Assessment and Grouting of Water Inrush Induced by Shaft-Freezing Holes in the Yingpanhao Coal Mine, Inner Mongolia, China

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Abstract

To better understand water inrushes originating from shaft-freezing holes, the hydrogeological conditions and water source were analyzed for a typical inrush case in the Yingpanhao coal mine in western China. The mechanism of this new type of water inrush was identified by considering the stratum movement caused by mining, the concentric annular channels of freezing holes, and the dynamic recharge of multiple aquifers. A new risk assessment model and corresponding grouting method were developed and the problems involving the prediction of water inrush and selection of the optimum grouting position were described. Detailed guidelines for grouting, including the layout of injection boreholes, slurries, grouting pressure and stopping criteria, were proposed. A grouting case targeting this type of water inrush in the Yingpanhao coal mine was introduced. Field studies indicated that open, concentric annular freezing hole channels provide favorable conditions for groundwater migration. The proposed method may effectively inhibit groundwater migration in multiple aquifers and prevent water inrushes through shaft freezing holes and provides an appropriate framework for water inrush prevention for similar mining areas in western China.

Introduction

With the exhaustion of coal resources in eastern China, the focus of coal mining has shifted to central and western areas, such as the Ordos region. Compared to eastern mining areas, western mining areas mainly exploit Jurassic coal seams. Overlying strata with shallow alluvial deposits, poor cementation, low strength, and multiple water-rich aquifers are widely distributed (Xue et al. 2020), which causes severe challenges in constructing large-diameter shafts. The freezing method has been widely used to in western areas to ensure safe shaft construction (Afshani and Akagi 2015; Cai et al. 2019; Han et al. 2021, 2020; Russo et al. 2015; Wu et al. 2021b; Zhang et al. 2019; Zheng et al. 2015, 2021a). The freezing process involves circulating low-temperature materials through freezing holes surrounding the design shaft to absorb heat and freeze the surrounding rock mass during the shaft excavation (Wu et al. 2015; Zhang and Ping 2012). The freezing method has great advantages in complicated and unique strata; it artificially controls the shape and range of the frozen body, effectively freezes flowing groundwater, and protects water resources.

However, after the excavation and construction of underground infrastructure are completed, the strata are allowed to thaw. Water disasters induced by shaft freezing holes have occurred in Inner Mongolia, Ningxia, Shaanxi, and other western areas (Guo et al. 2019; Wang et al. 2020; Wu et al. 2015, 2021a; Zheng et al. 2015; Zhou et al. 2017). Based on previous studies, the problems are generally one of two types: (1) Type I. Exposure of the concentric annular channels (CACs), the concentric gap between the freezing pipe and freezing hole wall. During the construction of wellbore

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subsidiary structures, such as the in-gate and mine roadway, direct exposure of the CAC may allow groundwater to rush in from an aquifer to the bottom of the roadway. These inrushes are rapid, high flow events and can even cause the surrounding rock to collapse due to the high water pressure (Wang et al. 2016; Zhang et al. 2019; Zhou et al. 2017). (2) Type II. During the freezing and thawing process of a formation, the internal pore water condenses into ice, thus producing a very high frost heaving force acting on the pore walls. Its force can far exceed the tensile strength of the rock, resulting in expansion of the fracture network and damage to the surrounding rock (Fan et al. 2019; Song and Zheng 2012; Wang and Zhou 2018; Yong et al. 2020). When the freezing holes and shaft lining are connected by this fracture network, a small amount of groundwater inflow may occur, originating from the shaft lining as a spray. Moreover, if the water damage is not treated in time, the flow of underground water and continuous softening of the rock mass can eventually cause a large water inrush, such as occurred in the Bayangaole and Menkeqing coal mines (Mu et al. 2020).

Generally, researchers and engineers have focused on the abovementioned types of water damage originating from shaft freezing holes (Bezuijen et al. 2011; Ge et al. 2020; Qian et al. 2018; Yao et al. 2019; Zhang et al. 2019) and a number of preventive methods has been proposed. The main techniques include perforating and grouting (PG), back-filled grouting (BFG), and an annular water-intercepting roadway (AWR). The PG uses the well perforation method commonly applied in the field of petroleum exploration. The freezing holes are then grouted using channels established with a high-energy jet (Shen et al. 2017). Although this method completely seals the freezing holes, it must be implemented from the surface. BFG is a point-to-point control method (Ye et al. 2009, 2019; Zheng et al. 2021b). If new fractures are generated by the hydrostatic pressure and mining disturbance, a complex process is required to repeatedly grout and seal any new channels. When AWR is used, an annular belt is built around freezing holes, so that the holes are cut and sealed (Zheng et al. 2015).

However, less research attention has been focused on water inrush or inflow induced by hidden water inrush channels originating from shaft freezing holes, which indirectly increases the cost of drainage in coal mines and causes water damage. In this paper, a case study in the Yingpanhao (YPH) coal mine is presented to assess and prevent this new type of water inrush disaster. The main objectives include:

- Describing the mechanism of the new type of water inrush disaster induced by hidden channels originating from shaft freezing holes.
- Proposing a new risk assessment model and corresponding grouting method for this type of water inrush disaster.

- Introducing countermeasures suitable for the YPH coal mine and proposing guidelines for the grouting.

The Study Area's Geologic and Hydrogeological Conditions

Study Area

The YPH coal mine is located in the Wushenqi territory, Ordos city, Inner Mongolia Autonomous Region, China (Fig. 1). The site occurs between 38°24′00″ N ~ 38°31′22″ N latitude and 108°54′27″ E ~ 109°0′17″ E longitude and covers an area of 113.41 km^2, which is spread over 13.63 km from north to south and along a distance of 8.32 km from east to west. The designed production of the YPH coal mine is 10 Mt/a.

Geological Conditions

The YPH coal mine belongs to the Ordos division of the north China stratum area, whose surface is covered by modern aeolian sand deposits. The underlying strata from bottom to top include the Yanchang, Yanan, Zhiluo, Anding, Zhidan Group (Gr.), and Quaternary formations (Fm.). Furthermore, coal-bearing strata occur in the Middle-Lower Jurassic Yanan Fm.; its thickness ranges from 307.8 to 393.1 m, with an average value of 350 m. The thickness of the coal seam ranges from 17.2 to 22.2 m, with an average value of 20 m. The mining area generally exhibits a monoclinic structure with a dip angle of ≈ 1°. No faults or obvious fold structures are found in the area.

Hydrogeological Conditions

There are a number of water-rich aquifers and aquicludes above the coal seam, including the Quaternary Fm. pore-phreatic aquifer, Zhidan Gr. pore-fissure confined aquifer, Zhiluo Fm. pore-fissure confined aquifer, and the Anding Fm. aquiclude (Fig. 2). The Zhidan Gr. aquifer, which largely consists of medium- and fine-grained sandstone layers, averages a thickness of 315 m. The water level elevation (H) is + 1240 m, the specific well yield (q) reaches 0.35 ~ 0.45 L/s·m, and the hydraulic conductivity (K) ranges from 0.14 to 0.58 m/day. The Zhiluo Fm. aquifer, which primarily comprises gray-white medium-grained and sandy mudstone, exhibits an average thickness of 53 m. H is + 1250 m, q is 0.04 L/s·m and K ranges from 0.14 to 0.20 m/day. In addition, the Anding Fm. aquiclude is widely distributed between the Zhidan Gr. and Zhiluo Fm. aquifers. On average, it is 86 m thick, which effectively prevents a hydraulic connection between these two aquifers.
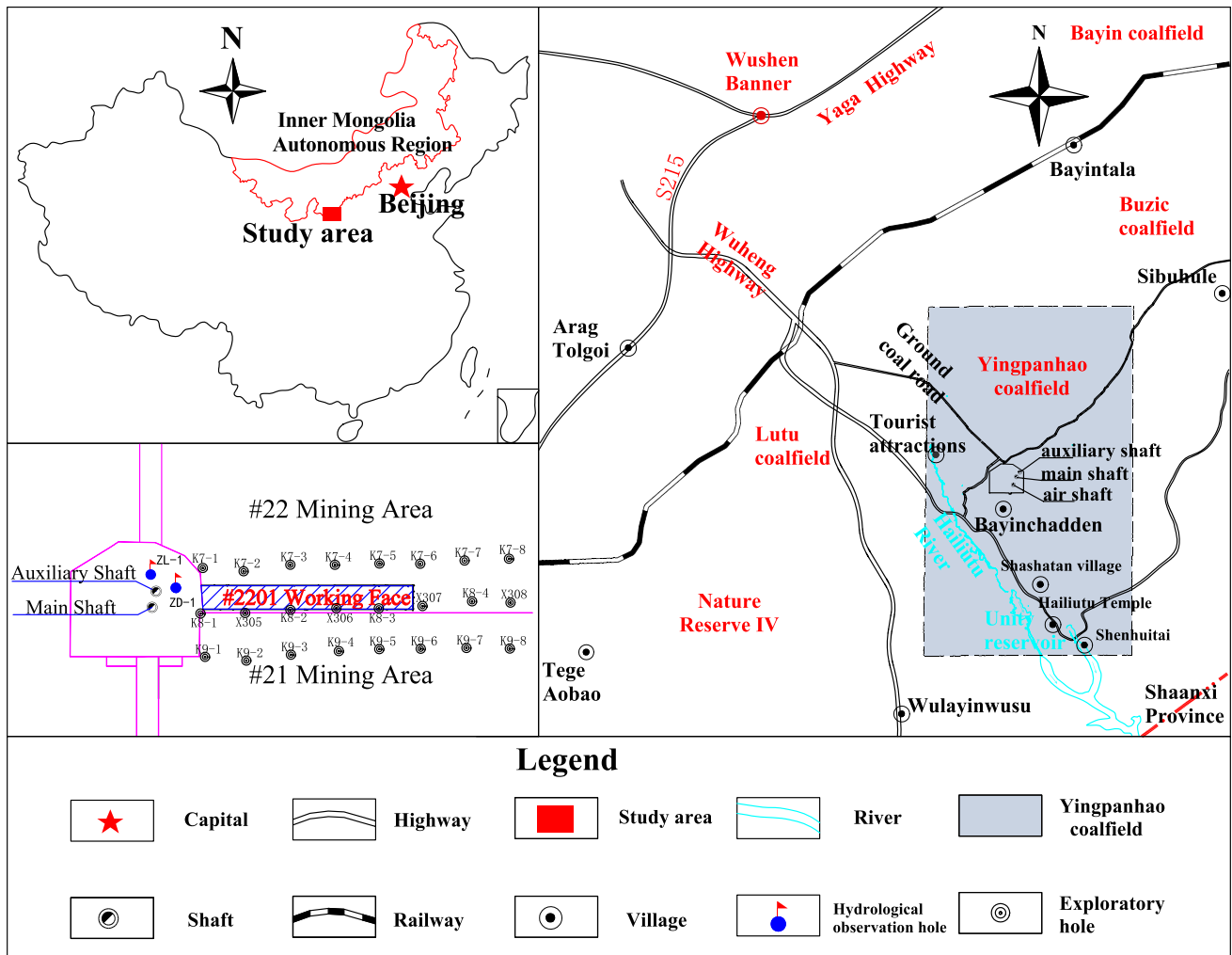
Fig. 1 Location map of the Yingpanhao coal mine

Full-Depth Freezing Method

To ensure safe shaft construction, the main, auxiliary, and air shafts in the YPH coal mine all constructed using the full-depth freezing method, in which the freezing depth exceeds the shaft depth. In this paper, groundwater inrush treatment of the auxiliary shaft is illustrated in detail as a case study describing the new type of water inrush induced by shaft freezing holes. The elevation of the auxiliary shaft with diameter 10 m in the YPH coal mine is +1247.5 m. The total shaft depth is 789 m, and the frozen depth reaches 807 m, which exceeds the total shaft depth by 18 m. The designed thickness of the freezing wall is 4.8 m, the designed average temperature of the freezing wall is −10 ℃, and the freezing time is 65 days. There are 42 freezing holes with a diameter of 192 mm, the freezing pipe is constructed of a seamless pipe with a diameter of 140 mm, and 3 temperature measuring tubes are adopted with a diameter of 127 mm. Before the installation of the freezing pipes, the bottom of the freezing

holes surrounding the auxiliary shaft below 180 m was filled using retarded cement to prevent type I water inrush disasters. The height of unsealed part of cement slurry in freezing holes was 627 m, whose formations from bottom to top mainly include the Zhiluo Fm, Anding Fm, Zhidan Gr., and Quaternary formations (Fig. 3).

Water Inrush Incident

Water Inrush Details

At 1:30 a.m. on April 7, 2016, a water inrush accident occurred near the auxiliary shaft. The total water inflow reached 59 m³/h. At 7:00 a.m. on April 7, the total water inflow rapidly increased to 120 m³/h. Subsequently, the maximum water inflow reached 160 m³/h. Thereafter, the total water inflow stabilized at 120 m³/h (Fig. 4). During the process of water inrush, the water level in the

Column	Strata	Formation	Thickness (m)	Description
	Quaternary		9.2-123.6	This section consists of siltstone, fine sandstone, and medium sandstone. q =0.27-0.52 L/s·m; K=0.43-4.12 m/d
	Cretaceous	Zhidan Group K_{1zh}	252.8-454.9	The upper section comprises dark red mudstone and sandy mudstone with fine sandstone. The lower section contains gray-green conglomerate. q=0.35-0.45 L/s·m; K=0.43-4.12 m/d
	Jurassic	Anding formation J_2a	40.9-136.2	The upper section comprises mudstone, sandy mudstone and siltstone. The lower section contains medium fine grained sandstone, with sandy mudstone and siltstone. q=0.04-0.05 L/s·m
		Zhiluo formation J_2z	89.1-228.6	The lower section contains medium and fine feldspar quartz sandstone. The middle section contains siltstone, sandy mudstone, and grey-green sandstone. The upper section contains medium-fine sandstone. q=0.27-0.52 L/s·m; K=0.4-4.12 m/d
		Yanan formation J_{1-2y}^{1-3}	42.8-185.0	The J_{1-2y}^3 formation contains fine-coarse sandstone with gray siltstone and sandy mudstone and the 2-2 and 2-3 coal seams.
			46.5-78.2	The J_{1-2y}^2 formation contains medium-fine sandstion, sandy mudstone and coal seam, includes the 3-1,4-1 and 4-2 coal seams.
			143.1-219.6	The J_{1-2y}^1 Formation includes a lower section consisting of medium-fine feldspar quartz sandstone.
	Triassic	Yanchang formation T_{3y}	>63	Thick fine-grained aragonite quartz sandstone with green thin sandy mudstone and siltstone beds.

Legend

Coarse sandstone

Sandstone

Fine-grained sandstone
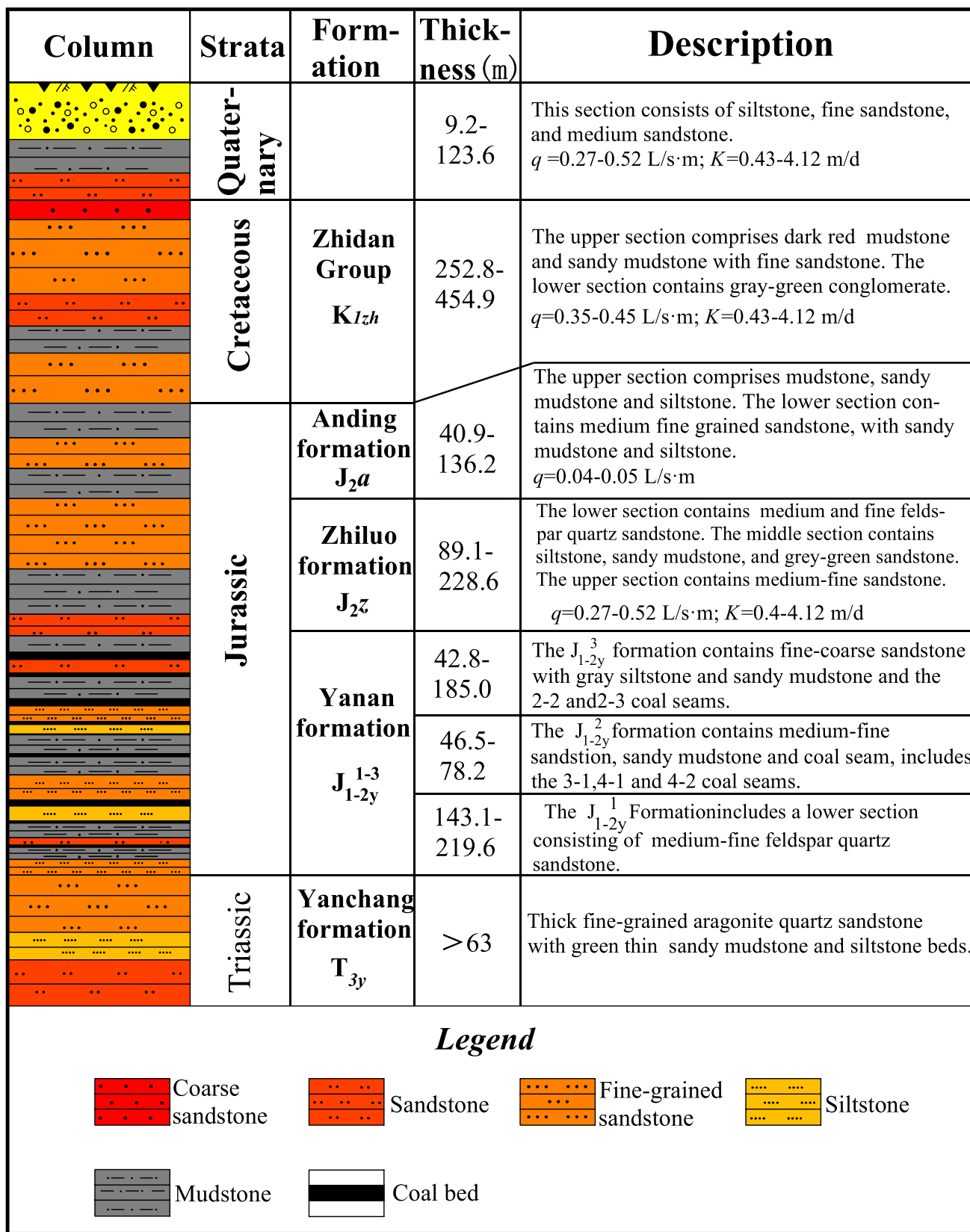
Siltstone

Mudstone

Coal bed

Fig. 2 Stratigraphic column of the Yingpanhao coal mine
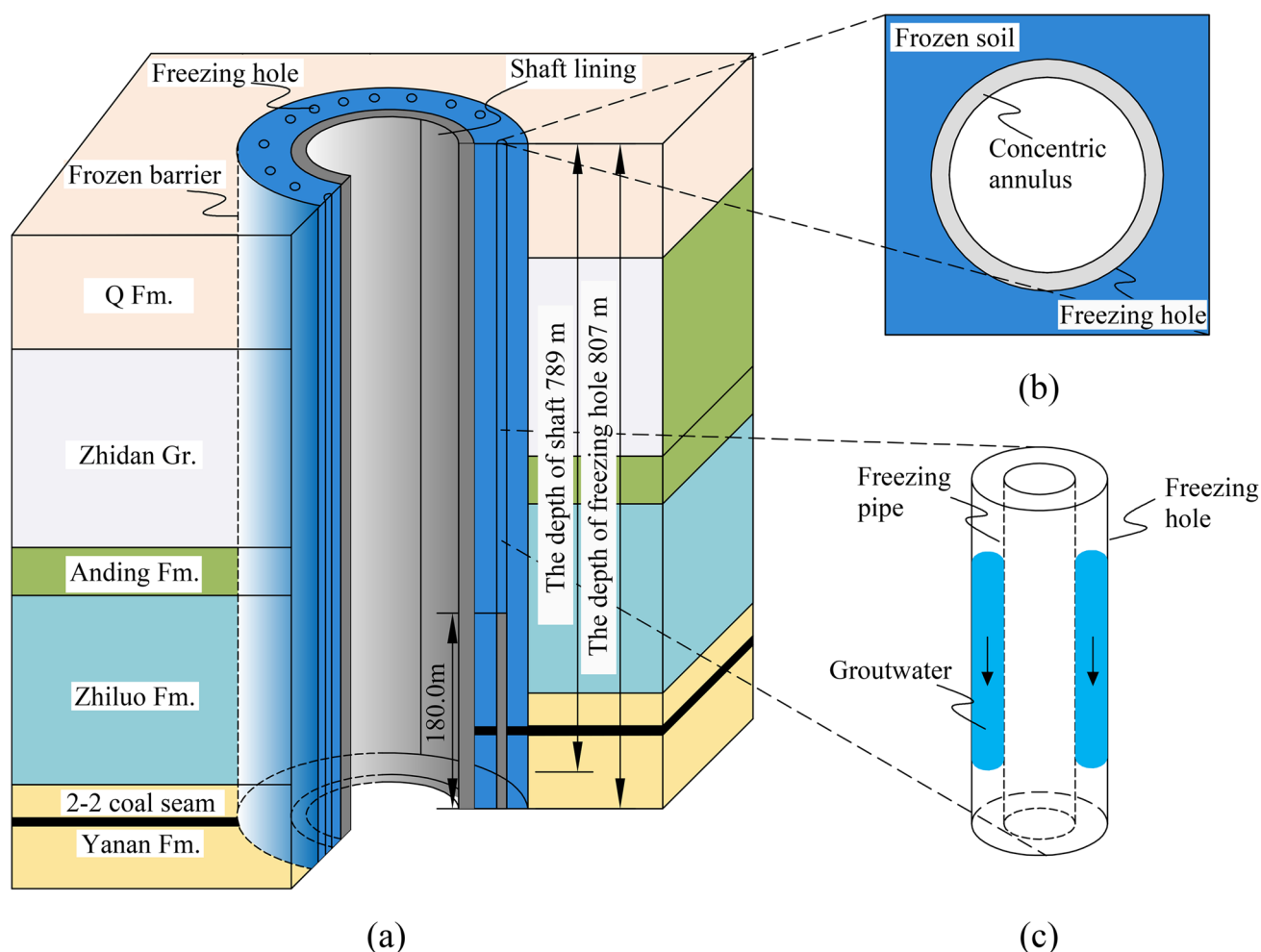
Fig. 3 Diagram of the full-depth freezing method in the auxiliary shaft of the YPH coal mine

hydrological observation holes in the Zhiluo Fm. and Zhidan Gr. obviously decreased. The water level depth in Zhiluo Fm. (ZL-1) decreased from 69 m at 9:50 a.m. on April 7 to 81 m at 9:19 a.m. on April 8, a decrease of 11 m. Moreover, the water level depth in the Zhidan Gr. (ZD-1) decreased by 4 m (Fig. 5). In summary, the main water inrush sources were the Zhiluo Fm. and Zhidan Gr.

However, the geological and hydrogeological conditions of the YPH coal mine showed that theoretically, the Anding Fm. aquifuge should isolate the Zhidan Gr. aquifer from the Zhiluo Fm. aquifer. Meanwhile, retarded cement was injected into the freezing holes to efficiently prevent type I water inrush disasters. Water inrush occurred in the roadway, not in the shaft lining, which indicates that the type II water inrush disaster did not occur. Hence, why did this water inrush accident occur?

Water Inrush Mechanism

Further investigations were conducted to study the water inrush hazard mechanism based on the aforementioned hydrological conditions. The inrush mechanism in the YPH mine can be summarized as:

On the one hand, mining caused disturbances and pressure redistribution in the overlying strata, which caused a caved zone, a fractured zone, and a continuous zone to develop. The two lower failure zones formed a water-conducting fractured zone (WCFZ) that provided space for groundwater flow and migration into the roadway or working face (Cheng et al. 2017; Miao et al. 2011). On the other hand, the CACs of the freezing holes became unobstructed vertical water channels connecting the multiple aquifers. Under the influence of the head pressure
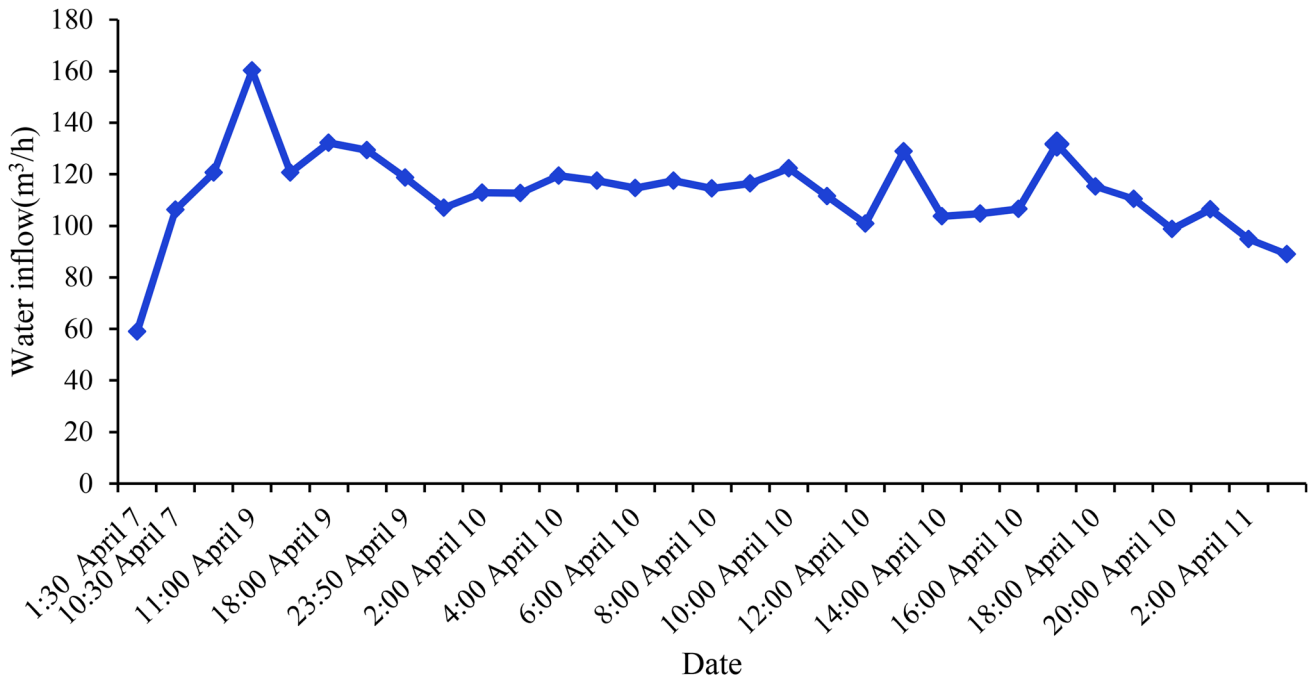
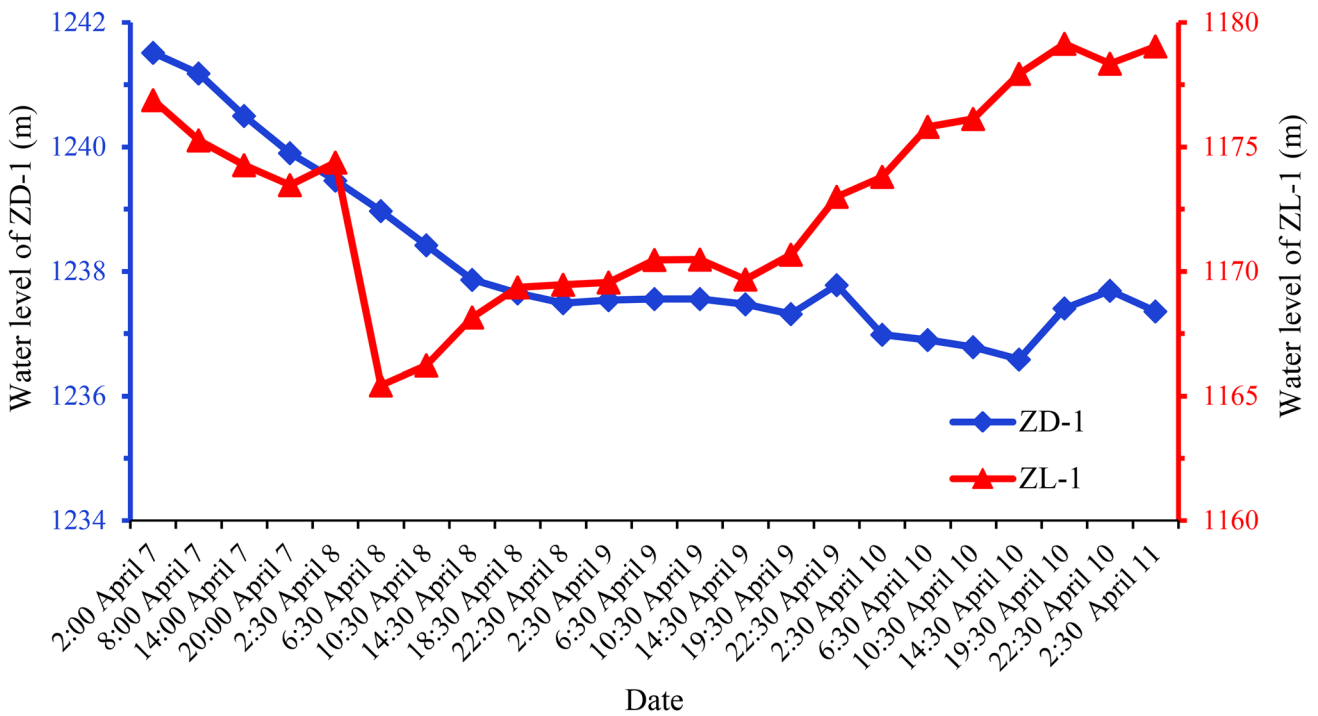**Fig. 4** Variation in water inflow over time

Fig. 5 Variation in the water level of the different aquifers over time

difference between the aquifers, the direct water-filled aquifers within the WCFZ were supplied from the indirect water-filled aquifers outside the WCFZ through the CACs of the freezing holes. Moreover, fractures emerged near the freezing holes due to the freezing and thawing process. Once the WCFZ connected with the native and secondary fractures occurring near the freezing holes, the flowing water eroded and transported loose soils from the indirect
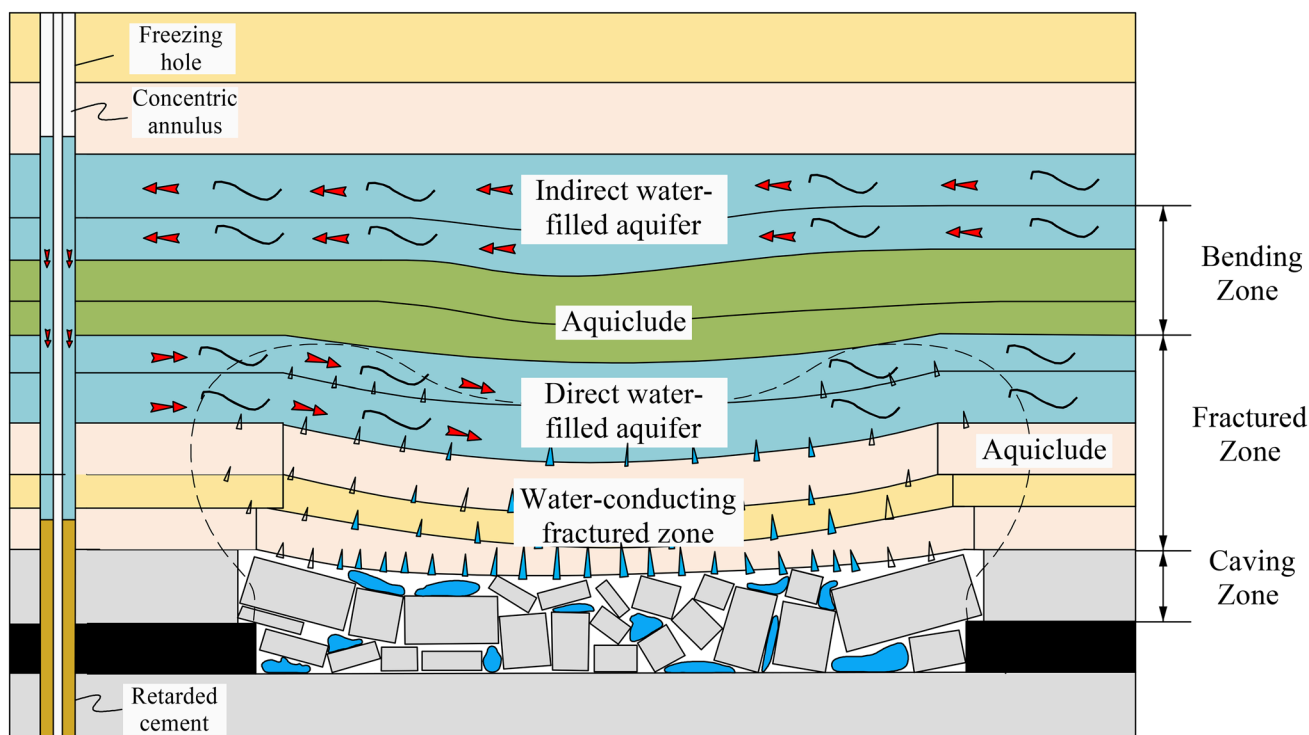
Fig. 6 Diagram of the new type of water inrush due to the freezing method

water-filled aquifers, and water entered into the roadway or working face through these fractures and the WCFZ, shown in Fig. 6. Furthermore, even if none of the fractures near the freezing holes connected with the WCFZ, groundwater would eventually migrate laterally into the WCFZ through the native pores and fractures in the aquifers. The total water inflow would increase, thus resulting in an increase in long-term drainage costs.

In this study, the main coal seam was the no. 2–2 coal seam, which has an average thickness of 7 m. According to previous studies, the ratio of the height of the WCFZ to the mining height is 20.5 in western China (Hou et al. 2020; Xue et al. 2020). Thus, the average height of the WCFZ is 144 m. We found that the height of the WFCZ exceeded the distance from the no. 2–2 coal seam to the bottom of the Zhiluo Fm. In other words, the Zhiluo Fm. is the direct water-filled aquifer, and the Zhidan Gr. overlying the WCFZ can be regarded as the indirect water-filled aquifer. Initially, due to the groundwater head pressure difference, the Zhiluo Fm. replenished the Zhidan Gr. via the CACs until the head pressure of the two aquifers equilibrated. Then, during seam extraction, water from the Zhiluo Fm. flowed into the working face, decreasing the Zhiluo Fm. water level. The CACs became hydraulic connection channels through which the Zhidan Gr. continuously supplied the Zhiluo Fm. When the WCFZ extended into the Zhiluo Fm. aquifer, groundwater rushed into the roadway.

Grouting to Control Water Inrush due to Freezing Holes

A number of coal mines in western China have a lithology that is similar to the YPH mine, have adopted the freezing method, and have faced the same water inrush problems, but the concealed water-conducting passageways and lagging water inrush can make this new type of inrush difficult to detect. Without effective governance, this condition may even worsen, resulting in long-term water inflow or inrush events, due to continuous groundwater recharge via indirect water-filled aquifers. To date, evaluation models and grouting treatments of water inrush by the freezing method have mainly focused on types I and II water inrush hazards. Hence, to prevent this new type of water inrush hazard, a new water inrush risk assessment approach is proposed, and a corresponding grouting method established. Note that the grouting method is effective whether the water disaster occurs or not. The specific procedures are shown in Fig. 7.

Risk Assessment of Water Inrush

There are two main reasons for the new type of water inrush hazard. One involves the unclosed CACs of the freezing holes and the other is due to the WCFZ caused by mining. Therefore, risk assessment of water inrush should be conducted considering these two aspects.
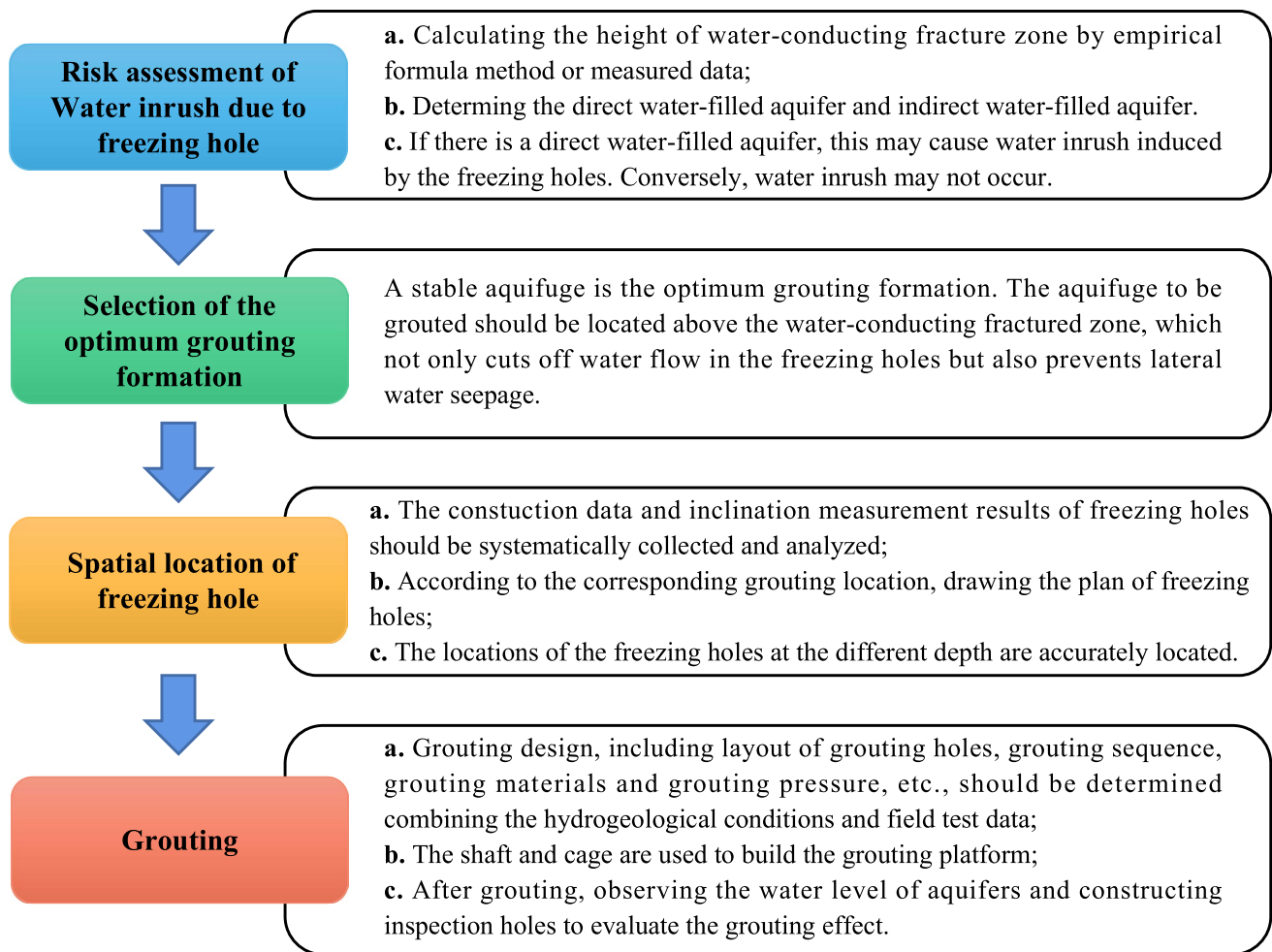
Risk assessment of Water inrush due to freezing hole	**a.** Calculating the height of water-conducting fracture zone by empirical formula method or measured data; **b.** Determing the direct water-filled aquifer and indirect water-filled aquifer. **c.** If there is a direct water-filled aquifer, this may cause water inrush induced by the freezing holes. Conversely, water inrush may not occur.
Selection of the optimum grouting formation	A stable aquifuge is the optimum grouting formation. The aquifuge to be grouted should be located above the water-conducting fractured zone, which not only cuts off water flow in the freezing holes but also prevents lateral water seepage.
Spatial location of freezing hole	**a.** The constuction data and inclination measurement results of freezing holes should be systematically collected and analyzed; **b.** According to the corresponding grouting location, drawing the plan of freezing holes; **c.** The locations of the freezing holes at the different depth are accurately located.
Grouting	**a.** Grouting design, including layout of grouting holes, grouting sequence, grouting materials and grouting pressure, etc., should be determined combining the hydrogeological conditions and field test data; **b.** The shaft and cage are used to build the grouting platform; **c.** After grouting, observing the water level of aquifers and constructing inspection holes to evaluate the grouting effect.

Fig. 7 Evaluation model and grouting method for the new type of water inrush

First, geological conditions, hydrogeological conditions, and freezing data must be comprehensively analyzed to ensure that coal extraction is not threatened by types I and II water inrush disasters originating from shaft freezing holes. Subsequently, the aquifers and aquicludes transected by the unclosed CACs of the freezing holes are examined for their susceptibility to the new water inrush type. The thickness of the different aquifers and aquicludes must be determined throughout the mining area using the exploration holes. A comprehensive understanding of the spatial location and water level of the multiple aquifers facilitates clarification of the recharge relationship. If the water level of the lower aquifer is far higher than that of the upper aquifer or the water abundance of the upper aquifer is lower, the aquifer below is not recharged. The lower aquifer is thus the main source of water inrush. Prevention should mainly target the roof aquifer of the coal seam instead of the CACs of the freezing holes. Conversely, if after drainage, the water level of the upper aquifer is higher than that of the lower aquifer, the CACs of the

freezing holes may become notable water-flowing channels to provide abundant groundwater to the lower aquifer.

Subsequently, the distribution of the height of the WCFZ in the mining area can be calculated via the empirical equation method, analogy method, or measured data (Gu et al. 2012; Miao et al. 2011; Wang et al. 2019). The WCFZ plays a key role in whether groundwater from the upper part flows into the roadway or working face. Generally, the aquifers inside the WCFZ are considered direct water-filled aquifers that determine the direct amount of water inflow into the working face. The aquifers outside the WCFZ are considered indirect water-filled aquifers. When no hydraulic connection exists, the indirect water-filled aquifers do not affect water inflow into the mine. However, the CACs of the freezing holes provide space for groundwater migration. When a direct water-filled aquifer occurs, water from the indirect water-filled aquifer may rush in. Therefore, according to the WCFZ, determination of the occurrence of a direct water-filled aquifer is critical.

Once both the above conditions are met, a new type of water inrush may occur to pose a great threat to mining.

Grouting Method

First, the optimum grouting section and location of the freezing holes at the different depths were determined. The whole CACs of the freezing holes are important to the dynamic recharge process among aquifers. However, the section between the top direct water-filled aquifer and bottom indirect water-filled aquifer is the crucial section. Sealing this section isolates any water-flowing channels. Even if a water level difference occurs between the aquifers, the intermediate aquiclude ensures their independence. Therefore, it was not necessary to seal the entire freezing hole. The optimum grouting section was the mudstone of the nearest aquiclude above the WCFZ.

In contrast, during the construction of the freezing holes, the different lithological associations, drilling pressure, etc., can cause inclination of the freezing holes at greater depth. Blind drilling of grouting holes delays grouting and increases the cost. Hence, the location of the freezing holes affects the precision of the grouting holes. Based on the freezing construction data and inclination measurements of the freezing holes, the location of the freezing holes at different design depths was visualized to reveal the drilling length and drilling angle. The grouting design includes the layout of the injection boreholes, grouting materials, grouting volume, injection pressure, stopping criteria, and evaluation of the grouting effect.

(1) *Layout of the injection holes* Dense construction of the grouting holes may endanger the stability of the shaft lining, so injection holes have were evenly arranged at different depths. In addition, data errors in the location of the freezing holes can cause the CACs of these freezing holes to not be detected. To guarantee that each freezing hole was exposed at least once, if the drilled grouting hole did not intersect the CACs of the freezing hole, another grouting hole was drilled in the designed grouting section.

(2) *Grouting material* The injection rate determines the initial water-cement ratio (*w/c*) of the slurry, which is the weight ratio of water to cement (Ruan 2005; Han et al. 2021; Zhang et al. 2017a). When the grouting flow was less than 20 L/min, the initial *w/c* was 1.4:1. When the injection rate was between 20 and 40 L/min, the initial *w/c* was 1.2:1. As the rate increased to 40~60 L/min, the initial *w/c* was 1.0:1. Finally, when the grouting rate exceeded 60 L/min, the initial *w/c* ratio was set to 0.6:1. Subsequently, the water inflow and grouting pressure are adopted as indices for slurry selection. When the water inflow is low or the injection pressure increases quickly, a cement slurry should be used; otherwise, a cement and sodium silicate (C–S) slurry should be employed instead. Considering the grouting conditions and cost, Portland cement (C) and sodium silicate (S) were used for this project.

(3) *Grouting volume and injection pressure* The grouting volume of a freezing hole can be estimated using Eq. (1).

$$Q = K\pi(R^2 - r^2) \cdot h/m$$

where R is the outer radius of the freezing hole, r is the inner radius of the freezing hole, h is the total diffusion height of the slurry, m is the stone rate which is the ratio of the consolidated volume of the injection slurry to the volume of the injection slurry, ranging from 0.8 to 1 (Zhao et al. 2012). K is the loss coefficient ranging from 1.1 to 1.3, considering the influence of hydrostatic pressure, mixing time, etc.

A water pressure test should be conducted before grouting to evaluate the tightness of the grouting system. The pressure of water pressure test used can be regarded as the initial grouting pressure.

The final grouting pressure can be determined using empirical Eq. (2).

$$P = P_w + P_L + (0.5 \sim 1)$$

where P_w is the hydrostatic pressure, P_L is the pipe friction loss pressure along the grout pipe, and (0.5 ~ 1) denotes the other combined pressures.

(1) *Stopping criteria* The grouting criteria comprehensively considers the grouting pressure, grouting volume, and grout absorption. Based on the designed grouting volume, after the grouting pressure reaches the final grouting pressure, grouting can be stopped when the grout absorption is reduced to 60 L/min. If a C–S slurry is used, after the grouting pressure has reached the final grouting pressure, the grouting process can be stopped when the grout absorption is less than 100 L/min.

(2) *Grouting effect* The objective of grouting is to plug the CACs of the freezing holes. Due to the fixed location and narrow migration space of the CACs, the commonly used geophysical methods are not effective. Inspection holes are suggested as a direct method to determine whether the hydraulic connection is cut off.

Grouting of the Auxiliary Shaft in the YPH Coal Mine

Based on the aforementioned analysis, the key parameters and grouting procedure for the auxiliary shaft in the YPH coal mine, including the layout of the grouting holes, grouting materials, grouting volume, grouting pressure, and grouting effect, are elaborated below.

Layout of the Grouting Holes

In the abovementioned water inrush, the main water source was the Zhidan Gr., which is connected with the Zhiluo Fm. via the CACs of the freezing holes. The Anding Fm. aquiclude was the optimum stratum to grout since sealing the CAC section of the Anding Fm would prevent groundwater from the Zhidan Gr. from flowing into the Zhiluo Fm. due to the high water-resistance of the Anding Fm. aquiclude. Therefore, the area of the auxiliary shaft that was selected for grouting to cut off the existing hydraulic connection was the depths between 436 to 500 m.

According to the lithological column, the rock from 493 to 500 m and 460 to 484 m was sandstone. Sandstone contains more water than mudstone, which means that grouting it would increase the risk of grouting project and should be avoided. Meanwhile, the hydraulic connection between the Zhiluo Fm. aquifer and Zhidan Gr. is mainly caused by the existence of the freezing holes, which destroys the integrity of the Anding Fm. The aim of grouting project is to built stable barriers in Anding Fm. to cut off the vertical supply between the two aquifers. Considering the budget and effectiveness, grouting the section between 436 ~ 460 m and 484 ~ 492 m should effectively prevent the dynamic replenishment from the Zhidan Gr. aquifer and the sandstone section in the Anding Fm.

The location of the freezing holes at the different depths had to be determined. The 42 freezing holes and three temperature measuring holes were evenly distributed around the auxiliary shaft (Fig. 8a). According to the obtained freezing construction data and inclination measurement results, a plan of the path line of the freezing holes was established. To avoid damaging the shaft lining, five groups of grouting holes were designed. Each cycle included three grouting parts. The distance between the grouting groups was 4 m (Fig. 8c). Figure 8b shows the layout of the grouting holes at a depth of 434 m. It should be noted that to carry out grouting, the cage of the auxiliary shaft was improved and employed to support the whole grouting process.

Grouting Materials

Ordinary Portland cement (P.O. 42.5), with a 28-day compressive strength exceeding 42.5 Mpa, and sodium silicate were used as the raw materials for grouting, as described below. Its w/c ratio ranged from 0.6:1 to 1.6:1. The concentration of sodium silicate ranged from 35 to 40°Bé measured by baume hydrometer, and the modulus reached 3.1 ~ 3.4. The volume ratio of the cement slurry and sodium silicate ranged from 1:0.5 to 1:1, and the gelation time ranged from 15 s to 14 min. To avoid grouting pipe blockage and failure caused by the short gelation time of C–S slurry, a two-shot injection system was adopted. Two slurries can be delivered by independent grouting pipe and mixed inside or outside the injection hole. The specific operation details were elaborated by Zhang et al. (2017b).

Grouting Volume and Grouting Pressure

During the grouting process, the grouting pressure and grouting volume were controlled. According to Eq. (1), assuming that grouting length h was 20 m, K was 1.1, and m was 0.87. The grouting volume of a single freezing hole was 0.41 m^3. Based on Eq. (2), the groundwater pressure was 5.16 MPa, the pressure drop was 0.2 MPa, and the final grouting pressure exceeded 5.86 ~ 6.36 MPa.

Grouting Effectiveness

Prior to the grouting of the CACs, 45 freezing holes were successfully exposed. Most of the measured flow in the grouting holes exceeded 0.5 m^3/h (Fig. 9a). Water inflows ranging from 0.5 to 1 m^3/h and 1 to 2 m^3/h accounted for 33.3 and 35.5%, respectively. The average water inflow reaches 1.6 m^3/h, and the water inflow totaled 72 m^3/h. The maximum water inflow in the no. 28 freezing hole was 7.0 m^3/h. This demonstrates that the CACs of the freezing holes were critical and dangerous hidden water channels connecting the Zhidan Gr. aquifer with the Zhiluo Fm. aquifer.

Figure 9b, c show the frequency of the grouting pressure and grouting volume, respectively, of the freezing holes. The grouting pressure in each freezing hole exceeded 6.0 MPa and the grouting volume of most of the freezing holes exceeded 0.4 m^3. All of the grouting holes satisfied the stopping criteria. Two stopping criteria constraints of grouting volume and injection pressure can be adjusted to accommodate other grouting engineering projects.

To evaluate the grouting effect, two groups of 17 inspection holes were drilled at depths of 444 and 486 m to observe the water inflow (Fig. 10). The results revealed that the water inflow in all inspection holes was less than 0.1 m^3/h. No groundwater gushing was observed in the four inspection holes. This demonstrates that the grouting effectively prevented groundwater recharge from the Zhidan Gr. aquifer.
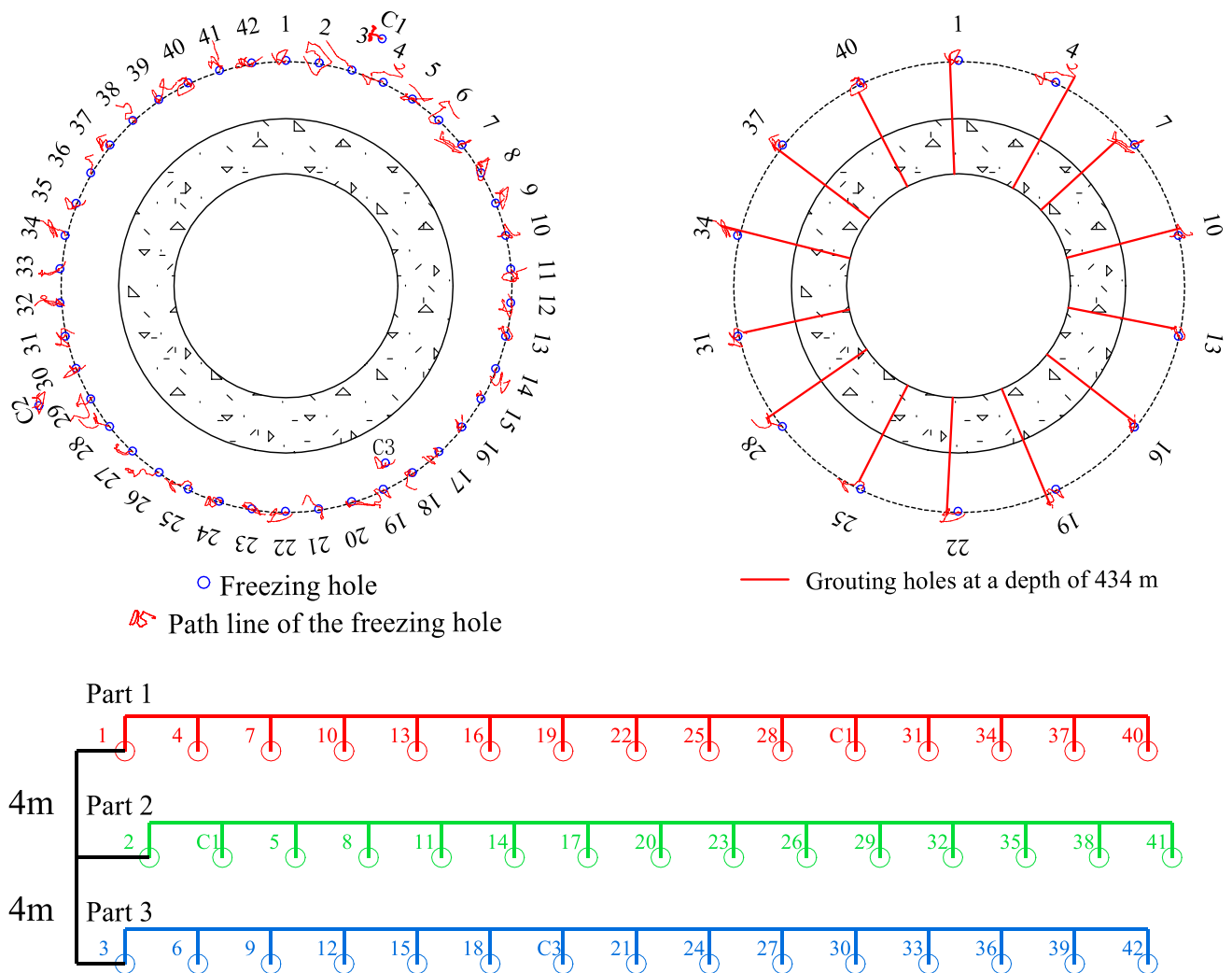
Fig. 8 Layout of the grouting holes surrounding the auxiliary shaft of the YPH coal mine. **a** Layout and path line of the freezing holes surrounding the auxiliary shaft. **b** Layout of the grouting holes at a depth of 434 m. **c** Diagram of the grouting sequence in a given grouting group

Conclusion

According to the water inrush details pertaining to the auxiliary shaft of the YPH coal mine, a new type of water inrush hazard due to the freezing method was proposed. The corresponding water inrush mechanism was further introduced by combining hydrogeological characteristics, stratum lithology, and freezing hole data. The investigation demonstrates that hidden CACs of the freezing holes connected multiple aquifers and caused the water inrush.

Based on the case study, an approach was established to evaluate the risk of this new type of water inrush originating from shaft freezing holes. A corresponding pregrouting method was developed and a method for selecting the optimum grouting formation and design location of the grouting holes was introduced. Detailed guidelines and parameters for grouting, including the layout of the injection holes, grouting materials, grouting volume, injection pressure, and stopping criteria, were proposed.

The method was successfully applied to grout the shaft freezing holes surrounding the auxiliary shaft of the YPH coal mine. The obtained field results further verified the new type of water inrush hazard and demonstrated that the proposed grouting method yields the advantages of CAC sealing and hydraulic connection isolation. This method is highly suitable for the prevention of the above new type of water inrush hazard originating from shaft freezing holes.
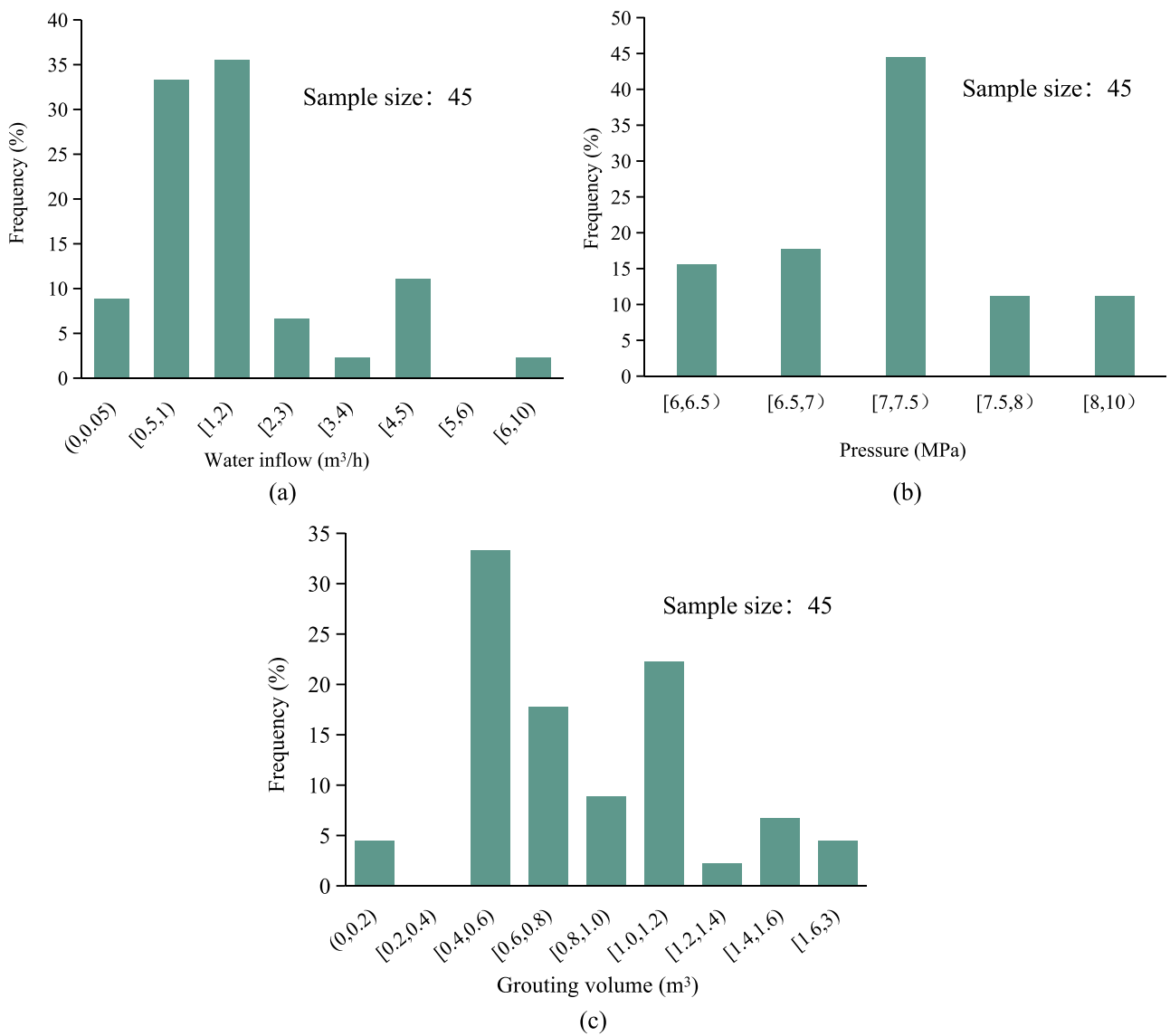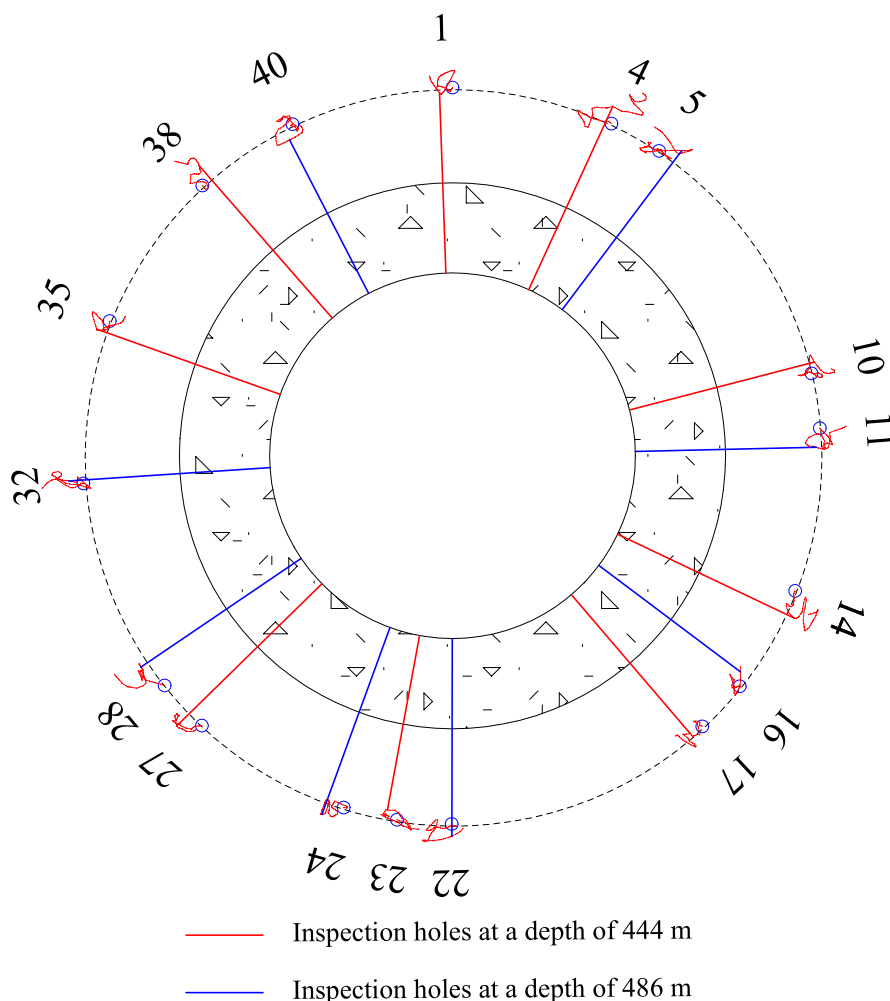
Fig. 9 Occurrence histogram of the different parameters. **a** Occurrence histogram of water inflow. **b** Occurrence histogram of the grouting pressure. **c** Occurrence histogram of the grouting volume

Fig. 10 Layout of the inspection holes

Inspection holes at a depth of 444 m

Inspection holes at a depth of 486 m

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