-in-borehole, sonar-in-borehole, and TEM-in-borehole methods. However, different techniques of geophysical exploration led to differing results (Su BY et al. 2016; Wang et al. 2020; Xue et al. 2013; Xue et al. 2019; Yang et al. 2017). According to these results, the position and volume of old goaf water were determined, conventional boreholes were used to drain old goaf water, the trajectory deviation of conventional boreholes was found to be large, and false appearance was rampant. Directional boreholes have also been successfully used to drain old goaf water in upper different coal seams. Certain technology systems exist for the prevention and control of old goaf water under the condition that the upper portion in the same thick coal seam was destroyed by a small-scale coal mine and re-mining. This old goaf water was scattered, isolated, concealed, complexly connected, and irregularly spatially distributed. Therefore, the treatment of such old goaf water has been an ongoing technical problem in controlling mine water.

A coal mine was present in the Xiangning mining area of the Hedong coalfield, where some portions of the no. 2 coal seam have been destroyed by small-scale coal mine, with some others being fully destroyed. The control of old goaf water was very difficult, and the excavation efficiency of roadways was significantly reduced. The old goaf waters effected on the 101 mining face were very serious, and an accident was once caused in terms of flooding equipment. The formation time of the 101 mining face was as long as 3.3 years. It can be seen that the production continuity was disrupted by the old goaf water disaster. This article focuses on a system for the prevention and control of old goaf water in the upper layers of the no. 2 coal seam at mining face 101, and improves *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018; Soltani et al. 2013; Yao et al. 2013).

1 Background

1.1 General Situation

The coal mine is located on the east bank of the Yellow River in Xiangning County, Shanxi Province, and comprises four small-scale coal mines and unsuitable resources. Coal seams no. 2 and no. 10 are the main seams being mined. At present, the no. 2 seam is being mined, which has an average coal thickness of 6 m. The location of the coal mine is shown in Fig. 1.

1.2 Distribution and Outflow Characteristics of the Goaf Water

It can be seen from Fig. 2 that the old goaf was not distributed in flakes, as old roadways and small-scale mining faces. The old goaf water was mainly stored in the caving zone and has the characteristics of a phreatic aquifer, while a small amount of old goaf water was stored in the fractured zone and had the characteristics of confined water. Old goaf water can easily accumulate in the relatively low level of the coal seam floor, or in the anticlinal wing, synclinal axis, and normal fault footwall. The type of old goaf water at the 101 mining face was dynamic recharge water and static sporadic water. The ground geophysical exploration estimated the water accumulation to be 13.8×10^4 m^3, and the actual total water discharge to be 91.9553×10^4 m^3, which was seven times that found through geophysical exploration. The main reason for this error was that there was about 36 m^3/h of dynamic recharge of old goaf water in the northeastern portion of the mining face. The elevation of the old goaf water was 596–620 m, and the head height was 4–14 m. The distribution of old goaf water is shown in Fig. 2.

1.3 Issues Caused by Goaf Water

Excavation of the 101 mining face began on September 30, 2016, and finished on December 15, 2019, lasting 3.3 years. It took 1.5 years for the haulage roadway to be excavated from 277 m to 440 m. When the haulage roadway was excavated to 440 m, there was still 36 m^3/h of dynamic recharge water in the roadway. Six months after the drainage of old goaf water by a large number of conventional boreholes combined with the auxiliary roadway, the roadway could not be excavated and the excavation efficiency was seriously affected.

2 Technology For The Prevention And Control Of Old Goaf Water In The Process Of Roadway Excavation

Usually, old goaf water inrush accidents occur during the process of roadway excavation, and are usually catastrophic. Therefore, prevention and control of old goaf water are very important during roadway excavation.

2.1 Ground Comprehensive Geophysical Exploration of Water-rich Anomalous Areas

The seismic method is used to detect the distribution of the old goaf, and the electrical method is used to detect the stagnant water in the old goaf. Using a single geophysical method has some limitations, so two or more geophysical methods should be adopted for comprehensive geophysical exploration.

2.2 Technology for Diversified Comprehensive Prevention and Control of Old Goaf Water in Underground Mines

Multiple Geophysical Exploration Methods Combined with Conventional Boreholes

During roadway excavation, in view of the unknown amounts of old goaf water, it was necessary to investigate the mining data of small-scale coal mines in the early stages and focus on exploring the anomalous areas through ground geophysical exploration. Firstly, the anomalous water-rich area ahead of the roadway was explored by using geophysical methods such as TEM and DC. According to *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018) and some local regulations, conventional boreholes for the exploration and drainage of water were arranged ahead of the roadway. The boreholes were fan-shaped in the horizontal plane and vertical plane along the direction of the roadway, the horizontal distance between the boreholes was not more than 3 m, and the vertical distance of the boreholes was not more than 1.5 m. This was because the cross-section size of the old roadway was not less than 3 m × 1.5 m. *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018) also stipulates that the size of the waterproof coal or rock column shall not be less than 20 m, and the advanced distance of boreholes for exploration and drainage shall not be less than 30 m, therefore, the exploration range of the two sides of the roadway was at least 20 m, the length of boreholes was designed to 100 m, and the maximum distance of a single excavation was 70 m. The Conventional borehole design for exploration and drainage is shown in Fig. 3.

If the geophysical results indicate a water-rich anomalous area, it is necessary to design boreholes to verify the anomalous area, until complete identification. All anomalous areas should be excluded to confirm that there was no threat of water disasters before excavation. Usually, there were a large number of conventional boreholes for water exploration and drainage, which can easily lead to blind areas; thus, an auxiliary roadway with relatively low elevation was used to drain the dynamic recharge water of old goaf along with conventional boreholes. During the process of draining, geophysical exploration was conducted several times to compare the changes in the area and water quantity of the old goaf water accumulation area until all anomalous areas were eliminated. It was very difficult to drain water from the bottom of the old goaf, and it was often impossible to drain or intercept the dynamic recharge of old goaf water. As a result, the water level of the old goaf water will not drop for a long time, which significantly limits the continuity of mining.

Multiple Geophysical Exploration Methods Combined with Two Kinds of Borehole Exploration and Drainage Techniques

In view of the technical limitations of underground geophysical exploration combined with conventional boreholes for the prevention and control of old goaf water, an advanced exploration and guarantee system for roadway excavation was optimized herein.

1) Advanced Detection and Guarantee System for Roadway Excavation

In view of the deviation between the actual trajectory and the design trajectory of conventional boreholes, blind areas were prevalent, the design of boreholes had a large manual workload, the degree of visualization was low, and it was impossible to analyse the actual measured information of the advanced position of the boreholes in multiple directions. An advanced exploration and guarantee system that combined borehole trajectory data with GIS software was developed, which realized the automatic analysis of borehole trajectory, and could supplement the design of boreholes in blind areas. The three-dimensional shape of the old goaf could also be constructed according to the borehole trajectory data. The 3D diagrams of borehole trajectory, roadway, roof and old goaf is shown in Fig. 4.

2) Multiple Geophysical Exploration Methods Combined with Conventional Boreholes and Directional Boreholes

It is stipulated in *The Detailed Rules for Water Disaster Prevention and Control of Coal Mines* (NCMSA 2018) that directional drilling rigs can be used to carry out long-distance, large-scale exploration and drainage of water in coal mines under certain conditions, but there are no clear requirements for the design of borehole parameters. The drainage effect on the dynamic recharge of old goaf by conventional boreholes was poor. To speed up the drainage of water and mitigate water disasters caused by old goaf, a technique to prevent and control old goaf water using multiple geophysical exploration methods combined with conventional boreholes and directional boreholes is put forward. The specific steps are as follows. The schematic of directional borehole for exploration and drainage is shown in Fig. 5.

Step 1: According to the water in the old goaf detected by ground TEM and three-dimensional seismic technology, the area where old goaf water may exist is taken as the target area for the directional borehole.

Step 2: According to production continuity and the target area of the directional borehole determined in step 1, the existing roadway is selected or the drilling field in the low elevation auxiliary roadway is built, and the orifice elevation of the borehole must be lower than that of the target area. A long-distance directional borehole is used to explore the potential old goaf water at low positions in advance.

Step 3: When excavating the roadway, TEM and DC are used to detect the anomalous water-rich areas of the old goaf ahead of the roadway.

Step 4: If no water-rich anomalous areas are present ahead of the roadway in step 3, conventional boreholes are arranged ahead of the roadway or auxiliary roadway according to *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018), and the trajectory of each borehole is measured. The deviation between the actual borehole trajectory and the design trajectory is compared using the advanced exploration and guarantee system, if the deviation is large, it is necessary to increase the number of exploration boreholes. If no anomalies are discovered, roadway excavation is allowed, and the old goaf water is prevented and controlled according to the cycle of exploration–excavation–exploration.

Step 5: If water-rich anomalous areas exist ahead of the roadway in step 3, they will be explored in accordance with the conventional borehole style in step 4. If there is water outflow in the borehole, it is necessary to increase the number of exploration boreholes, if the water outflow is small and attenuates quickly, it is deemed to be a static reserve, and conventional boreholes are used to continue to drain the old goaf water. According to the state of attenuation, a number of geophysical exploration and boreholes were adopted for cross-verification during water drainage. If no anomalies exist in terms of geophysics and boreholes, the roadway can be excavated safely, and the old goaf water can be prevented and controlled in accordance with the exploration–excavation–exploration cycle. If anomalous areas are still present, conventional boreholes and geophysical prospecting are used to verify and explore the situation each other again.

Step 6: If the amount of water drained from conventional boreholes in step 5 is stable for a long period of time, the water volume is deemed to have reached a dynamic balance and the water level does not drop, which indicates that dynamic recharge of old goaf water is occurring. At this time, long-distance directional boreholes are used in the low position to intercept the dynamic recharge water. The superimposed areas of water-rich anomalous areas of ground and underground geophysical prospecting are taken as the target area of the directional boreholes, and the position at the end of the conventional boreholes with the largest amount of water outflow is selected as the target spot of the directional borehole. The borehole structure is designed as a six-section arc structure comprising a casing pipe section, straight section, deflecting section, straight section, deflecting section, and straight section, which is drilled along the stable rock layer below the coal seam floor, from the bottom of the old goaf, at a large angle of 10–15°. After drilling into the old goaf, to ensure the safety of borehole and drilling tools, wide-vane spiral drilling tools are used to drill into the old goaf as much as possible. During the process of drainage, proper thru-boreholes can ensure the long-term stable drainage, and mutual verification between geophysical exploration and drilling are used to compare the area changes in strong water-rich anomalous superposition areas. When the water outflow and water pressure of conventional boreholes in the roadway are reduced to 0, geophysical exploration is used again, the results of which are compared with those of other iterations of geophysical exploration, and the drainage effect of old goaf water is analysed to ensure complete drainage. then, the roadway is excavated again. According to the exploration–excavation–exploration cycle, the old goaf water is prevented and controlled until the roadway system is formed. The borehole structure is shown in Fig. 6, the borehole trajectory design is shown in Fig. 7.

3) Technical Advantages

a. This technology realized the interception of the old goaf water with a large drop, long distance, and high precision, while also reducing the requirement for the construction of auxiliary roadways, ensuring the safety of personnel. It also laid out a timeline for the safe excavation of the roadway.
b. This technology realized drainage of the old goaf water ahead of time, and increased the probability of drainage in low-lying positions of the old goaf.
c. The drainage of the old goaf water at low elevations of the mining area ensured free flow with a large drop from high to low positions.
d. The six-section arc borehole structure ensured that directional boreholes were drilled horizontally along the stable strata below the coal seam floor, avoiding the sticking and collapse phenomena caused by the destruction of the old roadway in the lower layer of the coal seam or the destruction of the local coal seam.
e. The overlapping area of the water-rich anomalous area detected by multiple geophysical exploration methods was taken as the target area, and the location at the end of the conventional boreholes with the largest water outflow was selected as the target, which improved the accuracy of the drilling into the dynamic recharge source of the old goaf water.

f. During the period of drainage, the method of mutual verification between geophysical exploration and boreholes was adopted, and the trajectories of conventional boreholes were measured. Further, the drainage effect of old goaf water was constantly compared and analysed, which could ensure that the old goaf water was completely drained.
g. By comparing and analysing the overlapping area of several water-rich anomalous areas combined with the exploration results of boreholes, the recharge laws of dynamic water in old goaf can be analysed.
h. *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018) stipulated that double roadway excavation should be adopted when exploring water in upward sloping roadways, one of which was used to explore and collect water in advance. The other was used to evacuate people safely, but the technology only necessitates the excavation of one roadway, which saves the cost of double roadway excavation.

Advanced Short-distance Exploration Technology

To ensure the safe excavation of roadways in real-time and thoroughly drain the static scattered old goaf water in low-lying areas ahead of the roadway, an advanced short-distance exploration technology was proposed. In this technique, nine boreholes were arranged in each cycle, and the effective detection distance was maintained at 13 m by using small drilling rigs. The shortest borehole length was taken as the effective detection distance, the advanced distance was 5 m, and the excavation distance was 8 m. The borehole design for advanced short distance exploration is shown in Fig. 8.

3 Technology For The Prevention And Control Of Old Goaf Water In The Mining Face

3.1 Full Space Exploration Technology for Geophysical Exploration

After the roadway system was set up, the distribution of the water-rich area in the mining face and the rock of the roof and floor of the coal seam were investigated using audio-frequency electrical penetration in the roadway, and the development of the coal seam and structure were investigated using the radio-wave perspective technology in the mining face.

3.2 Borehole Exploration Technology Based on Geophysical-result Verification

Conventional boreholes for geophysical verification were designed for geophysical water-rich anomalous areas and geological anomalous areas. These boreholes were designed to fully cover the geophysical anomalous areas, and the trajectory must be measured to ensure blind-area exploration has taken place.

3.3 Full Coverage Exploration Technology for Conventional Boreholes

After the formation of the roadway system, a set of boreholes were designed with intervals of 20 m from the initial set-up entry to the terminal line, each group had five boreholes, among which the no. 1 borehole was drilled horizontally along the dip angle of the coal seam to explore the lower-portion old goaf. The other four boreholes were spaced 50 m apart on the plane to explore the upper-portion old goaf, and the roof of the coal seam was used as the final borehole position. The five boreholes ran through the entire mining face to realize full coverage exploration. The geophysical-verification boreholes and full-cover exploration boreholes were designed and constructed simultaneously to make full use of them. The Conventional borehole plan design is shown in Fig. 9, The conventional borehole profile design is shown in Fig. 10.

4 Technology For Prevention And Control Of Old Goaf Water In The Process Of Mining

4.1 Advanced Short-distance Exploration Technology

After the prevention and control of old goaf water in the roadway and mining face were completed, the mining will commence. During the mining period, the drilling rig will be used to conduct advanced short-distance exploration from the coal wall vertically to the mining face to explore the location of old goaf and drain the trace water in the low-lying portion of the old goaf. The single exploration distance was 15 m, the advanced distance was maintained at 5 m, and the mining length was 10 m. The design of the advanced short-distance exploration borehole was cycle A and cycle B. For cycle A, one group of boreholes was designed with intervals of 10 m, and two boreholes were designed for each group. All boreholes were drilled straight ahead, among them, the no. 1 borehole was designed to be drilled to the roof of the coal seam, and the no. 2 borehole was designed to be drilled in front of the coal seam. All boreholes took the shortest borehole depth as the effective detection distance. After the safe mining length reached 10 m, cycle B exploration began. One group of boreholes was designed with an interval of 10 m for cycle B and was interlaced with cycle A at intervals of 5 m, which avoided the formation of blind areas and improved the exploration and mining efficiency. The conventional borehole design for advanced short-distance exploration is shown in Fig. 11.

4.2 Advanced Estimate Technology

Focus is placed on water-rich anomalous areas through geophysical exploration, along with the exposed old goaf roadway. The signs of old goaf permeability, such as sweat hanging on the coal wall and water seepage, were analysed at any time during the process of mining. If seepage signs were detected, mining was ceased immediately, and the drilling rig was used to explore and drain old goaf water in front of the coal wall until all anomalies were eliminated, following which mining was commenced again.

4.3 Roadway Exploration Technique

The complete detection of the mining face was influenced by factors such as borehole density/inclination, and drainage using conventional boreholes in the old goaf roadway may not be able to drain the water completely. Therefore, if the old roadway is exposed during the mining process, the location and water accumulation of the old roadway should be determined to ensure safety. By investigating the old roadway to drain the old goaf water, the hidden danger of old goaf water damage should be mitigated as far as possible.

4.4 Drainage Technology of Dynamic Old Goaf Water

Because of mining, the borehole collapsed and became blocked, resulting in a rise in the water level and water volume, which posed a threat to mining. Therefore, conventional or directional boreholes were constructed to drain old goaf water in the direction of dynamic supply, or steel pipes were buried in the goaf to drain old goaf water, to stop the water level and water volume from rising again.

5 Engineering Applications

The upper layer of the 101 mining face was seriously damaged because of the small-scale old coal mine, and the excavation efficiency of the roadway was low. The system for the prevention and control of old goaf water under conditions of coal mine re-mining was adopted, and the efficient formation and safe mining of the mining face were realized.

5.1 Engineering for the Prevention and Control of Old Goaf Water in the Process of Roadway Excavation

Ground Comprehensive Geophysical Engineering

Before mining took place, three-dimensional seismic and TEM exploration were carried out on the ground, and a large amount of water-rich anomalous area in the mining face was identified, with an estimated water accumulation of 13.8×10^4 m^3 and a water accumulation area of 17.64×10^4 m^2, which accounted for 68.36% of the mining face area.

Engineering for Diversified Comprehensive Prevention and Control of Old Goaf Water in Underground Mine

1) Engineering for the Prevention and Control of Old Goaf Water in the Auxiliary Haulage Roadway

The length of the auxiliary haulage roadway was 1200 m, the excavation time was 1.8 years, and the average excavation efficiency was 1.8 m per day. Multiple geophysical exploration were combined with conventional boreholes and advanced short-distance exploration technology to ensure the real-time safety of the roadway, with a total of 30 iterations of exploration and drainage, the longest lasting 47 days in a single exploration and drainage cycle. The maximum number of boreholes in a single exploration and drainage cycle was 35, and the shortest excavation distance of a single excavation was 5 m (the longest was 70 m). As can be seen in Fig. 2, the distribution of the old goaf in the auxiliary haulage roadway was relatively less, which was consistent with the actual exposure. In the process of excavation, nine lower layered old roadways were exposed, multiple boreholes encountered old goaf and became stuck, the outflow boreholes were few, and the roadway had been safely formed.

2) Engineering for the Prevention and Control of Old Goaf Water in the Haulage Roadway

The length of the haulage roadway of the 101 mining face was 1200 m. It can be seen in Fig. 2 that the water accumulation in the haulage roadway was severe, the excavation time was 2.7 years, and the excavation efficiency was low. The exploration and drainage process for water was conducted 33 times, the longest duration for a single run of exploration and drainage was 7 months, the maximum number of boreholes in a single exploration and drainage cycle was 45, the shortest excavation distance for a single excavation was 5 m (the longest was 70 m), and the maximum rate of water outflow for the conventional boreholes was 108 m^3/h. The haulage roadway encountered old goaf dynamically recharged water at 277 m, and multiple geophysical exploration techniques combined with conventional boreholes were adopted until 440 m. The time spent from 277 m to 440 m was 1.5 years, and the average excavation efficiency was 0.3 m/d. It was clear that the old goaf water severely restricted the excavation efficient of the roadway. The water level and water volume at 440 m of the haulage roadway cannot drop for a long time, therefore, multiple geophysical exploration combined with conventional boreholes and directional boreholes were adopted to prevent and control the old goaf water at 440 m and 658 m, which greatly improved the excavation efficiency.

a. Engineering for the Prevention and Control of Old Goaf Water at 440 m in the Haulage Roadway

The TEM and DC exploration at 440 m of the haulage roadway showed that there was water accumulation in front of the head on the left. Therefore, 21 conventional boreholes were constructed for water exploration and drainage, numbered 1–16 and B1–B5, among which the B5 borehole had the largest amount of water outflow (16.7 m^3/h). Further, there was only a small amount of water seepage in a few boreholes, so it can be inferred that the distribution of the old goaf was scattered and isolated, and their connections were unknown. Within two months, the excavation and drainage of the haulage roadway were stopped, and the total water outflow from the borehole had been stable for a long time (at 36 m^3/h), the water pressure was 0.3 MPa, and the drainage effect was poor. Two months later, TEM and DC were carried out again to compare the drainage effect. The exploration results showed that the strong water-rich area was particularly significant at the front-left, and there were four boreholes in this area, including the B5 borehole. Therefore, it can be determined that the front-left was water-rich; therefore, five conventional boreholes were constructed east of the auxiliary roadway to intercept the old goaf water (B17–B21), and the interception effect was poor. The exploration results at 440 m in the haulage roadway are shown in Fig. 12.

After 6 months of drainage, the no. 1 directional borehole was arranged at a position where the elevation was 34 m lower than the level of the old goaf water. The no. B5 borehole was taken as the target spot, and the strong water-rich anomalous area was taken as the target area. In accordance with the principle of avoiding drilling into coal seams and lower stratified old roadways, the orifice inclination angle was designed to be negative, and the borehole structure was designed as a six-section arc structure. This allowed stable drilling along the sand–mudstone strata below the coal seam floor, which ran obliquely through the old goaf at a large angle from its bottom. This can not only drain the old goaf water in the lower layered old roadway, but also improve the formation rate of the borehole. The no. 1 directional borehole was finally drilled into the old goaf at a depth of 526.4 m, and the initial rate of water outflow was 134 m^3/h, which was much larger than that of the no. B5 borehole. The stable rate of water outflow was 89 m^3/h, and the total old goaf water was 3.6×10^4 m^3. The drainage effect was obviously better than that of conventional boreholes, and a proper thru-borehole can ensure the long-term stable drainage. After 17 days of drainage, the conventional boreholes no longer experienced water outflow and can be excavated safely again, indicating that there was an accumulation area of interconnected old goaf water on the north side of the haulage roadway. Subsequently, it took 6 months to adopt multiple geophysical exploration combined with conventional boreholes to safely excavate to 658 m, with an average excavation efficiency of 1.2 m/d. This efficiency exhibited an increase of 4 times, which showed that the directional borehole was successfully drilled to the bottom of the old goaf and effectively intercepted the old goaf water. The directional boreholes information is shown in Table 1.

b. Engineering for the Prevention and Control of Old Goaf Water in Ground Geophysical Anomalous Areas

According to the results of three-dimensional seismic and TEM exploration, in combination with experience regarding the control of old goaf water in haulage roadways, it was considered that dynamic recharge of the old goaf water took place in the northeast of the mining face. At low positions, the no. 2 directional borehole was arranged along the sand–mudstone strata below the coal seam floor to drill into the geophysical anomalous area, and the final borehole depth was 585 m (Table 1). The initial rate of water outflow was 65 m^3/h, and the total old goaf water was 3.93×10^4 m^3 (Fig. 2). No. 4 and no. 4-1 Directional boreholes were also designed to explore geophysical anomalies in advance at low levels, and all of them were drilled into the old goaf, but there was no stagnant water in the goaf (Fig. 2, Table 1).

c. Engineering for the Prevention and Control of Old Goaf Water at 658 m in the Haulage Roadway

The underground TEM exploration of the haulage roadway at 658 m showed that there was a large areas of old goaf water in front of the head on the left and right sides of the roadway, within the anomalous area of geophysical exploration, there were 28 boreholes for conventional exploration and drainage. There were nine boreholes with water, among which the maximum rate of water outflow in the no. 8 borehole was 108 m^3/h, and after 15 days of drainage, the rate of water outflow attenuated to 50 m^3/h. Seventeen conventional boreholes were constructed on the left side. There were two boreholes with water, among which the maximum rate of water outflow in the no. 4 borehole was 68.85 m^3/h, and the rate of water outflow in the no. 8 borehole was suddenly reduced to 0.6 m^3/h, showing that the no. 4 borehole can effectively intercept the dynamic recharge water for the no. 8 borehole. The initial rate of water outflow for the no. 17 borehole (on the right) was 78 m^3/h, which continued to supplement the other boreholes and speed up the process of water drainage, after 8 days of drainage, the rate of water outflow reduced to 0.2 m^3/h; the analysis showed that there was no connection between the water accumulation area of the old goaf in front of the right side and that on the left side, which was in an isolated island state. Using conventional borehole verification, it was found that only a small amount of water in the old goaf remained in the low-lying position, in an unpressurized and self-flowing state, 80 m away from the roadway side. It had no effect on the excavation. The exploration results at 658 m in the haulage roadway are shown in Fig. 13.

After 20 days of drainage, the rate of water outflow from the no. 4 conventional borehole did not decrease, so the no. 4 conventional borehole located in the geophysical water-rich anomalous area was taken as the target spot, and the no. 1 geophysical water-rich anomalous area was taken as the target area. Particularly at lower elevations, the no. 3 directional borehole was designed to steadily drill along the sand–mudstone strata below the coal seam floor to the low-lying area of the old goaf to intercept the old goaf water, with a borehole depth of 699 m and water outflow of 67 m^3/h (Table 1). At this time, the rate of water outflow from no. 4 conventional borehole was suddenly reduced to 0.1 m^3/h. After 5 days of drainage, TEM and DC exploration were carried out again, and it was found that the area of the no. 1 geophysical anomalous area was significantly reduced (by 63%), indicating that the directional borehole had achieved very good results in intercepting old goaf water at low positions. At the same time, the no. 3 geophysical anomalous area had disappeared, and it was verified once again that the stagnant water area was of the isolated island type and was easy to release. However, the no. 2 geophysical water-rich anomalous area was detected in front of the roadway, and then verified by a number of conventional boreholes, all of which did not come out of the water. To speed up the drainage progress of the no. 1 water-rich abnormal area, branch 3-1 and 3-2 boreholes were constructed in the no. 3 directional borehole, all of which were drilled into the old goaf, with borehole depths of 690 m and 741 m, respectively, and a water outflow of 63 m^3/h and 73 m^3/h, respectively (Table 1). The analysis showed that the space at the front-left of the old goaf was narrow and continuous, and after 15 days of continuous drainage, all conventional boreholes had no water outflow and could be excavated safely again. A total of 4.53×10^4 $m^3$of the old goaf water was drained from the no. 3 directional borehole, and it took 44 days to explore and drain the water there. After using the no. 3 directional borehole to prevent and control the old goaf water, it took 5.6 months to complete the haulage roadway by using multiple geophysical exploration combined with conventional boreholes. The average excavation efficiency was 2.6 m/d, which represented an increase of 9 times.

3) Engineering for the Prevention and Control of Old Goaf Water in the Initial Cut off the Set-up Entry

The length of the initial cut off the set-up entry was 215 m. Fig. 2 shows that the water disaster in the north-eastern portion of the initial cut off the set-up entry was severe. During the process of excavation, multiple geophysical exploration combined with conventional boreholes were adopted, with a total of nine iterations of water exploration and drainage. The average distance for a single exploration was 21 m, and the total excavation time was nine months. The average excavation efficiency was 0.8 m/d, the excavation speed was very slow, the longest time for a single exploration and drainage was 34 days, and the maximum number of boreholes for a single exploration and drainage cycle was 58. The shortest excavation distance was 6 m and the longest was 50 m for a single exploration and drainage, and the maximum rate of water outflow from a single borehole was 20 m^3/h. In the process of excavating the initial cut off the set-up entry, it was found that there was dynamic recharge of old goaf in the north-eastern direction, and the no. 5 directional borehole was specially designed for long distances and large drops to intercept the old goaf water (Table 1). However, the borehole was drilled into the coal seam at a location of 600 m, resulting in a sticking accident, resulting in a serious efficiency drop for excavation.

The TEM and DC exploration at the intersection of the haulage roadway and the initial cut off the set-up entry showed that there was an anomalous area in the north-eastern direction. Therefore, 17 conventional boreholes were arranged in this direction, and two boreholes run water, of which the no. +8 borehole had a flow rate of 71.3 m^3/h and the no. +4 borehole had a flow rate of 53 m^3/h (Fig. 2). The water accumulation area in the old goaf was about 20 m from the initial cut off the set-up entry, and the water volume was not attenuated after one month of drainage. Therefore, the no. +8 borehole – with the largest water outflow capacity – was taken as the target spot, the geophysical water-rich anomalous area was taken as the target area, and the long-distance directional borehole at a lower elevation was used to intercept the old goaf water. The no. 6 directional borehole was specially designed to steadily drill along the sand–mudstone strata below the coal seam floor to the low-lying area of the old goaf to intercept the old goaf water (Table 1). Finally, the borehole depth was 670 m and the rate of water outflow was 40 m^3/h. At this time, the rate of water outflow for the no. +8 borehole was suddenly reduced to 13 m^3/h, and the rate of water outflow from the no. +4 borehole was suddenly reduced to 0. Because the no. 6 directional borehole could drain the old goaf water about 39.25×10^4 m^3, the safe excavation of the roadway was ensured. The plane distance between the no. 5 and no. 6 directional boreholes was only 50 m, but the no. 5 borehole entered the coal seam and the no. 6 borehole entered the old goaf, which showed that connections within the old goaf were complex and the distribution was disorderly.

5.2 Engineering for the Prevention and Control of Old Goaf Water in the Mining Face

According to the data available for the small-sacle old coal mine and underground exploration, it was considered that the height of the old roadway was 2.2 m, and there was generally the recharge of sandstone fissure water in the roof and the residual production water in the goaf. Therefore, there may be ‘isolated island’ static old goaf water in the mining face. To ensure safe mining, it was necessary to fully cover the old goaf water inside the mining face.

Audio-frequency electric perspective and radio-wave perspective detection of the roof and floor were carried out in the haulage roadway and auxiliary haulage roadway. The detection length was 1200 m, and the results shown that there were two strong water-rich anomalous areas in the upper layer, along with one fault and three old goaf areas in the mining face.

According to the detection results for the water-rich anomalous area, 37 conventional boreholes were designed and constructed in the haulage roadway, including nine boreholes in the lower-layer old goaf, 23 boreholes in the upper-layer old goaf, and five boreholes in the roof sandstone, further, 18 conventional boreholes were designed and constructed in the auxiliary haulage roadway.

In view of the geological anomalous areas, 43 groups of geological exploration boreholes were designed and constructed in the haulage roadway – each group was 20 m apart. Considering the exploration results, there were 3–4 boreholes in each group, and the maximum length of the designed borehole plane was 200 m. Fifty-one groups of boreholes were designed and constructed in the auxiliary haulage roadway, with one borehole in each group. The plane length of the designed boreholes was generally 30 m. Two groups of boreholes were designed and constructed in the initial cut off the set-up entry, with four boreholes in each group, and the maximum length of the designed borehole plane was 100 m. These geological boreholes fully covered the exploration area of the mining face and provided a geological guarantee for safe mining through the old goaf. The boreholes trajectory of the 101 mining face are shown in Fig. 14.

5.3 Engineering for the Prevention and Control of Goaf Water in the Process of Mining

During the process of mining, the advanced short-distance exploration was carried out stringently, and the mining reached lengths of 61 m and 347 m. Advanced short-distance exploration found that the old goaf stagnant water was left in low-lying areas in front of the coal wall, and advanced short-distance exploration boreholes were added to ensure safe mining. Owing to the mining process, on the rock strata of the roof and floor, the destruction phenomenon of ‘three zones above coal seams’ appears. To ensure that the no. +8 borehole – at the intersection of the haulage roadway and the initial cut off the set-up entry – had long-term stable drainage of dynamic recharge water, the seamless steel pipe was buried here and extended to the outside of the roadway. After 13 months of mining, the rate of water outflow from the seamless steel pipe was still about 30 m^3/h. At present, the mining face has been safely mined to 850 m and 1.37 Mt of coal resources have been liberated.

Discussion

Significantly positive results have been achieved by using directional boreholes at low levels in the mining area to drain the dynamic recharge water of old goaf. However, this was a passive technique, and the gap in the old goaf water in the upper portion of the same coal seam was limited. Based on the prevention and control of water inrush from Ordovician limestone strata with horizontal directional drilling technology, the teams of Professor Dong Shuning put forward a model that used comb directional boreholes with branch boreholes in the lower unmined no. 10 coal seam, and arranging the main boreholes in the stable strata of the no. 10 coal seam roof. Combined with TEM detection in boreholes, laser and sonar detection in the goaf, and three-dimensional seismic tomography technology in the coal mine could actively prevent and control old goaf water in the upper portion of the no. 2 coal seam. It is understood that the old goaf water is safely drained in advance, and the mode of prevention and control of roadway excavation is transformed into regional and active prevention and control. This can guarantee the accuracy and efficiency of exploration and prevention. It can also realize the exploration of the old goaf, separate exploration and mining engineering, avoid mutual interference, and lay the foundation for transparent mining in the mining face. This will be the focus of our follow-up research, and we will continue to study the prevention and control of water disasters in coal mines. The borehole trajectories of regional and active prevention and control of old goaf water in the upper portion of the no. 2 coal seam are shown in Fig. 15.

Conclusions

The recharge laws governing old goaf dynamic water can be ascertained by using the technique of multiple geophysical exploration both on the ground and underground, in combination with conventional boreholes and directional boreholes. The proposed technique realized the advanced, efficient, safe, accurate, large-gap, and long-distance interception of dynamic recharge water in old goaf, which improved the excavation efficiency, effectively mitigating the need for construction of auxiliary roadways and invalid boreholes, saved the cost of a double roadway, and ensured safe mining.

The long-distance directional borehole was arranged in the stable rock strata at the lower part of the coal-seam floor. The borehole structure was designed as a six-section arc structure, which effectively mitigated the risk of drilling into the lower portion of the old goaf roadway, ensuring an adequate formation rate of the borehole, and improving *The Detailed Rules for Water Disaster Prevention and Control of Coal Mine* (NCMSA 2018).

The advanced geophysical exploration and drilling technique cannot be used as the only means for the prevention and control of old goaf water. The improved system for the prevention and control of old goaf water in roadway excavation, mining face interiors, and the mining process ensured the safe mining of the 101 mining face, and realized the real-time safety of the entire space of the mining face, allowing the safe mining of 1.37 Mt of coal.

Declarations

Acknowledgements

This work was financially supported by National Key R&D Program of China (Grant No. 2017YFC0804102), and the Shaanxi Key Laboratory of Preventing and Controlling Coal Mine Water

Hazard. The authors would like to express sincere thanks to the reviewers for their thorough reviews and valuable advice.

References

1. Cui FP, Wu Q, Lin YH, Zeng YF, Zhang KL (2018a) Damage Features and Formation Mechanism of the Strong Water Inrush Disaster at the Daxing Coal Mine, Guangdong Province, China. Mine Water Environ 37:346–350
2. Cui FP, Wu Q, Zhang S, Wu NG, Ji Y (2018b) Damage Characteristics and Mechanism of a Strong Water Inrush Disaster at the Wangjialing Coal Mine, Shanxi Province, China. Geofluids https://doi.org/10.1155/2018/3253641
3. Cui FP, Wu Q, Zhao SQ, Sun WJ (2014) Major characteristics, categories and control technique of coal mine water disaster in China. Ener Educ Sci Tech A 32(5):3747–3760
4. Dong SN, Zheng LW, Tang SL, Shi PZ (2020) A scientometric analysis of trends in coal mine water inrush prevention and control for the period 2000–2019. Mine Water Environ 39:3-12
5. Li PY (2018) Mine water problems and solutions in China. Mine Water Environ 37:217-221
6. Li XL, Dong SN, Liu KD (2021) Prevention and Control of Water Inrushes from Subseam Karstic Ordovician Limestone during Coal Mining above Ultra-thin Aquitards. Mine Water Environ. https://doi.org/10.1007/s10230-021-00765-3
7. Liu CY, Yang JX, Wu FF (2015) A proposed method of coal pillar design, goaf filling, and grouting of steeply inclined coal seams under waterfilled strata. Mine Water Environ 34(1):87–94.
8. Mou L, Dong SN, Zhou WF, Wang W, Li A, Shi ZY (2020) Data Analysis and Key Parameters of Typical Water Hazard Control Engineering in Coal Mines of China. Mine Water Environ 39:331-344
9. NCMSA (National Coal Mine Safety Administration) (2018) The Detailed Rules for Water Disaster Prevention and Control of Coal Mines. Coal Industry Publishing House of China, Beijing, pp 62–63 (in Chinese)
10. Soltani S, Hezarkhani A (2013) Proposed algorithm for optimization of directional additional exploratory drill holes and computer coding. Arab J Geosci 6(2):455–462.
11. Su BY, Malekian R, Yu JC, Feng XH, Liu ZX (2016) Electrical anisotropic response of water conducted fractured zone in the mining goaf. IEEE Access 4:6216–6224.
12. Sun WJ, Wanfang Zhou WF, Jiao J (2016) Hydrogeological Classification and Water Inrush Accidents in China's Coal Mines. Mine Water Environ 35:214-220
13. Vutukuri VS, Singh RN (1995) Mine inundation-case histories. Mine Water Environ 14(9):107–130
14. Wang P, Wang Q, Wang Y, Wang C (2020) Detection of Abandoned Coal Mine Goaf in China's Ordos Basin Using the Transient Electromagnetic Method. Mine Water Environ. https://doi.org/10.1007/s10230-020-00724-4
15. Xue YG, Li SC, Su MX, Li HY, Tian H (2013) Response and test of whole space transient electromagnetic field in mine goaf water. Appl Mech Mater 353-356:1136–1139.

16. Xue, GQ, Chen W, Cheng JL, Liu SC, Yu JC, Lei KX, Guo WB, Feng XH (2019), A review of electrical and electromagnetic methods for coal mine exploration in China. IEEE Access, 7:177332-177341
17. Yang C, Liu SD, Wu RX (2017) Quantitative prediction of water volumes within a coal mine underlying limestone strata using geophysical methods. Mine Water Environ 36:51–58
18. Yao NP, Zhang J, Li QX, Song YB, Liu RQ, Li H (2013) Tracing design and control technology of directional drilling borehole in underground mine. Coal Sci Technol 41(3):7–11 46 (in Chinese)

Figures

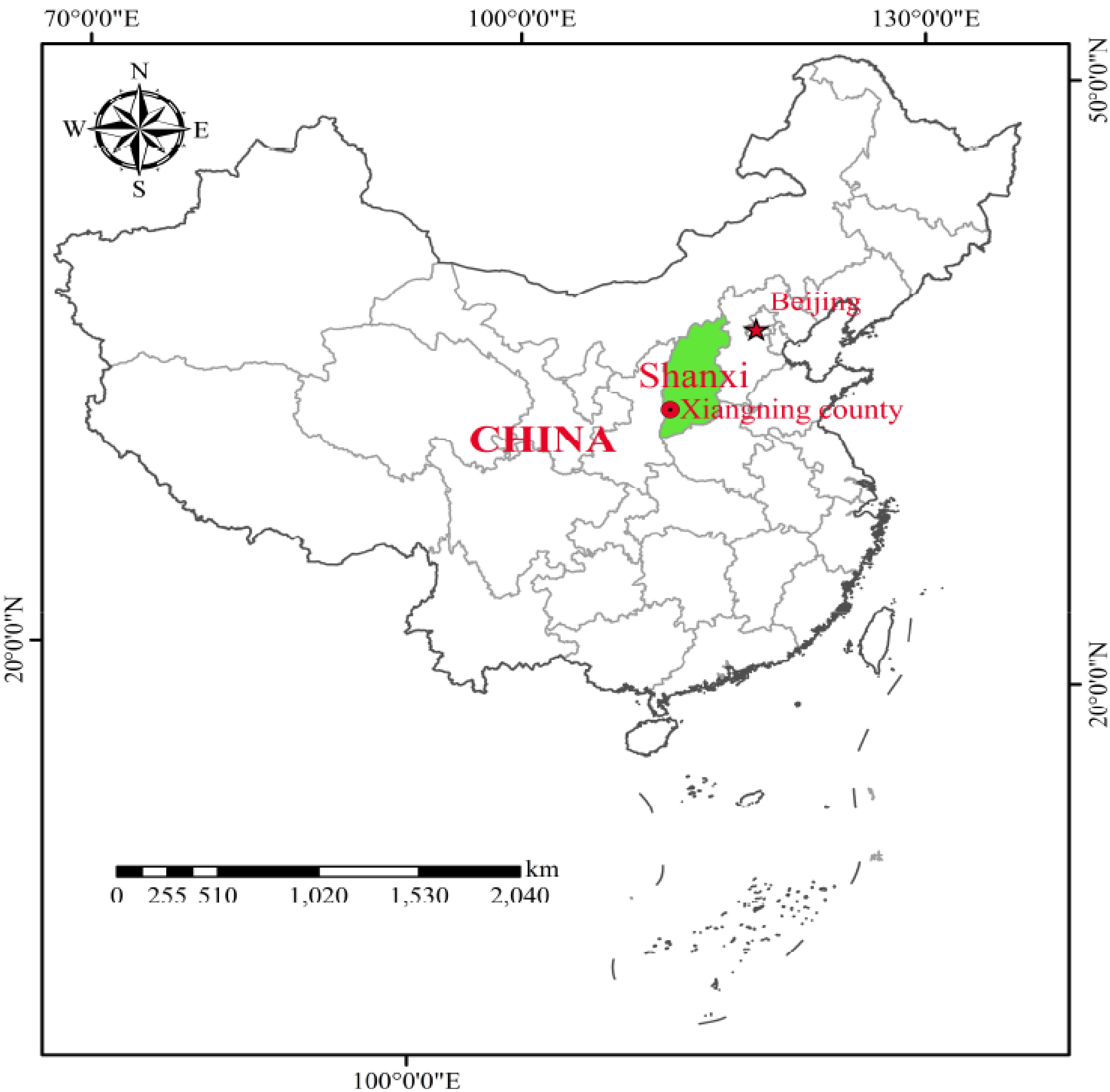

Figure 1

Location of the coal mine Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

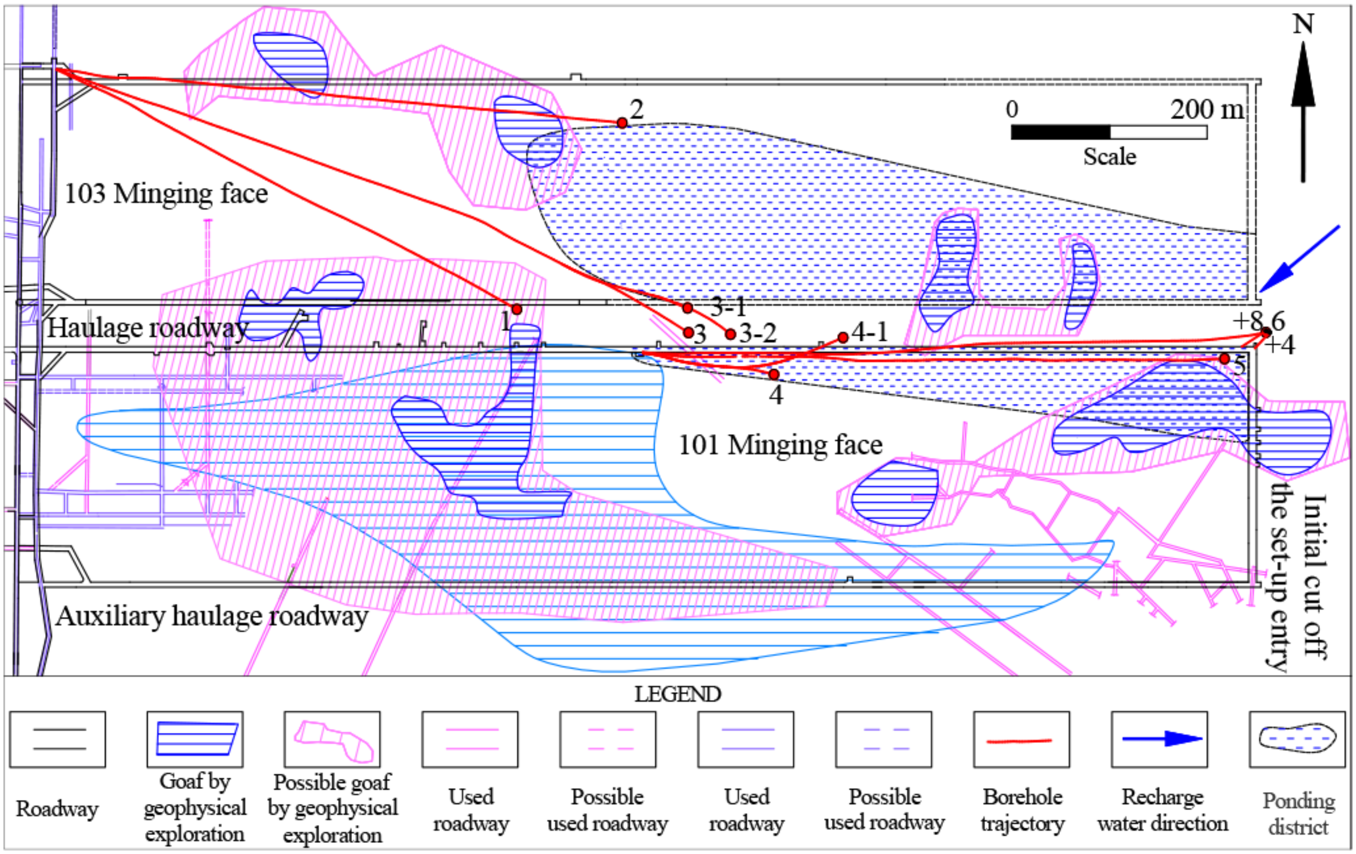

Figure 2

Distribution of old goaf water

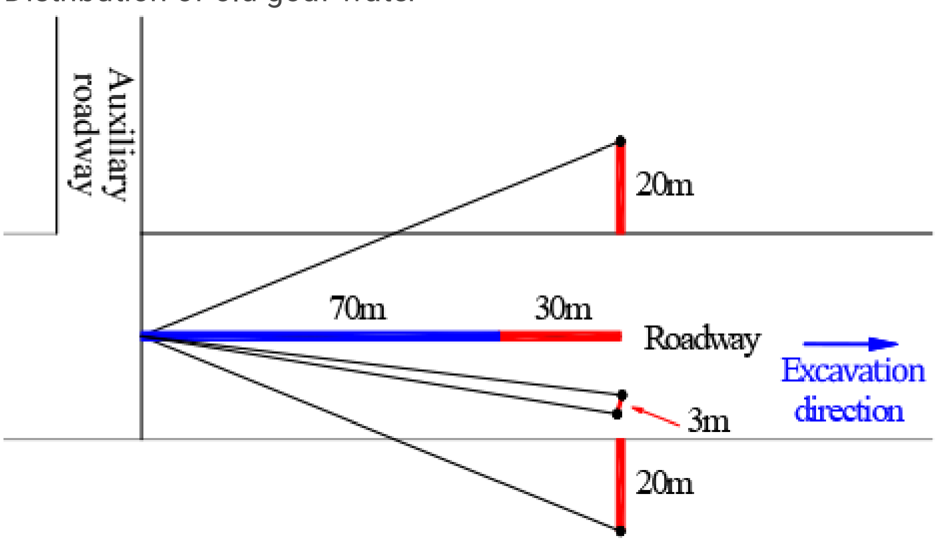

Figure 3

Conventional borehole design for exploration and drainage

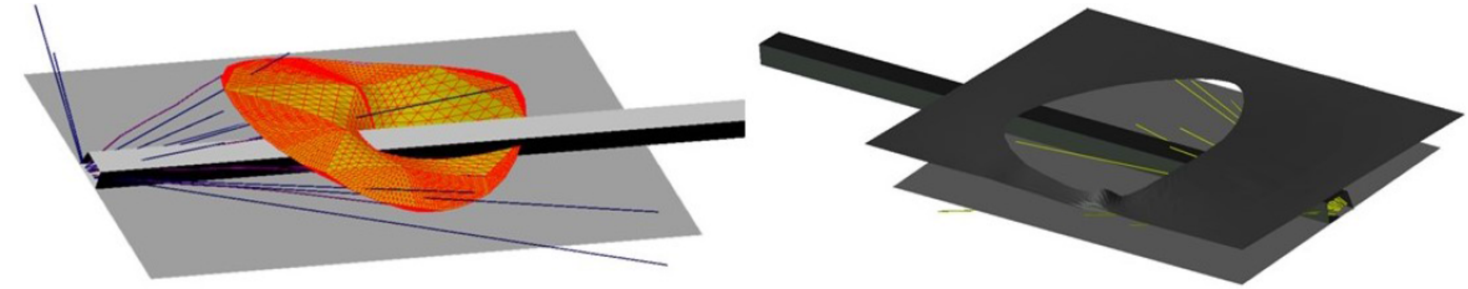

Figure 4

3D diagrams of borehole trajectory, roadway, roof and old goaf

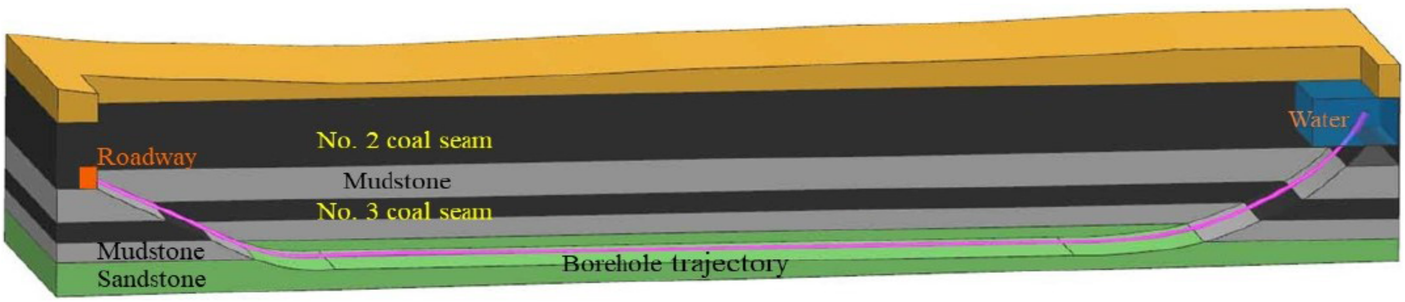

Figure 5

Schematic of directional borehole for exploration and drainage

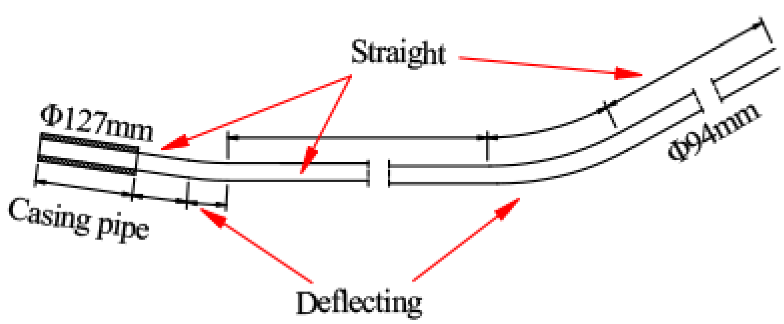

Figure 6

Borehole structure

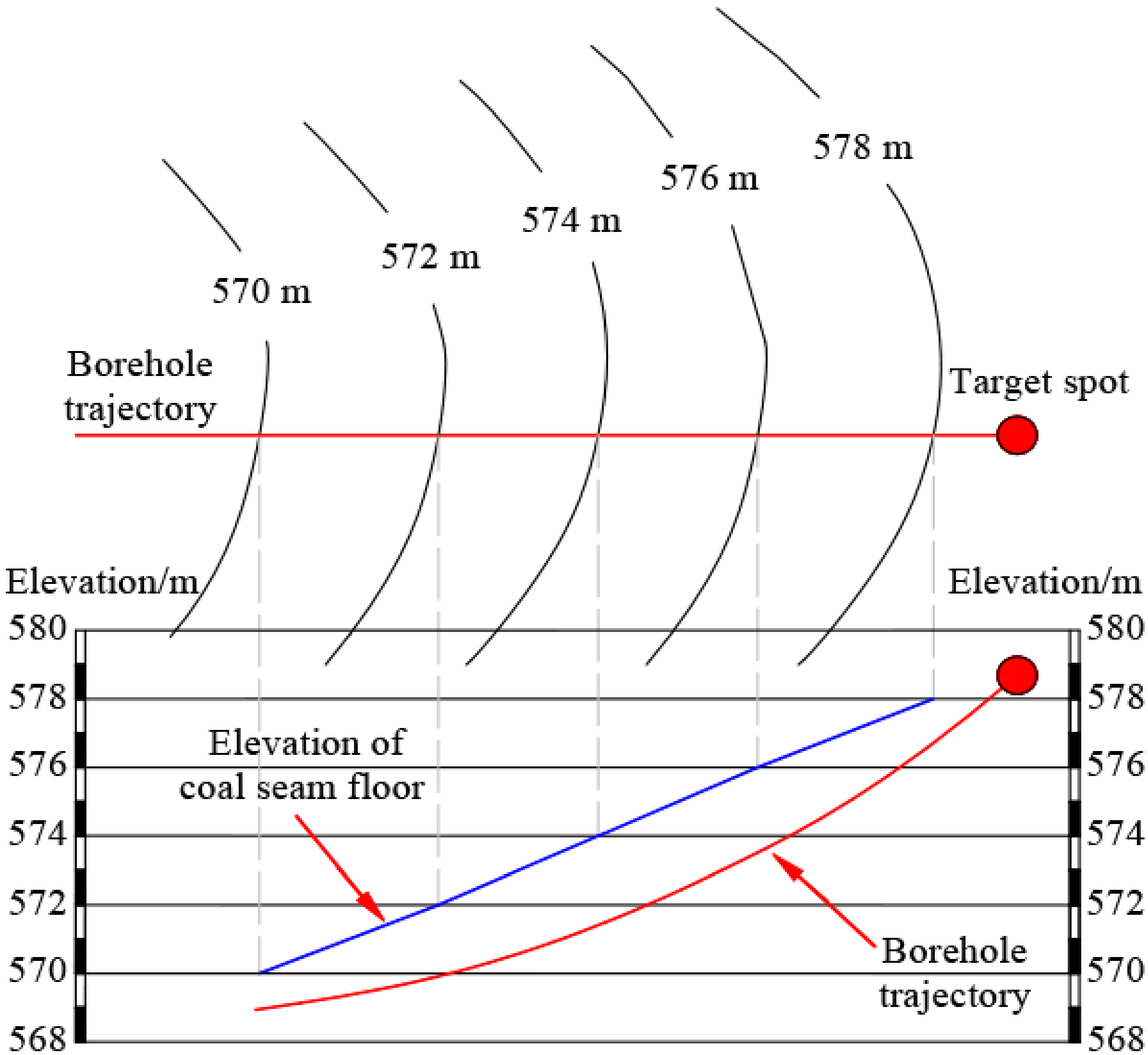

Figure 7

Borehole trajectory design

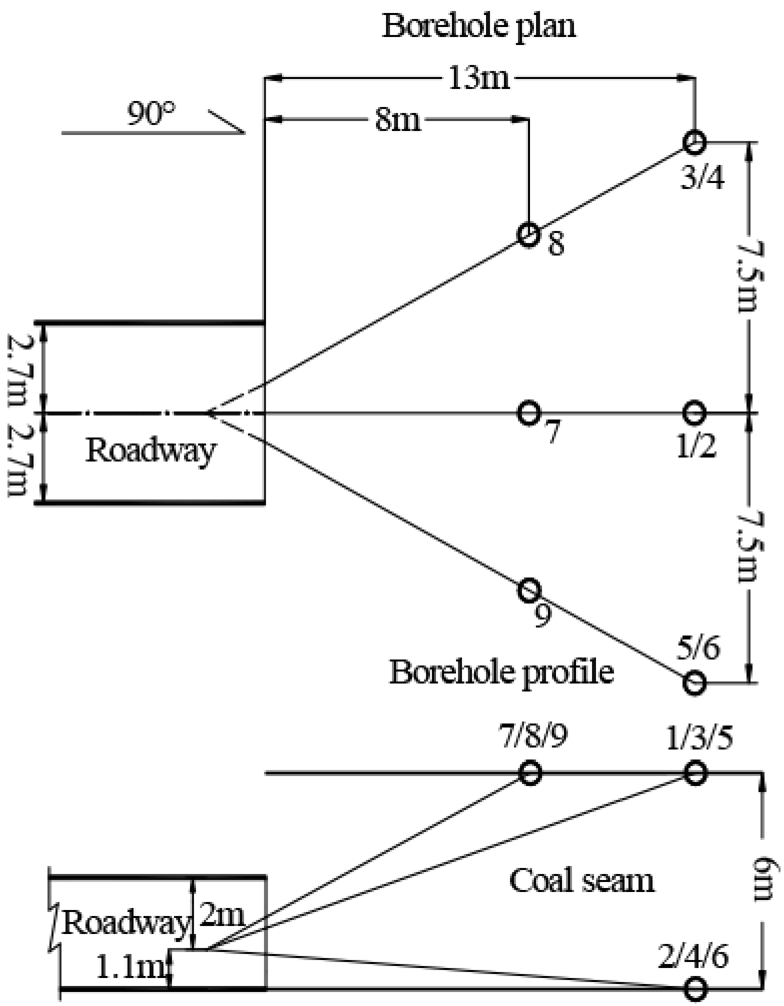

Figure 8

Borehole design for advanced short-distance exploration

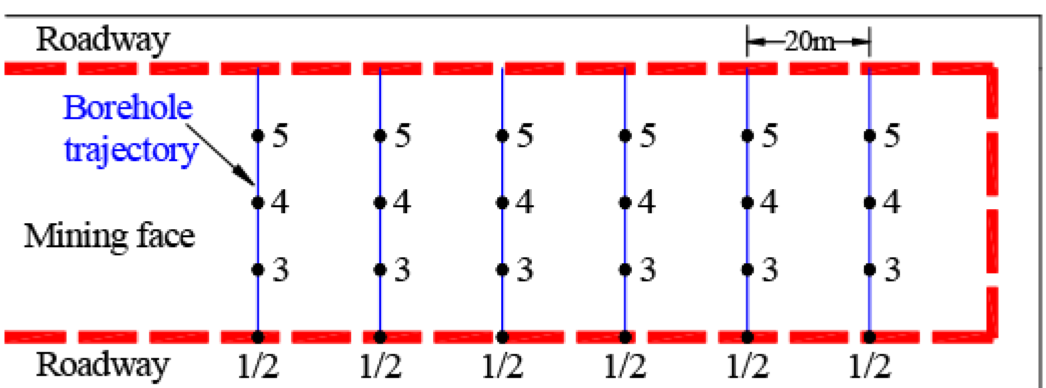

Figure 9

Conventional borehole plan design

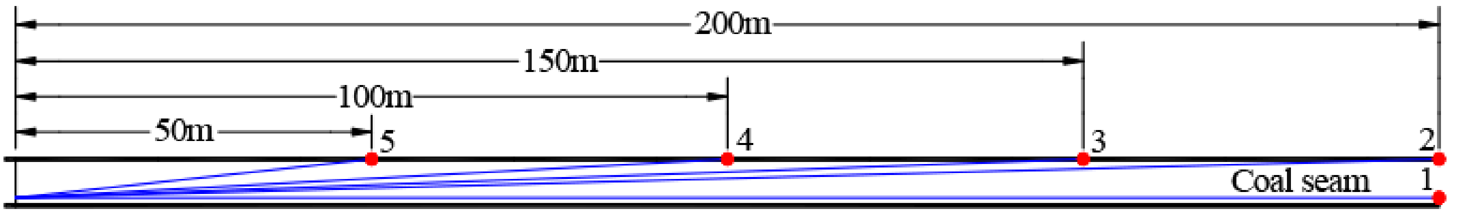

Figure 10

Conventional borehole profile design

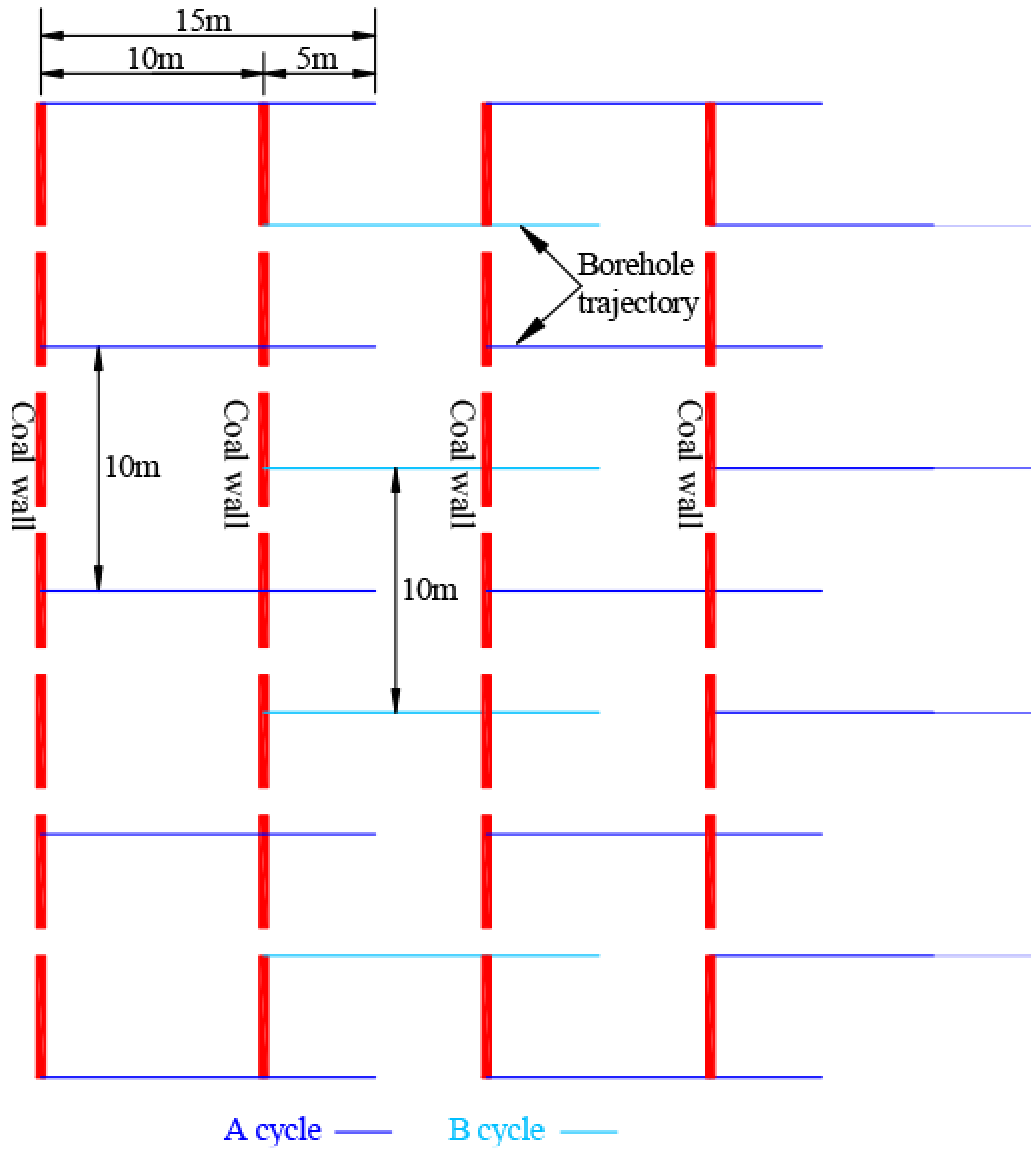

Figure 11

Conventional borehole design for advanced short-distance exploration

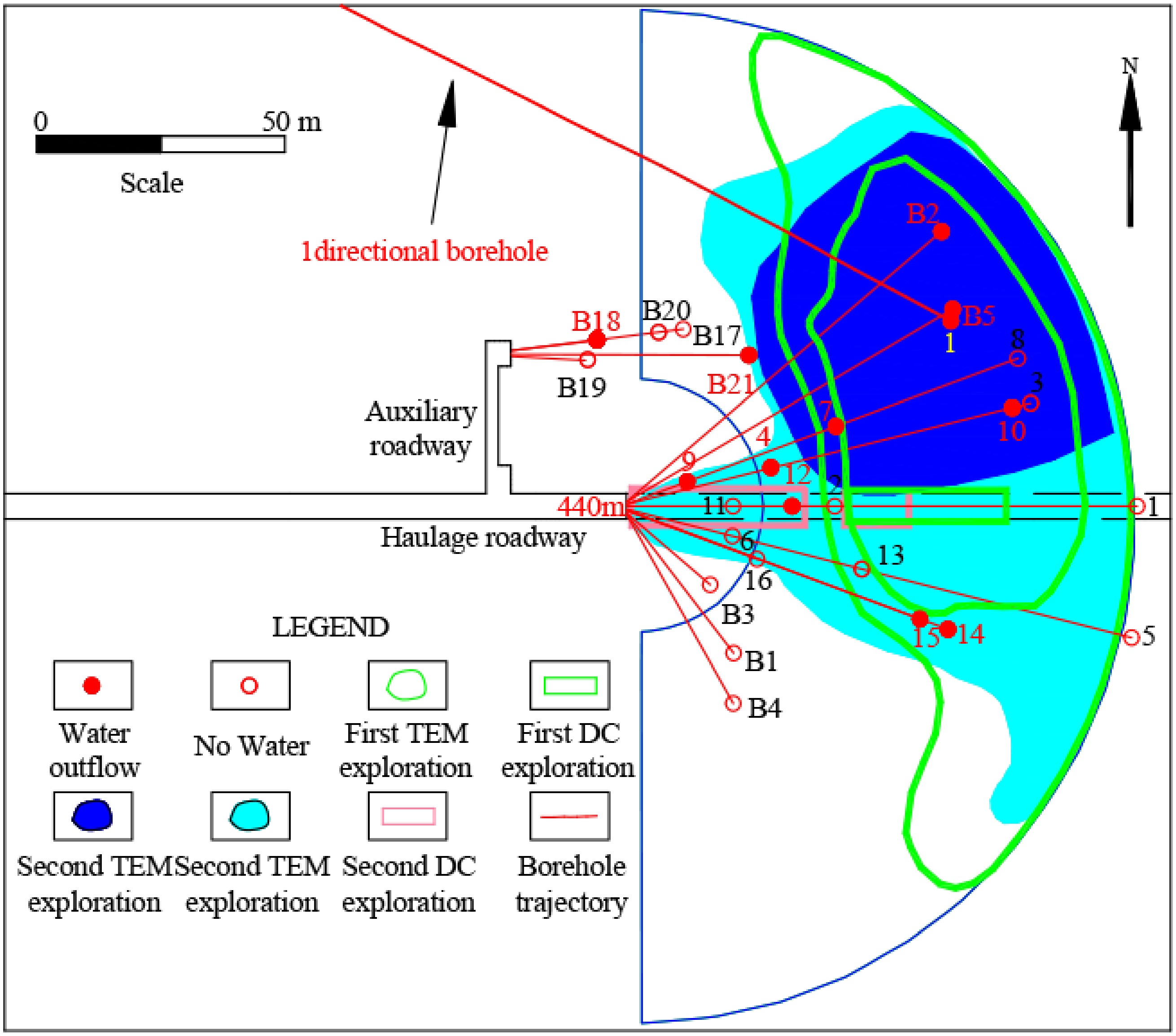

Figure 12

Exploration results at 440m in the haulage roadway

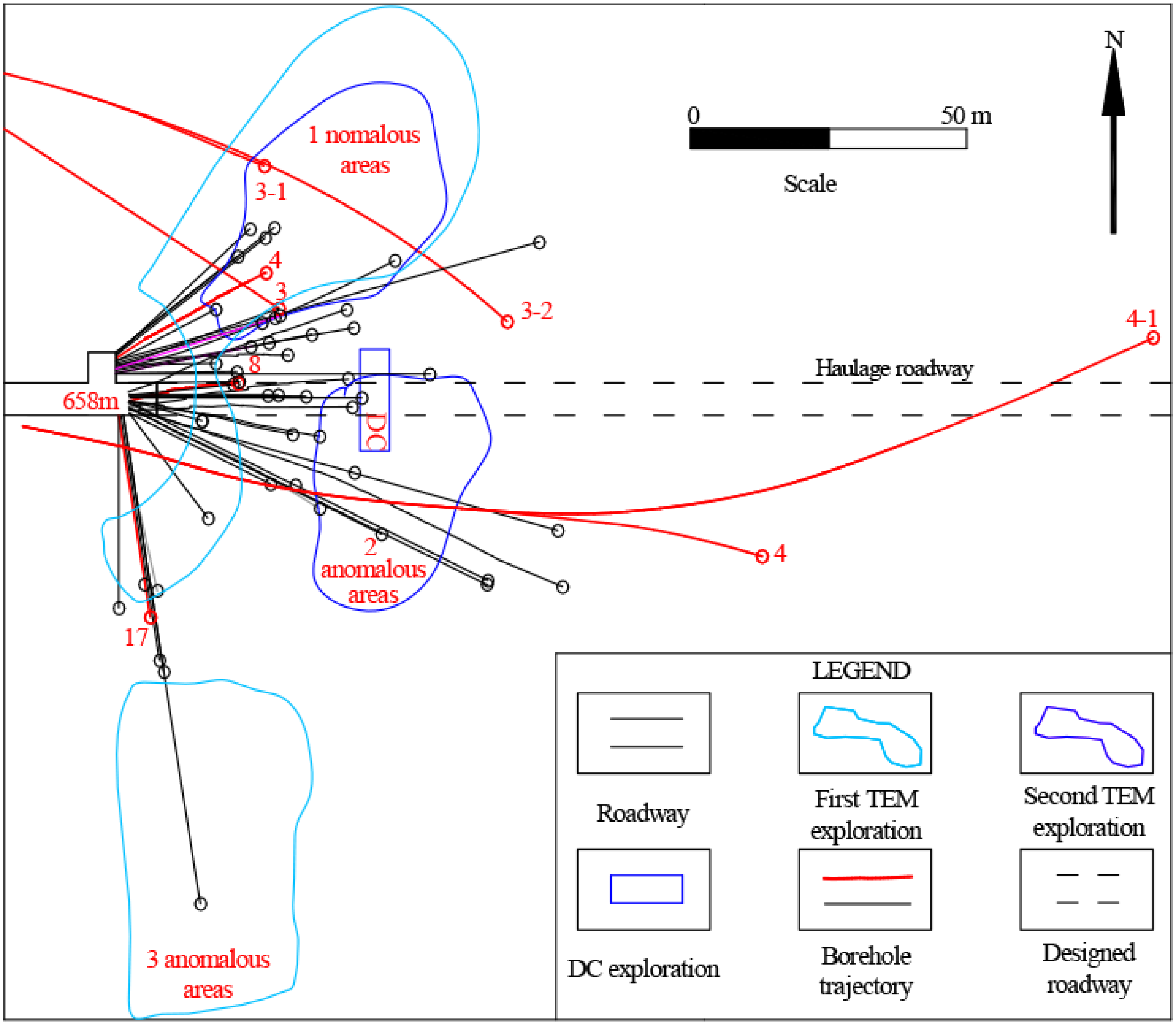

Figure 13

Exploration results at 658m of the haulage roadway

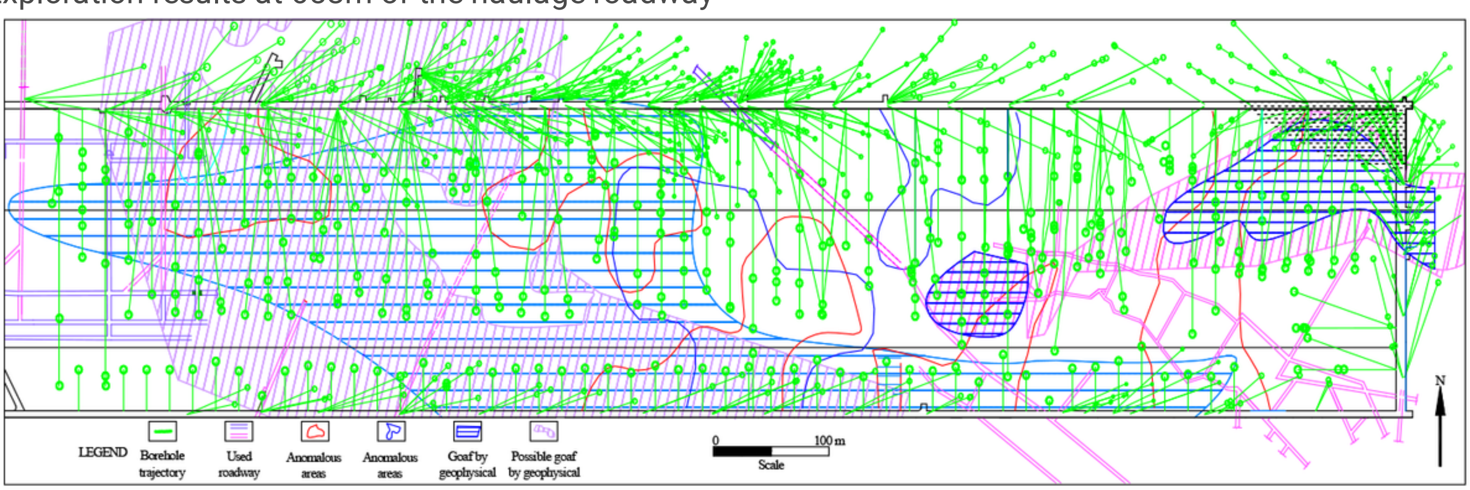

Figure 14

The boreholes trajectory of the 101 mining face

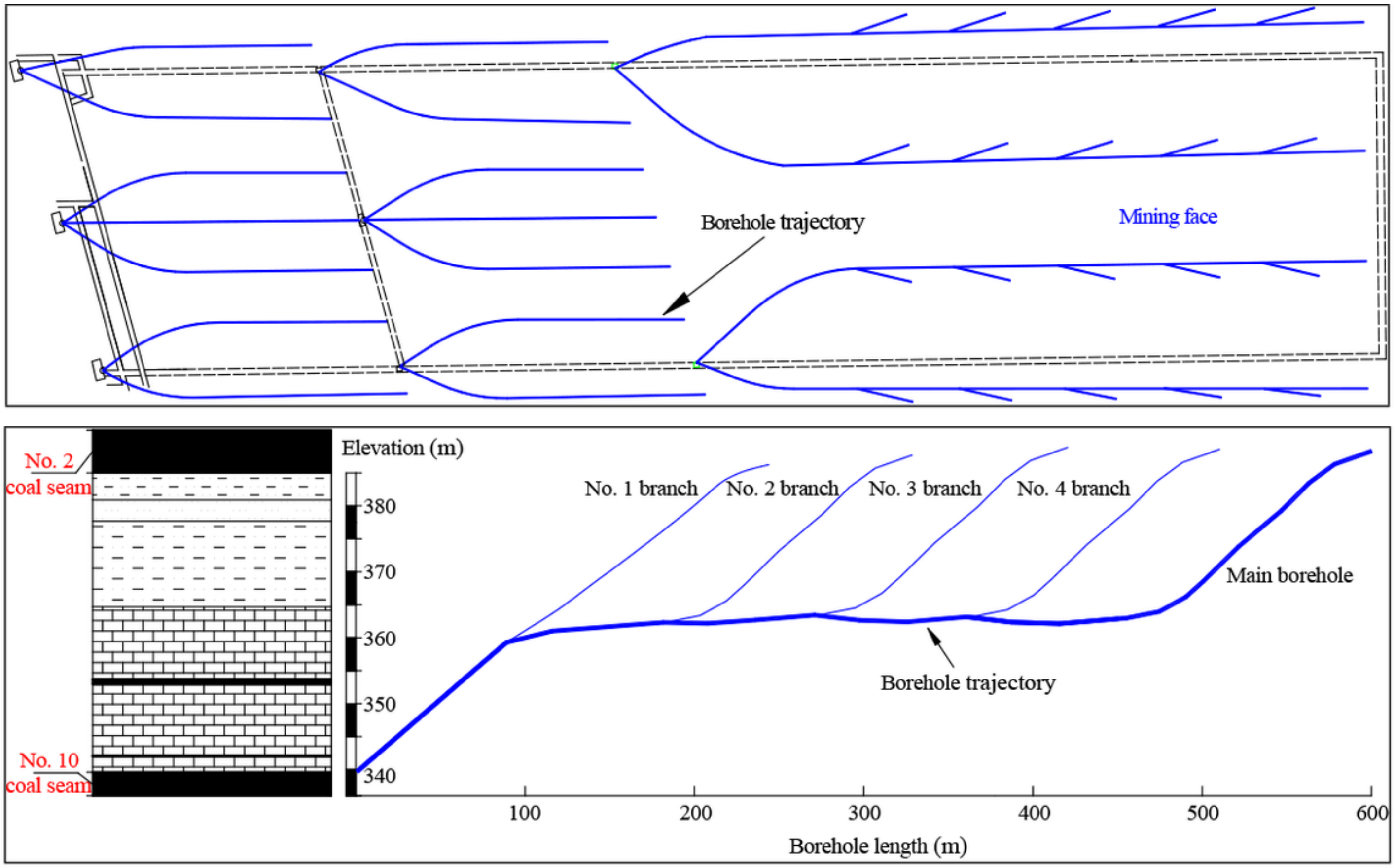

Figure 15

The borehole trajectories of regional and active prevention and control of old goaf water in the upper portion of the no. 2 coal seam