Journal of Engineering Science and Technology Review 15 (4) (2022) 90 - 95

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Optimized Transportation of the Open-pit Coal Mine

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Received 6 May 2022; Accepted 30 July 2022

Abstract

With the increase in the production scale of open-pit coal mines, the safety management, economic benefits, and sustainable development of open-pit coal mines are constantly being challenged. A new optimization method for the internal circulation transportation was proposed to improve the transportation benefit of the open-pit coal mine and reveal its temporal and spatial evolution laws in such a mine. The applicable conditions of the proposed transportation were described. The applicable conditions of the two internal circulation transportations, single and double bridges, were also compared and analyzed. The adaptability, key parameters, and space-time benefits of the introduced method were verified through the Hongshaquan opencast coal mine. Results show that the saving cost of internal circulation transportations increases as the working line length L rises. Critical internal circulation length L_1 and critical double-bridge length L_2 are also observed. The proposed transportation can be constructed when L is larger than L_1, and the transportation scheme with double bridges can be profitable when L is larger than L_2. The Hongshaquan opencast coal mine has the following conditions for building internal circulation transportation: the critical internal transportation length L_1 = 430.8 m and the critical double-bridge length L_1 = 515 m. This study can provide a reference for the open-pit coal mine transportation system and improve the benefits of the transportation system.

Keywords: Open-pit coal mine, transportation system, intermediate bridge, parameter optimization

1. Introduction

Opencast coal mines have good quality and mining conditions. However, the coal price is relatively low due to geographical location restrictions, industrial-level constraints, and limited coal demand. Opencast coal mines cannot improve the economy and avoid the passive situation by only increasing the production scale [1-3]. Therefore, improving the safety management level through technological innovation, reducing production costs, and accomplishing safe, economic, and efficient mining is necessary [4-6]. Transportation costs account for a large proportion of the overall production costs of open-pit mines. Adopting reasonable transportation and shortening transport distances are crucial to reducing mining costs. Therefore, optimizing the transportation system is the primary means of realizing safety management, economic benefits, and sustainable development [3, 6-8].

However, with the continuous expansion of open-pit coal mines, the distance between extraction and coal mining gradually increases, the existing single-row transportation cost increases, and the production efficiency decreases. Proposing an optimization scheme for multi-cycle transportation to reduce coal mining transportation costs and improve production efficiency. However, when to construct the multi-cycle transportations and what form of multi-cycle transportations are still determined by engineering experience. It is difficult to accurately grasp the optimal nodes and transportation for open-pit mine transportation.

Therefore, many scholars have focused on the optimization of opencast coal mine transportation [3, 9-11]. However, these studies are mostly on specific open-pit coal mines and are difficult to promote. The specific optimal timing is not provided, and applying the calculation method in practice is complex. Therefore, proposing a feasible open-pit mine transportation scheme and finding its optimal timing in the transportation scheme is an urgent problem.

Thus, this study proposes internal circulation transportation based on existing open-pit mine transportation cases. Through the analysis of transportation economic benefits, the applicable conditions of the internal circulation transportation are described, and the advantages, disadvantages, and applicable conditions of the two internal circulation transportations (single and double bridges) are analyzed. The adaptability, key parameters, and comprehensive benefits of the proposed transportation were verified by the application in Hongshaquan opencast coal mine. This method could be a reference for efficient production practice and improve the benefit of the open-pit mine transportation system.

2. State of the art

The cost of transportation occupies a huge proportion of total cost of open-pit mines. Therefore transportation optimization can effectively reduce mining costs. At present, scholars have conducted a considerable amount of work on the transportation of open-pit mines.

Osanloo et al. [3] found that reducing the cost of trucking removal has become increasingly important, and trucking costs are approximately half the costs of mining operations. In the transportation efficiency of open-pit mines, Saderova et al. [12] used mathematical equations and

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ISSN: 1791-2377 © 2022 School of Science, IHU. All rights reserved.
doi:10.25103/jestr.154.13

software ExtendSim8 to simulate the traffic system performance at different transporting and shifting times of vehicles. They found that numerical simulation helps improve transportation systems. Considering transportation optimization, Shamsi et al.[13] developed a mathematical integer programming model with operational constraints. The model uses the maximum net present value as the optimal objective and effectively improves the system efficiency of the open-pit mine. Zhang et al. [14] analyzed the internal dump occupancy, dragging operation efficiency, coal meaning distance, coal stripping distance, and handling capacity in the typical coal conveying channel. Igor et al. [15] proposed a simulation model for the intelligent open-pit mine transportation control system by combining telemetry data processing and fuzzy inference tools. Abbaspour et al. [16] found that the fully mobile in-pit crushing and conveying system is leading in the safety indicators, and the truck–shovel system is the first in the social index. Zhao et al. [17] proposed a route planning method based on digital maps. This method can plan the optimal truck transportation, consider terrain factors, and reduce the total transportation cost by 10%–20%. Abbaspour et al. [10] also found the optimal location and relocation plan of the semi-mobile the In-pit crushing and conveying (SMIPCC) system to obtain the lowest operating cost. Krysa et al. [11] simulated the open-pit limestone mine circulation transportation system in Haulsim software. They analyzed the consumption time and cost of the transportation system under different factors. Choi et al. [18] optimized the truck transport system in an open-pit mine based on big data and machine learning. Temkin [19] discussed the construction of a digital platform for open-pit mining management. He believed that the digital platform is a modern modeling technology, which can be widely used to manage mining and transportation.

Overall, many scholars have focused on safety control, early warning system, mining theory, program optimization design, road route selection, and intelligent transportation under different complex geological conditions. However, the above optimization is difficult and cannot solve all existing problems in the subsequent development and utilization process. Therefore, the current study proposes an optimized transportation method for internal circulation transportation. Through the transportation economic benefits, the applicable conditions of the proposed transportation are described and the advantages, disadvantages, and suitable conditions of the two internal circulation transportations (single and double bridges) are analyzed. The Hongshaquan opencast coal mine verified the adaptability, key parameters, and comprehensive space-time benefits. This study could be a reference for the practice of open-pit coal mine transportation systems and help improve the transportation system.

This study is organized as follows. The third section describes the proposed optimal transportation method, deduces the critical transportation length and the critical double-bridge length formula, and obtains the proper optimization timing. The fourth section verifies the adaptability, critical parameters, and comprehensive benefits of the proposed Hongshaquan open-pit coal mine method. The last section summarizes the full text and provides relevant conclusions.

3. Methodology

Internal circulation transportation of the central bridge can realize the uninterrupted and smooth transportation of stops and dumps, effectively shortening the transport distance and reducing the transport cost. It can solve the problem of coal pressing on end-to-end roads and improve the recovery rate and economic benefits of coal mining [9, 12, 20]. A new optimization method for the internal circulation transportation was proposed to improve the transportation benefit of the open-pit coal mine. This section will present a detailed description of the proposed method.

3.1 Optimal internal circulation transportation

The optimal internal circulation transportation of the central bridge can be divided into two forms, the single bridge form and double bridge form. The details of two different transportation schemes are present as follows.

3.1.1 Single bridge

The internal circulation transportation with a single bridge is shown in Figure 1. The inner dumping pathway at the lower horizontal passes through a middle bridge across the goaf and the coal-bearing steps on both sides on the lower horizontal side. The backfill and stripping materials are alternately connected and penetrated when coal mining is near the boundary based on the stability of the slope. When the intermediate bridges are connected, the coal-containing benches are close to the boundary and then backfilled to connect the transportation passage at the end. The coal-containing step of the mining end gangue is close to the boundary and then backfilled with the peeling material to connect the transportation path that penetrates the end gangue position. The lagging coal pressed by the middle bridge across the goaf is mined when the end-to-end transportation passages are connected. The development of the work gangue alternately advances the development.

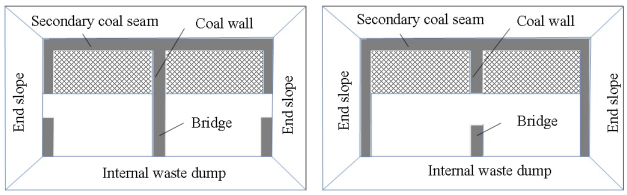

Fig. 1. Internal circulation transportation with a single bridge

3.1.2 Double bridge

As shown in Figure 2, the double bridge is built in the middle, and the lower horizontal inner soil dumping passage is connected and penetrated by two intermediate bridges across the goaf. The coal-bearing steps on both sides of the lower horizontal side of the stope will not be backfilled when they are drawn close to the boundary. The lag coal pressed by the right and left bridges is extracted when the left and right bridges are connected, respectively. With the advancement of the work gangue, the two intermediate bridges are alternately employed to progress the development

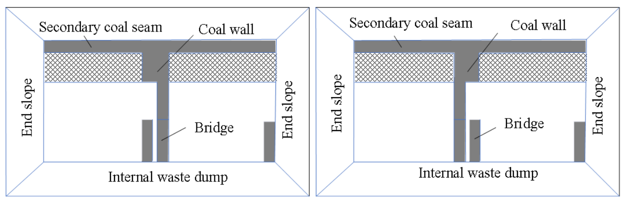

Fig. 2. Internal circulation transportation with a double bridge

3.2 Conditions for the internal circulation transportation

The advancing position and the size of the mine pit are the same for the two bridge methods. For the non-bridge mining scheme, the transportation task Q_0 can be expressed as formula (1), where *G* is the total amount of stripped material within a year, L is the length of the working line, D_k is the low width of the foundation pit, and D_z is the width of the intermediate bridge. D_d is the width of the pathway at the end-to-end transportation.

$$Q_0 = \frac{2G}{L} \times \frac{L - 2D_d}{2} \times (\frac{L}{2} + D_k) \tag{1}$$

Within a working stage *Y*, the transportation task Q_1 for internal circulation transportation with a single bridge can be calculated as formula (2):

$$\begin{aligned} Q_1 = 2G / L \times [(L_z + D_z + D_k) \times L_z + L_d \times (L_d + D_d + D_k)] \\ + G \times D_z / L \times (D_z + L_z + L_d + D_k + D_d / 2) \end{aligned} \tag{2}$$

The critical internal circulation length Q_2 can be calculated from $Q_0 \geq Q_1$.

3.3 Comparison between transformations with single and double bridges

The bridge of the proposed method can be divided into single and double bridges. Combined with the distance model, the economic benefits of the two methods are analyzed. With the establishment of double bridges, the bridge is always connected and double-loop transportation can be realized. Building bridges save a considerable number of transport distance. Double bridges have an additional secondary stripping. Therefore, the critical work line length of the double bridge can be determined on the basis of the minimum cost. Within one work stage length Y, the total amount of transportation with double bridge Q_2 is displayed as formula (3) below.

$$\begin{aligned} Q_2 = 2G / L \times [&L_r \times (L_r + D_z + D_k) \\ &+ L_s \times (L_s + D_z + D_k) \\ &+ L_c \times (L_c + D_z + D_k)] \\ &+ 2G \times D_z / L \times (D_z + L_s + D_k) \end{aligned} \tag{3}$$

When $Q_1 \geq Q_2$, the cost of transportation with double bridges is the smallest, and the building conditions for transportation with double bridges are shown as formula (4):

$$Q_1 = Q_{ZD} + Q_{DY} \geq Q_2 = Q_{RD1} + Q_{RD2} + Q_{ZY} \tag{4}$$

3.5 Economic benefit of the proposed transportation with double bridges

The annual output of the open-pit mine is *K*, which can be expressed as $K = LMa$, where *a* is the propulsion degree, *M* is the average thickness, and *L* is the working line length. The gangue volume is the total amount of exfoliation *G* in annual propulsion. *G* is determined by the following formula:

$$G = H_j \times L \times a \tag{5}$$

Substituting $K = LMa$ into formula (5), the *G* can be obtained as formula (6):

$$G = K / L \times H_j \tag{6}$$

The shift step *Y* is the same in each propulsion stage to model the bridge cost. For the non-bridge scheme, the haulage distance per unit stage advancing length is shown as formulas (7) and (8).

1) Outboard transport distance:

$$L_{RZ1} = L_r + D_z + D_k \tag{7}$$

where L_r is the width of the outer mining area of the double bridge and can be calculated from the formula below:

$$L_r = (L - 2D_d - 2D_z - L_s) / 2 \tag{8}$$

2) Inside transport distance:

$$L_{RZ2} = L_s + D_z + D_k \tag{9}$$

In the absence of a bridge, the separation distance L_Z can be determined as follows:

$$L_Z = L / 2 + D_k \tag{10}$$

The annual number of construction bridges is determined by the propulsion degree and the distance from the working to the dumping site.

$$n' = a / (D_k + b) = K / [(L \times M)(D_k + b)] \tag{11}$$

Where n' is the annual number of building bridges; D_k is the tracking distance of the open-pit mine, m; b is the width of the working flat plate of the dump, m. Secondary stripping costs (yuan) W_0 in the process of building a bridge can be calculated as follows:

$$W_0 = V \times a \times c_d / (D_k + b) \tag{12}$$

where c_d is the unit stripping cost (yuan/ m^3) for the transportation scheme with non-bridge, and the transportation cost W_1 can be expressed as formula (13).

$$W_1 = \frac{G}{L}(L - 2D_d)(L / 2 + D_k)C_y \tag{13}$$

where *G* is the total amount of peelings within the annual advance range, m^3 ; C_y is the unit transportation cost, yuan/ m^3. The transportation cost W_2 for the transportation scheme with double bridges is as follows:

$$\begin{aligned} W_2 = 2G / L \times C_y \times [L_r \times (L_r + D_z + D_k) \\ + L_s \times (L_s + D_z + D_k) + L_c \times (L_c + D_z + D_k)] \end{aligned} \tag{14}$$

Finally, the transportation scheme with double bridges can save cost *W*, which is determined by the following formula:

$$W = W_1 - W_2 - W_0 \quad (15)$$

4 Result Analysis and Discussion

In this section, the adaptability, key parameters, and space-time benefits of the introduced method were verified through the Hongshaquan opencast coal mine.

4.1 Hongshaquan opencast coal mine

The Hongshaquan opencast coal mine is located in the east of the Xiheishan mining area, which is in the Zhundong coalfield and 78 km away from Qitai county, Xinjiang province, China. The coal reserves are abundant and resources are reliable in this mine. This coal mine is suitable for large-scale opencast mine development. The mining area is divided into eight fields and one small area. The Hongshaquan opencast coal mine produces 145 million tons of coal a year. The strata of the opencast mine generally dip to the south, with a gentle dip angle of 4°–10°. A total of 11 coal seams demonstrated an average thickness of 66.03 m, an average gangue thickness of 2.26 m, and a gangue content of 3.31%, and the dip angle of the coal seam is 3°–10°. The amount of coal that can be mined is 3676.28 Mt. The mining life of the Hongshaquan opencast coal mine is 334.20 a according to the product scale of 10.00 Mt/a and the reserve coefficient of 1.10. Therefore, the mining conditions of this coal mine are excellent.

The slope angles of the open pitstop, the outer damp, and the inner dump are 35°, 22°, and 22°, respectively. The average width of the surface boundary is 9.4 km from east to west, the average width is 7.5 km from north to south, and the area is 70.32 km^2. The maximum exploitation depth is approximately 700 m. The ore field is divided into different mining areas along the inclination of the coal seam. The first mining area is selected at the hidden outcrop of the coal seam northwest of the open-pit mine. The initial pull ditch is located in the west of the first mining area; along the B2' coal seam hidden outcrop pull ditch, the length of the initial ditch is 1200 m and the working line is arranged along the strike and advanced along the inclination. After the delineation of the first mining area, the surface zoning boundary is 2.54 km long, 1.55 km wide, and 3.93 km^2 in area. The boundary of the deep partition is 2.21 km long, 1.30 km wide, and has an area of 2.87 km^2. The recoverable reserves in the first mining area are 75.06 Mt and the mining life is 6.82 years.

The first mining area adopts the overall slowing and steering schemes to the south. In the early stage, dual-working gangues were adopted, wherein the east and south gangues were working gangues. With the development of the stop position, the working line is gradually straightened to become the mining at the south gangues. Except for B1 coal, B2' coal, and the slant division of the gangue between B1 and B2' coals, other stripping steps are divided horizontally. This plan ensures that the east gangue will advance in a fan shape with an annual thrust of 300 m and the north gangue will accelerate to the boundary. The space of the inner row is released as soon as possible, and conditions are created for the following external dump. Simultaneously, the exploit of the north and south gangues are exploited to meet the production requirements and the subsequent demand for production capacity expansion. The length of the working line is larger than 2 km during the overall process of southward advancement, demonstrating a long transportation distance problem.

4.2 Internal cycle transportation in the Hongshaquan opencast coal mine

The Hongshaquan opencast coal mine is currently mined in the middle of the first mining area. The average thickness of the B1 coal seam is 10.3 m and the average thickness of B2' is 15.7 m. At this time, the average thickness of the coal seam in the first mining area is calculated as 26 m. The production stripping ratio is 3.5. At present, the length of the working line is approximately 1.4 km. All the stripped materials in the stope are transported to the inner dump through the end gangue in the absence of a bridge. The stope is divided into two parts along the middle of the stope.

Load transport distance: $L_z = L/2 + D_k = 760$ m.

Empty transport distance: $L_k = L/2 + D_k = 760$ m.

Based on the annual output of 15 Mt/a, the annual advancement is approximately 316.99 m. The advancing distance of each stage is *Y*. The advancing position, the size of the mine pit, and the width of the block are all the same. The building parameters in the Hongshaquan opencast coal mine are shown in Table 1.

Table. 1. Parameters in the Hongshaquan opencast coal mine

Parameter	Symbol	Numerical value
length of working line	L	Related to v, take 1400 m
degree of advancement	v	Related to L
annual output/10,000 t	Q	1500 m
width of the end-to-end transportation path	D_d	91.59 m
width of intermediate bridge	D_z	91.59 m
width of the pit bottom	D_k	60 m
mining area width	L_z, L_d, L_r, L_c	Related to L
end slope angle for stabilization	α_1, α_2	27°

Bringing the parameters from Table 1 into formulas (1) and (2), the critical working length is calculated as 441.48 m by $Q_0 \geq Q_1$, which is far less than 1400 m. Therefore, the Hongshaquan opencast coal mine can build transportation with a bridge. Further bringing the actual parameters into Equations (2) and (3), the critical working length is 430.8 m. That is, the transportation scheme with a double bridge is better than that with a single bridge when the working line length $L \geq 430.8$ m. The working length will increase as the production of the Hongshaquan opencast coal rises. Therefore, the Hongshaquan opencast coal mine should adopt the transportation scheme with double bridges.

4.2 Economic benefit of the transportation scheme with double bridges in the Hongshaquan opencast coal mine

The annual output of the opencast mine is K, which can be expressed as $K = LMa$, wherein a is the propulsion degree, M is the average thickness, and L is the working line length. The propulsion degree a is inversely proportional to the working length L.

Table 2. Economic benefit of the transportation scheme with double bridges

Parameter	Symbol	Numerical value

Amount of stripping	G	$3.051\times10^{8}/L$
Outboard distance	L_{RZ1}	$L/2-36.59$
Inside distance	L_{RZ2}	181.59
Distance of stripping	L_Z	$L/2+60$
Annual number	n'	$6072.87/L$
Costs for bridging stripping	W_0	$4.77\times10^{9}c_d/L$
Costs with no bridging	W_1	$(1.525\times10^{8}+1.83\times10^{9}/L)C_y$

The average thickness of gangue between B1 and B2' coals is $H_j = 20.34$ m, bringing the parameters in Table 1 into formulas (6)–(15). The economic benefit formulation of the Hongshaquan open-pit mine is shown in Table 2. The volume of the secondary exfoliation is $V = 78,500$ m³. According to the production status in the Hongshaquan open-pit mine, the unit stripping cost c_d is 3.75 yuan/m³ and the unit transportation cost C_y is 6.25 yuan/m³. Therefore, the saving cost W can be obtained as formula (15). The saving cost W is from the transportation scheme with double bridges in the Hongshaquan open-pit mine. In the range of 500–3000 m and the calculated step of 500 m, the final saving costs W are shown in Figure 3.

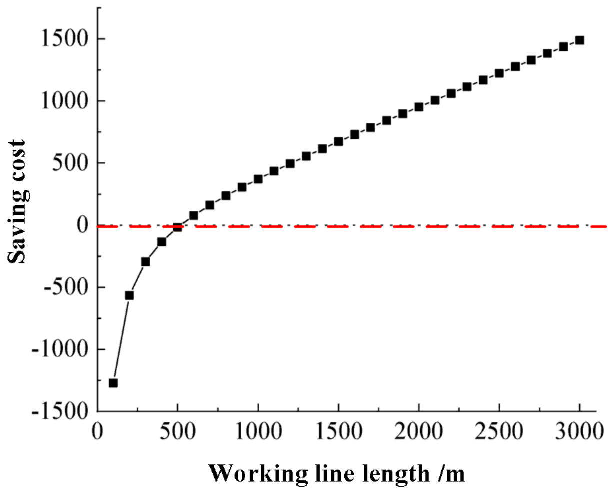

Fig. 3. Relationship between cost saving and working length

Overall, the saving cost increases with the rising working length L. When L = 515.35 m, the saving cost is sufficient to compensate for the secondary stripping cost of the bridge body. In the long term, the Hongshaquan open-pit mine accepts a transportation scheme with double bridges to reduce the cost.

5. Conclusions

This study analyzed the problems in the transportation system and proposed a method for an internal circulation transportation scheme to improve transportation and reveal the evolution laws of transportation benefits in opencast coal mines. The adaptability, key parameters, and benefits of the proposed method were then applied in the Hongshaquan opencast coal mine. The following conclusions can be drawn.

(1) Critical internal circulation length L_1 and critical double-bridge length L_2 are observed. When L is larger than L_1, the proposed method can be constructed; when L is larger than L_2, the transportation scheme with double bridges can be profitable.

(2) The Hongshaquan open-pit coal mine demonstrates the following conditions for internal circulation transportation: the critical internal transportation length $L_1 = 430.8$ m and the critical double transportation length $L_2 = 515$ m.

(3) As the work line length L increases, the saving cost of the proposed method increases. The bridge in the Hongshaquan opencast coal mine should be located at the shortest path for transporting materials through this bridge.

A new method for the internal circulation transportation scheme is proposed, and the adaptability, key parameters, and benefits of the proposed method were verified through Hongshaquan opencast coal mine. However, the actual open-pit coal mine transportation involves many complex factors. The factors in the proposed method are relatively simple. Therefore, directly applying the proposed method to the transportation systems in the actual opencast coal mine is difficult. The proposed method will be gradually extended to other open-pit coal mines and actual factors will be considered to obtain superior promotional benefits and values.

Acknowledgements
This work was supported by the Key R & D Projects of Deyang City (Grant NO.2022SZ059), the Innovation Guidance Projects of Science and Technology Plan of Deyang City (Grant NO.2022SCZ088), and the Scientific Research Project of Sichuan College of Architectural Technology (Grant NO.2018KJ11, and NO.2022KJ10).

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