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Research on the Optimization of Open-Pit Mine Cast Blasting Parameters Based on the Optimal Economy of Dragline Stripping Technology

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Abstract: As the key technology of high-step stripping and blasting engineering, throwing blasting will be the development trend of the production optimization and benefit maximization of the open-pit mine in the future. In order to break with the research idea of optimizing the cast blasting effect by improving the effective throwing rate for a long period of time, maximizing the economic benefit of the subsequent dragline stripping technology and stabilizing the engineering connection, this paper takes the Heidaigou open-pit mine as the research object. Through data acquisition, analysis, and data fusion of the heaped-up bulk characteristics, the heaped-up bulk profile can be obtained to characterize the cast blasting effect. Secondly, the key factors influencing the cast blasting effect are determined based on the gray relational degree theory. Then, the black box principle of the system control theory is adopted as the guiding principle of the blasting optimization. Based on the production data of field cast blasting, the dynamic change law between the controllable variables of system input and the observable variables of system feedback in the black box system are studied and explored without consideration of the internal structure or the energy transformation relationship of the cast blasting system. Finally, the optimal blasting parameter combination under different working conditions is obtained. If the research results are successfully applied, it is expected that the dragline stripping technology cost of the Heidaigou open-pit mine can be reduced by 5~10%, and the results can also provide new ideas and new ways of optimizing the design of cast blasting.

Keywords: open-pit mine; cast blasting; dragline stripping technology; black box theory; gray correlation degree theory

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1. Introduction

With the continuous improvement of the national economic level and the continuous rise in energy demand from all walks of life, the coal industry still plays a pivotal role in economic development, and thus also promotes the further development of open-pit coal mine output [1,2]. However, with the continuous expansion of the open-pit mining scale and the improvement in mining promotion speed, the equipment operation efficiency has gradually reduced, and the production operation cost has gradually increased. Therefore, open-pit mines are in a period of rapid development, but they also face the challenge of technological upgrades. Engineering blasting is an essential production link in most open-pit mines [3]. Among them, cast blasting is a blasting method with a throwing effect. In other words, part of the rock can be directly thrown to the adjacent goaf under the action of explosive gas expansion, which occurs due to the use of explosive energy. The cost of open-pit mining can be greatly reduced by avoiding the need for secondary operations of the equipment. Then, the materials not entered into the goaf are carried out via the dumping operation by the dragline. The dragline has less equipment than others, and logging and dumping are often joined closely. Due to the energy saving and high efficiency of this production process, the production cost is further controlled [4,5].

The research and application of cast blasting technology started late in China, and the application practice of open-pit mines is sparse (currently, only the Heidaigou open-pit mine adopts this technology for mining) and the degree of attention is not high. There are no mature experiences or technology to be referenced in China, and the application effect of this technology lags behind the level of foreign countries [6]. Particularly with respect to the blasting effect, with the stope extending deeper and the geological conditions becoming more and more complex, the current blasting design precision and construction control precision cannot meet the needs of cast blasting; furthermore, the cast blasting effect is not good. In terms of economic benefits, the poor effect of cast blasting directly leads to a gradual reduction in the advantages of dragline stripping technology and also contributes to low operation efficiency and a gradually higher production cost, which seriously restrict the economic development of open-pit mines [7,8].

Therefore, in order to improve the effect of rock throwing, many scholars have carried out a great deal of research on the application of cast blasting technology [9–11]. In terms of cast blasting parameter design, Xiao Shuangshuang [12] used regression analysis to construct the relationship model between the step parameters of cast blasting and the stripping cost. From the perspective of blasting design, Hu Tao and Nicholas P Chironis [13,14] summarized many of the factors affecting cast blasting, such as the parameter design and material characteristics. Anthony P Grippo [15] analyzed and studied how to improve the effective throwing rate and the value of the main influencing parameters. Li Xianglong [16] used blasting experiments to discuss the optimal row spacing of cast blasting. Wang Pingliang [17] studied the determination method of the row spacing according to the relationship between hole spacing and the blasting effect. Mark and Kanchibotla S S [18,19] conducted an analysis and research on the influencing factors of the blasting effect. In predictions of the cast blasting effect, Wang Yuchen [20] proposed a Marine Predator algorithm (MPA) to optimize the support vector machine (SVM), and the applicability of MPA-SVM to the morphology prediction of heaped-up bulk was proved. Ma Li [21] proposed a genetic algorithm (GA) to optimize the least square support vector machine (LSSVM) prediction model of the cast blasting effect, and the research results improved the prediction accuracy of the cast blasting effect in an open-pit coal mine. Cao Yong [22] used a Shotplus-iproSV blasting design and analysis software to carry out a cast blasting design and simulation analysis of the projectile blasting effect in the Heidaigou open-pit coal mine. Huang Yonghui [23] proposed a model that used ELM neural network and Weibull function to predict the morphology of the heaped-up bulk. In terms of cast blasting effect evaluations, Zhao Hongze [24] established an integrated evaluation system of gray correlation—the analytic hierarchy process and entropy weight method—which is an analytic hierarchy process to evaluate the cast blasting effect of 10 heaped-up bulks in an open-pit mine. Zhang Zhaoliang [25] built a comprehensive evaluation model for the cast blasting effect of open-pit coal mines based on cloud model theory. Kang Haijiang [26] used the BP neural network to comprehensively evaluate the effect of cast blasting.

To summarize, previous researchers have believed that the effective throw rate is the basic index through which to evaluate the quality of the cast blasting effect; as such, the current research mainly focuses on how to optimize the blasting design and how to improve the effective throw rate. However, by considering the cast blasting and dragline stripping technology as a complex system, the overall economic benefits of the system and the stable operation of the system are more important to the open-pit mine. Pursuing only an increase in the effective throwing rate cannot help with reducing the overall stripping cost of the system, nor can it help to achieve the optimal comprehensive benefit. Secondly, there is a certain error in evaluating the blasting effect only according to the effective throwing rate. Therefore, the authors break the blasting effect optimization method based on the ideal condition, and they study and propose an optimization method of open-pit blasting parameters that is based on the optimal economy of dragline stripping technology. By determining the optimal heaped-up bulk characteristics, the parameters design of cast blasting can be optimized.

2. Methods and Steps

2.1. Engineering Background

The Heidaigou open-pit coal mine in China is the first to introduce cast blasting technology, which is mainly used for the stripping of the rock above the roof of the 6# coal seam, and it is successfully combined with the dragline to form dragline stripping technology (the 2D dragline stripping technology of the Heidaigou open-pit coal mine schematic diagram is shown in Figure 1). Since its initiation, the Heidaigou open-pit mine has seen the accumulation of rich experience in field practice. However, the conventional research considers that the effective throwing quantity (the total amount of material thrown directly into the goaf) is the key index through which to evaluate the cast blasting effect. The current research and practice mainly aim at optimizing cast blasting parameters and increasing the effective projectile quantity. However, after long-term field investigation, it was found that the characteristics of cast blasting as the pre-step of the dragline stripping technology play a key role in the production cost of the subsequent overcasting stripping. According to the field statistics, under the condition of the same amount of effective throwing, the production cost of the subsequent pouring process can vary by up to 30% due to different heaped-up bulk characteristics. Moreover, the heaped-up bulk characteristics also have a certain influence on the subsequent dragline stripping technology production connection. Therefore, the authors take the characteristics of heaped-up bulk as the research object, take reducing the overall production cost of dragline stripping technology as the research objective, and find the corresponding blasting parameter combination by determining the optimal characteristics of the heaped-up bulk under different geological conditions and different blasting parameters, and this is performed so as to optimize the parameter design of the on-site cast blasting.

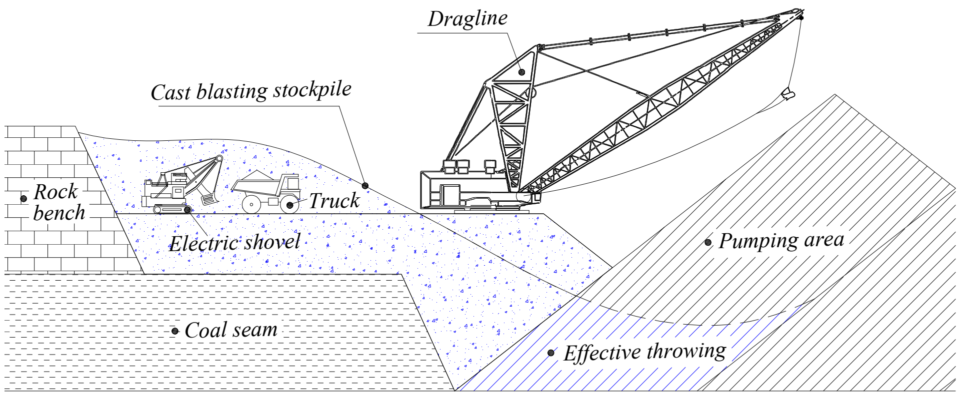

Figure 1. The 2D dragline stripping technology schematic diagram.

2.2. Data Acquisition and Processing Methods

2.2.1. Data Collection Method

In order to improve the acquisition accuracy of the data related to heaped-up bulks, the quarrymen 3D laser scanner was selected as the data acquisition equipment in this paper. The relevant performance parameters are shown in Table 1, and the equipment layout points are shown in Figure 2. Among them, points 1# and 6# are mainly responsible for collecting the related data of goafs and the lower heaped-up bulk areas; points 3# and 4# are mainly responsible for collecting the related data of the high step near goafs and the central heaped-up bulk area; and points 2# and 5# are mainly responsible for collecting the related data of local goafs and upper heaped-up bulk areas, so as to build a complete 3D model of the cast blasting area.

Table 1. Equipment parameters of the high-precision scanner.

Project	Parameter	Description
The data collection	—	360° scan and panoramic photo collection
The laser wavelength	1550 nm	No visible light
The scanning angle	0° to 360° −45° to 80°	Horizontal angle The vertical angle
The scanning distance	0.5 m to 700 m	—
The scanning speed	7000 p/h	—
The transmitter resolution	1 cm	Precision can be up to 10 cm
Scanning angular resolution	0.01°	Accurate to 0.02°
Image acquisition	432 million pixels	Panoramic scope
The sensor	—	IMU obliquity sensor, altimeter, GNSS
Wireless communications	802.11 b/g/n	Integrated wireless communication module of WLAN
Data storage	256 GB,USB3.0	External storage
Length of equipment	209 mm × 243 mm × 419 mm	Length, width, and height
Appropriate temperature	−10 °C to 45 °C	Working temperature

Figure 2. Schematic diagram of the field equipment collection.

2.2.2. Data Sample Processing Method

In order to restore the real heaped-up bulk characteristics after cast blasting as much as possible, the sample size of the 3D point cloud data should be increased on the basis of the collected 3D point cloud data, so as to improve the restoration accuracy of the heaped-up bulk characteristics. Through a literature review and analysis, this paper intends to adopt the method of the discrete point moving fitting distance weighted average interpolation to increase the sample size of the 3D point cloud data [27]. Secondly, for the added sample data, it is also necessary to conduct a data feature test, so as to improve the accuracy of the data.

Firstly, the idea of a data dimension reduction was proposed. In order to simplify the research process and reduce the dimension of the data index, 2D space was used to replace 3D space; that is, the surface characteristics of the heaped-up bulk were used to replace the 3D characteristics of the heaped-up bulk. Secondly, considering that the bending degree of each position of the heaped-up bulk surface is determined by the curvature of each point, according to the bending characteristics of the surface, this study divided the shape of the heaped-up bulk surface into a convex surface, a concave surface, and a straight surface. Finally, the characteristic model of the heaped-up bulk surface was constructed. Suppose $n(x_n, j_n)$ as the fitting surface after $\overline{Z} = \overline{f}(x,y)$; the location of the points on the tangent plane with the center point and the relative position of the surface are used to determine the relationship between the changes in the concave and convex surfaces. As such, the $n(x_n,j_n)$ location points fitting the surface $\overline{Z} = \overline{f}(x,y)$ center (x_0,y_0) are expressed as follows:

$$\overline{Z} = \overline{f}(x_0, y_0) + \frac{\partial \overline{f}}{\partial x}(x_0, y_0) \cdot (x - x_0) + \frac{\partial \overline{f}}{\partial y}(x_0, y_0) \cdot (y - y_0) \tag{1}$$

If the tangent plane is located above the fitting surface, the surface of the heaped-up bulk element is convex. If the tangent plane is located below the fitting surface, the surface of the heaped-up bulk element is concave. If the tangent plane coincides with the fitting surface, then the surface of the heaped-up bulk element is a straight face. Therefore, with the elevation at its center position $\overline{Z}(p_k)$ and its actual elevation value $Z(p_k)$ of the mean value being defined as the difference between the surface point location in form features, we have the following:

$$G = \frac{1}{n} \sum_{k=1}^{n} \left[\overline{Z}(p_k) - Z(p_k) \right] \tag{2}$$

When $G > 0$, the heaped-up bulk slope is convex, and the larger G is, the greater the convexity. When $G < 0$, the heaped-up bulk slope surface is concave, and the larger G is, the greater the concavity, And, when $G = 0$, the slope of the heaped-up bulk is direct.

2.3. Explosion Surface Fitting Based on Data Fusion Method

2.3.1. Proposed Data Fusion Algorithm

Data fusion technology refers to the information processing technology that adopts computers to automatically analyze and synthesize several pieces of observational information, which are obtained in a time sequence according to certain criteria, to complete the required decision-making and evaluation tasks [28]. This technology can analyze and process multi-source pieces of information data with characteristics of redundancy, complementarity, and cooperation, so as to obtain more accurate results [29].

Considering that the heaped-up bulk after cast blasting is a 3D entity with a certain length in the direction of strike and inclination, the research needs to obtain the typical heaped-up bulk profile curve under different explosive pile forms. Therefore, this study proposes to cut the heaped-up bulk into a sample system that is composed of a series of heaped-up bulk profiles. During data analysis, the sample system is extracted according to certain principles. Each extraction is regarded as an observation of the sample system, and the final heaped-up bulk profile curve is the combination of multiple pieces of systematic observation data.

2.3.2. Data Fusion Algorithm Process

a. Sampling principle of the heaped-up bulk data

After construction of the heaped-up bulk 3D model is completed using 3D laser scanning technology, profile cutting is made along the strike direction of the heaped-up bulk model at every interval distance a, and then the control point position is taken along the inclination direction of the heaped-up bulk model at every interval distance b on the profile (the schematic diagram of 2D and 3D heaped-up bulk models is shown in Figures 3 and 4). It is assumed that m sections are cut along the strike direction of the heaped-up bulk model in total, and that they are marked as vectors Z_1, Z_2, Z_3, $\cdots$, Z_m. If there are n control points in the inclination direction of the section of the ith heaped-up bulk model, then they denote h_{i1}, h_{i2}, h_{i3}, $\cdots$, and h_{in}, respectively. If this is such, then the existing relationship can be expressed as follows:

$$Z_i = \begin{bmatrix} h_{i1} & h_{i2} & h_{i3} & \cdots & h_{in} \end{bmatrix} \tag{3}$$

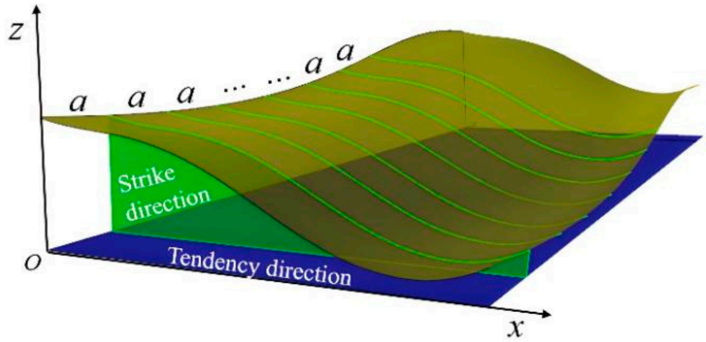

Figure 3. Schematic diagram of the heaped-up bulk cutting surface along the strike direction.

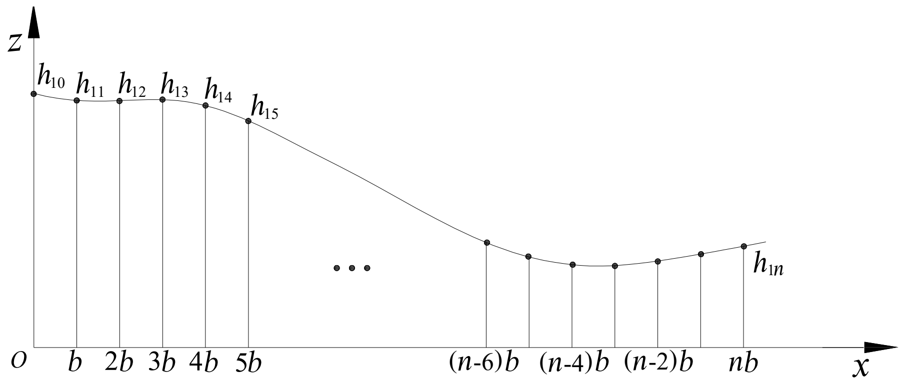

Figure 4. Schematic diagram of the heaped-up bulk profile along the tendency direction.

If Matrix A is used to describe the morphological characteristics of the 3D model of the entire heaped-up bulk, then the relation of A can be expressed as follows:

$$A_i = \begin{bmatrix} Z_1 & Z_2 & Z_3 & \cdots & Z_m \end{bmatrix}^T = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \cdots & h_{1n} \\ h_{21} & h_{22} & h_{23} & \cdots & h_{2n} \\ \vdots & & \cdots & & \vdots \\ h_{m1} & h_{m2} & h_{m3} & \cdots & h_{mn} \end{bmatrix} \tag{4}$$

b. Research and judgment of the point cloud data accuracy

The assumption of the 3D model's m section elevation observation data measurement error of the equation, $\sigma_1^2, \sigma_2^2, \sigma_3^2 \cdots \sigma_m^2$, involves the use of a little P, and its real value is the h_{zp} elevation. If the elevation value at point P on the heaped-up bulk simulation curve is h_{zp} after processing with the data fusion method, then in order to determine the accuracy of the elevation value after data fusion, the relationship of the research and judgment method can be expressed as follows:

$$H_{zp} = \sum_{i=1}^{m} \omega_i h_{ip} \tag{5}$$

$$\sum_{i=1}^{m} \omega_i = 1 \tag{6}$$

After processing with the data fusion method, the accuracy σ^2 relation of each heaped-up bulk profile at position P can be expressed as follows:

$$\begin{aligned}\sigma^2 &= E\left[\left(h_{zp} - H_{zp}\right)^2\right] \\ &= E\left[\left(\sum_{i=1}^{m} \omega_i h_{zp} - \sum_{i=1}^{m} \omega_i h_{ip}\right)^2\right] \\ &= E\left[\left(\sum_{i=1}^{m} \omega_i \left(h_{zp} - h_{ip}\right)\right)^2\right] \\ &= E\left[\sum_{i=1}^{m} \omega_i^2 \left(h_{zp} - h_{ip}\right) + 2 \sum_{\substack{i=1, j=1 \\ i \neq j}}^{m} \left(h_{zp} - h_{ip}\right)\left(h_{zp} - h_{jp}\right)\right]\end{aligned} \tag{7}$$

According to the above Formula (7), if the calculation result's precision σ^2 is smaller, it indicates that the data fusion effect is better; otherwise, it is worse.

Considering that the observed elevation data h_{1p}, h_{2p}, h_{3p}, $\cdots$, h_{ip} $\cdots$ and h_{mp} of each section of the 3D model of the heaped-up bulk at P are independent of each other, and that h_{zp} is an unbiased estimation, then there is the following relationship:

$$\begin{aligned}&E\left(h_{zp} - h_{ip}\right)\left(h_{zp} - h_{jp}\right) = 0 \\ &i = 1, 2, \cdots, m; j = 1, 2, \cdots, m; \text{ and } i \neq j\end{aligned} \tag{8}$$

Therefore, after processing with the data fusion method, the accuracy σ^2 of each heaped-up bulk profile at position P can be further simplified as follows:

$$\sigma^2 = E\left[\sum_{i=1}^{m} \omega_i^2 \left(h_{zp} - h_{ip}\right)^2\right] = \sum_{i=1}^{m} \omega_i^2 \sigma_i^2 \tag{9}$$

As can be seen from the above Equation (10), the precision σ^2 processed by the data fusion method is a multivariate quadratic function with weighted factors. Therefore, σ^2 has a minimum value after data fusion at P for each 3D model section of the heaped-up bulk, and the satisfied relationship can be expressed as follows:

$$\sigma_{\min}^2 = \min\left(\sum_{i=1}^{m} W_i^2 \sigma_i^2\right) \tag{10}$$

Then, the optimal weight relation of the elevation observation values of each 3D model section of the heaped-up bulk in P can be expressed as per the following:

$$W_i^* = \frac{1}{\left(\sigma_i^2 \sum_{i=1}^{m} \frac{1}{\sigma_i^2}\right)} \tag{11}$$

After integrating and combining the above relations, the corresponding minimum precision σ^2 can be expressed as follows:

$$\sigma_{\min}^2 = \frac{1}{\sum_{i=1}^{m} \frac{1}{\sigma_i^2}} \tag{12}$$

According to Equation (12), the weight value is closely related to the measurement accuracy of all of the observed data. Therefore, only by obtaining the measurement accuracy of all of the observed data can the optimal weight value be calculated.

c. Calculation of the optimal weight value of data fusion

Considering that the true value of each elevation point on the profile curve of the 3D model of the heaped-up bulk is unknown, the measured value after averaging all profiles at any point P is taken as the reference value in the research process. Then, the deviation between the measured value and the reference value is regarded as the deviation from the real value; thus, the variance of the deviation of the measured value at point P and the optimal weight value are obtained. The relationship between the measured mean value at point P can be expressed as follows:

$$h_i(P) = \frac{1}{m}\sum_{i=1}^{m} h_i(P) \tag{13}$$

Then, the deviation relation between the measured elevation values and reference values of all of the 3D model profiles of the heaped-up bulk at point P can be expressed as per the following:

$$\Delta h_i(P) = h_i(P) - \overline{h}_i(P) \tag{14}$$

The mean value relation of the elevation deviation of all of the 3D model profiles of heaped-up bulk at different measuring places can be expressed as follows:

$$\Delta h_i(P) = \frac{1}{n}\sum_{p=1}^{n} \Delta h_i(P) \tag{15}$$

The accuracy of the blasting curve corresponding to all 3D model sections of the heaped-up bulk—that is, the standard deviation relation of the deviation—can be expressed as per the following:

$$\sigma_h(i) = \sqrt{\frac{\sum\limits_{p=1}^{n} (\Delta h_i(P) - \Delta h)^2}{n-1}} \tag{16}$$

The optimal weight value relation of the profile measurement values of all of the 3D models of the heaped-up bulk can be expressed as follows:

$$\omega_i = \frac{1}{\sigma_h^2(i)\sum\limits_{i=1}^{m} \frac{1}{\sigma_h^2(i)}} \tag{17}$$

After the integration of the above relations, the elevation fusion value of all of the 3D model profiles of heaped-up bulk at each position can be expressed as follows:

$$H_{ZP} = \sum_{i=1}^{m} \omega_i \times h_i(P) \tag{18}$$

In view of this, the 3D shape simulation curve of the heaped-up bulk model can be calculated from the elevation fusion value H_{ZP}. Finally, the height fusion value obtained through the data fusion is shown in Table 2.

Table 2. Elevation fusion value of part of the cast blasting.

Position	No 1	No 2	No 3	No 4	No 5	No 6	No 7	…
0	1094.0	1093.9	1096.2	1106.6	1095.3	1095.0	1096.4	…
10	1094.5	1093.5	1086.6	1106.3	1095.3	1094.7	1095.8	…
20	1095.1	1093.4	1086.5	1106.6	1094.6	1094.2	1095.2	…
30	1095.0	1094.1	1087.3	1107.8	1097.1	1096.1	1094.8	…
…	…	…	…	…	…	…	…	…
180	1047.7	1047.3	1049.5	1064.1	1061.9	1062.5	1062.4	…
190	1047.8	1047.5	1050.6	1063.4	1063.5	1062.3	1064.2	…
200	1047.4	1047.8	1051.4	1063.1	1059.4	1061.6	1063.6	…

2.4. Sensitivity Analysis Method for the Influencing Factors of the Heaped-Up Bulk Characteristics

There are many factors affecting the effect of cast blasting. these factors are coupled and superimposed with each other, and they finally form the different characteristics of the heaped-up bulk. Therefore, in order to accurately grasp the degree of influence among the various blasting parameters on the heaped-up bulk, as well as to provide guidance for the subsequent design and optimization of cast blasting parameters, a gray correlation analysis was proposed as the sensitivity analysis method of the influencing factors of the cast blasting effect [30]. By dividing the relative variables and characteristic variables of the cast blasting and their gray correlation degree, the sensitivity ranking of the influencing factors of the cast blasting was carried out. Finally the main controlling factors affecting the blasting effect were determined, so as to serve as the scientific basis for the parameter adjustment and design of the cast blasting [31].

2.4.1. Characteristic Variables and Related Dependent Variables

According to the relevant definition of the characteristic variable and related factor variable, the controllable factor variable controlling the cast blasting target was taken as the dependent variable in this study and is denoted as x_i = (i = 1, 2, 3, ⋯, n). Meanwhile, the parameter index representing the cast blasting effect was taken as the characteristic variable and is denoted as y_i = (i =1, 2, 3, ⋯, m).

Then, the sequence of the system correlation variables and system characteristic variables formed by each system's correlation factor variable x_{i} and characteristic variable y_i were obtained after s times of cast blasting. These were represented as follows:

$$\begin{cases} X_i = [x_i(1), x_i(2), x_i(3), \cdots, x_i(k), \cdots, x_i(s)] \\ Y_j = [y_j(1), y_j(2), y_j(3), \cdots, y_j(k), \cdots, y_j(s)] \end{cases} \tag{19}$$

where $x_i(k)$ represents the sample data of the ith system's relevant dependent variable in the kth cast blasting test and $y_j(k)$ represents the sample data of the j system characteristic variable tested in the k cast blasting.

Considering that there are many factors affecting the effect of cast blasting, part of the cast blasting data is selected as the system variable sample in this study. The height of bench (x_1) represents the height of the rock step to be blasted; bench width (x_2) represents the width of the rock step to be blasted; unit explosive consumption (x_3) represents the amount of explosive used per unit of rock blasting; bench slope angle (x_4) represents the inclination angle of the rock step with blasting; row spacing (x_5) represents the distance between two adjacent rows of holes; hole spacing (x_6) represents the distance between two adjacent rows of holes; minimum burden (x_7) represents the minimum distance between the hole and the free surface; length of stemming (x_8) represents the filling length of the material inside the hole; delay blasting (x_9) represents the time interval of detonation of adjacent holes; expansion ratio (y_1) represents the ratio of the volume of loose rock to the natural volume of rock before blasting; casting ratio of coyote blasting (y_2) represents the ratio of the material quantity of rock directly into the goaf to the total volume of the blasting pile; and throw length (y_3) represents the farthest distance between the rock landing position and the explosion zone. Some parameters are shown in Figure 5. And, the variable samples of the partial cast blasting system are shown in Table 3 below.

Table 3. Partial variable samples of the cast blasting system.

No	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	y_1	y_2	y_3
1	36.2	85	0.69	65	6.8	12.1	7.2	7.4	9	1.24	32.2	93.4
2	36.5	85	0.72	65	7.1	12.2	6.8	7.1	9	1.26	34.1	94.5
3	36.8	85	0.73	65	7.1	12.3	6.9	7.6	9	1.24	33.6	96.1
4	37.1	85	0.7	65	6.9	11.8	7.1	6.8	9	1.25	33.1	94.8
5	37.4	85	0.69	65	6.8	12.3	6.9	7.2	9	1.24	34.7	96.4
6	37.4	85	0.67	65	7.1	11.8	7.3	6.9	9	1.22	33.2	95.2

Table 3. *Cont.*

No	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	y_1	y_2	y_3
7	37.8	85	0.73	65	7.2	11.9	7.2	7.2	9	1.27	34.7	100.5
8	38.2	85	0.73	65	6.9	11.9	6.9	7.3	9	1.25	33.9	103.2
9	38.5	85	0.67	65	6.5	12.3	6.7	7.5	9	1.26	32.8	99.4
…	…	…	…	…	…	…	…	…	…	…	…	…

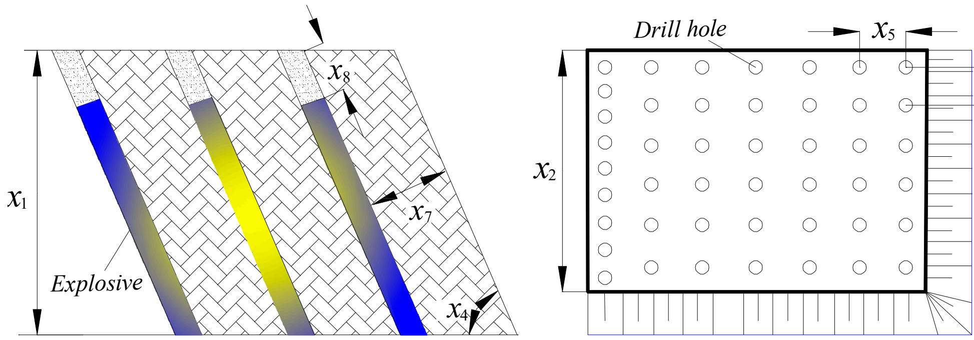

Figure 5. Schematic diagram of the parameters of the cast blasting step.

2.4.2. Gray Correlation Degree and Its Calculation Method

a. The mean value image is obtained by means of variable averaging

Considering the different units of cast blasting factor variables and characteristic variables, in order to ensure the accuracy and convenience of the correlation degree calculation, it is necessary to average the variables before the correlation degree calculation to obtain the corresponding mean image so as to achieve the purpose of unit unity. Then, based on the averaging operator D_1, the mean image of the variable sequence can be obtained as follows:

$$\begin{cases} X_i^1 = X_i D_1 = \left[x_i^1(1), x_i^1(2), x_i^1(3), \cdots, x_i^1(k), \cdots, x_i^1(s)\right] \\ Y_i^1 = Y_i D_1 = \left[y_i^1(1), y_i^1(2), y_i^1(3), \cdots, y_i^1(k), \cdots, y_i^1(s)\right] \end{cases} \tag{20}$$

Among these, we have the following:

$$\begin{cases} x_i^1(k) = x_i(k)/x, x = \frac{1}{n}\sum\limits_{k=1}^{n} x_i(k) \\ y_i^1(k) = y_i(k)/y, y = \frac{1}{n}\sum\limits_{k=1}^{n} y_i(k) \end{cases} \tag{21}$$

According to the above calculation process, after calculating the variable samples of the cast blasting system, the corresponding mean values that were obtained are shown in Table 4 below.

Table 4. Partial mean image of the cast blasting system.

No	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	y_1	y_2	y_3
1	0.861	1.000	0.953	1.000	0.978	1.006	1.026	1.028	1.000	0.990	0.915	0.904
2	0.869	1.000	0.994	1.000	1.022	1.015	0.969	0.986	1.000	1.006	0.969	0.915
3	0.876	1.000	1.008	1.000	1.022	1.023	0.983	1.056	1.000	0.990	0.955	0.930
4	0.883	1.000	0.967	1.000	0.993	0.981	1.012	0.944	1.000	0.998	0.940	0.918
5	0.890	1.000	0.953	1.000	0.978	1.023	0.983	1.000	1.000	0.990	0.986	0.934
6	0.890	1.000	0.925	1.000	1.022	0.981	1.040	0.958	1.000	0.974	0.943	0.922
7	0.900	1.000	1.008	1.000	1.036	0.990	1.026	1.000	1.000	1.014	0.986	0.974
8	0.909	1.000	1.008	1.000	0.993	0.990	0.983	1.014	1.000	0.998	0.963	0.999
9	0.916	1.000	0.925	1.000	0.935	1.023	0.955	1.042	1.000	1.006	0.932	0.963
…	…	…	…	…	…	…	…	…	…	…	…	…

b. Construction of the absolute correlation matrix

$$y_i^0(k) = y_i^1(k) - y_i^1(1) \quad (22)$$

Among these, we have the following:

$$\begin{cases} |XS_i| = \left| \sum\limits_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(s) \right| \\ |YS_j| = \left| \sum\limits_{k=2}^{n-1} y_j^0(k) + \frac{1}{2} y_j^0(s) \right| \end{cases} \quad (23)$$

$$|XS_i - YS_j| = \left| \sum_{k=2}^{n-1} x_i^0(k) - y_j^0(k) \right| + \frac{1}{2}\left[x_i^0(s) - y_j^0(s) \right] \quad (24)$$

By calculating the gray absolute correlation degree of the related variables of the cast blasting above, the corresponding absolute correlation matrix can be obtained at last:

$$A = (\varepsilon_{ij}) = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \cdots & \varepsilon_{1m} \\ \varepsilon_{21} & \varepsilon_{22} & \cdots & \varepsilon_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \varepsilon_{n1} & \varepsilon_{n2} & \cdots & \varepsilon_{nm} \end{bmatrix} \quad (25)$$

According to the sample mean image of the cast blasting system and the calculation method of the gray absolute correlation degree, the corresponding absolute correlation matrix is obtained, as shown in Table 5.

Table 5. The gray absolute correlation matrix of the cast blasting system.

Matrix *E*	$\varepsilon_{i1}(x_1)$	$\varepsilon_{i2}(x_2)$	$\varepsilon_{i3}(x_3)$	$\varepsilon_{i4}(x_4)$	$\varepsilon_{i5}(x_5)$	$\varepsilon_{i6}(x_6)$	$\varepsilon_{i7}(x_7)$	$\varepsilon_{i8}(x_8)$	$\varepsilon_{i9}(x_9)$
$\varepsilon_{1j}(y_1)$	0.507	0.804	0.375	0.632	0.39	0.404	0.391	0.391	0.396
$\varepsilon_{2j}(y_2)$	0.873	0.378	0.474	0.513	0.528	0.582	0.529	0.53	0.549
$\varepsilon_{3j}(y_3)$	0.513	0.337	0.998	0.401	0.89	0.804	0.888	0.885	0.853
Correlation degree	1.893	1.519	1.847	1.546	1.808	1.79	1.808	1.806	1.798
Sensitivity sorting	1	9	2	8	3	7	4	5	6

By calculating the absolute correlation matrix of the sample variables of the cast blasting system, the sensitivity of the blasting parameter index, which affects the cast blasting effect, was obtained. Then, according to the degree of sensitivity from large to small, the order was found to be $\varepsilon_{i1} > \varepsilon_{i3} > \varepsilon_{i5} = \varepsilon_{i7} > \varepsilon_{i8} > \varepsilon_{i9} > \varepsilon_{i6} > \varepsilon_{i4} > \varepsilon_{i2}$. Therefore, the blasting effect was mainly determined by the blasting parameters, such as ε_{i1}, ε_{i3}, ε_{i5}, ε_{i7}, and ε_{i8}. Subsequently, the key blasting parameters with greater influence can be optimized and adjusted to improve the cast blasting effect.

2.5. Optimization Method of the Cast Blasting Parameters Based on Black Box Theory

Considering that cast blasting is a large system with a large scale, numerous influencing factors, and complex synthesis [32], its internal structure (rock properties, pore parameters, explosive parameters, etc.) is extremely complex, and these factors interact and influence each other. Moreover, as the stope advances to the depth gradually, the geological conditions become more and more complicated, which further increases the difficulty of the parameter design and site implementation of the cast blasting. Previous studies took the blasting mechanism as the starting point through the construction of a more ideal mathematical model, and this was conducted to find the change law of the internal structure of the blasting system. As such, a blasting parameter optimization method based on the dynamic change law of blasting was then proposed. However, as the blasting environment becomes more complex and limited by the ideal state of blasting, it is difficult for the optimization effect to bring practical guiding significance to the parameter design and specific implementation of cast blasting in open-pit mines [33].

In view of this, this study puts forward the theory of a black box as the theoretical guidance. This theory is based on the production data of field cast blasting, and it is used without considering the internal structure and energy transformation of the cast blasting system. Moreover, only the information transmission and information processing in the "black box of cast blasting system" are considered. Through the observation of the input of the cast blasting parameters (also known as controllable variables) and the output of the cast blasting effect information (also known as observable variables), the optimal combination of the blasting parameters can be found to make the downpour process economical. Once this is achieved, then the optimal design of the parameters of on-site cast blasting can be guided.

2.5.1. Construction of the Cast Blasting Black Box System

The black box coupling system [34–36] was constructed to determine the controllable variables of the black box system, as well as the observable variables derived from the system feedback. Then, in the cast blasting black box system, the input information of the black box system selected the related cast blasting parameters, such as the hole mesh parameters, step parameters, explosive parameters, etc., while the output information returned by the black box system selected the 3D characteristics of the explosive pile formed after the cast blasting. As such, the corresponding relevant mathematical model can be expressed as follows:

$$Y(s) = K(s)X(s) \tag{26}$$

where $Y(s)$ is the output function of the system, $K(s)$ is a dynamic relation function, and $X(s)$ is the system input function.

In Figure 6, the parameters of cast blasting were $x_1, x_2, x_3, \ldots, x_9$, and the characteristics of the cast blasting were y_1, y_2, y_3.

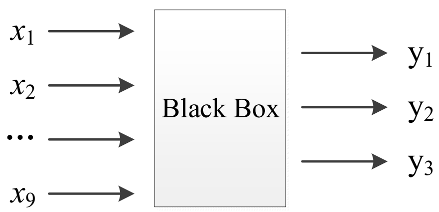

Figure 6. The black box system.

2.5.2. Construction of a Controllable Variable Database

Since the introduction of cast blasting technology, the Heidaigou open-pit coal mine has accumulated a massive amount of blasting data after a long period of technical practice. In this paper, through a sensitivity analysis of the blasting parameters, the key blasting parameters that affect the cast blasting effect were determined. Then, according to the analysis, screening, and processing of the blasting parameter data of the key blasting parameters, the controllable variable database of the black box system of the cast blasting under different environmental conditions was formed. Table 6 lists some of the parameters of the controllable variable database.

Table 6. Some of the parameters of the controllable variable database.

Position	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	⋯
21-N1	32	85	0.78	65	6.6	12.1	6.7	6.5	9	⋯
21-N2	33	85	0.75	65	6.9	11.8	6.2	7	9	⋯
21-N3	33	85	0.8	65	7.1	12.1	6.5	6.5	9	⋯
21-N4	38	85	0.76	65	7.1	11.9	6.4	7	9	⋯
21-N5	37	85	0.75	65	6.8	11.8	6.2	6.5	9	⋯

Table 6. *Cont.*

Position	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	⋯
21-N6	38	85	0.76	65	6.9	12.1	6.3	7	9	⋯
21-N7	38	85	0.78	65	7.1	11.9	6.5	6.5	9	⋯
21-N8	38	85	0.75	65	6.9	12.2	6.4	7	9	⋯
21-N9	40	85	0.82	65	7.2	12.2	6.5	7	9	⋯
21-N10	40	85	0.8	65	7.1	12	6.5	7	9	⋯
⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯

2.5.3. Construction of Observable Variable Database

As a pre-stage of the dragline stripping technology, the effect of cast blasting plays a decisive role in the subsequent dragline stripping technology engineering succession and operation cost [37–40]. In order to ensure that the characteristics of the heaped-up bulk after cast blasting can meet the economic cost optimization of the subsequent dragline stripping technology, this paper needs to further study the subsequent dragline stripping technology and dissect the internal operation mechanism of the system as well as the logical relationship between operations on the basis of the surface of heaped-up bulk data acquisition and data fusion. An economic database that can represent the production cost of the dragline stripping technology was constructed. Finally, the optimal cast blasting parameter combination under different working conditions was deduced by comparing the economic data.

a. Dragline stripping technology business flow

Step 1: Perforate, charge, and connect the solid high step, and then complete the directional cast blasting.

Step 2: The bulldozer starts leveling the heaped-up bulk and pushes part of the material into the goaf.

Step 3: The electric shovel works with the dump truck on the layered materials on the heaped-up bulk and builds the step of the dragline.

Step 4: The layered materials under the heaped-up bulk are gradually discharged to the pumping area by the dragline, and the coal seam begins to be exposed.

Step 5: The dragline discharges the remaining materials in the coal ditch to the pumping area, and the coal seam is completely exposed.

Among them, the steps are shown in Figure 7.

b. Dragline stripping technology model based on cast blasting characteristics

In order to accurately grasp the characteristics of the heaped-up bulk and to reasonably optimize the production distribution of the various business links within the dragline stripping technology, the distribution mechanism model of dragline stripping technology was studied and proposed [41,42]. A plane coordinate system was constructed with the characteristics profile of cast blasting as the research object, $y = y_a(x)$ was used to represent the characteristics equation of the heaped-up bulk, and $y = y_b(x)$ was used to represent the correlation equation of the line segment *ABCDFF*. Other relevant parameters are shown in Figure 8. Where, A, B, C, D, ⋯, Q represent the position of each point in the figure; α, β, γ represent the angle of the line segment in the figure.

In the above Figure 8, 1 is the physical high step, 2 is the lower layer of the heaped-up bulk, 3 is the coal seam, 4 is the coal ditch, 5 is the dragline extension platform (standing steps), 6 is the goaf, 7 is the pumping area, and 8 is the heaped-up bulk surface.

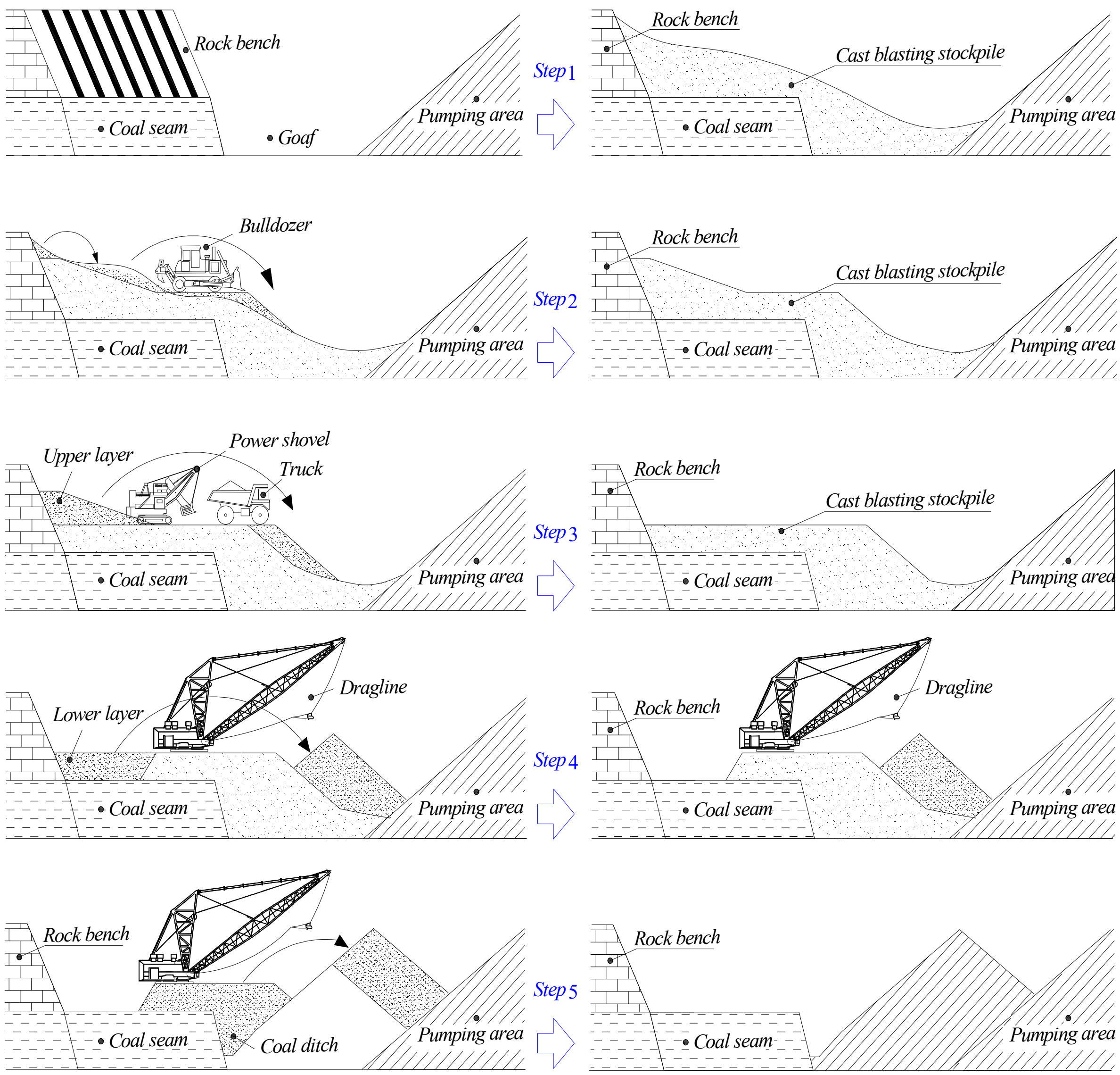

Figure 7. Operation flow chart of the dragline stripping technology.

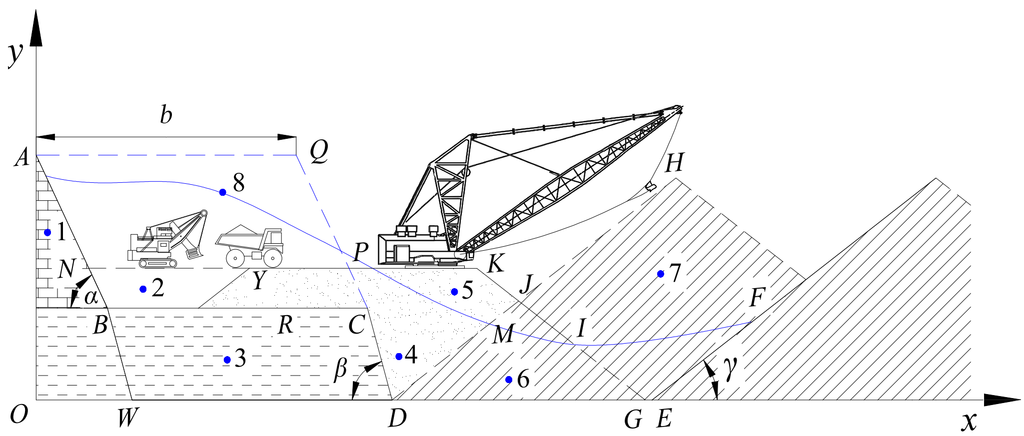

Figure 8. Schematic diagram of construction of the heaped-up bulk coordinate system.

(a) The *AMFEDCBA* cross-sectional area (the total amount of blasting) of the heaped-up bulk:

After the implementation of the cast blasting, the characteristic profile of the entire heaped-up bulk can be represented by the cross-sectional area *AMFEDCBA*. Combined with the calculus theorem, the cross-sectional area relation of the heaped-up bulk can be expressed as follows:

$$S_{Bu} = \int_{o}^{f} [y_a(x) - y_b(x)]dx \tag{27}$$

$$= \int_{o}^{f} y_a(x)dx - \left[\frac{{H_r}^2}{2\tan\alpha} + \frac{1}{2}(\frac{2H_r}{\tan\alpha} + \frac{H_m}{\tan\beta})H_m + H_m b + \frac{1}{2}(x_F - x_E)\tan r\right] \tag{28}$$

$$x_E = \frac{H_r \tan\beta + H_m \tan\alpha}{\tan\alpha\tan\beta} + 2b \quad x_D = \frac{H_r \tan\beta + H_m \tan\alpha}{\tan\alpha\tan\beta} + b \tag{29}$$

In the formula, S_{Bu} represents the cross-sectional area of the cast blasting characteristics/m^2, α represents the slope angle of the solid high step/°, b represents the width of the solid high step/m, β represents the slope angle of the coal seam step/°, H_r represents the height of the solid step/m, H_m represents the height of the coal seam step/m; r represents the angle of the rest of the rock material/°, and x_F and x_E represent the abscissa of F and E, respectively.

(b) Cross-sectional area of the effective cast blasting quantity *DMFED*:

The effective quantity of cast blasting refers to the quantity of the heaped-up bulk that is directly thrown into the goaf after cast blasting and which avoids the secondary operation of equipment. Assuming that the linear *EF* has the relation y_{EF} = tanγ(x_x_E) and the linear *EM* has the relation y_{DH} = tanγ(x_x_D), combined with the relation of the heaped-up bulk morphology profile, the coordinate positions of coordinate points F and M can be obtained as (x_F, y_F) and (x_M, y_M), respectively. Then, the cross-sectional area relation of effective throwing quantity can be expressed as follows:

$$S_{Ef} = \int_{f}^{m} y_{DM}(x)dx + \int_{m}^{f} [y_a(x) - y_b(x)]dx \tag{30}$$

$$= \int_{m}^{f} y_a(x)dx + \frac{1}{2}\tan\gamma\left[(x_M - x_D)^2 - (x_F - x_E)^2\right] \tag{31}$$

(c) Layered cross-sectional area *ANPA* on the heaped-up bulk characteristic profile:

In the process of field operation, with the standing step working face of the dragline as the critical surface, the upper heaped-up bulk is called the upper layer of the heaped-up bulk, and the lower heaped-up bulk is called the lower layer of the heaped-up bulk. Among them, the stripping work of the layered materials on the heaped-up bulk was mainly assisted by a hydraulic backhoe brush, and bulldozer leveling was subjected to the heaped-up bulk, as well the single bucket and truck. Combined with the theorem of calculus, the relationship of the stratified cross-sectional area on the heaped-up bulk characteristic profile can be expressed as follows:

$$S_{Up} = \int_{0}^{p} [y_a(x) - (H_r + H_m)]dx - \frac{(H_r - H_s)^2}{2\tan\alpha} \tag{32}$$

(d) *PMJKP* cross-sectional area of the secondary operation volume of the dragline:

Due to the influence of its working radius, certain rock materials cannot be dumped directly into the pumping area. Therefore, in the process of operation, it is necessary to expand the standing step to the side of the dump site first, periodically move to the appropriate aircraft position, and then dump the material of the extended standing step to the pumping area. Therefore, the material amount of repeated operation is called the second operation amount of the dragline. Similarly, the cross-sectional area relation of the secondary operation quantity can be expressed as follows:

$$S_{Se} = \int_p^k y_{KP}(x)dx + \int_k^j y_{KJ}(x)dx - \int_p^m y_{PM}(x)dx - \int_m^j y_{JM}(x)dx \tag{33}$$

(e) Stratified cross-sectional area *NBRYN* under the heaped-up bulk shape profile:

Assuming the coordinate of point R is (x_R, y_R), then the coordinate of point Y is (x_R + $H_s\tan\gamma$, H_1 + H_m). Similarly, the relationship between the stratified cross-sectional area under the cast blasting shape profile can be expressed as follows:

$$S_{Do} = \int_n^y H_s dx - \frac{{H_s}^2}{2\tan\alpha} - \frac{{H_s}^2}{2\tan r} \tag{34}$$

where H_1 represents the height of the standing step of the dragline/m and H_m represents the thickness of coal seam/m.

(f) *YRCDMY* cross-sectional area of the coal ditch:

Assuming that the coordinate of point P on the standing step face of the dragline is (x_P, y_P), then the cross-sectional area relation at the coal ditch can be expressed as follows:

$$S_{Di} = \int_y^p H_s dx + \int_p^m y_a(x)dx - \int_r^m y_b(x)dx \tag{35}$$

$$= \int_m^p [y_a(x) - y_b(x)]dx + \frac{1}{2}(x_P - x_Y)(1 + H_s\tan r)H_s - \frac{1}{2}(x_M - x_D)^2\tan r \tag{36}$$

According to the obtained heaped-up bulk profile and the calculation formula of the task assignment in each link of the dragline stripping technology, the task assignment in the dragline stripping technology can be calculated. The second part of the calculation results are shown in Table 7 below.

Table 7. Part of the dragline stripping technology task assignment table.

Position	X_1	X_2	X_3	X_4	X_5	X_6
21-N1	1301	982	202	735	994	1236
21-N2	1346	982	227	768	966	1279
21-N3	1369	1003	254	963	981	1301
21-N4	1368	1060	259	1158	972	1300
21-N5	1247	1062	375	1387	942	1185
21-N6	1237	1080	513	1508	911	1175
21-N7	1296	1100	448	1575	877	1231
21-N8	1308	1113	478	1531	858	1243
21-N9	1585	1076	614	1577	848	1506
…	…	…	…	…	…	…

In Table 7, X_1 represents the amount of layered material on the heaped-up bulk/m^3, X_2 represents the amount of layered material under the heaped-up bulk/m^3, X_3 represents the coal ditch material quantity/m^3, X_4 represents the effective material quantity thrown/m^3, X_5 represents the material quantity in the second operation of the dragline/m^3, and X_6 represents the material quantity of the heaped-up bulk pressure/m^3.

c. Economic cost model of the dragline stripping technology

According to the brief introduction of the internal structure and operation mechanism of the process system of the cast blasting and dragline stripping technology in the Heidaigou open-pit coal mine, the production cost of the whole process system mainly includes the cost of high-step blasting, the cost of bulldozer leveling and blasting heaps, the cost of single bucket and truck joint auxiliary stripping, and the cost of the dragline operation.

$$C = C_{bp} + C_{pz} + C_{fz} + C_{dd} \tag{37}$$

According to the calculated distribution amount of each operation task in the dragline stripping technology, combined with the above economic cost model, the operation cost of each link in the dragline stripping technology can be calculated. Part of the calculation results are shown in Table 8 below.

Table 8. The operating cost of the cast blasting and dragline stripping technology.

Position	C_1	C_2	C_3	C_4	C_5	C_6
19-N51	12,942	9426	6178	1837	6738	37,121
19-S14	12,925	10,108	6505	1934	7050	38,522
20-N05	11,240	9551	5929	1458	6346	34,524
20-S46	11,821	9478	5648	1858	6793	35,598
20-N03	13,941	11,132	7936	1911	6950	41,870
20-S25	14,832	11,824	7578	4309	5984	44,527
20-N15	16,953	15,870	7937	4947	5952	51,659
21-N1	13,740	10,564	6953	1430	7038	39,724
21-N2	13,775	10,930	6953	1607	6839	40,104
21-N3	13,829	11,116	7101	1798	6945	40,790
21-N4	13,925	11,108	7505	1834	6882	41,254
21-N5	14,070	10,126	7519	2655	6669	41,039
21-N6	14,092	10,044	7646	3632	6450	41,865
21-N7	14,168	10,524	7788	3172	6209	41,861
21-N8	14,278	10,621	7880	3384	6075	42,238
21-N9	15,838	12,870	7618	4347	6004	46,677
21-S12	12,740	9564	5953	1437	6338	36,032
21-N52	13,729	11,016	6201	1794	7145	39,885
21-S52	16,838	13,870	7630	4547	5967	48,852
22-S09	19,092	17,044	8646	3432	6384	54,530
22-S57	19,362	17,930	8846	3932	6667	56,737
…	…	…	…	…	…	…

In Table 8, C_1 represents the cost of cast blasting/CNY; C_2 represents the stripping cost of layered material on heaped-up bulk/CNY; C_3 represents the stripping cost of layered material under heaped-up bulk/CNY; C_4 represents the stripping cost of coal ditch material in heaped-up bulk/CNY; C_5 represents the stripping cost of the dragline/CNY; and C_6 represents the total stripping cost of cast blasting and dragline stripping technology/CNY.

2.5.4. Determination of the Optimal Heaped-Up Bulk Characteristic

Based on the characteristics of the heaped-up bulk, the internal distribution mechanism model of the dragline stripping technology was constructed in this paper, and the operation cost database of the cast blasting and dragline stripping technology under different working conditions was obtained. In order to accurately obtain the best characteristics of heaped-up bulk under different working conditions, this paper also took the optimal economic process of the cast blasting and dragline stripping technology as the objective and constructed the objective function Z, in which the functional relation can be expressed as follows:

$$Z = \min(C_h(\beta)) \tag{38}$$

where C represents the cost of cast blasting and dragline stripping technology/CNY; h represents the height of cast blasting step/m; and β represents the coal seam dip angle/°.

Limited by space, this paper only takes the typical cast blasting step heights of 35 m, 40 m, and 45 m as examples, as well as the coal seam dip angles of 0°, 1°, 2°, and 3° as examples. The specific research results were as follows.

a. The height of the cast blasting step was 35 m

Through data statistics and data analysis, when the height of the cast blasting step was 35 m, the optimum cast blasting profile number was shown (as represented in Table 9) under the conditions of the coal seam dip angle of 0°, 1°, 2°, and 3°. In addition, the partial data of the operation cost of the cast blasting and dragline stripping technology are shown in Figure 9.

Table 9. Optimum profile information of the heaped-up bulk with a step height of 35 m.

No	Step Height *h*/m	Coal Seam Dip Angle *β*/°	Z_i = min ($C_h(\beta)$)	Position
1	35	0	34,524	20-N05
2	35	1	35,598	20-S46
3	35	2	36,032	21-S12
4	35	3	37,121	19-N51

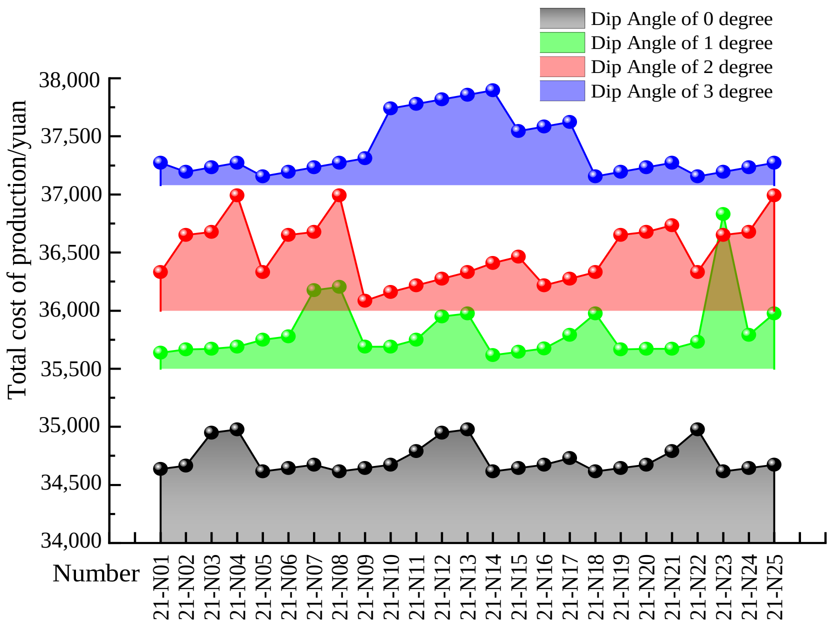

Figure 9. Statistical chart of the partial operation cost of the system under a step height of 35 m.

b. The height of the cast blasting step is 40 m

Similarly, when the height of the throwing blasting step is 40 m, the optimum cast blasting profile number is shown (as represented in Table 10) under the conditions of coal seam dip angles of 0°, 1°, 2°, and 3°. Moreover, the partial data of the operation cost of the cast blasting and dragline stripping technology are shown in Figure 10.

Table 10. Optimum profile information of the heaped-up bulk with step height of 40 m.

No	Step Height *h*/m	Coal Seam Dip Angle *β*/°	Z_i = min ($C_h(\beta)$)	Position
1	40	0	38,522	19-S14
2	40	1	39,885	21-N52
3	40	2	41,870	20-N03
4	40	3	44,527	20-S25

c. The height of the cast blasting step is 45 m

Similarly, when the height of the throwing blasting step is 40 m, the optimum cast blasting profile number is shown (as represented in Table 11) under the conditions of coal seam dip angles of 0°, 1°, 2°, and 3°, while the partial data of the operation cost of the cast blasting and dragline stripping technology are shown in Figure 11.

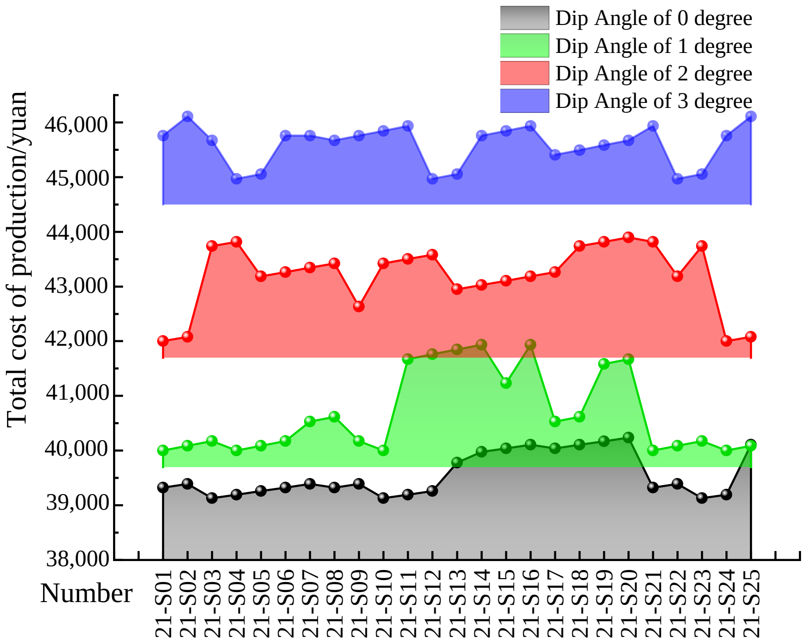

Figure 10. Statistical chart of the partial operation cost of the system under a step height of 40 m.

Table 11. Optimum profile information of heaped-up bulk with a step height of 45 m.

No	Step Height h/m	Coal Seam Dip Angle β/°	Z_i = min ($C_h(\beta)$)	Position
1	45	0	48,852	21-S52
2	45	1	51,659	20-N15
3	45	2	54,530	22-S09
4	45	3	56,737	22-S57

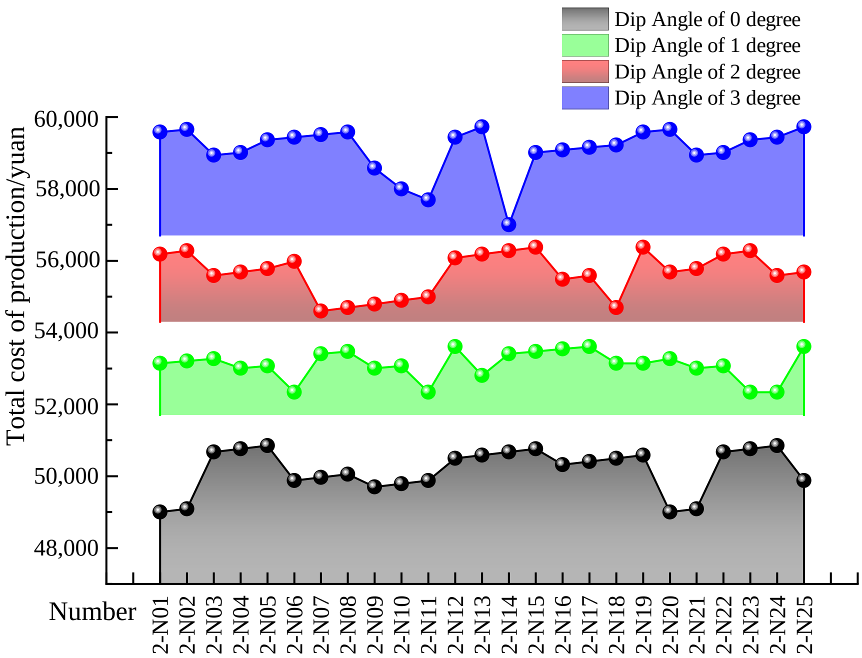

Figure 11. Statistical chart of the partial operation cost of the system under a step height of 45 m.

3. Results

Based on the cost economy database of the cast blasting and dragline stripping technology obtained, this paper aims at the optimal economic benefit of dragline stripping technology and obtains the optimal profile data information of the cast blasting. Then, according to the profile data information of the heaped-up bulk and the sensitivity analysis results of cast blasting parameters, the optimal cast blasting parameter combination input in the black box system of cast blasting under different working conditions can be obtained. The parameters of the partial cast blasting are shown in Table 12.

Table 12. Optimum cast blasting parameter design under different working conditions.

Position	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	···
20-N05	0°	35 m	0.758	6.8	6.1	6.5	9	11.8	···
20-S46	1°		0.759	6.9	6.3	7.0	9	11.9	···
21-S12	2°		0.762	6.9	6.2	7.4	9	12.2	···
19-N51	3°		0.763	7.0	6.3	7.3	9	11.9	···
19-S14	0°	40 m	0.765	7.0	6.4	6.2	9	11.8	···
21-N52	1		0.77	6.9	6.4	6.7	9	11.8	···
20-N03	2		0.772	7.1	6.3	7.1	9	12.1	···
20-S25	3		0.777	6.7	6.1	7.6	9	12.2	···
21-S52	0	45 m	0.778	7.1	6.5	6.9	9	11.8	···
20-N15	1		0.78	6.9	6.3	7.0	9	12.0	···
22-S09	2		0.782	7.0	6.0	7.5	9	11.9	···
22-S57	3		0.789	7.1	6.2	6.8	9	12.1	···

4. Discussion and Analysis

In order to put forward a blasting optimization method that is more suitable for the geological conditions and production process of open-pit mines as much as possible, and to break the blasting effect optimization method that is based on the ideal condition, this paper puts forward an optimization method of cast blasting parameters that is based on the optimal economic dragline stripping technology. However, the cast blasting project is a large, complex system and its internal structure is complex. In addition, there are many influencing factors, the factors are coupled and interact with each other, and the quality of the cast blasting effect has a decisive influence on the production organization and economic benefits of the dragline stripping technology. Therefore, in the process of research, there are still certain aspects of content to be completed and improved.

a. Since the introduction of the cast blasting technology in the Heidaigou open-pit mine, the cast blasting project has been completed more than 260 times, and a large number of cast blasting parameter design schemes and related data characterization of the effect of cast blasting have been accumulated. However, this paper has not sorted out or analyzed all of the blasting parameter data or the blasting effect data effectively. In addition, the sample size in the research process is limited, thus resulting in part of the cast blasting environment and the cast blasting results not being effectively restored.
b. The production cost of the whole system of the Heidaigou open-pit mine cast blasting and dragline stripping technology is mainly composed of the perforation cost, the cast blasting cost, the hydraulic backhoe and bulldozer auxiliary operation costs, the single bucket truck process auxiliary operation cost, the bucket shovel operation costs, etc. However, in the process of cost analysis, due to the limited cost data, the cost of hydraulic backhoes and bulldozer auxiliary operations cannot be effectively split or calculated; as such, this part of the cost was ignored in the process of cost analysis, thus resulting in certain errors in the system's cost.
c. Due to being affected by the fluctuation of the equipment operating cost, the optimal blasting parameter combination based on the throwing blasting effect will be

dynamically adjusted in order to achieve the optimal economic cost of the dragline stripping technology.

5. Conclusions

Different from conventional cast blasting parameter optimization methods, which aim at improving the effective throwing rate, this paper studied and proposed an optimization method for the cast blasting parameters of an open-pit mine based on the dragline stripping technology. Taking the Heidaigou open-pit mine as the research object, firstly, through the data acquisition, data analysis, and data fusion of the site blast characteristics, the blast profile characterizing the cast blasting effect was obtained by fitting. Secondly, the key influencing factors of the cast blasting effect were determined based on gray relational degree theory. Finally, the black box principle in the system control theory was adopted as the guiding principle of blasting optimization. Based on the production data of the field cast blasting, the input variable (controllable variable) of the black box system and the output variable (observable variable) obtained from the feedback of the system were adopted without considering the internal structure and energy transformation of the cast blasting system. Thus, the optimal combination of the blasting parameters under different working conditions was obtained.

The results show the following: (a) The surface fitting method of the heaped-up bulk is proposed, and it can characterize the effect of cast blasting. The fitting results of the heaped-up bulk were basically consistent with the characteristics of the real heaped-up bulk. Thus, it can characterize and reconstruct the characteristics of real heaped-up bulk. (b) Sensitivity analysis was carried out on the factors affecting the cast blasting effect, and a sensitivity analysis method based on the gray relational degree was proposed to study and determine the key factors affecting the cast blasting effect. (c) With the black box theory of system cybernetics as the guiding ideology, the optimal combination of blasting parameters under different working conditions was studied. If the best combination of blasting parameters is applied, it was estimated that the dragline stripping technology cost of the Heidaigou open-pit mine can be saved by 5~10%. In addition, the optimization design idea of the cast blasting, which breaks with convention and only focuses on improving the effective throwing rate, provides a new idea and a new way in which to optimize blasting design.

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