In this paper, the blasting parameters are designed based on the drilling data of the exploration geological stage, the geophysical and mechanical parameters of the mining area, and the geological age information, and then the numerical simulation of the blasting of the layered rock steps is carried out to optimize the blasting parameters. Multiple sets of blasting tests were carried out on-site, and the large block rate, average block size satisfaction rate, large block satisfaction rate, cost satisfaction rate, shovel loading efficiency, and blasting effect satisfaction rate were set as the blasting effect evaluation indicators, which verified the feasibility of the optimized scheme.

1. Introduction

In open-pit mine, blasting is one of the key basic operations in the mining chain. The cost of blasting accounts for 30% of the total cost of open-pit mining. The cost of blasting directly affects the safety, efficiency, and cost of subsequent operations [1–3]. Reasonable blasting parameters and techniques are of great significance for controlling blasting costs, improving blasting effects, and increasing the economic benefits of open-pit mining [4–8].

Traditional rock damage and fracture criteria have certain limitations on composite rock blasting. Liu Yongsheng [9] has studied the mechanical properties of layered rocks under triaxial and impact compression loads. The experimental results show the mechanical properties of layered rocks. Affected by many factors, such as the distribution of soft and hard rocks, the inclination angle and spacing of the interface, and the confining pressure, it is very different from homogeneous rocks. Teng Junyang [10] researched the damage evolution law and fractal characteristics of the layered composite rock mass and found that in the initial stage of loading of the composite rock layer, the weaker rock layer is laterally restrained by the adjacent rock layers, showing a three-dimensional compressive stress state, and the failure strength is greater than the strength under a single layer of rock is in the form of “false triaxial” failure.

The pressure distribution and expansion of the rock mass are affected by the original joints and fissures in the rock. The addition of the interface between soft and hard rock layers makes the blasting of composite rock layers more difficult to control [11]. The research on the blasting failure evolution mechanism and fracture mode of layered composite rock masses involves the reflection transmission mode of blasting stress waves of nonstructural joints and fractured rock masses and the general laws of microstructure, crack propagation, and damage evolution processes [12–14]. Therefore, it is necessary to optimize the design of the blasting network parameters of the composite rock slope, taking into account the effects of joint cracks, soft and hard
rock strength, and thickness on bench blasting. In this paper, based on the existing composite rock blasting theory in Pingshuo East Open-pit Coal Mine, the composite rock blasting parameters are optimized through numerical simulation and field tests.

2. Blasting Geological Model

The harder rock strata originally located in the middle and lower layers gradually spread upward with the advancement of the flat plate, forming a unique stratigraphic structure such as upper hard and lower soft, upper soft and lower hard, upper and lower hard and middle soft, and upper and lower hard and middle soft, as well as the interlayer. Different lithologies and degrees of fissure development produce typical weak interlayers, which reduce step blasting efficiency, increase rock lumpiness, and raise secondary crushing costs. Simultaneously, it negatively impacts downstream operations such as mining, transportation, and dumping. Using the Pingshuo East Open-pit Coal Mine as an example, the main technologies for open-pit slope blasting of heterogeneous rock masses are presented through field test analysis and integrated with the application of open-pit coal mine blasting. The blasting parameters and methods of the hole network, the method of hole arrangement, the charge structure, and the sequence of blasting have been optimized to solve the technical problems of blasting composite rock formations in open-pit mines.

The physical and mechanical properties of the rock in the mining area are crucial for understanding the mine bench’s blasting mechanism and crushing effect. The database’s rock physical and mechanical parameter table contains not only the rock’s code but also the rock’s physical and mechanical parameter information. It is significantly used to create a 3D model of an open-pit mine.

The East Open-pit Mine is located in Shuozhou City, Shanxi Province, in the northeastern part of the city. It has a lot of coal reserves. It is surrounded by large open-pit coal mines such as Anjialing, Antaibao, Harwusu, and Heidai-gou, and the coal it contains forms the Ningwu Coalfield. The Ordovician, Taiyuan Formation, Upper Shihezi Formation, and Lower Shanxi Formation are the most common internal rock formations in the mining area. The blast zone lies within the 1290 flat plate.

South of the east open pit, with the shot zone running north-south. Table 1 shows the top-down classification of the flat rock formation based on current geological drilling and test data analysis, and Figure 1 shows the geological drilling information.

After sorting out the original geological data from the East Open-pit Mine, it’s important to examine it and create a database so that the mine’s geological age information, as well as the physical and mechanical parameters of the rock, can be displayed more intuitively and blasting parameters can be optimized and made more efficient. To guide mine production design, analyze the rules of mine geology and build relevant texture models. To create a mine geological model, we must first create a database for the mine, which has a significant impact on how prior data is used and how the blasting process is predicted.

The establishment of a geological database corresponding to a mine needs to include geological borehole data, geological age information data, and rock physical and mechanical parameter information. According to the coordinate information of all points, a three-dimensional geological model is preliminarily constructed, and the three-dimensional display effect diagram is shown in Figure 2–3.

3. Blasting Scheme

3.1 Parameter Simulation of Blasting Mesh. In order to study the influence of reasonable hole network parameters on step blasting of different rock formations, three sets of bench blasting simulation tests with different hole network parameters were set up. The rest of the conditions are the same. The specific settings are shown in Table 2.

A blasting model is established with a total height of 15m, a slope angle of 75°, and a model width of 20m. The upper 7m is soft rock, and the lower 8m is hard rock. Five special positions around the No. 2 blast hole were selected and named as A, B, C, D, and E at a distance of 5m from the top of the slope in the blasting simulation model. As shown in Figure 3, the stress changes at the special positions were measured for three different hole networks. The point of the parametric model is when the peak stress exceeds the dynamic tensile strength of the formation, the formation is assumed to have failed at that location.

Analyzing Figure 3, Table 2, and Table 3, the following conclusions can be drawn:

1. In Model 1, the effective stress peaks of the five special points are larger than the dynamic tensile strength of the lower hard rock. Crushing compression failure and throwing phenomena may occur, and the effective stress peaks of each special point fluctuate greatly. The blasting energy distribution is not uniform, the blasting block size may be uneven, and the blasting effect is poor;

2. The effective stress peaks at special points in Model 2 are slightly larger than the dynamic tensile strength of the lower hard rock, showing that not only does the upper soft rock have a good blasting impact, but the lower hard rock has superior fragmentation, which meets the mine’s needs. The stress distribution is relatively uniform during the blasting process, the blasting energy utilization is relatively reasonable, and the blasting fragmentation is relatively uniform, which fulfills the shovel loading and transportation requirements of the mining industry.

3. In Model 3, the effective stress peak value of some special points is greater than the dynamic tensile strength of the upper soft rock but less than the dynamic tensile strength of the lower hard rock. In the actual production process, the lower hard rock may not be completely blasted. The roots are
generated, and the stress distribution is uneven. The size of the blast may be uneven after blasting, and the blasting effect is poor.

3.2. Blasting Plan. Comparative experiments were carried out under the same geological conditions by varying the hole spacing, row spacing, super-depth, packing length, and other parameters. For each blasting, we keep accurate records and keep a close eye on the situation. We monitor and adjust the geological condition parameters and blasting parameters of the blasting area, calculate the mass rate, average fragmentation satisfaction rate, mass satisfaction rate, cost satisfaction rate, blasting effect satisfaction rate, and shoveling efficiency, to get the best blasting optimization parameters.
3.2.1. Blasting Test with Different Hole Mesh Parameters. Firstly, we find out the distribution of rock strata in the blasting area, calculate the blast ability level of the rock, and optimize the design according to the theoretical analysis and open-pit blasting experience in accordance with the geological conditions and surrounding environmental protection requirements, under the same conditions as the charging structure and blasting sequence. When we propose multiple hole network parameter schemes, conduct multiple blasting tests under the same geological conditions, count blasting effects data such as blasting fragmentation and determine reasonable blasting parameters under different rock formations through data analysis. Table 4 summarizes the different blasting parameters, and Figure 4 shows the structure of the filled explosive.

3.2.2. Statistics of Fragmentation of Blasting Rock. After blasting, we observe the rock fragmentation on the surface of the blasting area through a three-dimensional scanner. After field surveying the blasting site, we track the shovel loading and transportation process of the rock in the blasting area, collect the size of the shoveled rock, determine the bulk rate, and determine the mass rate of the rock. Then we analyze the crushing quality, save the pictures and video information, and summarize the rock mass distribution law, which is used as the basis for evaluating the blasting effect and optimizing the blasting design.

3.3. Blasting Effect Monitoring Method

3.3.1. High-Speed Photographic Observation of Blasting Process. A high-speed camera is set up 200 meters from the side of the blasted region, ground marking points are placed...
around the blasting area, observation sites are placed in the blasting area, and high-speed photography is used to analyze the dust movement characteristics of throwing blasting. The purpose of this instrument is to observe the blasting process. The blast arrangement is shown in Figure 5.

3.3.2. Three-Dimensional Laser Scanning of Explosive Piles. A three-dimensional laser scanner is used to scan the blast pile before and after blasting to obtain its three-dimensional spatial shape. The three-dimensional scanning and data statistics of the blasting area before and after blasting are shown in Figure 6. Since laser scanning can only obtain the surface fragmentation of the blasting pile, it is important to also manually observe the mine's shovel loading efficiency to determine the blasting effect's pros and cons.

4. Results and Discussion

Due to the staggered distribution of soft and hard rocks, as well as the staggered distribution of rock formations of different lithologies, large faults, and other factors, the Pingshuo East Open-pit Coal Mine produces an excessively high block rate, which has a serious impact on subsequent shoveling and transportation. The lump rate in the original blasting process is normally around 10%. Since the minimum width of the electric shovel mainly used in the Pingshuo East Open-pit Mine is 2 m, it is stipulated that the rock lumpiness that is greater than 200 cm after blasting is a big lump, and manual registration is adopted. Table 5 shows the calculated blasting results as well as the statistical data.

4.1. Bulk Rate. The block rate of step blasting is the most direct reflection of the blasting effect, and the blasting effect of step blasting can be seen through statistics.

4.2. Average Block Degree Satisfaction Rate. Suppose the average size distribution of the rock after blasting is normal, then

$$U_A = \exp\left(-0.5 \times \frac{(K - Y)}{D}\right).$$  (1)

In the formula, K is the average blockiness value of blasting prediction, Y is the average blockiness value, and D is the normal distribution curve parameter.

4.3. Satisfaction Rate of Bulk Rate. For the mine production process, the lower the bulk rate, the more it can meet the requirements of mine transportation, so its satisfaction rate is

$$U_{Br} = \left(1 + k \cdot D^2\right)^{-1}.$$  (2)

In the above formula, k is the correction parameter of different rock formations and D is the block rate.

According to the statistics in Table 5, the blasting rates of options 3 and 5 did not decrease significantly. Options 1, 2, 4, and 6 all effectively reduced the rate of blasting. Among them, the blasting rate of option 6 was 7.57%. Compared with the existing blasting plan of the mine, the average bulk rate of 10.40% is reduced by nearly 20%, and the maximum size of the bulk is reduced. Therefore, considering the bulk rate, plan 6 has a better blasting effect.

The average fragmentation satisfaction rate of scheme 6 is significantly higher than that of the other schemes, indicating that the blasting fragmentation uniformity coefficient curve of scheme 6 is relatively smooth, the stress distribution during blasting is very uniform, the rock fragmentation distribution after blasting is uniform, and the blasting effect is good. The big block satisfaction rate is inversely proportional to the big-block rate. The higher the big block rate, the lower the big block satisfaction rate and the bigger blocks that exist in the blast pile after blasting. Therefore, scheme 6 has the highest big block satisfaction rate, the lowest big block rate, and the least chunks produced by blasting.

4.4. Satisfaction Rate of Blasting Effect. After the above three evaluation indicators have been calculated multiple times to obtain the average value, the weighted calculation is obtained according to different weights.

$$U_{Be} = \sum \text{U(i) \cdot W(i)}.$$  (3)

In the above formula, U(i) is the satisfaction rate of the i-th index and W(i) is the weight value of the i-th index.
Figure 5: High-speed photography of the blasting process: (a) high-speed camera, (b) presplit hole initiation, (c) detonation of the main blast hole, and (d) a large amount of smoke and dust.

Figure 6: Three-dimensional scanning and data statistics of blasting area before and after blasting.
The blasting effect satisfaction rate statistics of each scheme are shown in Figure 7.

### 4.5. Cost Satisfaction Rate

The blasting effect of the mine directly affects the production cost of the mine. So the blasting cost of the mine is also one of the factors that determine the blasting effect.

\[
U_C = \begin{cases} 
1, & C < C_0, \\
1 + 0.5 \times (C - C_0), & C > C_0.
\end{cases} \quad (4)
\]

The blasting effect satisfaction rate statistics of each scheme are shown in Figure 7.

#### Table 5: Average lumpiness satisfaction rate statistical table.

<table>
<thead>
<tr>
<th>Number</th>
<th>Number of blocks</th>
<th>Bulk size (m³)</th>
<th>Biggest size/cm</th>
<th>Bulk rate (%)</th>
<th>Average block degree satisfaction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-1</td>
<td>25</td>
<td>3490</td>
<td>346</td>
<td>10.39</td>
<td>55</td>
</tr>
<tr>
<td>O-2</td>
<td>17</td>
<td>2693</td>
<td>298</td>
<td>10.41</td>
<td>62</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>2461</td>
<td>216</td>
<td>9.15</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>2351</td>
<td>254</td>
<td>9.23</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>2579</td>
<td>254</td>
<td>10.12</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>2786</td>
<td>264</td>
<td>8.91</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>2696</td>
<td>299</td>
<td>10.31</td>
<td>61</td>
</tr>
<tr>
<td>6</td>
<td>29</td>
<td>2641</td>
<td>239</td>
<td>7.57</td>
<td>88</td>
</tr>
</tbody>
</table>
In the above formula, $C$ is the actual cost and $C_0$ is the standard cost.

The cost satisfaction rate statistics of each plan are shown in Figure 8:

It can be seen from Figure 5 that the original plan of the mine greatly exceeds the standard cost of blasting and reduces the economic benefits of the mine. The blasting costs of optimized blasting plans 1, 5, and 6 are less than the standard cost of a single blasting, which can save blasting costs and improve the economic efficiency of the mine.

4.6. Shovel Loading Efficiency. The shovel loading efficiency directly affects the subsequent transportation and blasting efficiency of the mine. Calculated based on the 12 hours of daily transportation operation of the dump mining trucks in the East Open-pit Mine, there are a total of 30 mining trucks. The specific shovel loading data are collected manually.

According to Figure 9, the average shoveling efficiency of the original scheme of the mine was 862.2 t/h. scheme 1 and scheme 5 did not improve the shoveling efficiency, while the shoveling efficiency of scheme 3 and scheme 4 did not increase but decreased. The reason may be that the blasting effect is not good, resulting in an uneven distribution of shoveling after blasting, which reduces the efficiency of shoveling, and both options 2 and 6 can effectively improve the efficiency of shoveling.

After taking into consideration each plan’s large block rate, average block size satisfaction rate, large block satisfaction rate, cost satisfaction rate, and shoveling efficiency, plan 6 gave the best results with the filling length of 5.0 m, the ultra-depth of 1.0 m, the hole spacing of 5m, and the row spacing of 5m, uniform blasting fragmentation, small rate of large blocks, low cost, and high transportation efficiency, in line with mine production standards.

5. Conclusion

According to the original geological drilling data of the mine, the mine geological model is constructed, which can visually display the mine geological information, facilitate the analysis of the mine geological law, and efficiently guide the mine production design and management.

The blasting of bedded rock steps was investigated using numerical simulations. On this foundation, six sets of field tests with different blasting parameter combinations were set up, and 6 influencing factors were selected, namely, the large block rate after blasting, the average block degree satisfaction rate, the large block satisfaction rate, the cost satisfaction rate, the shovel loading efficiency, and the blasting effect satisfaction rate. By comparing the blasting block size, blasting cost, and shovel loading efficiency of each scheme, the optimal blasting optimization scheme (the filling length is 5.0 m, the super-depth is 1.0 m, the hole spacing is 5 m, and the row spacing is 5 m) is obtained, and the numerical value is verified to simulate the feasibility of the optimization scheme.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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