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Research Article

Mining Scheme and Slope Stability Analysis of the First Mining Area of an Open-Pit Mine

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Abstract

Reasonable mining procedures are very important for energy saving in open-pit mines. However, studies on mining procedures in the first mining area of large open-pit mines characterized by thick and inclined coal seams are limited. The Hongshaquan open-pit mine located in Xinjiang, China was used as an example in this study to relieve space strain of soil drainage and reduce stripping weighted transport distance of the mining scheme in the first mining area of large open-pit mines characterized by thick and inclined coal seams. Three mining schemes, including eastward fan-shaped, southward partial gentle, and southward overall gentle turning schemes, were put forward. Stripping ratio, coal mining, stripping distance, and lifting height of the three schemes were compared and analyzed while considering technical and economic indicators. Accordingly, the stability of typical slopes in the stope and inner and outer dumps of the open-pit mine under the optimal mining scheme was analyzed using numerical simulation. Results demonstrate that stripping ratios of the three schemes are stable below 4 cubic metres per ton. The eastward fan-shaped turning scheme presents the minimum stripping distance, stripping lifting height, and mining distance, while the southward overall gentle turning scheme shows the minimum lifting height. The eastward fan-shaped turning scheme demonstrates enhanced short-term economic benefits, while the southward overall gentle turning scheme exhibits improved long-term economic benefits. The southward overall gentle turning scheme combined with the future expansion demand of the Hongshaquan open-pit mine, difficulty in the mining process, upgrading of mining technology, and other factors was adopted to mine the first mining area. Slope stability coefficients of the stope and inner and outer dumps meet the safety reserve coefficient and safety production requirements under this scheme. This study can provide a reference for the comparison and selection of mining procedures and slope stability analysis of similar open-pit coal mines.

Keywords: Open-pit coal mine, First mining area, Mining procedure, Scheme comparison and selection, Slope stability

1. Introduction

Large open-pit coal mines generally adopt a zoning mining model to reduce the capital construction investment, reduce the area of the outer dump, and shorten the distance of the inner drainage. Technical problems, such as transportation system layout and mining technology plan transition and connection, inevitably appear when the mining area changes direction. The direct correlation of the reasonable choice of mining area turning mode to the size of external displacement during the transition period of the open-pit mining area, distance between the discharge and abandonment of the stripping, difficulty of engineering location, and the continuity of output seriously affects the overall economic benefit of the open-pit mine [1-4]. The distance between stripping and discarding, engineering location, and difficulty of production continuity also seriously affects the overall economic benefits of the open-pit mine [5-8]. The mining plan of large open-pit mines have been extensively investigated, and production scheduling method [2, 5, 9] and mining optimization algorithm [7] and model [10, 11] have been proposed to relieve the space tension of soil drainage and reduce the stripping weight distance of mining plans. These studies have mainly focused on large open-pit mines with near horizontal and gently inclined coal seams.

However, studies on the mining procedure of large and thick inclined coal seams are lacking. The transition and connection difficulty of engineering position, output, transportation system layout and process layout scheme lead to the shortage of soil discharge space, increase of mining and stripping weight distance due to poor conditions and late scheduling time of internal discharge in thick and inclined coal seams [9, 12-14]. Evident differences in exploitation methods and internal drainage conditions before and after the turning of the mining procedure increase the difficulty in the transition of engineering position, output, transportation system layout, and technological layout scheme. Therefore, investigating the mining program of this kind of open-pit mining area is necessary to solve these problems. The mining program also needs to meet the safety and stability requirements of the stope and internal and external dumps while guaranteeing the safety and stability of typical slopes [14-17].

Therefore, the Hongshaquan open-pit mine located in Xinjiang, China was used as the case study. Eastward fan-shaped (scheme A), southward partial gentle (scheme B), and southward overall gentle (scheme C) turning schemes were proposed while considering the production status, production demand, average stripping ratio, stripping distance, and other factors. The advantages and disadvantages of the three schemes are compared on the basis of technical and economic indexes to determine the

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optimal mining procedure scheme. Accordingly, the stability of typical slopes affecting the safety and stability of the stope and internal and external dumps is calculated and analyzed to meet the requirements of slope safety reserve factor and safety production.

2. State of the art

Mining procedures and slope stability of large open-pit coal mines have been extensively investigated. Danish et al. [2] proposed a simulated annealing-based approach for open-pit mine production scheduling with stockpiling option, demonstrated the performance and efficiency of the proposed approach using three case studies, and revealed that the proposed approach produces near-optimal solutions within a reasonable amount of time. Armstrong et al. [5] developed an adaptive stochastic optimization approach for multiperiod production scheduling in open-pit mines under geological uncertainty and compared it with an existing two-stage optimization method. Xu et al. [8] presented a method for open-pit production scheduling that regards ecological costs as internal cost items and incorporated ecological costs in economic evaluation formulations. Gu et al. [10] put forward a dynamic phase-mining optimization model in open-pit metal mines, applied it to a large deposit consisting of 2 044 224 blocks, and demonstrated its efficiency and practicality. Liu and Kozan [9] developed and validated two new graph-based algorithms based on network flow and conjunctive graph theories by optimizing problem properties to achieve a competent mine scheduling optimization expert system. Goodfellow and Dimitrakopoulos [11] proposed a new two-stage stochastic global optimization model for the production scheduling of open-pit mining complexes with uncertainty. The optimizer could generate designs that improve the probability of meeting production targets, with a 6.6% and 22.6% increase of expected net present value compared with the deterministic-equivalent design and an industry-standard deterministic mine planning software, respectively. Franco–Sepúlveda et al. [7] applied metaheuristics and artificial neural networks to open-pit mining for the global optimization of mining complexes and briefly described how these techniques can be applied to optimize operations and previous variables of the mining planning as well as implement them in several mines around the world. Han et al. [18] established analytical models for the monitoring system to investigate the slope stability of open-pit mines and provide a basis for the application of a new type of steep slope stability monitoring technology to open-pit mines. Wang et al. [19] put forward the multiscale decomposition and reconstruction architecture for eliminating the unmodeled systematic error, defined it on the basis of empirical mode decomposition theory, and presented the systematic error mitigation model. A standard of the scale selection for the systematic error elimination was provided in terms of the mean of accumulated standardized modes. The proposed scheme remarkably improved the reliability of ambiguity resolution and the precision of baseline vector after eliminating the systematic error and effectively achieved high-precision slope deformation monitoring in open-pit mines. Grenon and Laflamme [20] presented a methodology that allows for the rigorous determination of interrupt and bench face slope orientations on a digital elevation model of a designed open pit. This flexible methodology can be adapted depending on block sizes and the pit geometry of a given mine. Fleurisson [21] developed various techniques and tools to achieve these successive phases and illustrated their implementation and limitations through case studies of slope design in open-pit mines. Yang et al. [22] quantitatively evaluated the slope stability before and after actual mining below the slipping mass and provided scientific proof for the parameter optimization of open mine surface slope, security, and sustainable exploitation using sensitivity analysis on the main influencing factor. Tanyas and Ulusay [23] proposed a back analysis procedure with nonlinear failure envelopes for unstable slopes in the pit to assess failures along rough discontinuities. The results of the 2-D limit equilibrium back analyses and movement monitoring data suggested that wedges and/or planar blocks formed at the uppermost benches move down to fill the gap due to the previous movement of blocks in benches. Zheng et al. [24] developed a new computer code to perform both deterministic and probabilistic block theory analysis. The variability of the discontinuity orientation and shear strength was incorporated in the probabilistic block theory analysis. The results confirmed that the design value selected for the maximum safe slope angle for a particular region in the open-pit mine based on the deterministic block theory analysis can be on the unsafe side. Fang et al. [25] obtained the deformation band of the west slope and the slide mass structure of 34,600 profiles on the basis of hydrology, geology, and monitoring data to explore the stability of the west slope in the Buzhaoba open-pit mine and determine the aging stability coefficient during slide mass development. The stability coefficient was in a quadratic-linear relationship with the decreased height Δh of the side slope and in a linear relationship with anchoring force P when the slope was stable. Azhari and Ozbay [26] investigated the effect of earthquakes on open-pit mine slopes, the importance of considering seismic loading in slope stability analyses, and active dewatering for open-pit mines located in seismically active areas. Bednarczyk [27] presented geotechnical engineering studies for the design of a new lignite open-pit mine in central Poland. Comprehensive identification and monitoring of geotechnical risks for mine slopes and storage of overburden should be a continuous process. This activity should start from the beginning stages of construction, be conducted during exploration, and continued to mine the final reclamation and reduce potential natural hazard impact on mining and the natural environment. Tao et al. [28] conducted a physical model test on shear strength characteristics of the slope sliding surface in an open-pit mine and demonstrated that stress characteristics of negative Poisson's ratio of anchor cables during the test are consistent with the monitoring results of Newtonian force at the landslide site, thereby proving that the negative Poisson's ratio of anchor cables are effective and reasonable in landslide monitoring and early warning.

These results mainly focus on the mining scheme and slope stability of open-pit mines under general geological conditions as well as the production scheduling method, mining optimization algorithm, and model of open-pit mines [2, 5, 8-10]. Monitoring technology of open-pit mine slope stability, parameter optimization, and reinforcement measures are explored [18, 19, 26-28]. However, the mining procedure for the first mining area of large open-pit mines characterized by thick and inclined coal seams remains unverified. The inner dump condition of a large open-pit mine with thick and inclined coal seams is poor. The coal and rock steps in longitudinal mining are complete, and the development program of mine engineering emphasizes the speed of development and depth extension. The coal and rock coexist in the same step after turning to horizontal mining. Clear differences in exploitation methods and internal dump conditions before and after the turning of the mining scheme increase the difficulty in the transition and continuity of engineering position, output, transportation system layout, and technological layout scheme. In addition, the slope stability analysis under the corresponding mining procedure of this type of open-pit mine is rare. Therefore, the Hongshaquan open-pit mine located in Xinjiang, China is used as an example in this study. The three mining schemes of the first mining area of an open-pit mine are compared using theoretical and data comparison analyses. The change rules of stripping ratio, coal mining, and stripping distance of the three schemes are compared; technical and economic indicators are comprehensively considered; and advantages and disadvantages of each scheme are compared to determine the optimal mining program scheme. In addition, numerical simulation is employed to analyze the stability of typical slopes that affect the safety and stability of the stope and internal and external dumps as well as meet the requirements of slope safety reserve factor and safety production.

The remainder of this study is organized as follows. The general situation of the Hongshaquan open-pit mine is described and the division of the open-pit slope and the mining sequence of the first mining area are put forward in Section 3. The theoretical analysis and data comparison of the three mining schemes of the open-pit mine are presented in Section 4 to analyze the slope stability under the optimal mining scheme. The conclusions are summarized in Section 5.

3. Methodology

3.1 Background

The Hongshaquan open-pit mine is located east of the Xiheishan ore area of Zhundong coalfield. The ore field contains rich reserves and reliable resources suitable for large-scale open-pit mine development. The mining area is divided into eight ore (well) fields and one small coal mining area with a construction scale of 145 million tons/year. The formation of the open-pit mine is generally southward, with a slow dip angle of about 4°–10°. The main coal seam can be mined in 11 layers, the average total thickness of pure coal is 66.03 m, the average thickness of gangue is 2.26 m, the rate of gangue is 3.31%, and the coal seam dip angle is 3°–10°. The mining capacity is 3676 Mt, and the service life is 334 years.

The surface boundary of the open-pit mine presents an average width of 9.4 km from east to west and 7.5 km from north to south, with an area of 70.32 km2 and a maximum mining depth of about 700 m. The first mining area was selected in the northwest region of the open-pit coal seam hidden in the outcrop position. The western part of the first mining area was selected as the initial ditching location, and the ditching length was 1200 m. Surface and deep regions of the first mining area are 3.93 and 2.87 km², with a boundary length of 2.54 and 2.21 km and a width of 1.55 and 1.30 km, respectively. Recoverable reserves of the first mining area are 75 Mt, and the service life is 6.8 years.

The open-pit rock soil includes clay, coal, sandstone, mudstone, and conglomerate. Physical and mechanical properties of rock and soil suitable for this study are obtained through comprehensive analysis combined with laboratory tests and geological exploration, as shown in Table 1.

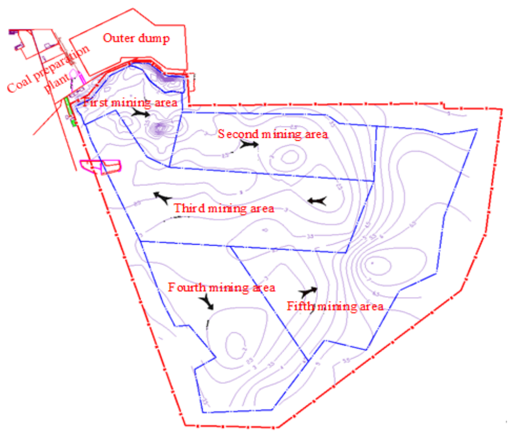
Table 1. Physical and mechanical parameters of rock and soil

Formation lithology	Unit Weight (kN/ m^3)	Cohesion (kPa)	Internal friction angle (°)
Quaternary clay	19.8	12.2	28.8
Coal	13.2	56.0	30.5
Mudstone	22.2	74.0	30.3
Argillaceous siltstone	22.9	80.0	32.6
Fine sandstone	24.2	115.0	38.2
Medium sandstone	21.3	110.0	36.9
Coarse sandstone	20.8	96.0	34.1
Conglomerate	24.8	122.0	38.9

3.2 Division of the mining area

The division and mining sequence of the mining area must ensure that the transition of the mining area is carried out immediately, the production is connected smoothly, and the mining area transition is stable. The division scheme of the mining area comprehensively considers the strike of the coal seam, deduction of mining and stripping engineering, and balanced stripping and mining ratio [10, 11, 29]. Three mining procedures for the first mining area, namely, eastward fan-shaped (scheme A), southward partial gentle (scheme B), and southward overall gentle (scheme C) turning schemes, are proposed (Fig. 1).

The whole orefield is divided into five mining areas, and the design of the mining sequence turns from the first mining area to the fifth mining area. The first mining area of the eastward fan-shaped turning scheme (Scheme A, Fig. 1a) is located northwest of the orefield and divided along with the dip of the coal seam. The second mining area of the eastward fan-shaped turning scheme is located north of the ore field and divided eastward along the northern ore right boundary. The third, fourth, and fifth mining areas are located in the middle, southwest, and east of the orefield, respectively, and all of which are divided along the coal seam strike. The southward partial gentle turning scheme (Scheme B, Fig. 1b) is divided along with the coal seam dip in the northwest of the ore field, the second and third mining areas are located in the middle of the orefield, while the fourth and fifth mining areas are located in the northeast and southwest of the orefield, respectively, and all of which are divided along with the coal seam dip. The east and south sides of the first mining area are fan-shaped and southward, respectively. After the east side to the boundary, the south side continued to push south into the second mining area. The first mining area in the northwest of the orefield of the southward overall gentle turning scheme (Scheme C, Fig. 1c) is divided along with the dip of the coal seam; the second and third mining areas are divided in the middle of the orefield; and the fourth and fifth mining areas are located in the northeast and southwest of the orefield, respectively, and all of which are divided along with the dip of the coal seam. According to the current mining situation, the east and south sides of the first mining area are fan-shaped and pushed southward, respectively. The south side continues to push southward and enters the second mining area after the east side of the first mining area reaches the boundary.



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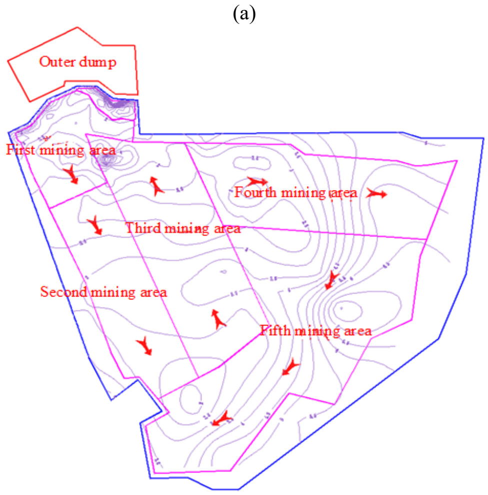

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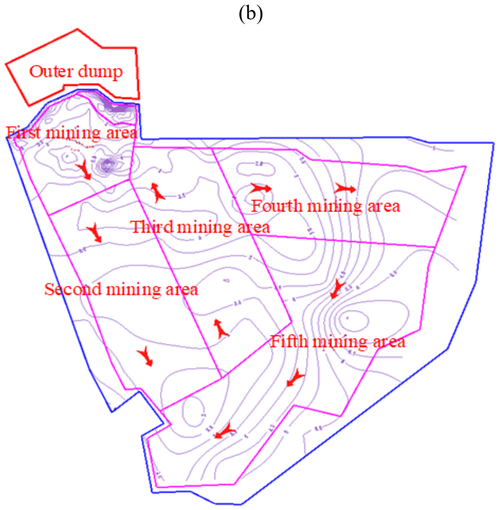


(c)

Fig. 1. Diagram of mining program schemes: (a) eastward fan-shaped (scheme A), (b) southward partial gentle (scheme B), and (c) southward overall gentle (scheme C) turning schemes.

3.3 Division of the mining area

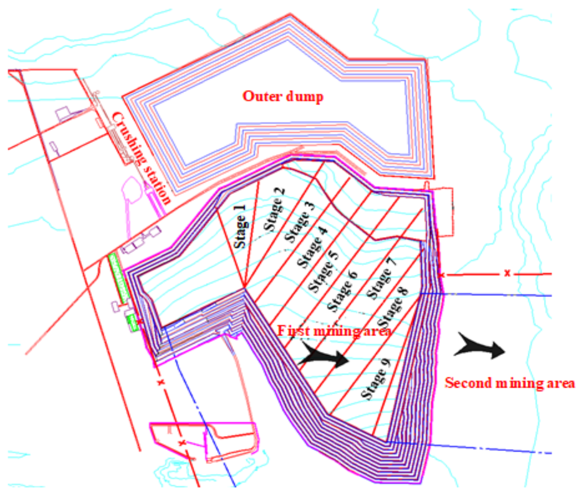
The schemes A, B, and C are proposed to solve the space shortage of soil dump and reduce the stripping weighted transport distance of the southward mining scheme given that the first mining area of the Hongshaquan open-pit mine presents a small stripping ratio and satisfactory internal dump conditions and is close to the dump. The stage position of the first mining area is illustrated in Fig. 2.

As shown in Fig. 2a, the eastward turning scheme is fan-shaped to advance to the second mining area and realize eastward mining along the northern mining right boundary. The length of the working line of the scheme is 1500 m, and the propulsion degree is maintained at 250 m.

As shown in Fig. 2b, the bottom working line of the pit in the southward partial gentle turning scheme is 1500 m. The scheme adopts a dual working side, the east side and south sides are both stope working sides, and the bottom working line of the east side is 900–1300 m. The bottom working line of the south side pit is 1500 m. Steps of the stope are divided horizontally, except for the inclined division of gangue among B1, $B2^{'}$, and B1 and $B2^{'}$ coals. The scheme ensures the fan-shaped advance of the eastern slope with an annual advance of 250 m and accelerates the northern slope to the limit because of the current problem of the limited capacity of soil dump in the Hongshaquan open-pit mine. The rapid release of the inner space also creates conditions for the follow-up of the outer dump if necessary.

As shown in Fig. 2c, two working sides are adopted and the east and south sides are both stope working sides in the early stage of the southward overall gentle turning scheme. The working line gradually straightens and becomes south side mining with the development of the stope engineering location. Steps of the stope are divided horizontally, except for the inclined division of gangue among B1, B2 ', B1, and B2' coals. The scheme ensures that the fan-shaped east side advances with an annual advance of nearly 300 m and accelerates the north side to the boundary.

Recoverable raw coals in the first mining area for the three mining schemes are 150.54, 174.86, and 20.01 million tons, with a stripping amount of 521.25, 572.73, and 665.82 million m^3 and an average stripping ratio of 3.46, 3.30, and 3.31 m^3/t, respectively.



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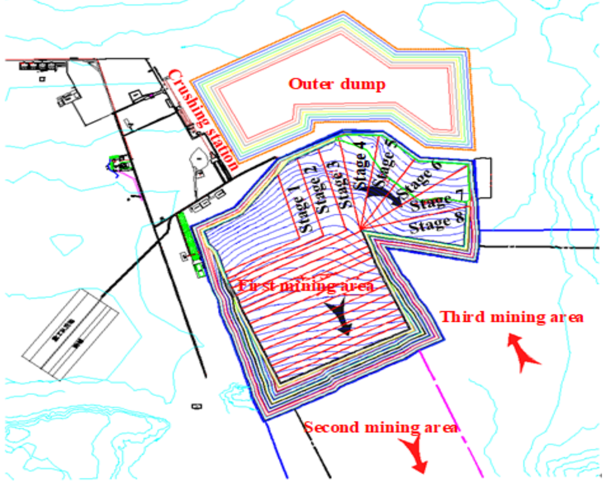

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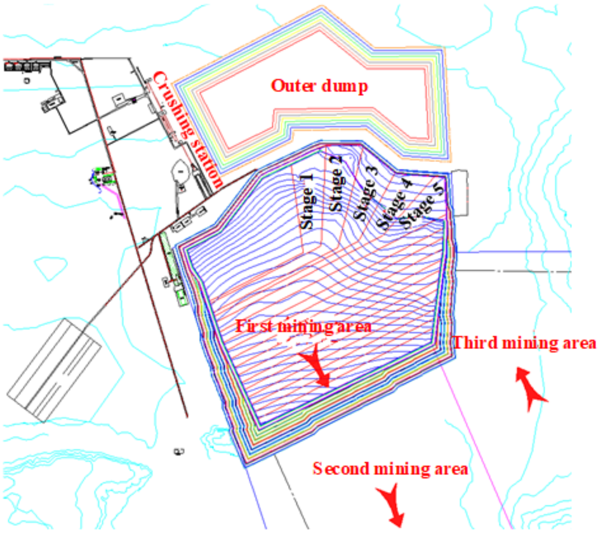


(c)

Fig. 2. Stage location map of the first mining area of each scheme: (a) eastward fan-shaped (scheme A), (b) southward partial gentle (scheme B), and (c) southward overall gentle (scheme C) turning schemes.

4 Result Analysis and Discussion

4.1 Comparison and selection of the mining procedure scheme

(1) Comparative analysis of the variation of stripping ratio

Fig. 3 shows the change rule of the stripping ratio of production each year from 2022 (first year) to 2026 (fifth year).

Stripping ratios of the eastward fan-shaped, southward partial gentle and southward overall gentle turning schemes generally remain stable in the next 5 years. The eastward fan-shaped turning scheme demonstrates no evident advantage in the control of the stripping ratio after 2 years. The stripping ratio of the southward overall gentle turning scheme is smaller than that of the eastward fan-shaped turning scheme after 4 years.

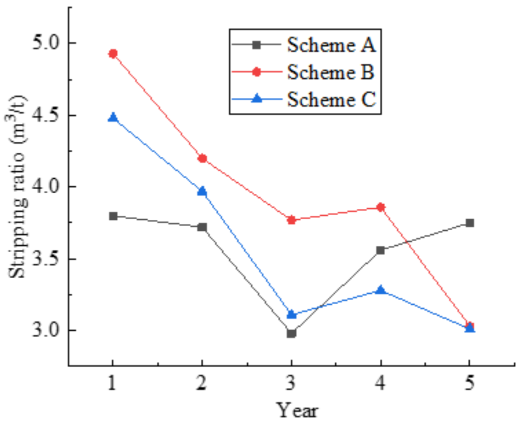


Fig. 3. Annual stripping ratio curve of the three schemes

(2) Variation of the coal mining distance and lifting height

According to the engineering development and transportation system arrangement of the three schemes, the annual weighted coal mining distance between 1 and 5 years can be taken out by the engineering location at the end of each year and the annual weighted lifting height of coal mining can also be calculated. The year-by-year comparison of the weighted mining distance of the three schemes is presented in Fig. 4. The mining distance of the eastward fan-shaped turning scheme is shorter than those of the two other schemes in the next 1-5 years. However, cross transportation problems exist in the eastward fan-shaped turning scheme. The horizontal transportation distance fails to reflect the transportation cost of raw coal fully and the influence of the lifting height of coal mining on the transportation cost should also be considered given that the transportation of raw coal contains both horizontal transportation distance and lifting height.

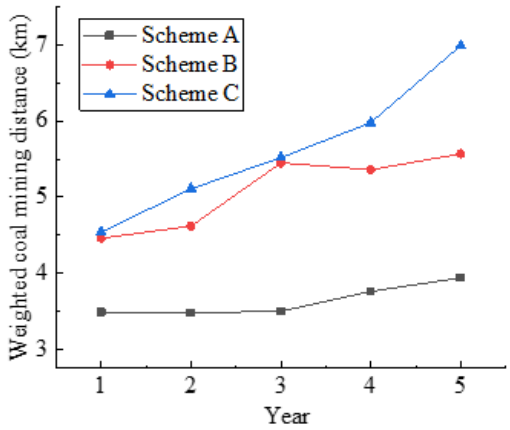


Fig. 4. Comparison curve of the weighted coal mining distance of the three schemes

Fig. 5 shows the year-by-year comparison of the weighted lifting height of coal mining of the three schemes.

The coal lifting height of the eastward fan-shaped turning scheme is significantly larger than that of the two other schemes in the next 1-5 years. Therefore, the raw coal lifting cost of the eastward fan-shaped turning scheme is significantly larger than that of the two other schemes. Although the southward overall gentle turning scheme presents many advantages in the aspect of decreasing the cost, the raw coal transportation cost is insufficient in determining the advantages of the scheme by relying on the variation of coal mining transportation cost alone because it accounts for about a quarter of the total transportation cost in the open-pit mine production process and the variation of stripping transportation cost should be considered.

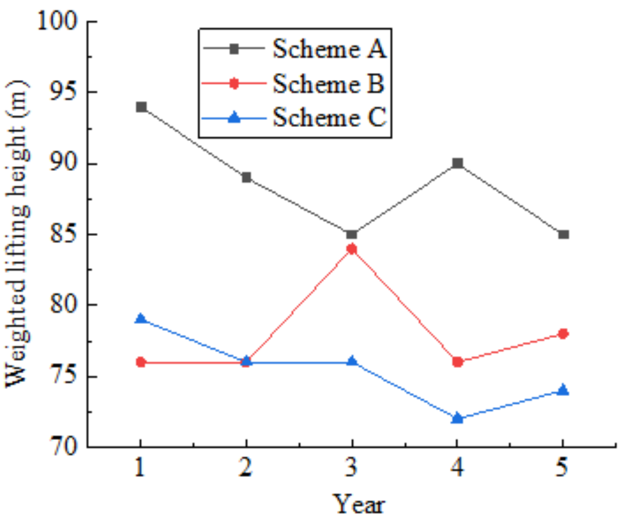


Fig. 5. Comparison curve of the weighted lifting height of coal mining of the three schemes

(3) Comparative analysis of stripping distance and lifting height

The horizontal distance and lifting height of stripping can reflect the changing variation of stripping transportation costs. Fig. 6 shows the year-by-year comparison of the weighted freight distance of the three schemes.

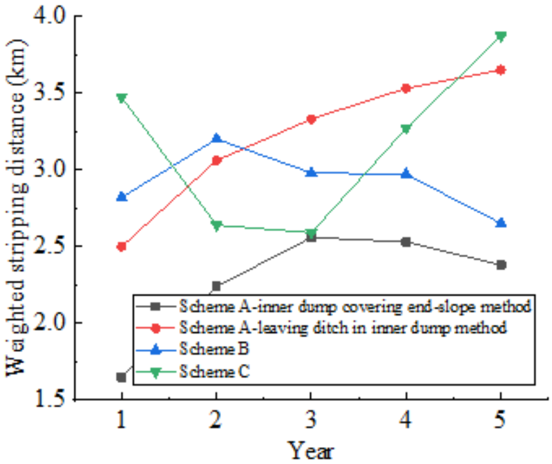


Fig. 6. Comparison curves of weighted stripping distance of the three schemes

The stripping distance of the eastward fan-shaped turning scheme with inner dump covering end-slope method is smaller than that of the two other schemes (schemes B and C) in the next 1-5 years, while that of leaving ditch in inner dump method is the largest after 2 years. Therefore, the horizontal stripping transportation cost of the eastward fan-shaped turning scheme with inner dump covering end-slope method is smaller than that of the two schemes with south gentle turning.

The horizontal transportation distance fails to reflect the transportation cost of stripping fully due to the influence of stope working side pit line layout and the presence of both horizontal transportation distance and lifting height of stripping. The influence of the lifting height of mining on transportation costs should also be considered, as shown in Fig. 7.

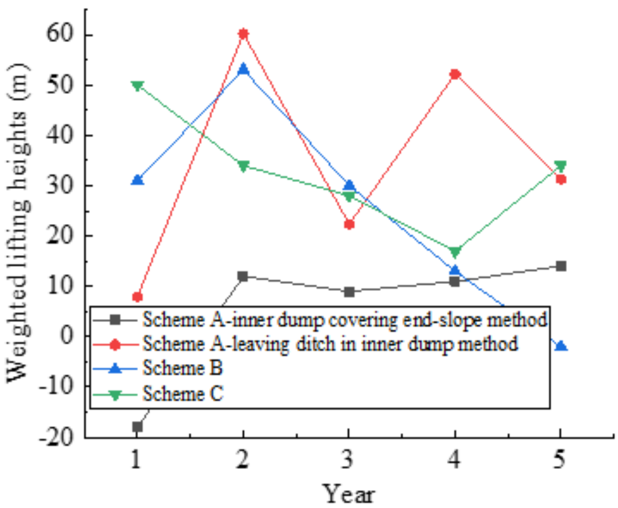


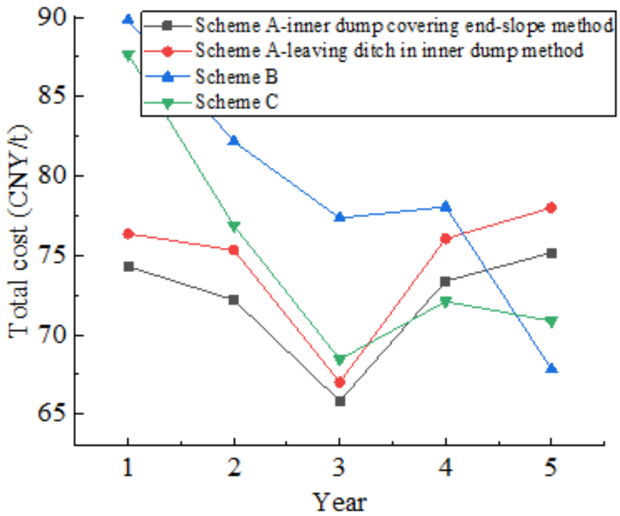
Fig. 7. Comparison curves of weighted lifting heights of the three schemes

The weighted lifting height of the eastward fan-shaped turning scheme with the inner dump covering end-slope method is smaller than that of the two other schemes (schemes B and C) in the next 1-5 years. Therefore, the weighted lifting height cost of the eastward fan-shaped turning scheme is smaller than that of the two other schemes (schemes B and C). The weighted lifting height of the eastward fan-shaped turning scheme with leaving ditch in inner dump method is larger than that of the inner dump covering the end-slope method.

(4) Analysis of comprehensive economic benefit

The annual mining and stripping quantity, weighted transport distance, weighted lifting height, mining and stripping costs, cost and profit, and loss of each diversion scheme in the first mining area of the Hongshaquan Open-pit Mine are shown in Fig. 8. The comparison of complete costs of the three schemes (Fig. 8b) demonstrated that the corresponding complete costs of the three schemes in the next three years generally first decrease and then increase in the next 4–5 years. The eastward fan-shaped turning scheme generally demonstrates minimal advantages in the long-term cost and control of profit and loss, while the southward overall gentle turning scheme presents advantages in comprehensive economics in the next 4–5 years.

Fig. 8b shows that the profit value of the southward partial gentle turning scheme continues to be the minimum in the first four years although the southward partial gentle turning scheme achieved the maximum profit in the fifth year. The economic benefit of this scheme is unsatisfactory. The profit value of the southward overall gentle turning scheme in the first year is significantly smaller than that of the eastward fan-shaped and eastward fan-shaped turning schemes, but the difference is significantly reduced in the second and third years. Compared with the eastward fan-shaped turning scheme with inner dump covering end-slope and leaving ditch in inner dump methods, profits of the southward overall gentle turning scheme increased by 50.0% and 69.3% in the fourth year and 91.3% and 94.5% in the fifth year, respectively. The economic benefit of the eastward fan-shaped turning scheme is optimal in the first three years, but the economic benefit is poor in the succeeding years while that of the southward overall gentle turning scheme is optimal after 4 years.



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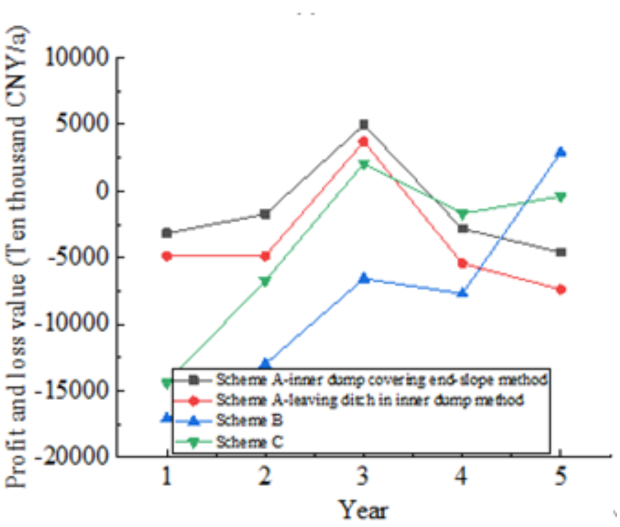


(b)

Fig. 8. Comparison curves of total cost and profit and loss of the three schemes: (a) complete cost and (b) profit and loss value.

(5) Comparison of other indicators

The cost, changing trend of the stripping ratio, difficulty of selecting and mining procedures, possibility of expanding production capacity, upgrading and transformation of mining technology, and difficulty of site organization and management of the three schemes were compared and analyzed in Table 2.

Table 2. Comparative analysis of indexes of each scheme

Contrast indicators	**Scheme A**	**Scheme B**	**Scheme C**
Change trend of cost and stripping ratio	It decreased annually before 4 years and increased after 4 years	It generally decreased in the next 1-5 years	It generally decreased in the next 1-5 years
Selected mining program	Difficult	Difficult	Easy
increment of retreating capacity	Difficult	Difficult	Easy
Technological transformation	Fitting large equipment and semicontinuous process is difficult	Fitting large equipment and semicontinuous process is difficult	Suitable for large equipment and semicontinuous process
Organization and management	Difficult	Difficult	Easy

The southward overall gentle turning scheme can easily realize the selection and mining of raw coal as well as improve the production capacity. Furthermore, this scheme is suitable for the layout of large equipment and the upgrading and transformation of mining technology. The project site organization and management can be easily applied to this scheme. The southward overall gentle turning scheme can be adopted for the first mining area given the demand for the future expansion of the Hongshaquan open-pit mine and the difficulty in upgrading the mining process and technology.

4.2 Slope stability analysis under the optimal mining scheme

(1) Selection of typical sections

The location and number of calculated sections directly affect the accuracy and workload of the calculation of slope stability [26, 30, 31]. The location plan of each section in the southward overall gentle turning scheme is selected in this calculation to meet the requirements of accuracy and calculation amount, as shown in Fig. 9.

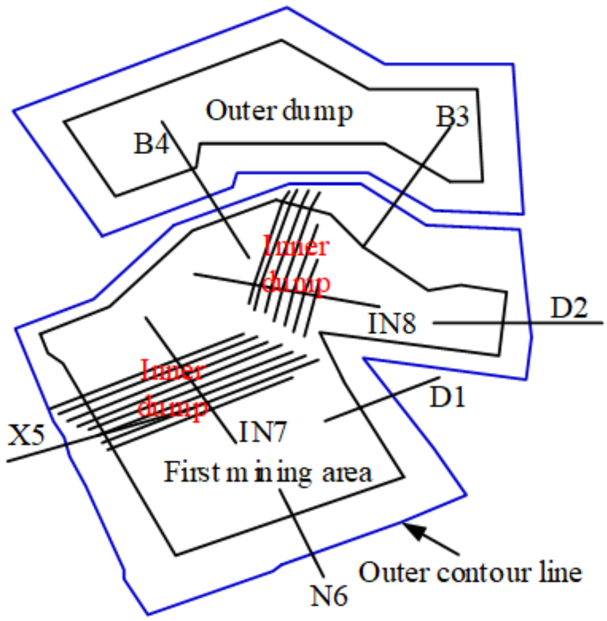
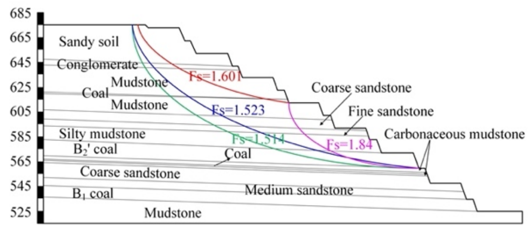


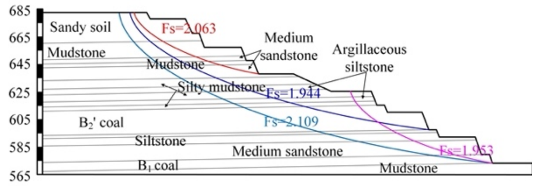
Fig. 9. Location plan of each section in the southward overall gentle turning scheme

(2) Comparison of other indicators

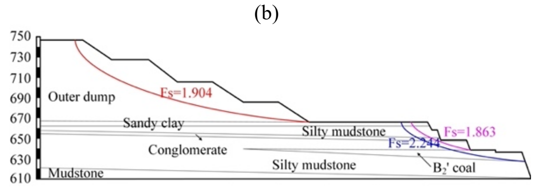
The limit equilibrium analysis algorithm was employed to analyze the stability of slopes. The most dangerous among the slip surfaces and the corresponding stability coefficient (Fs) of the slope were determined using the trial calculation of the most dangerous potential slip surface at different parts of the slope. The calculation results are shown in Fig. 10.



(a)



(b)



(c)

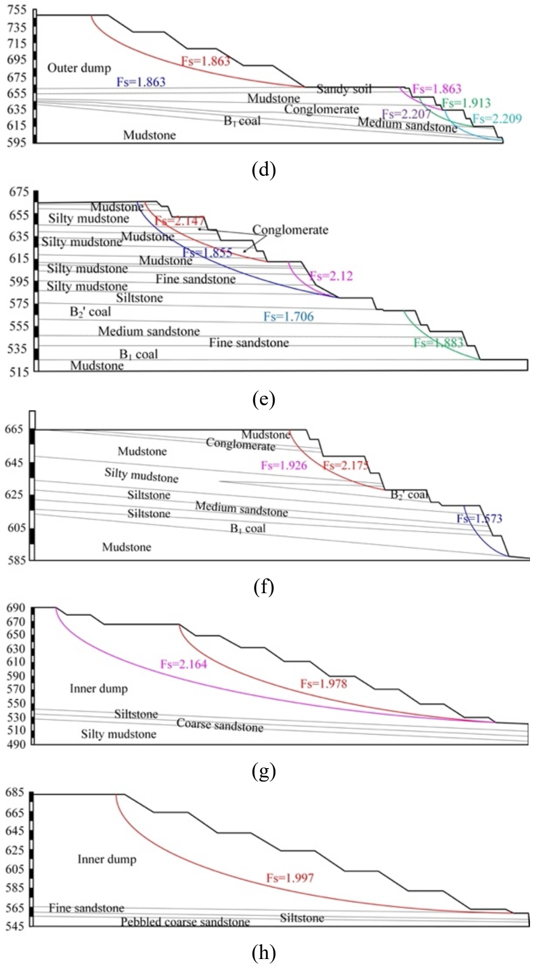


Fig. 10. Most dangerous among the sliding surfaces and stability coefficient of slopes. (a) D1 Section, (b) D2 Section, (c) B3 Section, (d) B4 Section, (e) X5 Section, (f) N6 Section, (g) IN7 Section, (h) IN8 Section

As shown in Fig. 10, the local and overall slip surfaces of the slope are calculated. The most dangerous among the potential slip surfaces of the D1 section is characterized by the overall circular slipping (Fig. 10a), with a stability coefficient of 1.514. The most dangerous among the potential slip surfaces of the D2 section is also characterized by the overall circular slipping and sliding along the floor of the $B2^{'}$ coal seam (Fig. 10b), with a stability coefficient of 1.944. The most dangerous among the potential slip surfaces of the dump of the B3 section is characterized by the overall circular slipping through the whole slope and sliding along the base and slope foot (Fig. 10c), with a stability coefficient of 1.904. The most dangerous among potential slip surfaces on the north side of the stope is the intersection of the partial step and the face of the slope with a stability coefficient of 1.863. The most dangerous among potential slip surfaces of the south and the north slopes of the dump of the B4 section (Fig. 10d) is characterized by the overall circular slide and sliding along the base and slope foot, with a stability coefficient of 1.881. The most dangerous among the potential slip surfaces on the north side of the stope is the circular slide along the intersection of the slope and the free face, with a stability coefficient of 1.9103. The most dangerous among the potential slip surfaces of the X5 section is the overall circular slip along the floor of the B1 coal seam and the slope foot (Fig. 10e), with a stability coefficient of 1.706. The most dangerous among potential slip surfaces on the south side of the stope is the circular slide along the local step of the slope and B1 coal floor (Fig. 10f), with a stability coefficient of 1.573. The most dangerous among the potential slip surfaces of the dump in the IN7 section is the local circular slip (Fig. 10g), with a stability coefficient of 1.978. The most dangerous among the potential slip surfaces of the IN8 dump is the overall circular slip cut through the dump slope along the base and slope foot (Fig. 10h), with a stability coefficient of 1.997. The calculation results of slope stabilities are listed in Table 3.

Table 3. Stability coefficients of each slope

Section	Circular sliding				
	Mining area		Inner dump		External dump
	Entirety	Local	Entirety	Local	
D1	1.514	1.601			
D2	1.944	1.953			
B3	2.244	1.863			Fs=1.904
B4	2.07	1.913			Fs=1.881
X5	1.706	1.883			
S6	1.926	1.573			
IN7	1.926	1.573	2.164	1.978	
IN8	1.813	1.602	1.997		

According to the safety factor of slope stipulated in China's specification for Design of Open-pit Mine for Coal Industry [32], the stability evaluation standard of the slope is as follows: the stability factor of the nonworking slope (north and west sides) is set to 1.3, while the stability coefficient of the working slope (south and east slopes) is set to 1.2. Important industrial facilities are unavailable around the dump, and the stability coefficient is determined at 1.2. The comparison of the calculation results of slope stability in Fig. 10 and Table 3 indicated that the stability of each slope meets the specification and design requirements with a certain margin.

5. Conclusions

Three mining schemes, including eastward fan-shaped, southward partial gentle, and southward overall gentle turning schemes, were put forward to relieve the space tension of soil dump and reduce the stripping weight distance of the mining scheme in the first mining area of large Hongshaquan open-pit mines, which are characterized by thick and inclined coal seams. The three schemes were compared and analyzed to obtain the optimal mining scheme. Furthermore, the stability of typical slopes in the stope and inner and outer dumps of the open-pit mine under the optimal mining scheme were analyzed using numerical simulation. The following conclusions could be drawn from this study:

(1) The annual average stripping ratios of eastward fan-shaped, southward partial gentle, and southward overall gentle turning schemes are stable below 4 m^3/t at 3.46, 3.30, and 3.31 m^3/t, respectively. The stripping ratio of the eastward fan-shaped turning scheme fluctuates less and is generally lower than that of the southward partial gentle and southward overall gentle turning schemes.

(2) The stripping distance, stripping lifting height, and mining distance of the eastward fan-shaped turning scheme is smaller than that of the southward partial gentle and southward overall gentle turning schemes. Meanwhile, the lifting height of the southward overall gentle turning scheme is smaller than the two other schemes.

(3) The economic benefit of the eastward fan-shaped turning scheme is optimal in the first three years but reduces

in the succeeding years. Compared with the eastward and southward fan-shaped turning schemes, long-term economic benefits of the southward overall gentle turning scheme is better because they exceed 50.0% and 91.3% in the fourth and fifth years, respectively. In addition, this scheme can easily realize raw coal mining, production capacity improvement, layout of large equipment, and mining technology upgrading transformation, and the first mining area can be given priority to the southward overall gentle turning scheme.

(4) Potential landslide modes of the stope and the inner and outer dump slopes of the Hongshaquan coal mine are circular sliding failures. Stability coefficients of east and south sides of the stope ranged from 1.514 to 1.953 and 1.573 to 1.926, while those of west and north sides of the stope ranged from 1.706 to 1.883 and 1.863 to 2.244 and the stability coefficients of the inner and outer dump slopes ranged from 1.978 to 2.164 and 1.881 to 1.904, respectively. The slope stability coefficient of the stope and the inner and outer dumps meet the requirements of the safety reserve coefficient of slope in the code and safety production requirements of the Hongshaquan open-pit coal mine.

Thus, the optimal scheme was selected for the first mining area of Hongshaquan open-pit mine engineering. The stability of the stope and the typical slope of the inner and outer dumps of the open-pit mine under the optimal mining scheme were analyzed. The research results can provide a reference for the comparison and selection of mining program schemes and slope stability analysis of similar open-pit coal mines. However, monitoring data will be compared with the numerical simulation results in this study in future studies due to the lack of monitoring data comparison with the field slope deformation. The results can improve the evaluation accuracy of the open-pit mine engineering slope stability.

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