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Review

Application and Prospect of Curtain Grouting Technology in Mine Water Safety Management in China: A Review

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Abstract: In China, mine curtain grouting has become an important technology to ensure the safe and efficient mining of deep mineral resources and protect regional groundwater resources after more than 60 years of development and improvement. This review paper summarizes and analyzes four aspects of the current situation of curtain grouting technology in deep underground mines: curtain construction conditions, theoretical design and effects, drilling structures, and grouting materials' research and development. In addition, several main problems of curtain grouting technology in deep underground mines are analyzed: planning and construction lag behind; the theory of mine curtain grouting is not mature enough; the investigation into the mechanism of consolidation and deterioration of grout slurry under long-term high pressure is insufficient; there is a lack of research on the long-term effectiveness of monitoring and evaluation, so precise drilling control technology needs further breakthroughs. In addition, the development directions of this technology are put forward from three aspects: precise directional drilling technology; the consolidation mechanism and durability of slurry under multi-field coupling conditions; and long-term dynamic monitoring, evaluation, and early warning for grouting curtain effectiveness. In the future, mine curtain grouting will become an important mine geological guarantee technology for safety, efficiency, accurate, sustainability, and green mining of the Earth's deep resources.

Keywords: deep mining; hydrogeological condition; mine water inrush; curtain grouting; precision drilling; monitoring and early warning

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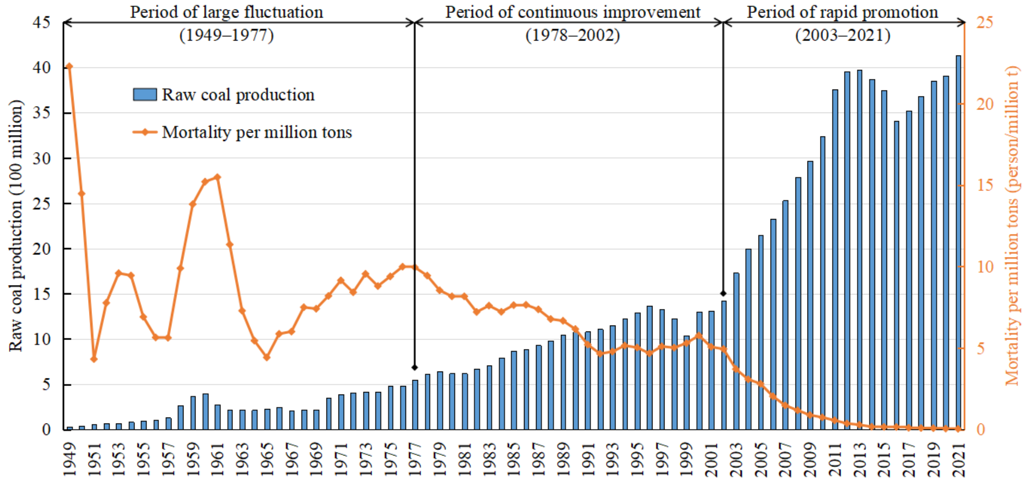
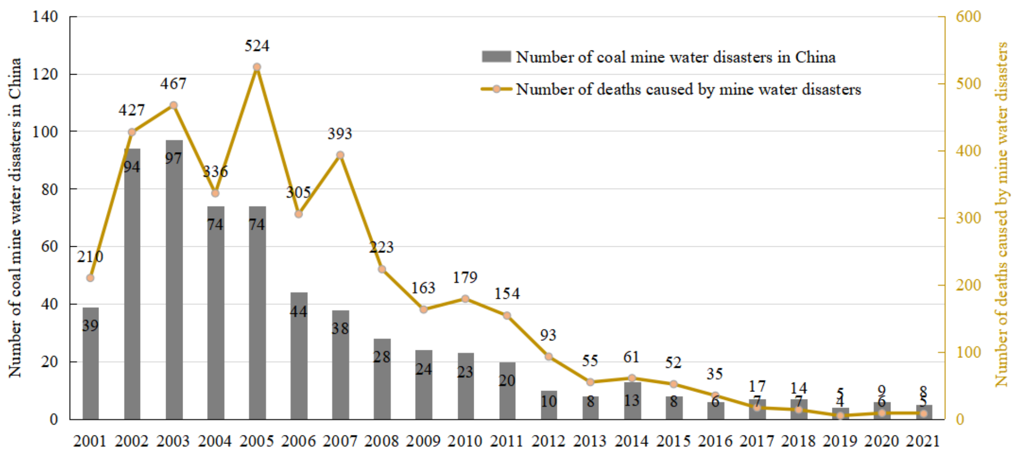
1. Introduction

With the gradual depletion of the Earth's surface and shallow mineral resources, global resource exploration and development is bound to enter the era of deep mining [1–3]. At present, there are more than 100 deep underground mines with a vertical mining depth that reaches the thousand-meter scale in the world, mainly distributed in South Africa, Canada, Germany, Russia, Poland, America, Japan, Belgium, India, and China [4–6]. Worldwide, the mine-shaft-sinking depth continues to increase at the rate of 10–25 m per year [7]. In China, more than 90% of the raw coal production is from underground mining, and approximately 5.9 trillion tons of coal resources lie at depths of 1000–2000 m, accounting for more than 50% of the total coal resources [8]. After entering the deep mining state from a shallow depth, as the in mining depth increases, the engineering geological, hydrogeological, and environmental geological conditions will become more complex and severe, and the threat of dynamic geological disasters will continue to increase, such as high pressure water inrush, high potential energy sand or mud inrush, high energy rock burst or mine earthquake, coal and gas outburst, high temperature and humidity disaster, etc. [9–12]. Since the foundation of the People's Republic of China, the development process of the coal mine safety production situation has gone through three periods with the continuous increase in raw coal production, namely the period of large fluctuation from 1949 to 1977, the period of continuous improvement from 1978 to 2002, and the period of rapid promotion from 2003 to 2021, as shown in Figure 1a. Though the coal mine safety production situation in China has been remarkably improving in recent years, there is still a severe situation in deep mining. From 2001 to 2021, there were 629 mine water disasters in China, with 3730 deaths, and the economic losses ranked first among all kinds of mine disasters, as shown in Figure 1b [13].



(**a**)



(**b**)

Figure 1. Development process of coal mine safety situation in China: (**a**) statistics of raw coal production and mortality per million tons (1949–2021); (**b**) statistics of coal mine water disasters and casualties (2001–2021).

Forced drainage of the groundwater is the most commonly used method to reduce the water yield and water inrush risk of the deep underground stopes for most water-rich mines in China [14–17]. However, this method consumes a large amount of electrical energy with the continuous downward extension of underground mines, which is extremely unsustainable. In addition, the highly intensive pumping of groundwater year by year will induce many kinds of geological and ecological disasters, such as land subsidence, regional groundwater resource depletion, regional groundwater balance destruction, farmland and house damage, ecological environment degradation, and other serious disasters [18–21]. For example, the Ordovician Karst limestone aquifer near the city of Xingtai in Hebei Province of China has created many cones of depression in the piezometric levels of the groundwater (>100 m of drawdown) due to the excessive groundwater withdrawal from the iron mines group in this region [22]. Western China is characterized by abundant coal resources, but it also faces the problems of extremely scarce water resources and a fragile ecological environment, which have become more prominent due to the large-scale mining of coal resources in recent years [23].

In the 1960s, curtain grouting technology was first used to cut off regional groundwater flow in the dam foundation seepage treatment of water conservancy and hydropower projects in China, achieving excellent effects of seepage resistance and rock mass reinforcement. Then, this technology was widely applied to deep underground mines, tunnels, underground engineering, and other fields [24–30]. At present, curtain grouting technology has become a mainstream method to ensure safe and efficient mining in deep underground water-rich mines with complex engineering geological and hydrogeological conditions in China [31–36]. Mine curtain grouting technology refers to a row of drillings and grouting equipment that are used on the surface or underground space to inject the coagulable slurry into the crack networks or pores of the rock mass to cut off the groundwater flow, forming a curtain-shaped artificial water barrier with a certain thickness around the ore body, to reduce the water yield inside the grout curtain and the risk of water inrush. Figure 2 shows the schematic relationship between the grouting curtain and the ore body–groundwater interaction. The relative water barrier formed by the curtain grouting technology can greatly reduce the hydraulic connection inside and outside of the curtain, which not only can greatly reduce the water yield and reduce the economic cost of mine drainage but also plays an effective role in protecting the regional groundwater resources, by reducing the threat of secondary geological disasters and protecting and conserving the surface ecological environment [37–39].

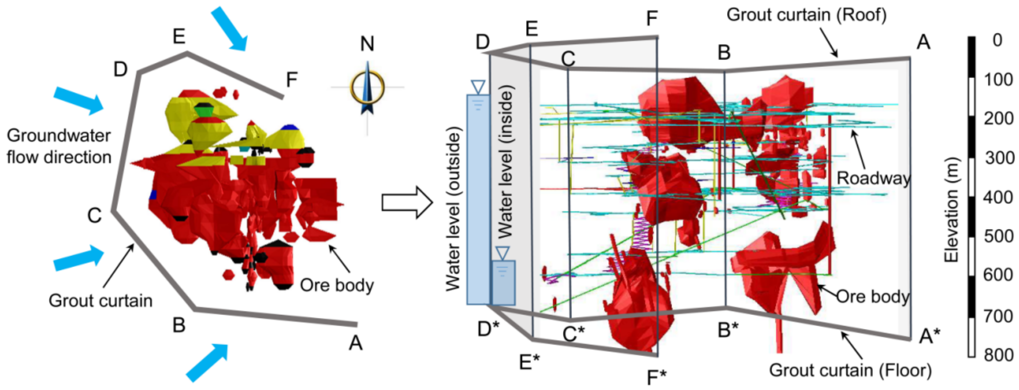


Figure 2. Schematic relationship of grouting curtain with ore body–groundwater interaction. The blue arrows represent the flow direction of groundwater. The letters A~F and A*~F* represent the turning points of the grout curtain axis.

According to the incomplete statistic data, more than 100 grouting curtains have been constructed or under construction in China's coal, metal, and nonmetal mines, which have released a large number of mines troubled by high water pressure, large water yield, and serious water inrush risk. In addition, curtain grouting technology has greatly promoted the effective development and utilization of deep underground resources [40,41]. For example, in the 1970s, the grouting curtain of the Shuikoushan lead-zinc mine, Changning City, Hunan Province, in the middle south region of China, was the first time constructed in a deep thick limestone aquifer with a length of 560 m, a width of 10 m, and a depth of 200–652 m. The reduction rate of water yield was 55%, which can save about RMB 730,000 of electricity charges for drainage every year, ensuring deep mining safety and controlling the land subsidence [42,43]. The curtain grouting project of the Zhongguan iron mine, Hebei Province, in north China, was constructed in 2009~2015, adopting a fully closed grouting curtain in the horizontal and vertical directions with a length of 3393 m, a width of 10 m, and a maximum depth of 830 m. This was one of the curtain grouting projects that directly proved the excellent water-sealing effect during the capital construction period.

The water-sealing efficiency of the Zhongguan iron mine grouting curtain reached 80%, the regional groundwater level obviously rose, and the spring water flowed again [39,44,45].

With the continuous progress of science and technology, the geological drilling technology, geophysical prospecting method, geological exploration technology, automation and intelligent equipment, and numerical modeling and simulation method are gradually maturing [46–48]. At the same time, the mine curtain grouting technology is also constantly updated and developed, such as wireless deviation correction technology for a long-distance directional drilling, flexible drill pipe to drill fast branch hole technology, high-resolution 3D seismic exploration technology, information dynamic transmission and management system, etc [49,50]. In this review paper, the application and prospect of mine curtain grouting technology being used to cut off the regional groundwater flow in deep underground mines are introduced and systematically analyzed, putting forward the future development trends and directions for this technology from four aspects of curtain grouting theory: engineering practice, research and development of instruments, materials, and equipment. This review paper can provide valuable references for the mining of mineral resources and regional ecological restoration and reconstruction under deep complex conditions.

2. Summary of Typical Cases in China

Since the 1960s, curtain grouting technology has been gradually applied from the fields of dam foundation seepage control and treatment to the field of deep underground mining in China [26]. The engineering geological and hydrogeological conditions of deep underground mines are increasingly more complex, given the continuous increase in the mining depth and intensity [51,52]. In China, mine water inrush disasters pose a major threat to the deep underground mining of metallic and nonmetallic ore deposits [53,54]. Mine curtain grouting technology is commonly used to prevent and control water inrush disasters in deep underground mines with challenging hydrogeological conditions [55]. Some typical cases of using curtain grouting technology being used to prevent and control mine water inrush disasters that have occurred in China since the 1960s are summarized, including the characteristic parameters of the grouting curtain, the hydrogeological conditions of the mining area, and the curtain grouting effects, as shown in Table 1.

Compared with the traditional schemes proposed in the past, mine curtain grouting technology has three obvious advantages for mine water inrush risk management and control, groundwater environment protection, and economic savings. Firstly, this technology can significantly reduce the risk of mine water inrush during deep mining. A large amount of slurry is injected into the crack networks and pores of the surrounding rocks, blocking the storage space and flowing pathways of groundwater and forming an underground structure that can serve the whole life cycle of the mine. Secondly, it can protect regional groundwater resources and maintain a regional groundwater balance. After a grouting curtain is installed, the daily drainage of the mining area can be greatly reduced, so the water level outside the grouting curtain rises significantly. Thirdly, it can greatly save electricity for drainage. Mine drainage consumes a lot of power resources, which makes it extremely unsustainable. Therefore, installing a grouting curtain can bring long-term environmental and ecological benefits to mines and realize the sustainable development of mining and the regional environment. Obviously, installing a grouting curtain means the early investment costs are larger, which consumes a longer period of time. Therefore, a full feasibility investigation and assessment must be conducted before implementation. At the same time, it must also be considered that a grouting curtain can result in significant savings in power and equipment costs as well as significant environmental and ecological benefits [39].

Table 1. Typical cases of using grouting curtain technology to cut off regional groundwater flow in China since the 1960s (part).

Mines	Cities (China)	Characteristic Parameters of the Grouting Curtain				Hydrogeological Conditions of the Mining Area			Curtain Grouting Effects		
		Length (m)	Thickness (m)	Depth (m)	Final Grouting Pressure (MPa)	Fissure Rate (%)	Permeability Coefficient (m/d)	Maximum Water Yield (m^3/d)	Water-Level Difference (m)	Sealing Effect (%)	Saved Cost (Million RMB/Year)
Qingshanquan coal mine	Xuzhou	565	10	10–150	0.4–0.8	20–30	/	1320	27	50–60	/
Yanmazhuang coal mine	Jiaozuo	930	/	50–70	1.76–2.45	/	15.26	6600	30–77	/	0.7
Guodong coal mine	Zaozhuang	262	/	3–37	0.5–1.3	25	/	/	/	/	0.05
Shuikoushan lead-zinc mine	Changning	560	10	200–652	2.8–6.0	2.4–30.6	35.32	2980	/	55	0.73
Huangbei coal mine	Zaozhuang	460	10	12–30.5	0.5–0.8	/	/	/	12	/	0.15
Xiezhuang coal mine	Xinwen	3115	/	35–40	1–3	33	/	1960	/	/	0.56
Zhangmatun iron mine	Jinan	480	10	305–566	7–10	2	7.79	850	211	82	2.135
Heiwang iron mine	Zibo	1520	10	100–150	1.5–2.25	5.52	/	8958	/	60	/
Fulingzhuang coal mine	Handan	630	/	273	3.5–6.5	/	10.25	1200	20	/	1.78
Tonglushan copper mine	Daye	450	/	76–302	0.32–0.5	2–52.3	0.59–9.15	2200	25–41	61	/
Tiantun coal mine	Zaozhuang	262	10	/	1–1.3	6.5–15.5	/	/	6.5	/	41.04
Dafeng coal mine	Zaozhuang	10	/	10	2–3	/	/	1172	/	95	1.5
Tongshanling mine	Hunan	410	10	113–262	0.2–1.0	0.85–12	5.62–9.56	264	10–12	/	0.155
Zhongguan iron mine	Xingtai	3393	10	830	6–8	0.5–3.5	/	90,000	27	80	1.50
Xinqiao pyrite mine	Tongling	700	10	260	0.3–3	1.5–49	0.01–25.13	/	/	50	/
Chengmenshan copper mine	Jiujiang	620	10	350	0.4–1.5	4.51–7.83	5.5–32.5	885	10	80	/
Zhanihe coal mine	Hailaer	6370	0.8	21–56	0.5–0.8	/	1.3–1.6	/	10	60	/
Huangtun iron mine	Lujiang	2722	6	350–400	3.2–4.2	/	0.3–1.33	108,000	70	65	/
Gaoyang iron mine	Zibo	141	1.8	270–285	/	28.5–30.2	20.12–23.3	7000	3–4	85.71	/
Nanlizhuang iron mine	Handan	1962	10	583	1.5–4.5	0.67–1.51	2.36–7.86	66,825	/	80	/

3. Theoretical and Technological Systems of the Mine Curtain Grouting Technology

3.1. Applications Conditions

The design and construction of a grouting curtain is an integral groundwater prevention and mine water risk-control project to cut off regional groundwater flow in deep underground mines, which is characterized by a large investment scale, a long implementation period, and great technical difficulty. However, it will serve the whole life cycle of the mine until the mine is closed [56]. Therefore, the design and construction of the grouting curtain require comprehensive analysis, discussion, and determination, as well as early necessary parameters and projects such as the occurrence regularity of mine resources, post-mining planning, hydrogeological conditions, engineering geological conditions, and accurate exploration results of geological structure [57]. According to the "Specification of Mine Curtain Grouting" (DZ/T 0285-2015) [58], there are four necessary prerequisites for the design and construction of a grouting curtain to cut off the regional groundwater flow in deep underground mines, which also determine the planar location and spatial structure of the designed grouting curtain.

(1) The groundwater recharge, runoff, and discharge conditions of the mining area and regional groundwater systems must be clearly identified. Meanwhile, the runoff pathways of the groundwater have the possibility to be blocked by a grouting curtain, such as natural or tectonic crack networks, small-scale hydraulic conductivity faults, and Karst or loose layer pores.
(2) There must be a stable water-resisting layer at the bottom of the target stratum for the grouting curtain, or it can be used as a stable water-resisting floor after grouting transformation, because the base of the grouting curtain needs to enter the stable water-resisting layer by at least 10 m [58].
(3) The regional geological tectonic activity is in a stable state, and the development of geological structure in the mining area is relatively simple. The mining blasting activity would not affect the long-term water isolation effectiveness of the grouting curtain.
(4) Topographical conditions for the drilling of grouting boreholes are available, and the economic costs are manageable. In addition, it must also be considered that a grouting curtain can result in significant savings in power and equipment costs as well as significant environmental and ecological benefits [39].

3.2. Theoretical Design and Effects

The selection and determination of the grouting curtain's location need to ensure the long-term stability and durability of the grouting curtain's body, considering the distribution of the mainly ore body and the detailed mining method. According to the "Specification of Mine Curtain Grouting" (DZ/T 0285-2015) [58], the grouting curtain line should be set 10 m away from the surface dislocation line of underground mining. The final boundary line of an open-pit mine or the staggered boundaries of the hydrostatic level should be more than 50 m away from the mine drainage system. The thickness of the grouting curtain body should not be less than 10 m, which can resist the high-water pressure formed inside and outside the grouting curtain for a long time, maintaining a certain safety factor. The calculation formula of the curtain thickness is as follows [58]:

$$\delta \geq \frac{H-h}{J_{\varphi}(1-\frac{K_{\varphi}}{K_0})} \tag{1}$$

where δ is the thickness of the grouting curtain body, m; H is the grouting curtain body's upstream bearing water head height, m; h is the grouting curtain body's downstream bearing water head height, m; J_{φ} is the allowable seepage gradient of the grouting curtain body; K_{φ} is the permeability coefficient of the grouting curtain body, m/s; and K_0 is the permeability coefficient of the formation, m/s.

In China, the industrial standard for the "Specification of Mine Curtain Grouting" (DZ/T 0285-2015) [58] was promulgated and implemented in 2015, which stipulated the calculation formula for the grouting curtain slurry's injection volume [58].

$$Q = \lambda \frac{Vn\beta}{m} \tag{2}$$

where Q is the grouting curtain slurry's injection volume, m^3; λ is the over-injection factor, with 1.1~1.5 being desirable, and Karst development or hydrodynamic conditions take the largest value; V is the volume of the designed grouting curtain body, m^3; n is the crack rate or Karst rate of the rock mass, %; β is the filling coefficient of the slurry, 0.8~0.9; and m is the ratio of the volume of the injected slurry after solidification to the volume of the injected slurry, %.

The stratigraphic conditions, slurry characteristics, and hydrodynamic conditions are three key factors affecting the slurry's diffusion radius. Therefore, when the diffusion radius of the I-sequence grouting holes cannot meet the design requirements, the II-sequence and III-sequence grouting holes need to be drilled in time to ensure the continuous lap of the grouting curtain body after the water pressure test and geophysical detection. II-sequence and III-sequence grouting holes can prevent the crack networks and pores that have been grouted and sealed in the early stage from being flushed under the action of the rebounding water head pressure [59]. Then, the average unit grouting quantity of all the grouting holes are connected in the order of I sequence, II sequence, and III sequence, respectively, and seven types of relationship curves can be obtained, as shown in Figure 3. The evaluation of rock mass cracks' development and the curtain grouting effects corresponding to each curve type are listed in Table 2.

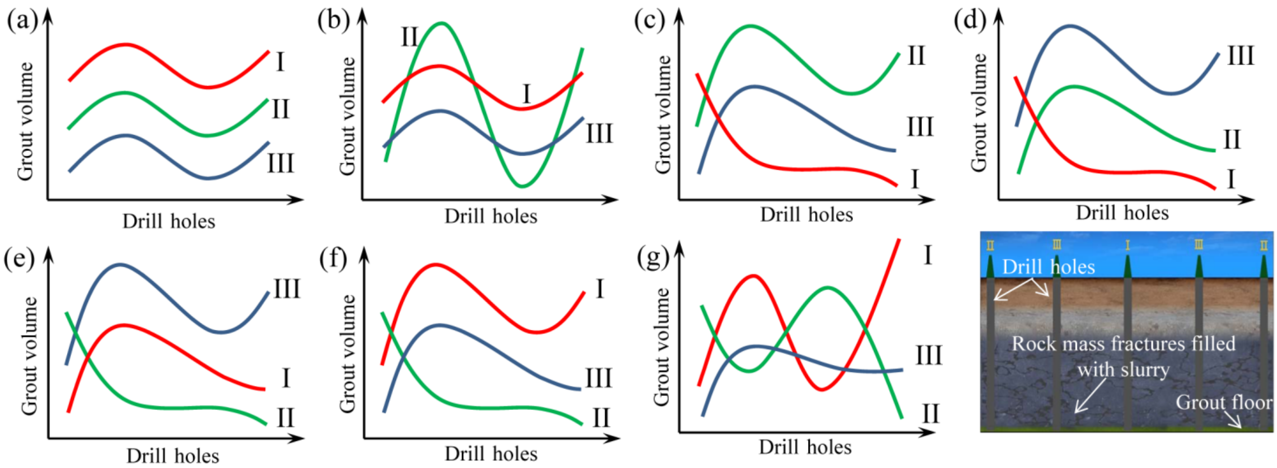


Figure 3. Relationship curves of unit grouting quantity of I-, II-, and III-sequence holes: (**a**) I > II > III; (**b**) II > I > III; (**c**) II > III > I; (**d**) III > II > I; (**e**) III > I > II; (**f**) I > III > II; (**g**) interaction.

Table 2. Interpretation of relationship curves of unit grouting quantity of each sequence hole and grouting effect.

Relationship Curve Types (Figure 3)	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**
Unit grouting quantity	I > II > III	II > I > III	II > III > I	III > II > I	III > I > II	I > III > II	Interaction
Cracks connectivity of the rock mass	Excellent	Good	Average	Poor	Poor	Average	Poor
Curtain grouting effect	Excellent	Good	Average	Poor	Poor	Average	Good

3.3. Directional Drilling Structure for the Grouting Curtain

With the increase in mining depth and intensity, the traditional ground vertical-drilling grouting has been unable to meet the design requirements of the mine curtain grouting. Therefore, the application of various types of directional drilling has solved the bottleneck of the mine curtain grouting drilling technology [60]. Directional drilling is first used in the fields of oil and gas exploration and development, referring to drilling in accordance with the pre-designed direction of the well slope and the shape of the axis of the borehole [61]. Small-diameter controlled directional branch drilling (S-shaped vertical directional drilling) is mainly applied to the grouting reinforcement of mine shaft or chute systems as well as the excavation of the vertical shaft and the treatment of water seepage [62]. The S-shaped vertical directional drilling structure can be divided into five sections from top to bottom, namely the upper straight-hole section, increasing inclination section, stabilizing inclination section, descending inclination section, and lower straight-hole section; the drilling structure is shown in Figure 4a. Branching, orientation, and inclining are the three key technical links to ensure that the drilling trajectory successfully hits the target area [63].

S-shaped vertical directional drilling can realize the parallel operation of freezing–grouting–chiseling, which greatly shortens the time of well construction or repair. At present, the maximum grouting depth is 1078.2 m, which is located in the gangue shaft curtain grouting of the Zhujixi coal mine of the Wanbei Coal-Electricity Group in Huainan City, Anhui Province, China [62].

Ground horizontal directional drilling (L-shaped horizontal directional drilling) is mainly used in the comprehensive control of water inrush disasters in coal mine roofs and floors, advanced treatment of faults, advanced grouting transformation of coal seam floors, grouting plugging of collapsed column, gas drainage of low-permeability coal seams, and other engineering fields. L-shaped horizontal directional drilling has achieved excellent treatment effects, when it is applied in the mine curtain grouting field. For example, the advanced curtain grouting treatment project of the Xuhui and Ordovician limestone aquifers in the floor and the fourth and fifth aquifers in the roof of the Qiuji coal mine (Dezhou City, Shandong Province, China) had liberated about 6 million tons of coal reserves in the left flank of the 11th mining area only; the maximum water level difference inside and outside of the grouting curtain reached 32 m. After L-shaped horizontal directional drilling was adopted in the mine curtain grouting project of the 5th conglomerate aquifer in the Zhuxianzhuang coal mine (Suzhou City, Anhui Province, China), a solid foundation was laid for the mine to resume production [64,65]. The rate of L-shaped horizontal directional drilling is more than 90%, which can expose the target layer to the maximum extent and reveal the water inrush pathways and Karst or tectonic water-rich zones. The target layer can be transformed by high-pressure continuous splitting grouting to form a relatively water-resisting layer, like a "water-blocking plug" in the area to increase the thickness of the water-resisting layer, as shown in Figure 4b.

Fishbone-shaped directional drilling (vertical drilling and inclined drilling with a low curvature) needs to use a flexible drill pipe and other combination apparatuses to drill branch holes with a curvature radius of less than 5 m, branch angles of more than 30°, and azimuth deviations of less than ±10°; the drilling structure is shown in Figure 4c. Fishbone-shaped directional drilling is suitable for these curtain grouting projects under special strata and topography conditions such as high dip-angle fractures and drilling grouting holes for underground roadways [34]. Fishbone-shaped directional drilling can improve the connection rate between the drilling hole and the rock mass cracks with a high dip angle. Through the extension of the offset of the branch hole, the effective influence radius of single hole grouting is increased, increasing the distance between the adjacent main holes. Branch holes with a low curvature are arranged in both directions and in layers along the direction of the curtain line in the main hole. The branch holes are constructed in opposite directions between adjacent main holes and made to stagger each other. While expanding the hole spacing, a mesh-like curtain wall is formed between adjacent holes to improve the curtain grouting and water-plugging effect. The curtain grouting project of the Maoping lead-zinc mine (Zhaotong City, Yunnan Province, China) achieved the ideal water-plugging effect through the implementation of fishbone-shaped directional drilling, and the grouting volume reached 1.5 times the designed grouting volume, meeting the industry requirement for the water-plugging rate [34].

3.4. Curtain Grouting Materials

The characteristics of curtain grouting materials are an important factor affecting the effects of curtain grouting. In a mine curtain grouting project, the selection and determination of grouting materials need to consider the diffusion radius, the strength and permeability of the consolidated body, the availability and economy of materials, etc. Of course, the engineering geological and hydrogeological conditions are also key factors. At present, the main grouting materials include inorganic and organic materials, such as the traditional cement slurry, cement and sodium silicate slurry, modified clay slurry, and organic polymer slurry [66–70]. In recent years, many new grouting materials and modifications of traditional grouting materials have been developed for different geological conditions [71–73].

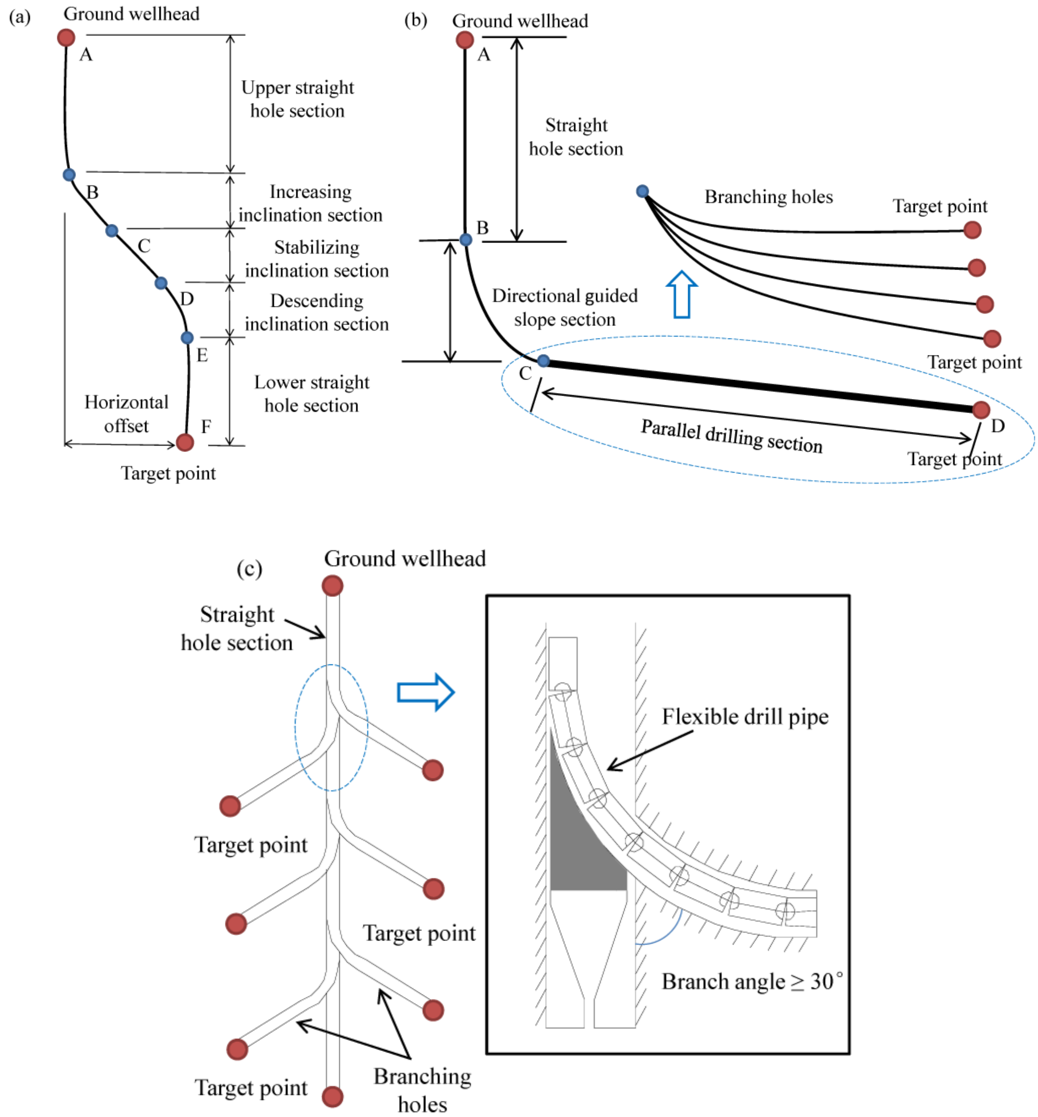


Figure 4. Directional drillings used in mine curtain grouting projects: (**a**) S-shaped directional drilling; (**b**) L-shaped directional drilling; (**c**) fishbone-shaped directional drilling.

The viscosity time-varying material of the SJP-type external admixture independently developed by Chengdu University of Technology can significantly improve the physicochemical properties of clay–cement slurry. Compared with the ordinary clay–cement slurry, the water precipitation rate is reduced by 9% after the addition of an SJP-type external admixture, the pumpable period can be adjusted from 8 to 70 min, the gel time can be controlled from 15 to 40 min, and the late strength of the consolidated body can be increased by 2 to 3.5 times. The additives in the SJP-type external admixture initially form a solvent film on the surface of cement particles to regulate the accelerated hydration period to control the rate of nucleation. The stabilizer can adjust the nucleation and diffusion of the cement hydration-decay period and regulate the gelling time of the slurry [74].

A two-component dynamic water grouting material (FS) for fractured rock mass with fly ash as a polymer and sodium silicate as an additive was independently developed by Shandong University, which has the characteristics of rapid setting, early strength, slight expansion, a high consolidation rate, and resistance to dynamic water erosion, which is of great significance for curtain grouting projects under strong dynamic water conditions [75].

Another new type of high-efficiency superfine cement-based grouting material (EMCG) has the advantages of good diffusivity, stable pumping, a controllable gel time, a stable volume, high hydration activity, high strength, reasonable mineral composition, and a dense structure in the water-rich sand layer. The effects of anti-seepage and reinforcement for the water-rich sand section of a curtain grouting project are superior [76]. A new type of polymer grouting material with an excellent expansion ratio is synthesized for plugging a Karst-pipe-type water inrush disaster. This grouting material is composed of a superabsorbent polymer (SAP), glycerol, and ethanol, which quickly absorbs water and has an expansion ratio of 1:300. Compared with the traditional cement-based or clay-based grouting materials, the SAP effectively plugged gushing water with high water pressure. Furthermore, the plugging time can be adjusted [77].

The organic-polymer modified-urea formaldehyde-resin slurry independently developed by China University of Mining and Technology successfully managed the water- and sand-gushing disasters in many coal mine shafts. It has good diffusion effects in micropores and cracks, the cementing time is controllable, and the environmental pollution is small, but the economic cost is high. Therefore, it is only used in a mine curtain grouting project to assist cement- or clay-based slurry, and the treatment effects show that the combined application is good [78].

4. Discussions and Current Limitations of Mine Curtain Grouting Technology

4.1. Planning and Construction Period

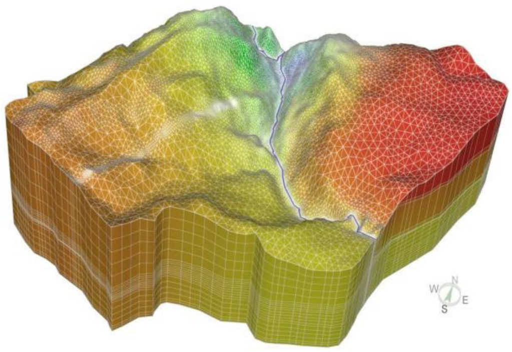
Curtain grouting, as an important integral water prevention and control project in mines, ensures the safe and efficient mining of mines for the whole life cycle. At present, most of the curtain grouting projects are a passive choice, when there is the high risk of water inrush or the high economic cost of long-term large flow drainage. At this time, due to the long-term drainage of a mine, the hydraulic gradient of the groundwater around the mine is extremely large, and the groundwater scours the rock mass cracks for a long time, resulting in a large number of connected water-flowing pathways that are difficult to seal with grouting, which causes great difficulties for the mine curtain grouting project [79,80]. Therefore, the feasibility planning, design, and construction of a curtain grouting project should be carried out before mining, after finding out the resource occurrence, hydrogeological conditions, and geological structure.

4.2. Complex Geological Conditions

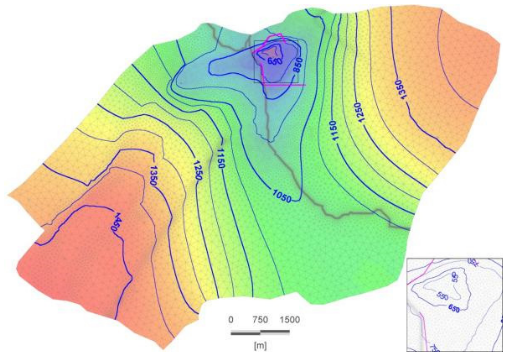
Curtain grouting technology is a practical science with strong empirical characteristics, which belongs to a typical concealed project. The research of grouting theory obviously lags behind the engineering practice. At present, some slurry diffusion laws are mostly based on indoor idealized model tests. Especially when the depth of the grouting hole reaches 1000 m, it will face the complex conditions of high water pressure, high geostress, high ground temperature, and a strong mining disturbance. It is very important to study the diffusion law and plugging mechanism of slurry under the condition of “three highs and one disturbance”. In addition, 3D mine and Rhino are the two most commonly used pieces of software for establishing a mine curtain grouting model. Next, engineering geological and hydrogeological software can be used for a numerical simulation analysis, for example Flac3D, UDEC, ANSYS, Feflow, Modflow, and GMS, as shown in Figure 5 [37,81,82].

4.3. Durability of Grouting Materials

The consolidation mechanism of grouting materials under normal pressure is quite different from that of underground pressure, static or dynamic water pressure, and grouting pressure, resulting in the determination of technical parameters such as the slurry ratio, slurry-preparation technology, and slurry-diffusion distance in the process of grouting construction; this is still based on empirical data, so its reliability is often poor. After the slurry is injected into the deep stratum, it is under the coupling conditions of the in situ stress field, seepage field, hydrochemical field, and geothermal field. Its consolidation mechanism and durability are very important for the long-term effectiveness of the whole curtain [83]. Therefore, research and development can carry out the multi-field coupling grouting material-consolidation mechanism and durability of the experimental device, to then reveal the deep high-pressure conditions of the slurry consolidation and decline mechanism, guide the improvement of the mine curtain grouting parameter selection and process, and improve the theoretical level of the curtain grouting engineering.



(a)



(b)

Figure 5. Mine curtain grouting model of a lead-zine mine, China: (**a**) Modflow model; (**b**) groundwater flow field after curtain grouting.

4.4. Long-Term Effectiveness of the Grouting Curtain

The long-term effectiveness of the grouting curtain is very important to ensure safe and efficient mining. The partial or overall failure of the grouting curtain will induce a serious groundwater inrush disaster. At present, there is still a lack of monitoring and early warning systems for the long-term effectiveness of the grouting curtain. How to use modern monitoring means to achieve all-weather, real-time reliability, accuracy, stability, economy, easy implementation monitoring, and early warning for the grouting curtain will be very critical [41,55,84].

4.5. Control of Drilling Trajectory

China's mine-drilling technology has experienced the development process from "uncontrolled drilling" to "controlled drilling" and then to "precise directional drilling". With the gradual increase in mining depth and intensity, the geological situation will become more and more complex. To achieve efficient curtain grouting, it depends on accurate directional drilling technology and equipment. Accurate directional drilling must rely on high-power directional drilling equipment and a high-precision measurement-while-drilling (MWD) system. In the new situation of mine curtain grouting for drilling technology needs, more information, intelligent precision, and rapid mine-drilling technology, equipment research, and development are imperative. Through the development of a downhole rotary-steering drilling system and a high-precision measurement-while-drilling system, the precise and intelligent measurement of drilling attitude parameters can be realized, and the well trajectory can be continuously controlled in real-time during the rotary drilling of a drill pipe string, which can significantly improve the quality of well trajectory control [85].

5. Future Prospects of Mine Curtain Grouting Technology

5.1. Precision Drilling and Efficient Target Drilling Technology

The precise control of the drilling trajectory of curtain grouting is a key factor to ensure continuous overlapping of the curtain. Through the development of rotary steering drilling technology, a drill pipe string can continuously adjust in real-time and control the drilling-guiding device during rotary drilling, to realize the precise control of the drilling trajectory and efficiently hit the target point of the grouting. With a high-precision MWD system, the parameters of torque, WOB (weight on bit), rotation speed, vibration, temperature, gamma, and resistivity of the bit position can be measured, which provide the basis for the effective extension of the drilling trajectory along the target formation and the accurate entry into the target area.

5.2. Grouting Theory, Equipment, and Slurry Durability under Multi-Field Coupling Conditions

The theoretical research of grouting under the coupling of multiple fields can guide the selection of grouting parameters in the process of curtain grouting, both qualitatively and quantitatively, such as grouting pressure, grouting quantity, slurry mix ratio, etc. Through the research and development of a laboratory simulation grouting system that includes stress, temperature, seepage, and chemical field, which can accurately simulate the grouting process under different hydrogeological conditions, the experimental investigation results can provide accurate guidance for engineering practices. The durability of the consolidated grouted body is a key factor to ensure the long-term effectiveness of the grouting curtain. Through the research and development of the new durable slurry or modification of the original foundation slurry, the long-term effective sealing of the water-flowing pathways of the surrounding rocks can be realized.

5.3. Dynamic Monitoring, Evaluation, and Early Warning of the Effectiveness of the Grouting Curtain

The mine grouting curtain belongs to an underground watertight structure based on formation reconstruction. After the grouting curtain is completed, it will affect the hydrogeological conditions of the mine. It is necessary to dynamically adjust the hydrogeological generalization model of the mine. Therefore, it is very important to carry out long-term dynamic monitoring, evaluation, and early warning for the effectiveness of the grouting curtain. The fine division of a mine's hydrogeological units; evaluation of hydrogeological characteristics; groundwater recharge, runoff, and discharge characteristics; hydrogeological parameters of each unit; fine depiction and evaluation of the influences of a grouting curtain on a mine's hydrogeological structures; hydrogeological conditions and parameters; and water-filling conditions and water-filling intensity can provide the basis and references for the effectiveness evaluation of a grouting curtain.

Through the establishment of a mine's hydrogeological parameters' real-time acquisition network, grouting curtain microseismic monitoring, and distributed optical fiber sensing system, the temporal and spatial evolution law of the surrounding rocks' failure and water-flowing cracks' development for the curtain body under mining conditions can be monitored for a long time. On the basis of the influence range and degree of ore body mining, combined with the spatial distribution of the grouting curtain, the stress, deformation, and displacement of the grouting curtain body and other related monitoring data as well as the stability and reliability of the grouting curtain under mining conditions can be evaluated, so the quantitative evaluation system for grouting curtain stability can be established. Based on this, the early warning model based on multiple factors can be established, and the warning threshold and prediction criteria can be determined, to realize the real-time monitoring and early warning for a water inrush caused by a mine grouting curtain failure.

6. Conclusions

With the rapidly increasing mining depth and intensity on a global scale, mining will face increasingly complex and severe hydrogeological, engineering geological, and environmental geological conditions, which bring great challenges to the sustainable exploitation and utilization of deep natural mineral resources. As an integral groundwater prevention and control project for the whole life cycle of a mine, curtain grouting technology plays an important role in ensuring the coordinated development of resource exploitation and regional ecological protection and is an inevitable choice to realize the sustainable development and building of a green mine (a green mine is a brand-new mine-development mode that has been considered as the optimal solution for mining's sustainable development). In view of the development status of mine curtain grouting technology to cut off regional groundwater flow in deep underground mines, this investigation summarizes and analyzes the construction conditions and theoretical design for grouting curtains, grouting drilling structures, grouting theories, and grouting materials. Four necessary conditions are summarized, on the preconditions for the construction of grouting curtains in mines, and the theoretical design requirements for the thickness of a curtain body and grouting amount are analyzed. There are mainly four kinds of grouting drilling-hole structures, which are a vertical-drilling hole, small-diameter controlled directional branch-drilling hole, horizontal directional drilling hole along a layer, and fishbone-shaped branch-drilling hole, respectively. In addition, the applicable conditions for different types of grouting drilling holes are proposed. At present, the main problems of mine curtain grouting technology are (1) planning and construction lags behind; (2) the theory of mine curtain grouting is not mature enough; (3) the investigation on the mechanism of the consolidation and deterioration of grout slurry under long-term high pressure is insufficient; (4) there is a lack of research on the long-term effectiveness monitoring and evaluation; and (5) precise drilling control technology needs further breakthrough. In the new development stage of geotechnical engineering technology and materials science, four aspects of the development prospect of mine curtain grouting technology are also analyzed. Firstly, the feasibility planning and design of a curtain grouting project should be carried out before mining and after ascertaining the characteristics of the resource occurrence state, hydrogeological conditions, and geological structure. Then, through the research and development of precision and rapid mine-drilling technology and equipment with information and intelligence, the precise control of the drilling trajectory and a high-efficiency hit of the grouting target area can be completed. Further, experimental models that can carry out the consolidation mechanism and durability of grouting materials under multi-field coupling conditions need to be developed and applied. Finally, an early warning model for grouting curtain failure and water inrush accidents should be established.

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