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TECHNICAL ARTICLE

The Influence of a Loose Layer Water Cut-off Curtain on the Slope Stability of Open-pit Coal Mines

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Abstract

Water-rich open-pit mines can have problems with large water inflows, slope reinforcement difficulties, and hazardous mining risks. The construction of a water cut-off curtain to control groundwater in the loose layer of an open-pit mine can effectively reduce the amount of water that must be pumped and eliminate the problem of flooding in the pit. However, the rise of the water level outside the curtain and changes in the geotechnical properties of the slope's material will affect the stability and safety of the pit's slope. A computational model was constructed and limit equilibrium and numerical simulation methods were used to determine the influence of a water cut-off curtain on the stability of the slope. Results show that with the the water cut-off curtain, the water level outside of the cut-off curtain in the loose layer of the open-pit mine continues to rise and the hydrostatic pressure and horizontal thrust of the slope body increases. As a result, the sliding force of the slope increases and the resisting force decreases, ultimately lessening the slope- stability coefficient (factor of safety) of the open pit. If the construction position of the curtain is moved outward, the stability coefficient of the slope will increase, assuming that the water level outside the curtain remains unchanged. Conversely, if the position of the curtain is moved toward the pit, the stability coefficient of the slope will decrease. The maximum shear stress on the slope increases as the water level outside the water curtain rises. The maximum shear stress is mainly concentrated at the toe of the slope of the first bench below the surface and at the interface between the curtain and the bottom of the loose material. If designed properly, the water curtain can control the water table in the slope's material, maintaining the stability of the slope.

Keywords Open-pit coal mine · Loose layer · Water cut-off curtain · Slope · Stability coefficient · Factor of safety

Introduction

China is rich in mineral resources and has a large number of mines. Open-pit mining has the advantages of high resource recovery rate, short infrastructure period, large mining area, high labor productivity, low mining cost, and high safety factor. However, slope-stability problems and water flooding can occur. There are more than 200 water-rich open-pit mines in China, of which more than 50 have a dewatering capacity of more than 30,000 m^3/d (Han 2021). Poor groundwater control and improper slope treatment in water-rich open-pit mines can easily cause landslides, resulting in economic losses and casualties, and seriously restricting production and development (Han 2021).

For the slope safety issue of open-pit mines, scholars in China and abroad mainly conduct research and analysis from theoretical calculations, numerical simulations, field monitoring, and engineering analogies. Given the increasing importance of stability analysis of open-pit slopes and in combination with the practice of slope engineering at the Manaoke open-pit mine, Zhang et al. (2010) used the strength reduction method and the fast Lagrangian analysis of continuum (FLAC) numerical simulation software to analyze open-pit slope stability. Case histories of slope instability with analysis of their features have also been investigated (Unoo 2018). A base friction testing method was proposed for the analysis of mining models in an open-pit slope, and a new method was proposed that combines digital image correlation and particle image velocimetry techniques to

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analyze the entire deformation process (Zhang et al. 2023). Whittall (2020) presented a dataset of 167 bench-scale open-pit slope failures, and tested runout and bench-width sizing methods to identify appropriate tools for estimating a stand-off distance from a fresh bench face. Shang et al. (2022) used the simplified Bishop method to analyze the slope stability of an open-pit coal mine with the limit equilibrium analysis method. Vanneschi et al. (2018) investigated landslide failure mechanisms adjacent to lignite mining operations in North Bohemia (Czech Republic) through a limit equilibrium/finite element modeling approach, which reduced system uncertainty and provided an improved understanding of the landslides under study. Importantly, two separate failure mechanisms were identified from the analyses performed and verified through comparisons with inclinometer data and field observations. Renani and Martin (2020) proposed a new relationship for estimating the appropriate range of confining stress for slope analysis. This would improve the conversion of Mohr–Coulomb and Hoek–Brown criteria for slope analysis and could also be used to bound the range of relevant stresses in laboratory experiments and numerical model calibration.

Most open-pit mines with water inflows lower groundwater to a reasonable level by pumping to ensure safe open-pit mining. As a result, the amount of water pumped from the mine pits can be as great as tens of thousands of m^3 to hundreds of thousands of m^3/d (Liu 2020; Wang 2018). The pumping of groundwater in open-pit mines wastes groundwater resources and causes ecological damage around the mines, resulting in the decline of groundwater levels, water quality pollution, land degradation, and reduced vegetative cover. The source of recharge of water gushing into open-pit mines can be reduced by constructing water cut-off curtains at the main water crossing channels or water crossing sections in open-pit mines (Dong et al. 2021; Huang et al. 2020; Wang et al. 2020b). Loose layer cut-off curtains can effectively reduce the amount of water pumped in the open pit and stop the downward trend of the groundwater level, thus protecting groundwater resources in and around the mine area (Wang et al. 2020a; Zhang et al. 2020).

Statistics from the 2010s show that there were nearly 2,000 landslide accidents in open-pit mines in China, ranking third in the number of safety accidents in open-pit mines in China and accounting for 15% of the total number of accidents (Han 2021). Table 1 provides statistics on some of the slope failures in open-pit mines in China in recent years. The large number of casualties and economic losses have had a major negative impact on companies and society.

A water cut-off curtain in the loose layer of an open-pit coal mine blocks the hydraulic connection between the pit and the outer loose layer and can reduce the amount of water pumped. However, it is unclear whether a water cut-off curtain adversely affects the slope stability of an open-pit coal mine. By analyzing the influence of the loose layer's water cut-off curtain on the stability of the slope of the open-pit coal mine, this study provides a reference for the selection of the groundwater control technology and the stability of slopes in similar open-pit mines.

Table 1 Statistics of landslide accidents in some open-pit mines in China

No	Location	Time	Accident consequence
1	Jianshan Iron Mine in Taiyuan City	2008.8.1	45 people were killed, one injured, direct economic loss RMB 30,802,300
2	Jiweishan Iron Mine, Wulong County, Chongqing	2009.6.5	26 people were killed, 61 others were missing, and about 2 million m^3 of land collapsed
3	Unauthorized rare earth mining, Dapo Town, Cangwu County, Guangxi	2011.11.26	9 people were killed
4	An iron ore mine in Xinyuan, Yili	2012.7.30	2 people were killed and 28 are missing
5	Nanlou Town Yu County,Yangquan City,	2013.1.19	A transport truck crashed into a mine
6	Jiama Mining area, Tibet Autonomous Region	2013.3.29	83 people were buried and more than 2 million cubic meters of land collapsed
7	Jinlong She Ying porcelain clay company, Heyuan City	2014.5.22	6 people were killed and 1injured
8	Feishuling Mine, Maoming City	2015.1.18	1 person was buried and another injured
9	open-pit mine of Baota Oil Shale Company, Chifeng City	2015.8.3	6 workers were buried
10	A limestone mine in Chaiwopu, Urumqi City	2015.12.31	2 people were buried
11	A Quarry of Fachong Village, Hongta District, Yuxi City	2016.9.6	1 person was killed and another injured, and about 50,000 m^3 of land collapsed
12	Jinneng Group Lv Xin coal industry	2017.8.11	8 people were killed, one is missing and one is injured
13	Hun Yuan Baichuan coal industry, Datong City	2018.6.24	2 people were killed
14	A mine in Gongshan Town, Bazhong City	2021.8.13	1 people was killed
15	Hongsheng Coal Industry, Jingtai County, Gansu Province	2022.7.23	10 people were killed and six injured

Materials and Methods

Study Area

The Yuanbaoshan open-pit coal mine (Fig. 1) is 35 km east of Chifeng City, in the Inner Mongolia Autonomous Region. The surface water system near the Yuanbaoshan Mine includes the Laoha and Yingjin Rivers, both of which are perennial. The Yingjin River is 194.6 km long, with a watershed area of 10,598 km^2, a maximum annual flood discharge of 2650 m^3/s, a total multi-year average discharge of 4.02×108 m^3, and a multi-year average volumetric discharge of 12.8 m^3/s. The Yingjin River originally flowed through the mine's location, dividing it into two parts: northeast and southwest, but was diverted before mining of the Yuanbaoshan open-pit. The Yingjin River is now located on the north side of the mining area; the riverbed is 200 to 900 m wide and the water depth is 0.25 to 0.60 m. The Yingjin River is the largest tributary on the left bank of the Laoha River and joins the Laoha River at Dongbajia. The Laoha River has a total length of 421.8 km, a watershed area of 33,067 km^2, a maximum annual flood flow of 9840 m^3/s, a multi-year total average discharge of 4.297×108 m^3, and a multi-year average volumetric discharge of 13.6 m^3/s. The Laoha River flows from southwest to northeast through the southern part of the river valley plain, 3 km from the Yuanbaoshan Mine.

The Yuanbaoshan open-pit coal mine has been operating since 1990, mining the no. 5 and 6 coal seams. The annual production capacity is about 10.0 Mt, forming a pit that is 3500 m long, 3000 m wide, and about 195 m deep. The northern slope of the open pit is the working slope and the south is the temporary working slope, with six to seven single-bucket excavator stripping steps.

As shown in Fig. 2, the stratigraphy of Yuanbaoshan open-pit coal mine is mainly sandy soil, rounded gravel and sand, a pebble layer, weathered sandstone, fine sandstone, coal, and mudstone. The grain size of the rounded gravel is 50 to150 mm, and the permeability coefficient of the loose layer of the Fourth Series is 127 to 700 m/d. Influenced by the Yingjin and Laoha Rivers, the main water source of the Yuanbaoshan open-pit coal mine is the Fourth Series aquifer. Lateral recharge from the rivers accounts for about 95% of the pit water.

The amount of water being pumped in the early stages of the Yuanbaoshan Mine reached 5,00,000 m^3/d, and in 2020, it was still 1,84,000 m^3/d. The groundwater pumping and dewatering extracts a large amount of groundwater, thus sharply lowering the groundwater level around the open-pit mine. This results in a serious waste of groundwater resources and deteriorates the ecological environment. To address these problems, a continuous lateral water cut-off curtain was constructed between the mine and the river. As shown on Fig. 3, a long, narrow, deep trench was excavated underground using large trench-forming machines such as double-wheel mills or hydraulic grabs on the loose layer of soil between the pit and the outer river. The deep trench was protected by a mud wall during excavation. When the excavation reached the design depth, the bottom of the trench was cleaned and then concrete was poured into the excavated trench using the conduit method to form a continuous concrete wall. The continuous constructed wall blocked the hydraulic connection between the loose layer of Quaternary material and the trench.

The water cut-off curtain at the pit boundary was constructed along the first slope bench of the existing pit in the Yuanbaoshan Mine to intercept water outside of the pit and minimize the amount of water inside the pit. As shown in Fig. 4, the water cut-off curtain extends from the bedrock outcrop at the southern end of the pit to the Yingjin River, with a length of ≈ 3665 km, a width of 0.80 m, and a depth of 22.00 to 70.00 m. The water cut-off curtain is made of an impermeable membrane and impermeable concrete material. The permeability coefficient of the impermeable membrane is 10^{-13} cm/s, and the strength of the impermeable concrete is 10 MPa, with a permeability coefficient of 10^{-7} cm/s. The combined impermeability coefficient of the two is 10^{-10} cm/s. The cost per meter of the cut-off curtain with a depth of 50.00 m and a width of 0.80 m was about 40,000 RMB.

The water level in the loose Quaternary layer outside of the curtain rose 8.18 to 9.12 m after construction of the curtain was completed; the water level in the loose layer inside the curtain was lowered by 6.84 m compared to the original water level. The water-level difference between the inside and outside of the curtain was as great as 15.02 to 15.96 m. The volume of water flowing into the pit was reduced by 70,000 m^3/d compared to before construction of the curtain. This shows that the water cut-off curtain had a major effect on water inflows and effectively protected the groundwater resources in the open-pit area. At the same time, it was necessary to further analyze whether the increased water level outside of the curtain might have affected the stability and safety of the slope of the open-pit mine.

Research Methods

A slope-stability calculation model was constructed to identify the influence of the water cut-off curtain on slope stability and safety in the loose layer of Yuanbaoshan Mine. The model was constructed by using the limit equilibrium and numerical simulation methods to study the stability coefficients of the slope of the open-pit coal mine under the condition of the water cut-off curtain.

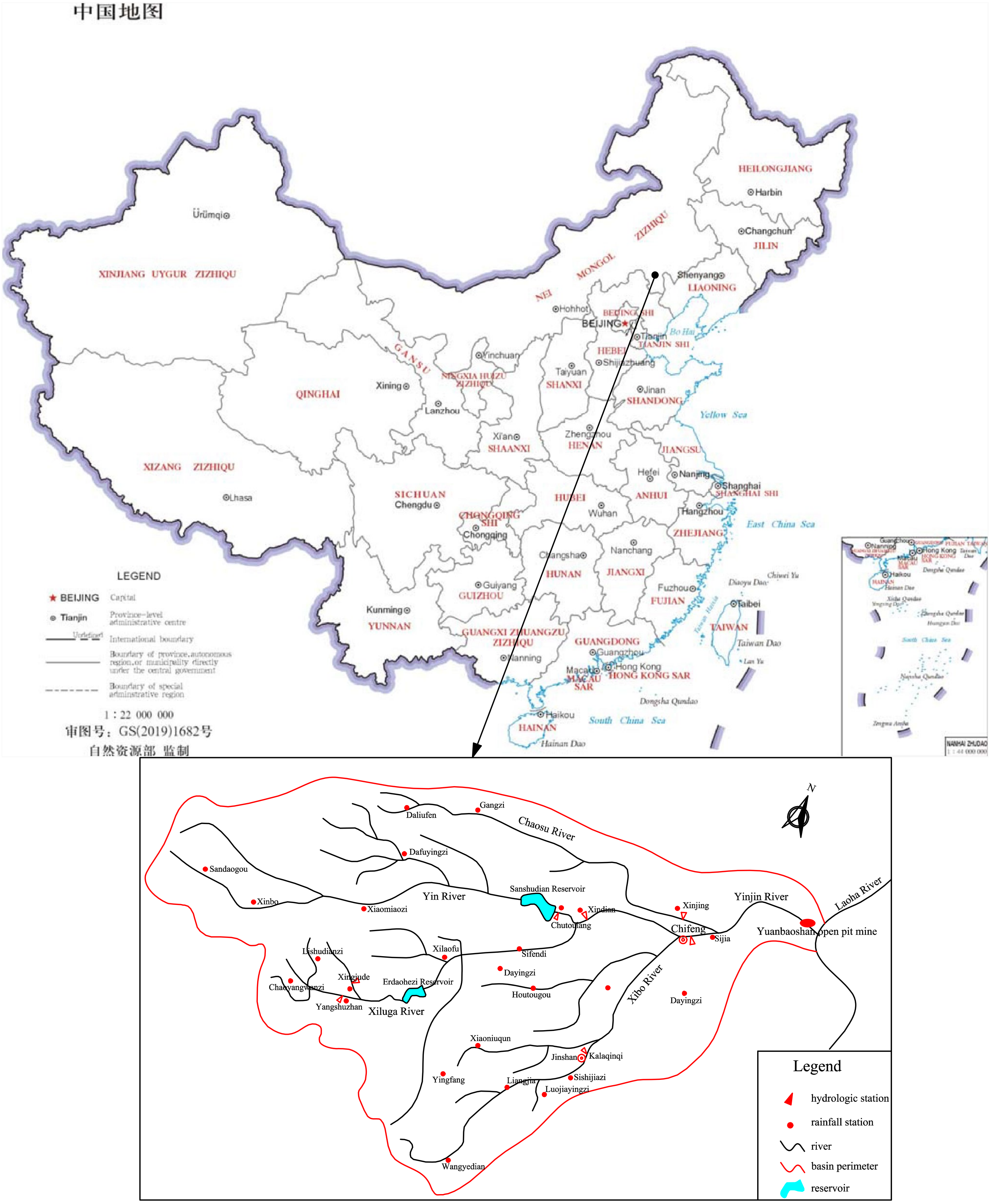


Fig. 1 Location of the Yuanbaoshan open-pit coal mine

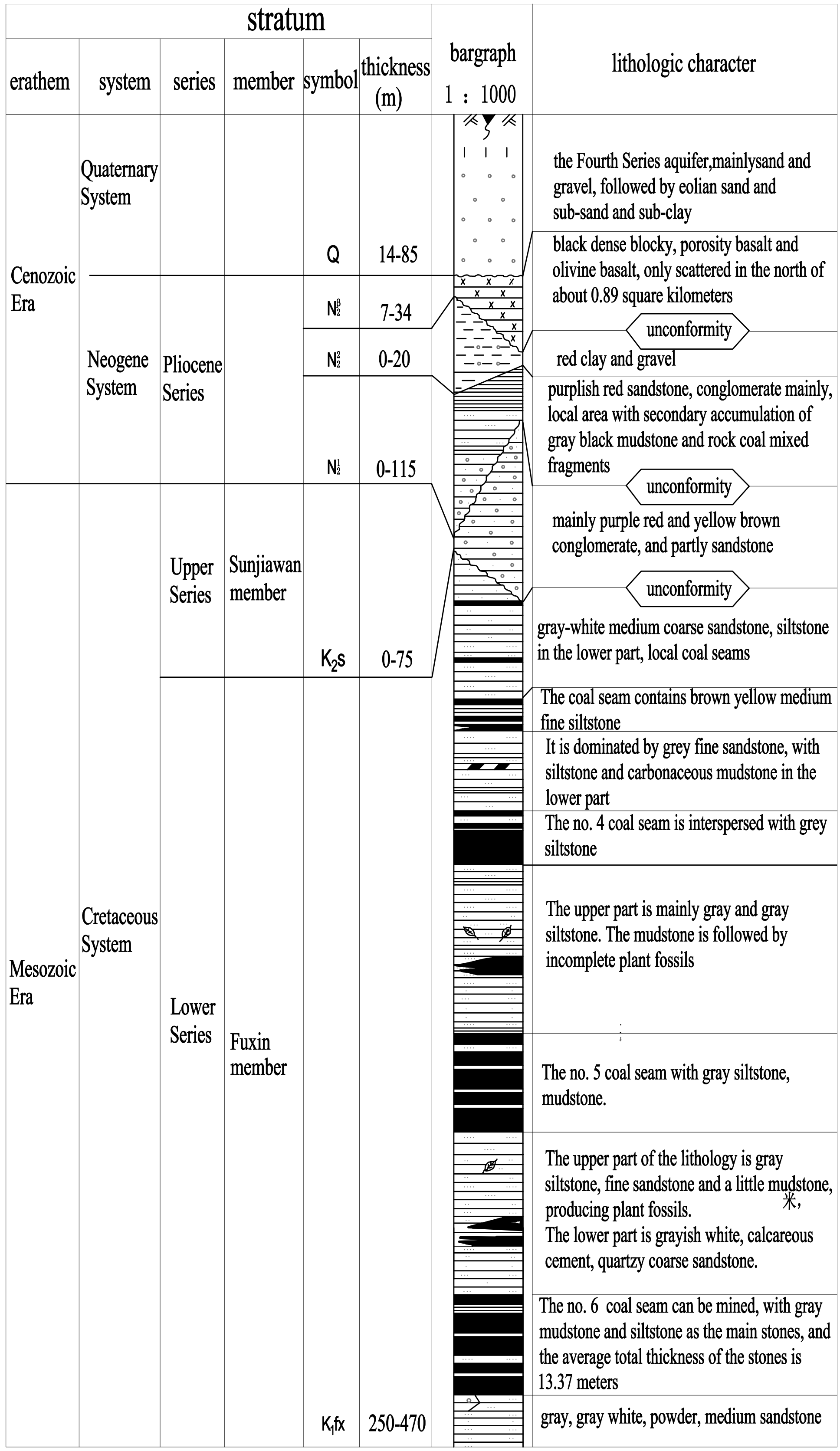


Fig. 2 Column chart of strata in the Yuanbaoshan open-pit coal mine

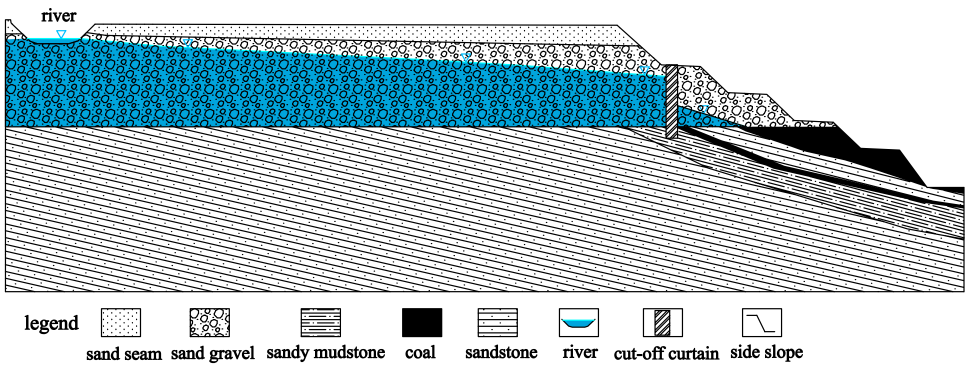


Fig. 3 Schematic of water cut-off curtain in open-pit coal mine

Fig. 4 Top view of Yuanbaoshan open-pit coal mine and cut-off curtain (shown in red)

Model Construction

Based on the geological engineering conditions of the Yuanbaoshan open-pit coal mine, the slope profile shown in Fig. 5 was described. The slope profile from top to bottom is composed of Quaternary sandy soil, a sand and gravel layer, Neoproterozoic sandstone, Jurassic no. 5 coal, sandstone, no. 6 coal, mudstone, and sandstone.

The pre-construction parameters of the geotechnical body of the Yuanbaoshan open-pit coal mine were studied and analyzed. Then, this was compared with the physical and mechanical indexes of the geotechnical body of information for the stratigraphy for the Yuanbaoshan Mine. The test results of the physical and mechanical parameters of the sandy soil, sand and gravel layer, fine sandstone, coal, sandstone, and mudstone layers are shown in Table 2. The slope profile of the Yuanbaoshan open-pit coal mine (Fig. 5), was

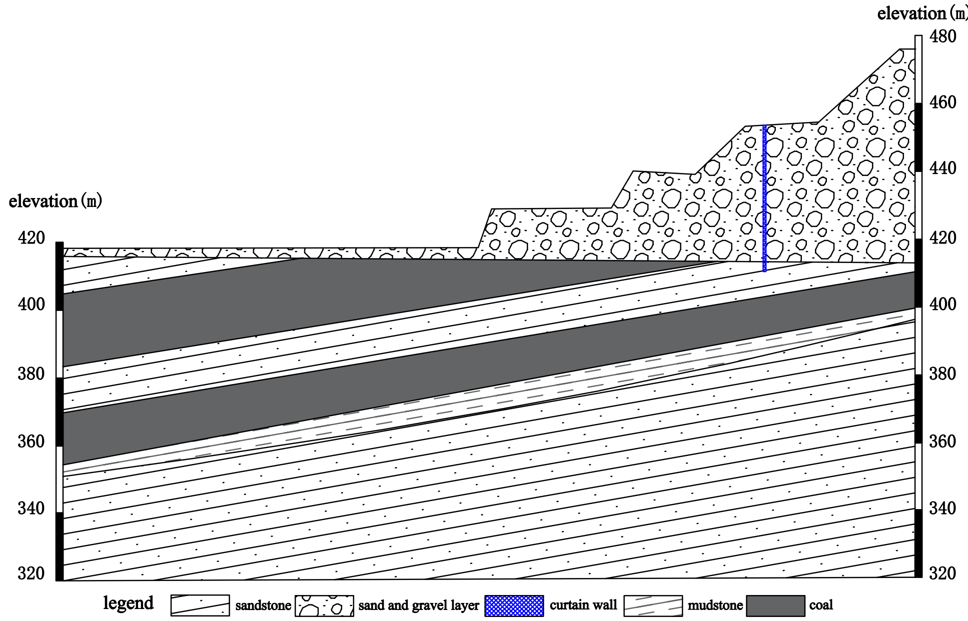


Fig. 5 Cross section of the Yuanbaoshan Open-Pit Coal Mine

simplified into a slope-stability calculation model (Fig. 6), with a first-level bench width of 16 m and an overall slope angle of 25°.

Limit Equilibrium Method

The geotechnical body of the slope of the Yuanbaoshan open-pit coal mine is mainly a Quaternary sand and gravel layer and soft rock, which has the characteristics of bulk structure. The Morgenstern-Price method based on the limit equilibrium theory was used to eliminate errors in the calculation method by considering all of the equilibrium conditions and boundary conditions at the same time. The stability of the slope was calculated and analyzed using Lizheng Geotechnical Calculation Software.

In the systematic calculation and analysis of the slope-stability coefficient (factor of safety) of the Yuanbaoshan open-pit coal mine after implementation of the water cut-off curtain, the difference between the water level inside and outside the water cut-off curtain and the position of the curtain wall were considered, in addition to the thickness of the water cut-off curtain itself (0.80 m). Three specific working conditions were taken into account.

1) ***Condition 1***. Before construction of the water curtain.
2) ***Condition 2.*** Different water-level elevations outside the curtain: ① the water level outside the curtain is raised to 448 m, ② the water level outside the curtain is raised to 452 m, and ③ the water level outside the curtain is raised to 462 m. The water level line inside the wall is at the bottom of the loose layer of the Quaternary system (sand and gravel).
3) ***Condition 3.*** The water level outside the curtain is restored, with different curtain positions: ① the curtain is located 10 m from the foot of the first bench slope, ② the curtain is located 1 m from the foot of the first bench slope, ③ the curtain is located 15 m from the foot of the first bench slope.

Numerical Modeling

Midas GTS geotechnical and tunneling simulation and analysis software was used to create a numerical model of the open-pit slope (Fig. 7). According to the requirements of calculation accuracy, the grid size of the whole geometric model of the slope was divided by 1 m and the curtain wall was divided by 0.4 m. A quadrilateral cell grid pattern was adopted, with a total of 38,203 cells.

The model calculation process adopted the Mohr–Coulomb strength criterion. The maximum number of iterations was set to 15 and a displacement convergence criterion was adopted. The strength reduction method was used to calculate the slope damage criterion and the reduction of the slope stability factor. The strength reduction method was used to gradually reduce the cohesion, c, and internal friction angle, φ, of the slope's geotechnical body during the simulation until the numerical solution converged.

The numerical simulation process considered two aspects: first, the increase of lateral pressure on the cut-off curtain by the high water table, and second, the weakening effect of water on the mechanical properties of the geotechnical body's slope.

Table 2 Physical and mechanical parameters of rock and soil mass of slope in the Yuanbaoshan open-pit mine

Formation age	Rock and soil type	Moisture content (%)	c(kpa)		φ(°)		E(MPa)		Poisson ratio		γ(kN/m^3)	
			Natural	Saturated	Natural	Saturated	Natural	Saturated	Natural	Saturated	Natural	Saturated
Quaternary system	Sandy soil		0	0	37.6	23.3	10.2	11.4	0.32	0.35	22.2	24.2
	Sand and gravel layer		8.9–27.0	2.7–8.1	31.9–34.8	26.1	18.8–24.4	15.6–20.3	0.25	0.28	18.4	24.8
Neoproterozoic	Fine sandstone		120.0	33.6	25.0	19.8	550.0	407.0	0.30	0.32	20.0	22.8
Jurassic systerm	Coal	20.1	60.0	16.2	31.0	20.2	600.0	402.0	0.29	0.33	13.1	17.7
	Fine sandstone	13.0	173.0	60.6	27.0	21.6	880.0	695.0	0.25	0.27	21.1	23.6
	Mudstone	11.5	109.0	10.2	24.7	19.2	500.0	380.0	0.35	0.39	21.1	25.7
	Weak layers	16.5	2.2	0.6	10.9	2.3	20.0	12.0	0.45	0.48	18.0	21.2

Results and Discussion

The results of calculating the slope-stability coefficient by the limit equilibrium method are shown in Table 3. Before implementation of the water cut-off curtain in the Yuanbaoshan open-pit coal mine, the groundwater level was controlled mainly by pumping, and the stability coefficient (i.e. FoS) of the slope of the open-pit mine was 1.47.

After the water cut-off curtain was simulated at a distance of 10 m from the foot of the slope on the first bench level, the water level on the outside of the curtain was gradually raised from 448 to 452 m and then to 462 m. At this time, the calculated stability coefficient of the slope of Yuanbaoshan Mine decreased from 1.43 to 1.42 and 1.28. The slope-stability coefficient decreased as the water level outside of the curtain was raised.

As shown in Table 3 and Fig. 8, when the water level outside the curtain of the Yuanbaoshan Mine was unchanged, the calculated slope-stability coefficient reflected the distance of the curtain position from the foot of the slope of the first stage bench. The slope stability coefficient increased as the curtain position moved toward the outside of the mine and decreased when the position of the water curtain moved toward the inside of the pit. When the distance between the position of the water curtain and the foot of the first bench was fixed, the slope stability coefficient decreased with the height of the water level outside of the water curtain. Under the three working conditions, the calculated slope-stability coefficient of the Yuanbaoshan open-pit coal mine was > 1.25, which meets China's current technical standards. This indicates that the slope of the Yuanbaoshan Mine is stable as a whole. (Li and Xu 2020; Zhang et al. 2016).

From the numerical simulation results of the effect of the water cut-off curtain on slope stability, the slope-stability coefficient decreased as the water level outside the curtain was increased from 448 m to 452 and 462 m. These results are consistent with the calculated results using the limit equilibrium method.

As the water level outside the curtain continued to rise, the maximum shear stress on the slope as a whole tended to increase. The maximum shear stresses were mainly concentrated at the toe of the slope of the first bench below the surface and at the interface between the water curtain and the floor of the Quaternary system's loose layer. The maximum shear stress of the slope did not change much, and the shear stress generated by the water interceptor curtain itself was mainly distributed in the middle and lower-middle parts of the slope.

As the water level outside the curtain continued to rise, the slope of the third and fourth level bench showed plasticity, and the stability coefficient of the slope continuously

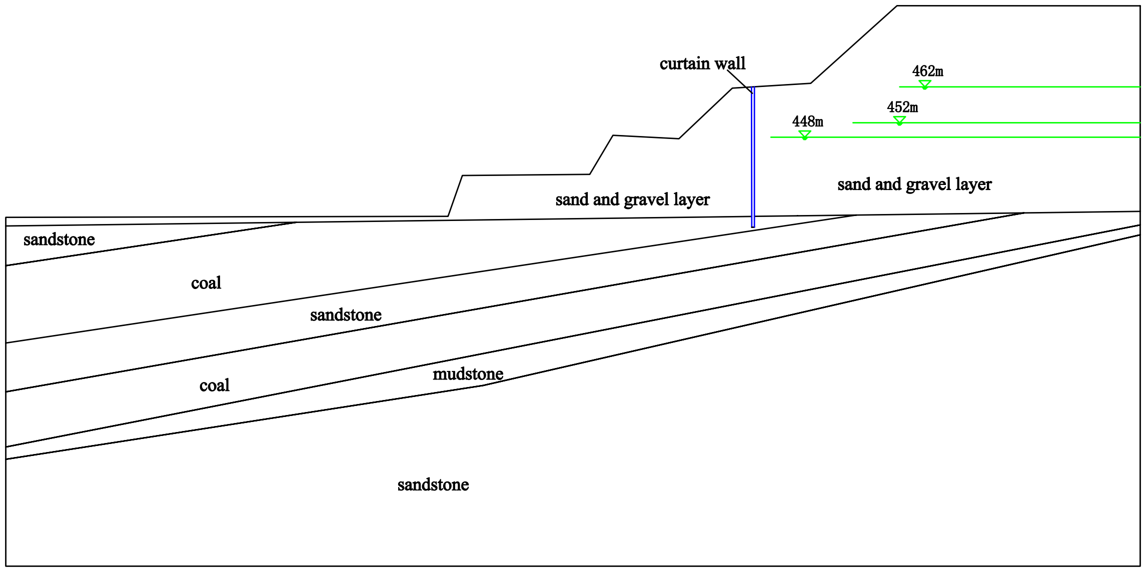
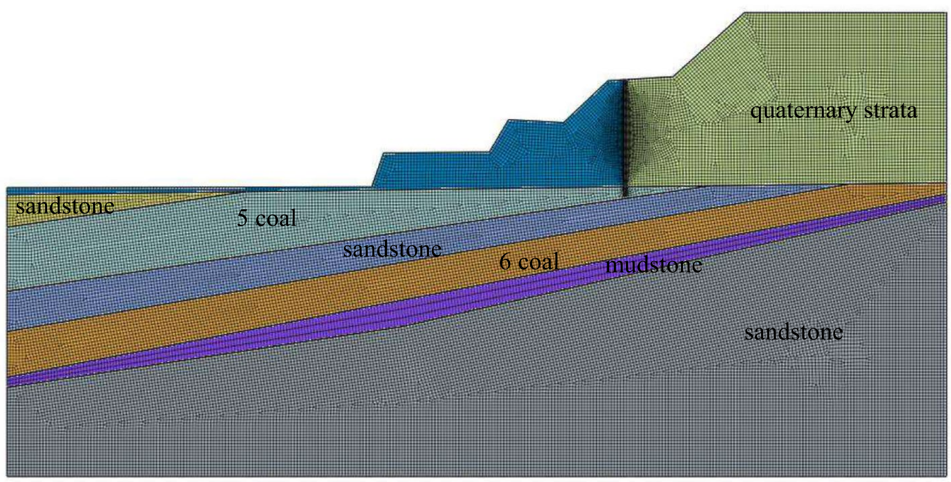


Fig. 6 Slope-stability calculation model of the Yuanbaoshan open-pit coal mine

Fig. 7 Slope model cell meshing



decreased. When the water level outside the curtain rose to 462 m, it was difficult to form a large potential slip surface on the slope, and there was only a possibility of partial slip at the slope entrance of the fourth level bench. The water curtain was outside the potential slip surface, so the curtain and slope are predicted to be safe.

The water cut-off curtain caused the water level of the loose layer outside of the curtain to increase, which decreased the mechanical properties of the slope's geotechnical body. Meanwhile, the water level of the loose layer inside the curtain was lowered, and the mechanical properties of the inner geotechnical body improved. The water level inside and outside of the cut-off curtain were obviously different, which subjects the curtain to the joint action of water pressure and geotechnical pressure, which increases the sliding force and decreases the resisting force of the slope, thereby decreasing the stability coefficient of the mine slope. The water level outside of the cut-off curtain should be maintained at a suitable level to ensure that the cut-off curtain and slope-stability coefficient both meet the relevant technical requirements. In this way, construction of the curtain can effectively reduce the amount of pumping required, raise the groundwater level, protect the surface ecological environment, and maintain slope stability.

Conclusions

A water cut-off curtain constructed in the loose layer of the Yuanbaoshan open-pit coal mine can raise the groundwater level outside the cut-off curtain, reduce the amount of water that must be pumped from the mine pit, and protect

Table 3 Influence of water cutting curtain and water level on slope stability in the Yuanbaoshan Mine

No	Working condition			Slope stability coefficient
1	Before the construction of the water curtain			1.47
2	Different water levels outside the curtain	Water level outside the curtain (m)	Water level inside the curtain	
		448	Quaternary system floor	1.43
		452	Quaternary system floor	1.42
		462	Quaternary system floor	1.28
3	Different water levels outside the curtain + Different curtain position	Water level outside the curtain (m)	The distance the curtain moves outward the mine (m)	
		448	9	1.50
		452		1.48
		462		1.39
		448	−5	1.41
		452		1.34
		462		1.27

groundwater resources. However, raising the water level outside the cut-off curtain increases the water content of the geotechnical body of the slope and increases the hydrostatic pressure and horizontal thrust of the slope body, resulting in an increase in the sliding force of the slope and decreasing the resisting shear force, which ultimately reduces the slope's stability coefficient (factor of safety).

When the distance between the position of the water cut-off curtain and the foot of the first bench is fixed, the slope stability coefficient decreases as the water level increases outside of the water cut-off curtain. Assuming a consistent water level outside of the curtain of Yuanbaoshan coal mine, the slope-stability coefficient increases when the position of the cut-off curtain is moved toward the outside of the mine and decreases as the position of the water curtain shifts toward the inside of the mine.

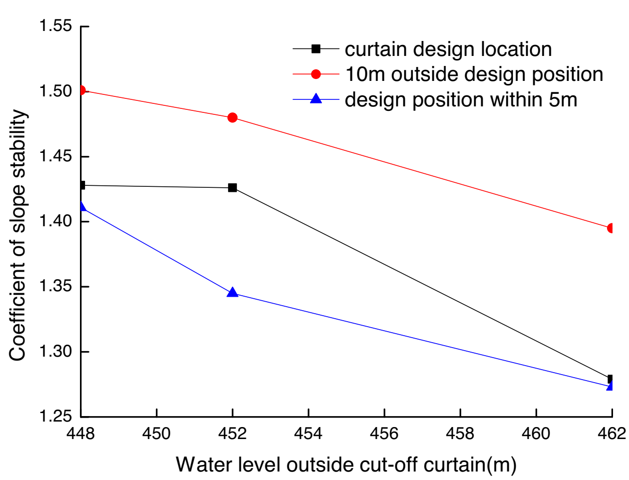


Fig. 8 Influence of water cut-off curtain and water level on slope stability in the Yuanbaoshan Mine

In general, the maximum shear stress on the slope tends to increase as the water level outside the water cut-off curtain rises and the slope-stability coefficient decreases. The maximum shear stress is mainly concentrated at the slope toe of the first bench below the surface and at the junction between the water cut-off curtain and the Quaternary system floor.

During the design and implementation of a water cut-off curtain project in an open-pit mine, the water level outside the curtain should be maintained at an appropriate level to keep the slope-stability coefficient within a safe range and ensure the stability of the mine slope. Thus, a balance between protecting groundwater resources and ensuring slope stability in an open-pit mine can be achieved.

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Data availability The data that support the findings of this study are available on request from the corresponding author (wanghai3777@163.com) upon reasonable request.

References

Dong SN, Wang H, Huang XM, Wang H, Cao HD, Wang XD, Zhang Y, Miao HC (2021) Research on active water conservation technology in open-pit coal mine based on ecological protection groundwater level. Coal Sci Technol 49(4):49–57 **(in Chinese)**

Han LQ (2021) Research on stability analysis method and treatment technology for water-rich open-pit mine slope in sandy gravel strata. Univ of Sci Technol Beijing 1–4:107–142 **(in Chinese)**

Huang XM, Zhang Y, Li WS, Tian ZL (2020) Summary of water disaster characteristics and water prevention and control technology in open-pit coal mines in China. Coal Geol Explor 48(4):53–60 **(in Chinese)**

Li MM, Xu YC (2020) Landslide treatment in south slope of Zhahanao'er open-pit coal mine. Opencast Min Technol 35(1):71–75 **(in Chinese)**

Liu HX (2020) Research on groundwater control of Xie'ertala open-pit coal mine. Opencast Min Technol 35(4):5–8 **(in Chinese)**

Renani HR, Martin CD (2020) Slope stability analysis using equivalent Mohr-Coulomb and Hoek-Brown criteria. Rock MechRock Eng 53(1):13–21. https://doi.org/10.1007/s00603-019-01889-3

Shang L, Nguyen H, Bui XN, Vu TH, Costache R, Hanh LTM (2022) Toward state-of-the-art techniques in predicting and controlling slope stability in open-pit mines based on limit equilibrium analysis, radial basis function neural network, and brainstorm optimization. Acta Geotech 17(4):1295–1314. https://doi.org/10.1007/s11440-021-01373-9

Unoo S (2018) Lessons learnt from open-pit wall instabilities: case studies of BC open-pit hard rock mines. J Min Sci 54(5):804–812. https://doi.org/10.1134/S1062739118054915

Vanneschi C, Eyre M, Burda J, Žižka L, Francioni M, Coggan JS (2018) Investigation of landslide failure mechanisms adjacent to lignite mining operations in North Bohemia (Czech Republic) through a limit equilibrium/finite element modelling approach. Geomorphology 320:142–153. https://doi.org/10.1016/j.geomorph.2018.08.006

Wang WW (2018) Study of groundwater control and flood control in typical open-pit mine of Xinjiang Tianshan. Opencast Min Technol 33(4):75–78 **(in Chinese)**

Wang H, Huang XM, Zhu MC, Cao HD, Zhang Y (2020a) Study on grouting material performance and water-blocking curtain wall technology injection to coal seam in open coal mine. Coal Sci Technol 48(11):241–247 **(in Chinese)**

Wang H, Huang XM, Cao HD, Zhang Y (2020b) Water-preserved coal mining technology in open-pit based on cutoff wall with high fly ash content. J China Coal Soc 45(3):1160–1169 **(in Chinese)**

Whittall J (2020) Runout estimates and risk-informed decision making for bench scale open-pit slope failures. Can Geotech J 57(7):1044–1057. https://doi.org/10.1139/cgj-2018-0462

Zhang DM, Yin GZ, Chen J, Dai GF (2010) Stability analysis of multi-step anti-tilt slope at open-pit mine. Disaster Adv 3(4):30–34

Zhang YB, Li HY, Qiu Y, Liu XX (2016) Research of disaster mechanism of open mine slope by water and its treatment. Met Mine 12:144–149 **(in Chinese)**

Zhang Y, Huang XM, Peng W, Zhu MC, Cao HD, Liu YZ, Tian ZL (2020) Application of water cutoff curtain in the seepage cutoff and drainage reduction of open-pit coal mine. J China Coal Soc 45(5):1865–1873 **(in Chinese)**

Zhang L, Chen Z, Nian G, Bao M, Zhou Z (2023) Base friction testing methodology for the deformation of rock masses caused by mining in an open-pit slope. Measurement 206:112235. https://doi.org/10.1016/j.measurement.2022.112235