



Dynamic capacity balance between stripping and mining of a dragline stripping system

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Abstract The reliability factors of a dragline stripping system were analyzed using system reliability theory to improve its reliability and ensure the stability of surface coal mine production. The relationship between the dragline scheduled stripping volume with both the weighted average thickness of the coal seam and the height of the blast casting bench was derived. The results show that the reliability of the dragline stripping system decreases with the weighted average thickness of the coal seam and increases with a reduced casting blast bench height and monthly raw coal production capacity. Furthermore, the dynamic monthly advance distance of the dragline stripping system was found, a new concept of the dragline stripping system reliability and measurement methodology were proposed, and a prediction model for the dragline production capacity was established using a generalized regression neural network. In addition, the steps and processes of the reliability were improved. The study on the Heidaigou surface mine shows that the height of the casting blast bench should be reduced to 10.5 m when its raw coal production capacity is improved from 20 to 30 Mt/a. During the normal production of surface coal, the system reliability can be improved by dynamically determining the weighted average coal seam thickness, accurately predicting the dragline production capacity, and taking other corresponding measures.

Keywords Surface mine · Stripping technology · Reliability · Dynamic adjustment

1 Introduction

Draglines are usually used for stripping overburden in an open-pit, which can be directly disposed of in an inner dump (Kyle and Costello 2006; Tuncay and Demirel 2017; Panishev and Kaimonov 2018). Compared with the shovel-truck approach, dragline stripping is a typical combined system that reduces production costs caused by loading and transportation (Sun et al. 2019). The combination of dragline stripping and blast casting technology can dramatically increase the capability and stripping costs of an open-pit mine (Fu and Li 2006; Li et al. 2006). Due to the deeply buried coal seams in China, blast casting-dragline

stripping systems can only be applied to strip the overburden, which significantly restricts surface coal mining operations (Shang et al. 2010; Yang et al. 1993).

In addition, some parameters, such as the coal seam thickness and the equipment production capacity, will be considered when creating the production schedule. The averages of these parameters are used in China, which is based on the hypothesis that they are relatively constant. This causes the dragline stripping system to be static without adjusting to the dynamic parameters, which increases the difficulty for the dragline stripping system to complete the planned tasks (Zhou et al. 2013). Therefore, optimization of the dragline stripping system reliability is essential to prevent unwanted stoppages (Che and Chen 2014). Changes in the coal seam thickness and adjustments to the dragline stripping system operational parameters will greatly improve the reliability of the dragline stripping

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system and ensure the sustained and stable production of surface coal mining.

To address the above problems, Ma et al. (2006) proposed the concept of a critical coal seam thickness and provided the process to adjust the associated dragline operational parameters. However, the critical coal seam thickness was calculated based on the annual sales volume of ore and the annual stripping volume of the dragline. Thus, the results could only be used as a guide to create the annual production schedule rather than the monthly schedule. Moreover, their adjustment method was too simple. Zhou et al. (2007) analyzed the impact of variations in the coal seam thicknesses on the reliability of the dragline stripping system. They proposed a formula to calculate the system reliability by considering changes in the coal seam thickness and provided a statistical method to estimate the average coal seam thickness based on borehole data. However, the lower level of exploration precision caused the estimated coal seam thickness to be completely different from the actual value. This influences the calculated reliability, and the desired results of the decision cannot be achieved. Cai et al. (2009) created a dragline stripping system and semi-continuous mining coal system as a model to determine the system reliability. They considered the increasing maintenance rate of the dragline as an effective measure to enhance the system reliability. The impact of mechanical faults on the system reliability were considered, but the influence of the coal seam thickness was ignored. Uzgoren et al. (2010) analyzed the mechanical faults of two draglines. Their analysis of the dragline reliability contributes to understanding its fault characteristics and allows creating a reasonable maintenance schedule, but only the reliability of a single dragline, rather than the entire system, was studied. Liu et al. (2018) formulated a mixed-integer linear program to capture the operational constraints imposed in the dragline excavation to optimize material movement for a prescribed sequence of dragline positions. Sun et al. (2018) proposed a multi-level coordination mechanism of a combined surface mining system to improve the system stability. Parikshit et al. (2019) discussed a case of premature failure for a coal-handling dragline and performed a failure investigation through visual examination, chemical analysis, metallography, mechanical property evaluation, and fractography.

The influence of dragline mechanical failures and variations of the coal seam thickness on the reliability of dragline stripping system were studied in the above references. However, the impact of other factors on the dragline stripping system, such as its production capacity, were not considered. This paper thoroughly studies the primary factors that influence the reliability of the dragline stripping system and proposes methods to improve the system

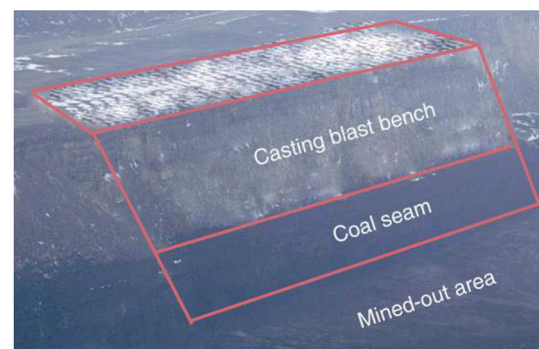
reliability based on changes in the coal seam thickness and the dragline production capacity.

2 Impact of coal seam thickness on advance distance

A dragline system is suitable for nearly horizontal or gently inclined coal seams whose angle change and thickness are well-known, and whose entire area can be mined (Ding 1998). Coal reserves for such areas can be calculated using the block method. The calculation error of the coal reserves is caused primarily by the representative errors in the coal thickness. The true coal seam thickness can be measured directly along the vertical seam between the roof and floor as the coal seam under the stripping bench of dragline stripping system is outcropped, as shown in Fig. 1. The measurement error can be easily controlled when the measuring distance is increased in the area where the coal thickness changes little, and the measurement points can be increased in areas with large coal thickness changes.

Based on the hypothesis that there is a large block of coal that consists of some n small blocks, as shown in Fig. 2, the coal reserve Q is expressed as

$$Q = \sum_{i=1}^n Q_i = \sum_{i=1}^n l_i h_i A \gamma = L \bar{h} A \gamma \quad (1)$$



(a)



(b)

Fig. 1 Photograph of blast casting bench and coal seam

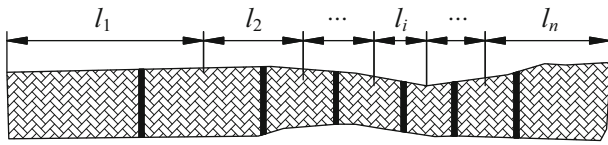


Fig. 2 Schematic for the coal seam reserve calculation

where, Q is the reserve for the large block of coal in t ; n is the number of small blocks; l_i is the length of the i -block in m ; h_i is the height of the i -block in m ; A is the width of mining panel in m ; γ is the density of coal in t/m^3 ; L is the length of the large block of coal in m , $L = \sum_{i=1}^n l_i$; and \bar{h} is the weighted average coal seam thickness in m , $\bar{h} = \frac{1}{L} \sum_{i=1}^n l_i h_i$.

Suppose the planned monthly raw coal production capacity of a surface mine is M and the coal recovery rate is k_c . Then, the coal reserve of the planned mining area Q_s is expressed as

$$Q_s = \frac{M}{k_c} \tag{2}$$

Let $Q_s = Q$, and the advance distance along the working line of the coal face is $L_m = \sum_{i=1}^n l_i = L$ according to Eqs. (1) and (2). To ensure the stable production of the surface mine, the monthly advance distance along the working line of the dragline stripping system and that of the coal face should be equal:

$$l_d = L_m = \frac{M}{hA\gamma k_c} \tag{3}$$

where, l_d is the monthly advance distance of the dragline stripping system in m .

3 Analyzing factors that influence the dragline stripping system reliability

Reliability is the probability that a system will carry out its specified mission for the stated duration when used under given conditions (Esmaeili et al. 2011; Hoseinie et al. 2011). The dragline stripping system reliability refers to the ability to complete the scheduled stripping tasks in the current operating conditions of a surface mine in the scheduled time. This can be expressed as

$$R = P(Q_a \geq Q_d) \tag{4}$$

where, R denotes the degree of reliability of the dragline stripping system; Q_a denotes the actual production capacity of the dragline in m^3 per month; and Q_d denotes the scheduled stripping volume of the dragline in m^3 per month.

A dragline stripping system fault is defined as when the scheduled stripping task cannot be completed as caused by

a system shutdown due to dragline failures, a larger than expected number of dragline scheduled stripping tasks, etc. The concept of the reliability measure for a dragline stripping system is introduced to evaluate the reliability as

$$F = \frac{Q_a}{Q_d} \tag{5}$$

where, F is called the Reliability Measure. The Reliability Measure F usually fluctuates around “1” when the surface mine operates normally. The ability to complete a scheduled stripping task can be measured from the value of F . When $F \geq 1$, the dragline stripping system reliability is $R = 1$; when $F < 1$, the dragline stripping system reliability is $R < 1$.

The scheduled stripping volume of the dragline can be deduced from the scheduled advance distance and the geometrical relationship shown in Fig. 3 as

$$Q_d = l_d H A k_s (1 - k_1 + k_2) \tag{6}$$

where, H is the height of the blast casting bench in m ; k_1 is the effective throw rate of the blast casting; k_2 is the rehandling strip rate; and k_s is the loose coefficient of the blast casting. Equation (7) is derived by combining Eqs. (3) and (6) as

$$Q_d = \frac{M H k_s (1 - k_1 + k_2)}{\bar{h} \gamma k_c} \tag{7}$$

Suppose the monthly raw coal production capacity is $M = 2.50$ Mt. When the height of the blast casting bench is constant ($H = 37$ m), the relationship for the scheduled stripping volume of the dragline Q_d and the weighted average coal seam thickness \bar{h} are obtained from Eq. (7), as shown in Fig. 4a.

Figure 4a illustrates that the scheduled stripping volume of a dragline increases with smaller weighted average coal seam thicknesses when the height of the blast casting bench and the monthly raw coal production capacity are constant. This leads to a decreased dragline stripping system reliability. The scheduled stripping task cannot be completed if the actual production capacity is less than the scheduled stripping volume, leading to a dragline stripping system fault. The scheduled stripping volume of a dragline

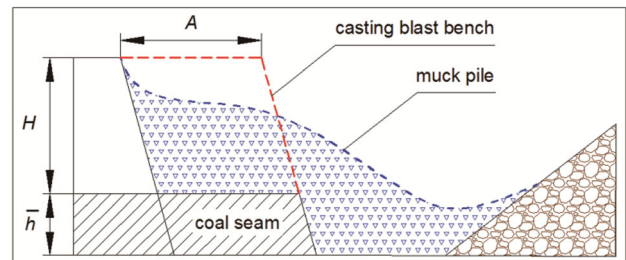


Fig. 3 Profile of the blast casting bench before and after a blast

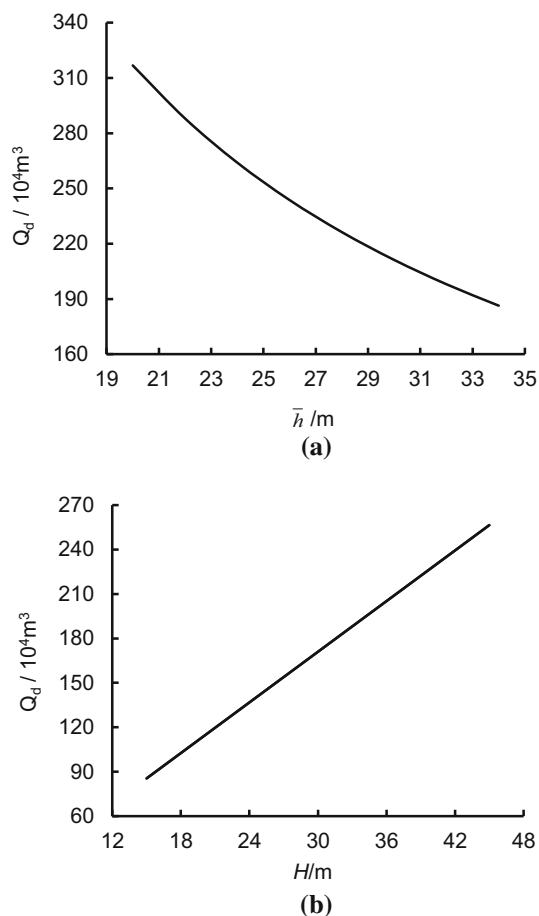


Fig. 4 Relationship between the scheduled dragline stripping volume and **a** the weighted average coal seam thickness and **b** the height of the blast casting bench

increases with the monthly raw coal production capacity and the height of the blast casting bench. Therefore, the dragline stripping system reliability decreases with a higher monthly raw coal production capacity and height of the blast casting bench.

In practical production, the monthly raw coal production capacity is set and it is impractical to quickly adjust the determined height of the blast casting bench. Therefore, variations in the coal seam thickness readily occur as the coal seam is uncovered. The actual production capacity of the dragline changes regularly as factors such as climate and the blasting quality change. For example, the coal seam thickness and dragline production capacity should be determined dynamically to enhance the dragline stripping system reliability.

4 Forecasting dragline production capacity

4.1 Established predictive model

The results of traditional forecasting methods, such as the grey method and time series methods, are not ideal for the production capacity due to the underlying complicated factors. Thus, a general regression neural network (GRNN) was selected to build the predictive model for the dragline production capacity. The GRNN is based on a nonlinear neural network model (Specht 1991; Jia et al. 2013). However, the kernel function is used to initialize the smoothing parameter and implement Parzen’s nonparametric estimation without setting a specific model based on a nonparametric kernel regression analysis and on the experimental conditions of the sample data (Schioler and Hartmann 1992). Compared with a back propagation neural network, the GRNN is widely applied in geotechnical engineering, transportation, and many other fields because of its advantages, such as a higher prediction accuracy and stability, faster convergence, smaller required computation, and better prediction results when there is limited training data (Yi et al. 2013; Rahman et al. 2012; Cigizoglu and Alp 2006). Four indexes (actual dragline working hours, powder factor, loading cycle, and climatic factors) and the dragline production capacity are chosen as the inputs and output of the GRNN, respectively. The analysis of the main factors that influence the dragline production capacity are used to build a model for the GRNN, as shown in Fig. 5. The actual working hours, loading cycle, and dragline production capacity are obtained through statistics of the surface mine. The rock volume of the blast casting and the consumption of explosives in a month are obtained based on the blast casting design of the surface coal mine to calculate the powder factor. Climatic factors can be assessed based on the monthly weather conditions, such as temperature, rainfall, snow, and haze.

In Fig. 5, the number of neurons m in the input layer is equal to the dimension of the input vector, and the input variables are passed directly to the model layer.

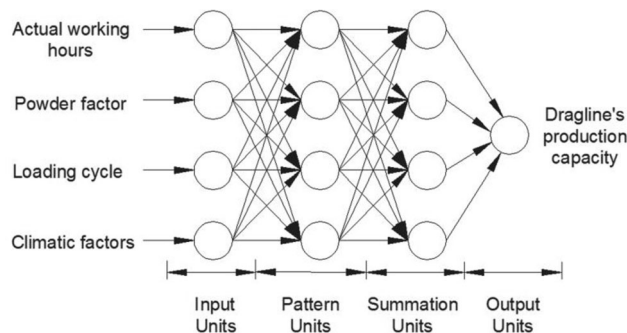


Fig. 5 Model of the GRNN

number of neurons in the model layer is equal to that of the learning samples, so each neuron corresponds to a different sample. The neuron transfer function is

$$p_i = \exp \left[-\frac{(X - X_i)^T (X - X_i)}{2\sigma^2} \right], \quad i = 1, 2, \dots, n \quad (8)$$

where, X is the network input variables; X_i , is the learning sample of the i -th neuron; and σ is the smoothing parameter. The summation layer contains two types of neurons. One type is the arithmetic sum of the output of all the neurons in the model layer with a transfer function of

$$S_D = \sum_{i=1}^n p_i \quad (9)$$

The other type is the weighted sum of the output for all neurons in the model layer with a transfer function of

$$S_{Nj} = \sum_{i=1}^n y_{ij} p_i, \quad j = 1, 2, \dots, k \quad (10)$$

The number of neurons in the output layer is equal to the dimension of the output vector. In the model, the output of each neuron is obtained from dividing by the sum layer prediction as

$$y_j = \frac{S_{Nj}}{S_D} \quad (11)$$

4.2 Model solution

The training and forecasting of the network is achieved through programming the function “newgrnn” to design the generalized regression neural network. Firstly, the sample data are loaded and divided into training samples and forecasting samples. Secondly, the circuit training method is used to solve the optimal smoothing parameter and is applied to the cross-validation method to train the network. Finally, the established network model is used for predictions.

To ensure the prediction effect, the sample data are normalized using Eq. (12) before network training. In the output layer, Eq. (13) is used to restore the output results (Liu et al. 2014).

$$\bar{x}_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad (12)$$

$$x_i = \bar{x}_i(x_{\max} - x_{\min}) + x_{\min} \quad (13)$$

where \bar{x}_i represents the normalized data; x_i represents the original data; x_{\max} is the maximum value in the data column; and x_{\min} is the minimum value in the data column.

5 Reliability improvement of dragline stripping system

The production costs will be too high, and the equipment utilization rate will be too low when the dragline stripping system reliability is extraordinarily high. In contrast, the stable production will be affected when the dragline stripping system reliability is too low. Methods such as dynamically determining the weighted average coal seam thickness, accurately predicting the dragline production capacity, utilizing a shovel-truck to assist the dragline stripping, and adjusting the height of the blast casting bench are used to improve the dragline stripping system reliability. The improvement steps are as follows:

(1) According to the planned monthly raw coal production capacity of the surface mine M and the measured thickness of the coal seam h_i , the scheduled dragline stripping volume can be deduced from Eqs. (1) and (7). The dragline production capacity Q_a can be predicted based on the established forecast model.

(2) If $Q_d \leq Q_a$, the scheduled stripping task can be completed by the dragline stripping system, the system reliability is $F = \frac{Q_a}{Q_d} \geq 1$, and the dragline production capacity is a surplus.

When $\frac{Q_a - Q_d}{Q_d} \leq 10\%$, no adjustments are needed to ensure the dragline production capacity is in surplus or that the system is reliable.

When $\frac{Q_a - Q_d}{Q_d} > 10\%$, to make full use of the dragline production capacity and decrease the production costs, the assisted stripping volume of bulldozer Q_t can be reduced and part of the assisted stripping volume can be completed by the dragline. The height of the casting blast bench or planned monthly raw coal production capacity of the surface mine can be increased appropriately to enhance the scheduled dragline stripping volume. Alternatively, the planning maintenance of the dragline can be scheduled to increase its actual subsequent working hours. As the dragline model is selected based on the production tasks, the case where the dragline production capacity is too great is not common. It is more likely to reduce Q_t or arrange for planned maintenance.

As the assisted operational volume of bulldozers is indispensable, it is assumed that the maximum assisted operations that can be reduced is $\Delta Q_{t\max}$, where $\Delta Q_{t\max} < Q_t$. If $Q_a - 1.1Q_d \leq \Delta Q_{t\max}$, the amount that the assisted operation volume of bulldozers can be reduced is $\Delta Q_t = Q_a - 1.1Q_d$. If $Q_a - 1.1Q_d > \Delta Q_{t\max}$, the value of ΔQ_t can be chosen in the range of $[0, \Delta Q_{t\max}]$ based on the actual situation. Thus, the dragline is arranged for planned maintenance, where the days of overhauling are $t = 30(Q_a - 1.1Q_d - \Delta Q_t)/Q_a$.

(3) If $Q_d > Q_a$, the scheduled dragline stripping task cannot be completed. The system is in fault and the system Reliability Measurement is $F = \frac{Q_a}{Q_d} < 1$. Thus, the system reliability should be enhanced by taking specific measures.

The assisted operation is completed by bulldozers, and a portion of the stripping volume is completed by the shovel-truck system. Only one set of shovel-truck systems can be arranged for stripping on the dragline working bench due to the working space. The maximum assisted stripping volume of the shovel-truck Q_f is the monthly production of a single-shovel excavator Q_w . Then, $Q_{fmax} = Q_w$.

(4) When $Q_{fmax} \geq 1.1Q_d - Q_a$, the assisted stripping volume of the shovel-truck is $Q_f = 1.1Q_d - Q_a$. When $Q_{fmax} < 1.1Q_d - Q_a$, the only available method is to reduce the height of the casting blast bench H . This reduced height is $\Delta H = \frac{Q_d - Q_a}{L A k_s}$, and the surplus is stripped with the shovel-truck system.

The improvement process of the dragline stripping system is shown in Fig. 6. Changes in the coal seam angle are not considered in the above analysis, so the model is only suitable for surface coal mines with gently inclined coal seams that change little and where a dragline stripping system is used.

6 Case study

In China, the dragline stripping system was first used in 2007 in the Heidaigou surface mine. The designed coal production capacity was 20 Mt/a and the other parameters are as listed in Table 1.

The coal production capacity was raised to 30.0 Mt/a due to business development, market needs, and other factors. When the other parameters are constant, the average coal seam thickness is chosen as $\bar{h} = 28.8$ m, and the monthly raw coal production capacity of the surface mine M increased from 1.67 to 2.50 Mt/month. The height of the casting blast bench needs to be reduced if the scheduled stripping volume increases from 1.79 to 2.68 Mm³ per month where the actual production capacity Q_a is the average value of 1.9 Mm³ per month and $1.1Q_d - Q_a = 1.04$ Mm³ per month $> Q_{fmax} = 0.6$ Mm³ per month. The reduced height of casting blast bench is $\Delta H = \frac{Q_d - Q_a}{L A k_s} = 10.5$ m, where $L = \frac{M}{A h \gamma k_c} = 774$ m. Now, the height of the casting blast bench is reduced to approximately 10.5 m, and the stable production of the dragline stripping system can be ensured based on the actual production.

For instance, the production schedule of the surface mine from November 2018 is given to illustrate the improved process of the dragline stripping system.

- (1) Calculate Q_d and predict Q_a

The planned monthly raw coal production capacity was $M = 2.60$ Mt per month, the weighted average coal seam thickness in the mining area was $\bar{h} = 29.7$ m; and $Q_d = 2.1$ Mm³ per month is calculated using Eq. (7). According to the statistical data shown in Table 2, the previous 12 samples are taken for network training and testing (3/4 and 1/4 are used for training and testing, respectively), and the final sample is taken as for predictions. The smoothing parameter performs cyclic training as varied from [0.1, 2] in steps of 0.1, where the optimal

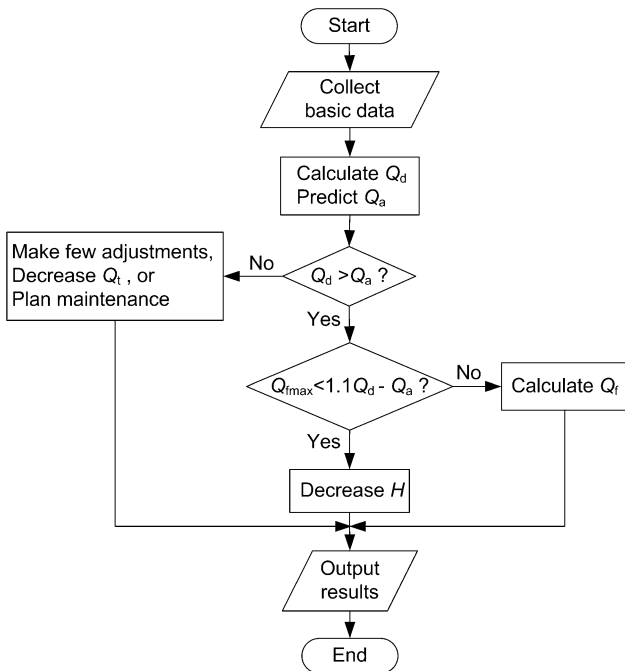


Fig. 6 Improvement flow chart of dragline stripping system

Table 1 Relevant parameters of the Heidaigou surface mine from 2007

Parameter	Units	Value
H	m	45
A	m	80
γ	ton/m ³	1.43
k_c	%	98
k_1	%	30
k_2	%	10
k_s	–	1.2
Q_{fmax}	Mm ³ per month	0.6

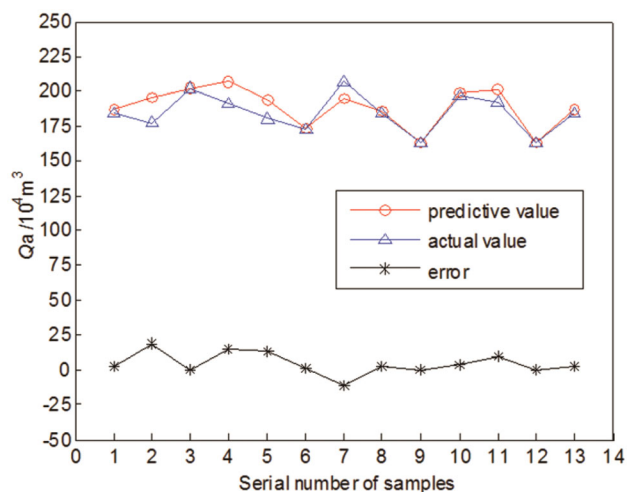
Table 2 Sample set of the GRNN model

No.	Year. Month	Actual working hours (h)	Powder factor (kg/m ³)	Loading cycle (s)	Climatic factors	Q_a (10 ⁴ m ³)
1	2017.11	433.7	0.636	54	0.80	184.11
2	2017.12	376.5	1.185	56	0.95	177.25
3	2018.1	463.5	0.735	50	0.95	202.43
4	2018.2	379.8	0.710	51	1.00	191.03
5	2018.3	425.3	1.211	59	0.95	180.25
6	2018.4	429.0	0.509	56	0.90	173.10
7	2018.5	460.0	0.663	49	1.00	206.25
8	2018.6	338.2	0.668	52	0.90	183.90
9	2018.7	428.2	0.820	55	0.85	162.80
10	2018.8	440.7	0.659	58	0.80	196.26
11	2018.9	376.3	0.790	52	0.90	192.06
12	2018.10	354.5	0.747	56	0.90	162.60
13	2018.11	369.7	0.583	53	0.95	184.28

smoothing factor was 0.2. The predicted result is $Q_a = 1.87 \text{ Mm}^3$ per month from the established GRNN prediction model, as shown in Fig. 7.

(2) Compare Q_d with Q_a

When $Q_d > Q_a$ and $1.1Q_d - Q_a = 0.44 \text{ Mm}^3$ per month $< Q_{fmax}$, a portion of the scheduled stripping volume should be completed by the shovel-truck system, where the assisted stripping volume of the shovel-truck is $Q_f = 1.1Q_d - Q_a = 0.44 \text{ Mm}^3$. As the production capacity of the dragline is in surplus for this case, the reliability of the dragline stripping system is ensured. However, the assisted stripping volume of the shovel-truck is 0.44 Mm^3 , which nearly reaches the maximum production capacity of

**Fig. 7** Results of the network training and prediction

0.6 Mm^3 . This illustrates the production assignment in November is challenging with a tight production process.

The production capacity of the dragline is 1.84 Mm^3 in the actual surface mine production, which is 0.03 Mm^3 smaller than the predicted value of 1.87 Mm^3 . The assisted stripping volume of the shovel-truck completed is 0.48 Mm^3 , which exceeds the task completion. The improvement results are nearly consistent with the actual surface mine production and can ensure the reliability of the dragline stripping system.

7 Conclusions and discussion

- (1) Coal seams that adopt the dragline technology are near horizontal and gently inclined, changes in the coal seam dip angle and thickness are regular, and the coal seams have been exposed. The coal reserves under the step can be determined by measuring the coal seam thicknesses using the block method to accurately calculate the advanced distance and planned stripping amount of the dragline system.
- (2) Apart from the internal and external faults of the dragline, there are several other factors that affect the dragline stripping system reliability, such as the scheduled stripping volume, changes in the coal seam thickness, height of the blast casting bench, and the actual production capacity of the dragline. The calculations indicate that the dragline stripping system reliability decreases with the weighted mean of the coal seam thickness and increases with a decreased height of the blast casting bench and monthly raw coal production capacity.
- (3) An improvement measure is needed to dynamically determine the weighted average coal seam thickness, accurately predict the production capacity of the dragline, and utilize a shovel-truck to assist the dragline in stripping to adjust the height of blast casting bench and improve the dragline stripping system reliability. The study of the Heidaigou surface mine shows that the blast casting bench height should be reduced to 10.5 m and the raw coal production capacity should be improved from 20 to 30 Mt/a.
- (4) The coal seam thickness and production capacity affect the dragline stripping system reliability, which are considered in this paper. The factors of mechanical dragline faults and the climate are included when predicting the dragline production. In actual production, the effective throw rate of the blast casting is related to several factors, such as the powder factor and the properties of the blast casting rock. While variable, the effective throw rate still

can be predicted based on its influencing factors. The prediction method is similar to that for the production capacity, so the details are not repeated here. This paper assumed that the effective throw rate is constant.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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