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TECHNICAL COMMUNICATION

Combined Drilling Methods to Install Grout Curtains in a Deep Underground Mine: A Case Study in Southwest China

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Abstract
Curtain grouting can be used to reduce the volume of water inrush in a mine and protect regional groundwater resources. However, traditional vertical drilling was not feasible for the Maoping lead zinc deposit in Yunnan, China, which is located in a high mountainous region with steep gorges. A full analysis of the regional tectonic framework, and geological and hydrogeological conditions of the Maoping deposit was carried out, combining the use of different drilling methods (vertical drilling, inclined drilling with low curvature, and S-shaped directional drilling) to install grout curtains from mine roadways. The combination of drilling methods resolved the difficulties of underground drilling and grouting under high water pressure and the presence of fractures with a high dip angle. Water injection tests, drilling to reveal grouting quality, and electrical resistivity for closely spaced wells were used to to determine the continuity and permeability of the grout curtain. The grouting has been effective, ensuring the safety of the miners, sustainable exploitation of the deep mine resources, and allowing mining of previously non-extractable resources.

Keywords Karst · Mine curtain grouting · Vertical and inclined drilling · Modified red clay slurry · Fractures with high dip angle

Introduction

Creating a grout curtain is an effective way to control to seal fractures in karst aquifers and prevent large water inrushes in deep mines (Li et al. 2019; Mou et al. 2020; Sui et al. 2011; Zhou et al. 2017), as shown in Fig. 1. There are two important reasons to install grout curtains in mines. One is the protection of regional groundwater resources, because a large volume of mine drainage reduces groundwater levels, which can cause surface subsidence, rivers to die out, springs to disappear, and so forth. The other reason is that grout curtains ensure the safety of miners as they prevent seepage and therefore water inrush. Curtain grouting can also be used to change the flow characteristics of an aquifer and reduce the permeability of the rock formation while increasing its strength (Bakalowicz 2005; Wu et al. 2017; Wang et al. 2018; Xia et al. 2019; Zhang et al. 2020).

In recent years, grout curtains have been installed in metal mines in China, such as the Zhongguan iron mine, Huangtun sulfur-iron mine, and Gaoyang iron mine in northern China, Zhangmatun iron mine in eastern China, and the Fankou lead–zinc deposit in southern China (He et al. 2012; Li et al. 2011; Yang et al. 2013, 2014; Zhou et al. 2017). As a typical example of a mine with a karst aquifer, water inflow in the Zhongguan iron mine, which is located in Hebei Province, can reach 150,000 m^3/day. Conventional mine drainage created a groundwater cone of depression over time, which caused severe damage to the regional groundwater resources (Yang et al. 2017). As a result, the water source of the Hundred Springs of Xingtai, one of the major water supply sources for Xingtai City, was cut off. Therefore, a 3393 m long, 10 m wide grout curtain was created in the Zhongguan iron mine

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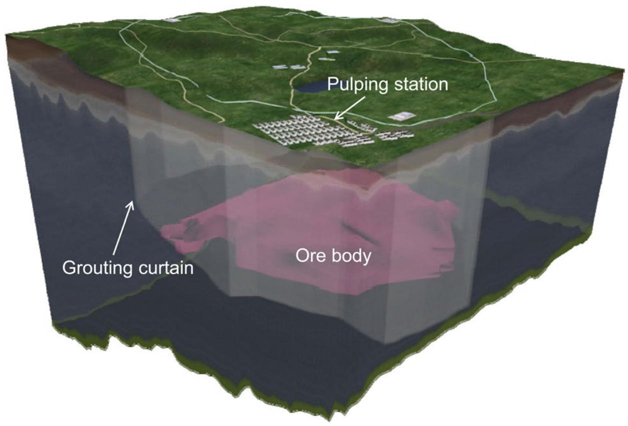

Fig. 1 Curtain grouting in metal mine

from January 2011 to October 2015. About 89% of the ore reserves in the mine is now enclosed by the grout curtain. The curtain grouting reduced water inflow into the mine by 80%, and recharged the Hundred Springs of Xingtai (Li et al. 2011; Song and Liu 2012).

All of these curtain grouting projects used vertical drilling from the surface for grouting, but horizontal drilling has been used to reinforce coal mine floors. For example, the China Measurement and Control Xi'an Research Institute Co. Ltd. and the China Coal Technology and Engineering Group Corp. used directional drilling to effectively control the borehole trajectory, and drilled a long borehole more than 3000 m along a coal seam in the Baode coal mine (Shi et al. 2019) in north China. Also, the Institute of Mine Construction, Tiandi Science and Technology Co. Ltd. drilled S-shaped boreholes with little displacement, using directional drilling to pre-grout the vertical shaft (Wang 2017).

In China, the standards for the "Specification of Mine Curtain Grouting" (DZ/T 0285-2015) stipulate that the distance between two drilled grout holes should be 8–12 m on the ground surface, and that the grouting pressure of the cement slurry be less than twice that of the hydrostatic pressure (The Industry Standard Editorial Committee of the People's Republic of China 2015). However, with increases in mining intensity and depth, there are many special conditions to take into consideration, such as building in a roadway or if the spacing of the drilled holes is more than 12 m. As such, additional technical requirements are needed. For instance, curtain grouting in the Maoping lead–zinc deposit required the drilling of boreholes underground, from a narrow roadway to seal deep karst fissures that has a water pressure that exceeds 4–6 MPa. A variety of drilling methods were used to install the grout curtains to counter the Maoping deposit's complex hydrogeological conditions.

The Studied Area

The Maoping lead–zinc deposit is located in Yunnan Province in southwest China; the mined area is about 14.51 km^2, as shown in Fig. 2a, b. Figure 2c, d show that the region is characterized by high mountains and steep gorges; the highest altitude is about 2194 m at Guanyin Mountain. The Luoze River is the main source of drainage, which runs through the mined area from south to north with a drainage datum of around 887 m above sea level, an annual average flow rate of 16.3 m^3/s, and a hydraulic gradient of 25.2%. According to statistics from the Yiliang county weather station, the average annual rainfall for the region is 746 mm, and the maximum annual rainfall is 1076.1 mm (2013), of which more than 80% of the rainfall is in the wet season, from June to September (Huang et al. 2019a, b).

Geological Conditions and Problems

Geological Conditions

The stratigraphic succession of the mined area consists of the Upper Devonian Formation of Zaige (D_3zg), Lower Carboniferous Formation of Wanshoushan (C_1f), Middle Carboniferous Formation of Weining (C_2w), Lower Permian Formation of Liangshan (P_1l), Qixia Formation (P_1q), Maokou Formation (P_1m), Upper Permian basalt–the Emeishan basalt ($P_2\beta$), Xuanwei Formation (P_2x), Lower Triassic Formation of Feixianguan (T_1f), Yongningzhen Formation (T_1y), Middle Triassic Formation of Guanling (T_2g), Upper Triassic Formation of Xujiahe (T_3x), Lower Jurassic Formation of Ziliujing (J_1z), Middle Jurassic Formation of Shaximiao (J_2s), Suining Formation (J_2sn), and Holocene alluvial deposits (Q_4^{al}) and diluvium (Q_4^{dl}) (Huang et al. 2019a, b). The Upper Carboniferous strata are not found in the mined area, and lie parallel to the underlying Devonian strata but with uneven contact. Except for the Lower Carboniferous Formation of Wanshoushan (C_1f) and the Lower Permian Formation of Liangshan (P_1l), which are alternating layers of sand and mudstone, the rest of the strata are all carbonate rocks. Therefore, the mined area consists of Permian, Carboniferous, and Devonian karst aquifers separated by sand and shale aquitards.

Regional Tectonic Framework

The Maoping lead–zinc deposit is located in a complex formation of north–south (NS) and north-east (NE) tectonic belts. The Maoping compression–torsion fault and Shimenkan anticline constitute the main tectonic structural

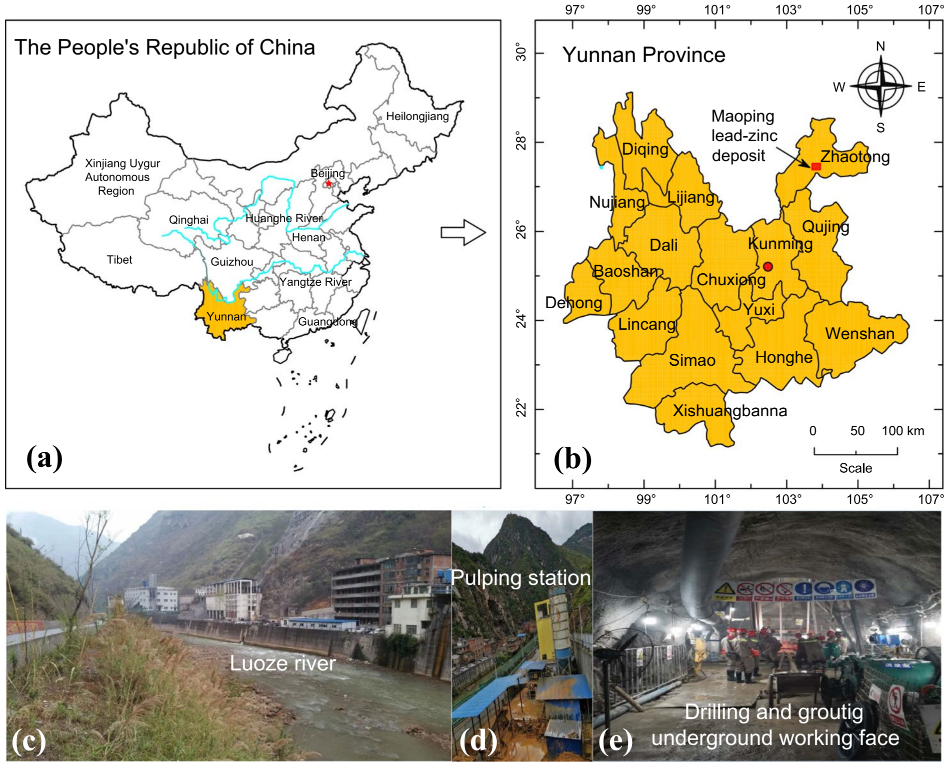

Fig. 2 Location and physical geography of Maoping lead–zinc deposit **a** map of the People's Republic of China; **b** location of the Maoping lead–zinc deposit; **c** topography of mined area; **d** pulping station; **e** drilling and grouting of working face in underground mine

framework of the mined area. The strata of the mined area have been affected by multiple periods of tectonic movement, folding, and faulting (Huang et al. 2019a, b). Therefore, the regional tectonic fabric is characterized by a complex array of dominantly NE-striking faults. Most of the dip angles of the faults are steep, and the faults are filled with ores and argillaceous and calcareous rocks. The ore bodies are mostly found in the steep incline of the overturned limb of the Shimenkan anticline, in dolomite or limestone, and mainly in D_3zg and C_2w (defined in the previous paragraph).

Hydrogeological Conditions

The Maoping compression–torsion fault and Shimenkan anticline influence the spatial distribution of the groundwater levels in the mined area. There are dozens of secondary faults, which interlink and form an extremely complex hydrogeological network, as shown in Fig. 3. The fracture zones of the Maoping compression–torsion fault and the affected regions connect the karst aquifers with fissures, which creates a unified groundwater reservoir in the mined area.

The entire water-bearing system of the mined area consists of upper and lower water-bearing subsystems, which have three fissured karst aquifers and two fractured clastic rock aquifers. The sources of water for both the upper and lower water-bearing subsystems originate from the karst aquifers, with fissures in P_1q and P_1m in the north of the

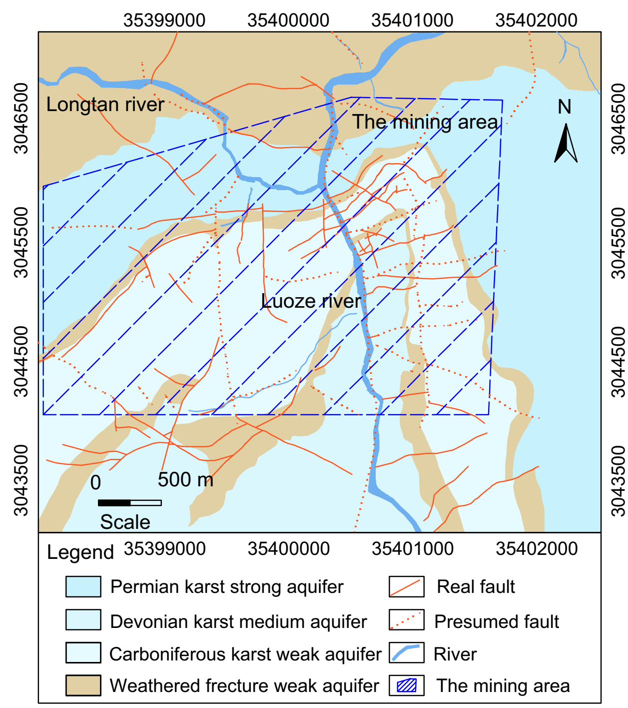

Fig. 3 Regional structure map of Maoping lead–zinc deposit

mined area, a lateral water source supply adjacent to the south of the mined area, and a small amount seepage from the Luoze River. According to the previous hydrological exploration that identified the groundwater inrush channels, the faults distributed in the sand and shale impermeable layers or aquicludes of the Liangshan Formation (P_1l) in the north are the main water infiltration channels into the Maoping deposit.

High Water Pressure Threatens Safety during Deep Mining

According to comprehensive geological data that have been collected for many years, the Maoping mine area is conducive to finding high quality ore from 310 m above sea level (masl) to 1000 m below sea level (mbsl), and is an important metal reserve for sustainable development of metal mining in the future. However, the deposit's complex hydrogeological conditions have caused high water pressures and the high risk of water inrush. The mined area comprises the east and west mining districts, which are bounded by the Luoze River. The unmined ore bodies are all found in the lowest erosional base of the river channel. During the wet season, it is anticipated that water inflow into the mine at 310 masl can reach 57,753 m^3/day, and can reach 63,327 m^3/day at zero elevation. As shown in Fig. 4, a high pressure water inrush occurred when mining was at 310 masl. The water pressure ranged from 4.5 to 6.5 MPa, while the inflow of water at the wellhead ranged from 15 to 400 m^3/h, and the safety of the miners was seriously threatened.

Two grout curtains were subsequently installed in the north and south of the mined area to cut off the main water flow channels. However, the mined area has high mountains and deep gorges, so it was not feasible to drill grout holes from the surface. Therefore, special roadways were built underground for the grouting process at 910 masl, and the drilling rig platforms were all placed in the roadway. Due to the structure of the mined area, the inclination angle of the fractures in the karst aquifers is mostly between 60° and 85°. If traditional vertical drilling had been used to install the grout curtain, the probability of fracture development in the strata to be grouted would have been very low, and the radius of the diffused zones of grouting would have been limited.

Therefore, a combination of different drilling methods was used, which consisted of vertical drilling, inclined drilling with low curvature, and S-shaped directional drilling to develop the fractures for grout seepage and ensure that the grout would be fully diffused (Fig. 5). The combined use of the different drilling methods was the key for ensuring successful implementation of curtain grouting in the Maoping deposit. The main technical specifications of the directional flexible drill rod is shown in Table 1. Details on the directional flexible drill rod are available in a Chinese patent submitted by the North China Engineering Investigation Institute Co., Ltd. (2016) called "Grout curtain drilling structure and construction technology" (ZL 201610964790.4).

Fig. 4 High pressure water inrush during drilling

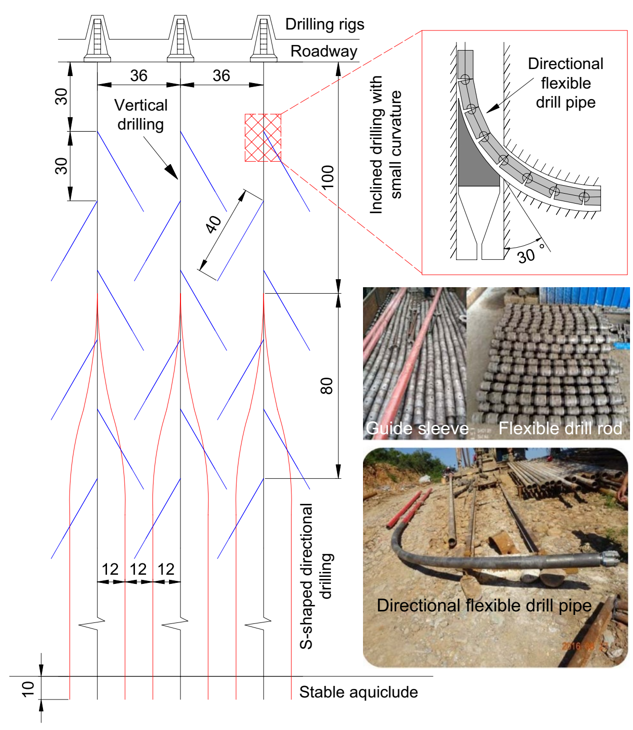

Fig. 5 Use of different drilling methods to install grout curtain in Maoping lead zinc mine (unit: m)

Table 1 Main technical specifications of flexible drill rod

External diameter (mm)	Inner diameter (mm)	Length to diameter ratio	Radius of curvature (m)	Bit pressure (t)	Bending direction	Tensile strength (t)	Ultimate torque (N m)
≤110	25–30	2–3	3–5	10	0°–360°	20	15,000

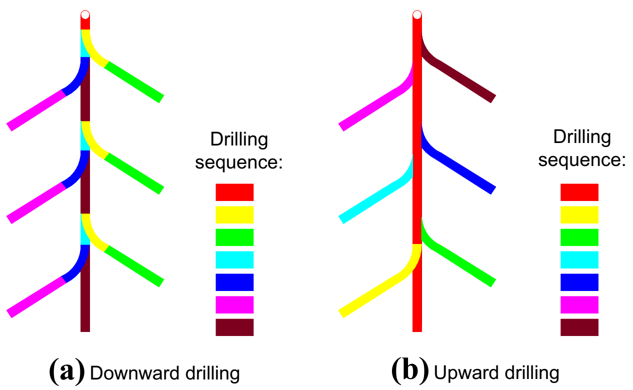

Fig. 6 Drilling sequences of vertical and inclined drilling methods **a** downward drilling; **b** upward drilling

Materials and Methods

Vertical Drilling and Inclined Drilling with Low Curvature

In view of the special formation structure of the Maoping lead–zinc deposit, there were three important reasons to use vertical drilling and inclined drilling with low curvature (hereafter, vertical and inclined drilling methods: (1) the spacing between drilled holes was increased, which reduced the cost and labour to drill the holes; (2) the number of sockets were reduced, which ensured roof stability in the roadway where the grout curtain was being installed; (3) the probability of fractures being exposed in the strata for grout seepage was greatly increased, thus increasing the effective sealing of the grout curtain against water seepage when the inclination of the drilled hole was at an angle of 30°, based on inclined drilling with low curvature. The primary tools used to carry out the vertical and inclined drilling methods are a flexible drill rod, guide sleeve, directional and traditional drill bits, inclinometer, and deflector (Fig. 5). Combined downward and upward drilling are used; the drilling sequence is shown in Fig. 6a, b.

The downward drilling process alternated vertical and inclined drilling in the grout curtain. When the vertical drilling reached the depth of the first branch drilling completed earlier, the traditional drill rod was replaced with a flexible drill rod. The directional and traditional drill bits were used respectively to construct the inclined and vertical sections of the grout curtain. After the first branch drilling was completed, high pressure grouting was performed. The cycle of vertical drilling, branch drilling, and high pressure grouting continued until the vertical drilling reached 10 m into the impermeable layer.

The upward drilling process consisted of vertical drilling and sectional grouting, followed by inclined drilling with low curvature from the bottom to the top of the grout curtain, as shown in Fig. 6b. The advantage of upward drilling with this method is that grouting can be carried out simultaneously after two or more holes are drilled by using inclined drilling with low curvature, while branch drilling carried out on one side of the roadway requires more elaborate procedures, as there are many factors that affect the precise drilling of the branch angles. Additionally, there are more risks during inclined drilling with low curvature, such as failure of the deflector and recovery of the flexible drill rod, stuck drill bits, etc.

S-shaped Directional Drilling

The reference point for the S-shaped directional drilling was about 100 m of vertical drilling, and the length of the directional drilling was about 80 m. Then the construction of the lower vertical section of the grout curtain was carried out. The adjacent spacing of the vertical section of the grout curtain was about 12 m (Fig. 5).

Grout

The Maoping lead–zinc deposit is located in the hinterland of the Yunnan–Guizhou Plateau, where red clay is abundantly found on the ground surface and is a good material for grouting (Fig. 7) (Yang and Yuan 2019). A certain amount of cement and sodium silicate are added to a red clay slurry to adjust the slurry fluidity, gelation time, strength, and permeability of the consolidation body. The density of the red clay slurry is 1.05×10^3–1.20×10^3 kg/m^3. The amount of cement added is 50–250 kg/m^3 of grout. The amount of sodium silicate is 3% of the mass of cement. The plasticity index of the red clay was at least 10, the clay content was at least 25%, the sand content was at least 5%, and the organic matter was at least 3%. Ordinary Portland cement with a cement strength grade of 42.5 MPa was used, and the specific surface area was at least 300 m^2/kg. Wet or hardened

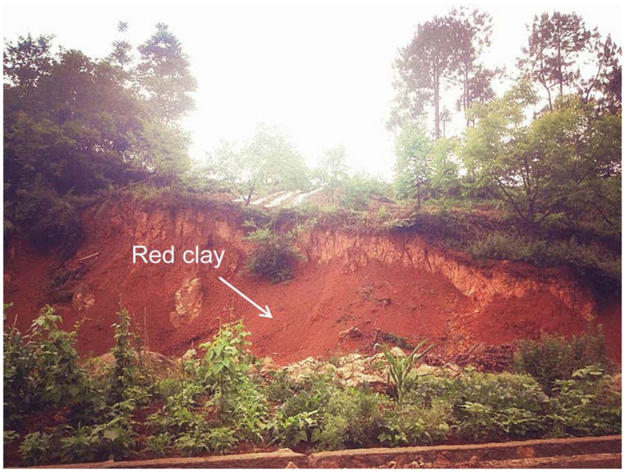

Fig. 7 Red clay widely distributed on the surface

cement should not be used. The sodium silicate ranged from 30–45° Baume, and the modulus was preferably 2.4–3.3. The slurry recipe needs to use impurity-free water for mixing, and the water temperature should not be less than 5 °C.

Results and Discussion

Inspection of Grouting Effect

Two boreholes were drilled for observation: NJ1 and NJ2. The water injection testing results for NJ1 and NJ2 are listed in Tables 2 and 3, respectively. The highest flow rate for each borehole was 0.75 Lugeon (Lu), of which 96.4% of the flow was less than 0.5 Lu. (Ed. Note: A Lugeon is defined as the loss of water in L/min/m of borehole at an over-pressure of 1 MPa). This indicates that the grout curtain of the tested section has good continuity and low permeability and meets the design requirements.

The drilling of NJ1 and NJ2 also showed that the high dip angle fractures were completely filled with slurry, and the radius of the diffused zones of grouting was 20–30 m (Fig. 8). Figure 9 shows the electrical resistivity values between NJ1 and NJ2; the resistivity was greater than 1500 Ω m, which means that the permeability of the strata was reduced.

There are four low-resistivity bands in Fig. 9 (indicated as Y1, Y2, Y3, and Y4), which are characterized by dark bands. They indicate the penetration of the grout into the formation; the resistivity value range from 500–1500 Ω m, which shows that the grouting was effective and met the design requirements.

Drilling Efficiency

During the grouting process in the inclined and vertical sections, a straight auger drill was used to carry out the drilling. It was found that, the pumping pressure increased rapidly with drilling depth in the early stages of drilling, which greatly reduced the service life of the auger screw and flexible drill rod. This was especially problematic after drilling to a depth of 30 m, as the drilling efficiency was reduced to 0.27 m/h.

The flexible drill rod was driven by the straight auger drill at drilling at depths that did not exceed 30 m. However, since the use of both the straight auger drill and water pump for a long period of time at a high pumping pressure would greatly reduce the service life of the drill, when the drilling

Table 2 Water injection test results for NJ1

Tested section around borehole	Roof elevation (m)	Floor elevation (m)	Thickness of stratum (m)	Flow rate of borehole (Lu)
NJ1-1	849.59	820.04	29.55	0.48
NJ1-2	820.04	800.44	19.60	0.75
NJ1-3	800.44	770.89	29.55	0.42
NJ1-4	770.89	739.95	30.94	0.39
NJ1-5	739.95	708.59	31.36	0.29
NJ1-6	708.59	680.29	28.30	0.33
NJ1-7	680.29	650.29	30.00	0.28
NJ1-8	650.29	619.59	30.70	0.31
NJ1-9	619.59	594.79	24.80	0.22
NJ1-10	594.79	564.59	30.20	0.24
NJ1-11	564.59	535.36	29.23	0.22
NJ1-12	535.36	505.36	30.00	0.19
NJ1-13	505.36	469.36	36.00	0.17
NJ1-14	469.36	432.29	37.07	0.14
Entire hole	895.24	432.29	462.95	0.03

Table 3 Water injection test results for NJ2

Tested section around borehole	Roof elevation (m)	Floor elevation (m)	Thickness of stratum (m)	Flow rate of borehole (Lu)
NJ2-1	849.65	820.25	29.40	0.45
NJ2-2	820.25	790.05	30.20	0.42
NJ2-3	790.05	759.65	30.40	0.37
NJ2-4	759.65	730.65	29.00	0.39
NJ2-5	730.65	699.65	31.00	0.31
NJ2-6	699.65	669.65	30.00	0.27
NJ2-7	669.65	640.15	29.50	0.28
NJ2-8	640.15	610.25	29.90	0.24
NJ2-9	610.25	579.51	30.74	0.24
NJ2-10	579.51	550.03	29.48	0.26
NJ2-11	550.03	520.68	29.35	0.29
NJ2-12	520.68	490.48	30.20	0.23
NJ2-13	490.48	460.07	30.41	0.24
NJ2-14	460.07	431.99	28.08	0.22
Entire hole	849.65	431.99	417.66	0.02

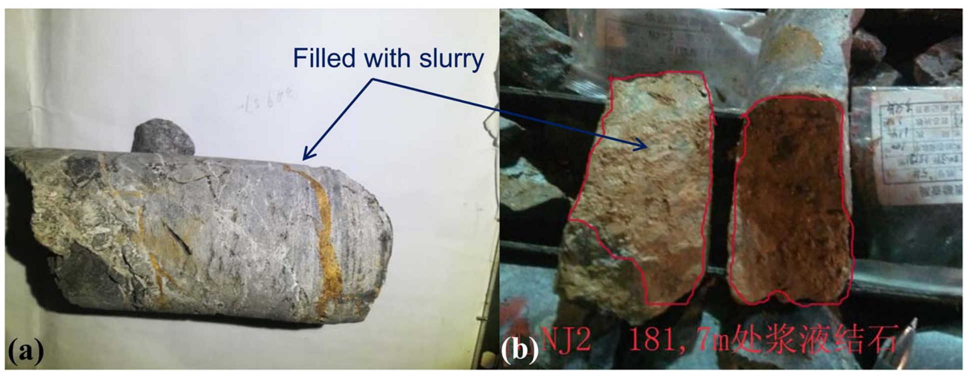

Fig. 8 Drilling carried out to reveal grouting quality: NJ1 and NJ2 **a** sample from NJ1 taken at depth of 349.6 m, **b** sample from NJ2 taken at depth of 181.7 m

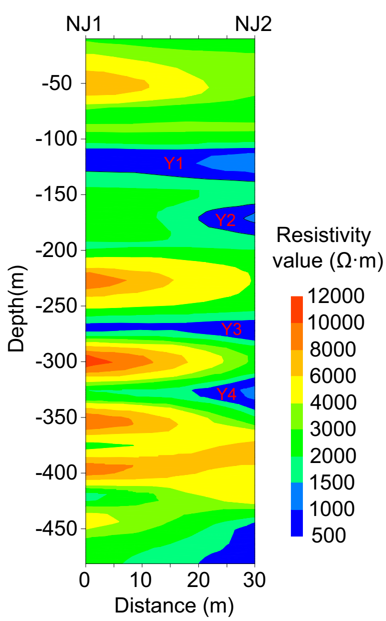

Fig. 9 Resistivity contour plot: NJ1 vs. NJ2

depth of the branches exceeded 30 m, the flexible drill rod was used along with a rotary table to help the drilling. This was less demanding on the water pump, ensured the proper rotation speed, and increased drilling efficiency (Table 4).

Conclusions

This paper has presented a study in which different drilling methods were combined for executing curtain grouting in a deep Maoping lead–zinc underground mine in southwestern China. A full analysis of the regional tectonic framework and the geological and hydrogeological conditions of the Maoping lead zinc mine showed that the regional tectonic fabric is characterized by a complex array of dominantly northeast-striking faults, along with developed fractures with a high dip angle, and high water pressure with mined depth. The use of a combination of different drilling methods (vertical drilling, inclined drilling with low curvature and S-shaped directional drilling) facilitated underground

Table 4 Drilling efficiency with different drilling methods

Drilling method	Depth of drilling (m)	Weight of bit (t)	Pump pressure (MPa)	Pump capacity (L/s)	Rate of drilling speed (m/h)
Auger screw	3–32.79	1.2–1.8	6.5–7.5	9.6–10.4	0.91
Auger screw	3279–34.05	1.4-2	6.5–7	9.3–9.6	0.2
Rotary table	34.05–35.55	1.6–1.8	5.5	10.6	1.3
Auger screw	35.55–36.77	1.6–1.8	7–8	9.1	0.27
Rotary table	36.77–40.1	1.6–1.8	6.0	10.6	0.69

drilling and grouting. The fractures with a high dip angle were revealed and filled with slurry, and the radius of the diffused zones of grouting was greatly increased. Finally, the study showed that the grout curtain has good stability and low permeability. Using a combination of different drilling methods thus increased the safety of miners and sustainable exploitation of deep mine resources in the Maoping lead zinc deposit.

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