Arabian Journal of Geosciences (2021) 14: 1086
https://doi.org/10.1007/s12517-021-07425-4

ORIGINAL PAPER

Numerical analysis of deep hole multi-stage cut blasting of vertical shaft using a continuum-based discrete element method

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Received: 22 January 2021 / Accepted: 24 May 2021 / Published online: 3 June 2021

Abstract
Due to the high in situ stress of the deep rock mass and the restraining effect of the surrounding rock, the deep hole blasting of vertical shaft faces the problems of low borehole utilization rate and poor blasting effect. In this regard, this paper proposes a deep hole multi-stage cut blasting technology of vertical shaft. Preliminary engineering practice shows that such cut blasting technology can make better use of explosive energy, reduce the restraining effect of surrounding rock, and increase the borehole utilization rate. Furthermore, based on the continuum-based discrete element method (CDEM), the fractal damage, fragmentation, and blasting cavity characteristics of deep hole multi-stage cut blasting of vertical shaft are studied and analyzed. The results show that in the multi-stage cut blasting of vertical shaft, if the length proportion of the first stage is too small or too large, it will lead to poor cavity formation along the cut direction. Characteristic parameters such as fractal damage of blasting cavity, fracture degree of element, and fracture degree of interface show a trend of first increasing and then decreasing as the length proportion of the first stage increases, and the length proportion of the first stage has an optimal value. Under the conditions of rock parameters, explosive performance and linear charge density set by the numerical simulation in this paper, when the length proportion of the first stage accounts for 0.42, the multi-stage cut blasting of vertical shaft can make better use of explosive energy and achieve the best blasting effect.

Keywords Vertical shaft · Cut blasting · Continuum-based discrete element method · Fractal damage · Fracture degree

Introduction

With the continuous increase of resource mining intensity, the shallow earth resources are decreasing, and the mining depth of mineral resources continues to increase. The number of vertical shafts with a depth of more than 1000 m has also increased year by year, and the construction depth of some vertical shafts even reaches more than 2000 m (Diering, 1997; Vogel & Andrast, 2000). Vertical shaft is the throat channel for deep resource exploitation. Calculated on the basis of the gangue amount, the engineering volume of the vertical shaft construction accounts for 12–30% of the total project, while the construction period accounts for 30–55% of the total construction period. Moreover, with the increase in depth and complexity of geological conditions, vertical shaft construction will have an increasing impact on deep mining (Wang, 1984).

Rock drilling and blasting is the core part of vertical shaft construction, and good blasting effects can effectively shorten the auxiliary operation time and speed up the construction. However, different from traditional shallow borehole blasting, the borehole depth in vertical shaft blasting is more than 5 m. During blasting, the restraining effect of the surrounding rock increases with the increase of the borehole depth, which leads to the deterioration of the blasting effect of the cut borehole, and it is difficult to provide sufficient expansion space for auxiliary borehole blasting (Yang et al., 2017; Zhang, 2016). This is a technical problem that needs to be solved urgently in deep hole blasting.

Responsible Editor: Murat Karakus

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In order to solve this problem, relevant scholars and technicians have proposed and tried some improved methods for cut blasting technology. Langefors et al. (Langefors & Kihstrom, 1963) earlier analyzed the throwing, deformation, and other damage characteristics of cut blasting and proposed a method of drilling large-diameter holes in the center of the tunnelling section and determined the positive role of large-diameter holes in cut blasting. On this basis, Cheng et al. (Cheng et al., 2020) and Liu et al. (Liu et al., 2019) carried out a numerical simulation study on the cut blasting of vertical shaft, which visually demonstrated the stress superposition and reflection stretching phenomena of the blasting stress wave at the large-diameter hole in the cut blasting, and verified the guiding effect of large-diameter holes. In addition, in order to increase the speed of rock tunnel excavation and overcome the shortcomings of parallel cut blasting technology and inclined-hole cut blasting technology, Shan et al. (Shan et al., 2011; Shan et al., 2012) proposed a quasi-parallel cut blasting technology. Such cut blasting technology changes traditional cut blasting design. Main cut boreholes (quasi-parallel boreholes) are slightly inclined, the hole-spacing at the bottom is large, and sub-cut boreholes are perpendicular to the free face. Practice shows that the application of this cut blasting technology can achieve better blasting effects and significant economic benefits.

At present, the research on the cut blasting technology is mainly focused on the optimization of the charge structure. Whether it is to use large-diameter holes or change the angle of the cut borehole, these improved methods have been well applied in the engineering practice of shallow hole blasting. However, in the deep hole cut blasting of vertical shaft, the application of these methods has obvious shortcomings. Specifically, the additional large-diameter hole will significantly increase the workload of drilling; drilling the inclined cut borehole puts stringent requirements on the working surface space and the operation accuracy of the worker, and it is difficult to ensure the quality of the drilling. Therefore, these optimized cut blasting technologies mentioned above are difficult to promote and apply in deep hole blasting of vertical shaft. Construction workers are more inclined to drill more cut boreholes or charge more explosives to improve the rock fragmentation effect of cut blasting. Obviously, this approach is inefficient and lacks scientific and theoretical guidance. In view of this, this paper takes the blasting excavation of the air-intake shaft of Shaling Gold Mine as the engineering background and proposes a deep hole multi-stage cut blasting of vertical shaft. Engineering practice has verified that the application of this cut blasting technology can achieve better blasting results. On this basis, by using the continuum-based discrete element method (CDEM), a numerical simulation study is carried out on deep hole multi-stage cut blasting of vertical shaft, and the influence of the length proportion of each stage on the cut blasting effect is analyzed. It is expected to provide a theoretical reference for the parameter design of engineering practice.

Engineering practice of deep hole multi-stage cut blasting of vertical shaft

Engineering overview

Shaling Gold Mine is located in Jincheng Town and Zhuqiao Town in the northeast of Laizhou City, Shandong Province, China, with a construction scale of 3.96 million tons per year. The ground industrial square in the mining area is equipped with four shafts: main shaft, auxiliary shaft, air-intake shaft, and air-return shaft. Among them, the main shaft has a design depth of 1600.2 m, a waste section diameter of 7.8 m, and a net section diameter of 6.8 m, which is the deepest vertical shaft in China; the air-intake shaft has a design depth of 1480 m and a waste section diameter of 7.3 m, and the net section diameter is 6.5 m. Both the main shaft and the air-intake shaft are constructed by drilling and blasting.

Engineering case

During the drilling and blasting construction process of the air-intake shaft of Shaling Gold Mine, the blasting design within −800 m level adopts the method of simultaneous detonation of explosives in the cut borehole. The used emulsion explosive has a diameter of 45 mm and a length of 450 mm, and the weight of each explosive is 0.8 kg. The borehole layout of deep hole blasting is shown in Fig. 1. The hydraulic umbrella drill is used for drilling. The total number of boreholes is 106 and the total charge is 476.2 kg. Among them, there are 10 cut boreholes with a depth of 5.1 m. Each cut borehole contains 8 rolls of explosives. The upper part of the cut borehole is sealed with stemming, and a nonel detonator is used to detonate from the bottom of the explosive. Within the level of −800 m, this cut blasting design can achieve a good blasting effect and a high single-cycle footage.

In May 2020, after the air-intake shaft of Shaling Gold Mine was excavated to a level of −800 m, the rock transformed into metagabbro and granite, with a Protogyakonov's coefficient of rock strength of 10–12. The in situ stress has increased significantly, and the restraining effect of the rock mass on the cut blasting has become larger, resulting in a decrease in the borehole utilization rate and the single-cycle footage. When the above-mentioned cut blasting design is continued, the single-cycle footage drops to 4.0–4.5 m, and the borehole utilization rate decreases to 78–88%. Therefore, it is considered to change the simultaneous detonation in the cut borehole to multiple detonation in stages, that is, deep hole multi-stage cut blasting, so as to reduce the restraining effect of the surrounding rock on the cut borehole with a large amount of charge. Based on this,

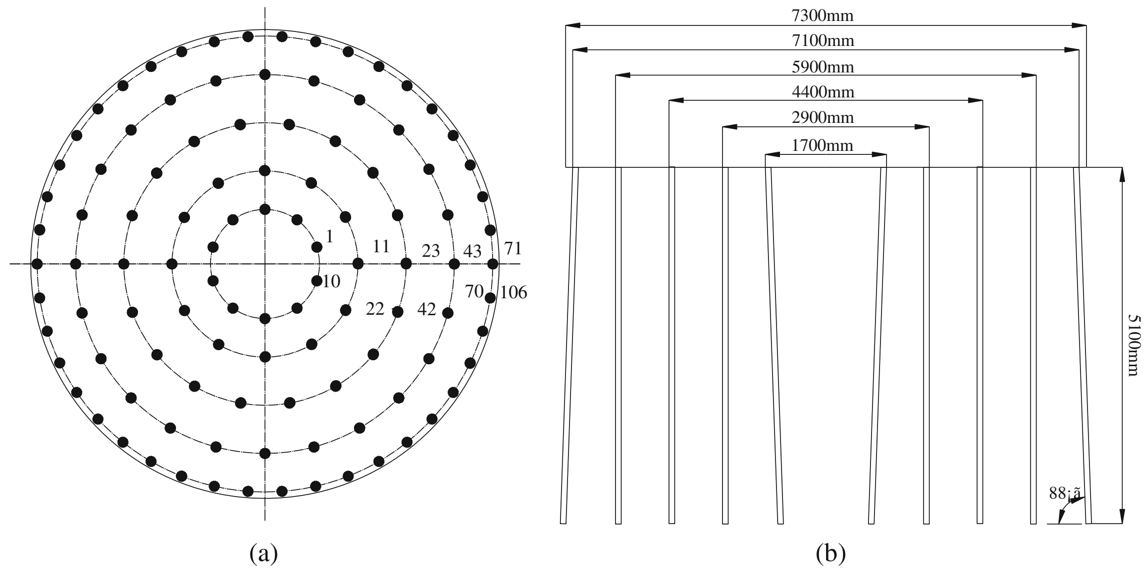

Fig. 1 Borehole layout of deep hole blasting

under the condition that the single-hole charge, the borehole number and the total charge are all unchanged, the cut borehole is detonated in stages. Specifically, place five rolls of explosive at the bottom of the cut borehole (the second stage), and then plug 0.8 m with stemming on the upper part of the explosive; then continue to place three rolls of explosive (the first stage), and plug the upper gap of the cut borehole with stemming. Among them, the first stage detonates first, and the second stage detonates afterwards. The engineering test was carried out using this multi-stage cut blasting plan, and the blasting effect was good. The single-cycle footage reaches 5 m, and the borehole utilization rate reaches 98%.

The above-mentioned engineering case show that in the deep hole blasting of vertical shafts, the multi-stage cut blasting technology can significantly improve the borehole utilization rate and increase the single-cycle footage to ensure efficient shaft excavation. In the multi-stage cut blasting, the explosives in the first stage first blast and fragment the upper rock mass of the cut borehole, thereby creating a free surface for the second stage blasting, and reducing the minimum resistance line and the restraining effect of surrounding rock for the second stage blasting, and finally achieve the goal of improving blasting efficiency. Engineering practice has proved that the multi-stage cut blasting technology can play an important role in the deep hole blasting of vertical shafts. However, there are many specific theoretical foundations for this technology to be studied in depth. Among them, the influence of the length proportion of each stage on the blasting effect is not clear, and the optimal length proportion of each stage under specific engineering conditions has yet to be determined. Based on this, the CDEM will be used in the following to carry out a numerical simulation to study on the length proportion of each stage in the multi-stage cut blasting of vertical shaft.

Establishment of the numerical model for deep hole multi-stage cut blasting of vertical shaft

Introduction to CDEM and material parameters

The continuum-based discrete element method (CDEM) (Li et al., 2007; Ju et al., 2019; Feng et al., 2019; Ding et al., 2021a) is an explicit dynamic numerical analysis method coupled with finite element and discrete element. Its theoretical basis is Lagrange's equation. This method introduces virtual cracks to characterize the propagation and penetration of multiple cracks. Specifically, the virtual crack is located on the boundary of the finite element, the normal and tangential penalty springs are used to link two adjacent finite elements, and the fracture criterion and strength parameters are set for the penalty spring. The force and fracture of the virtual crack are controlled by the penalty spring, and the virtual crack is transformed into a real crack after it breaks.

The CDEM is used to study on deep hole multi-stage cut blasting of vertical shaft. The rock element adopts the ideal elastoplastic constitutive model, and the main parameters are shown in Table 1. The virtual crack between the rock elements adopts the brittle fracture model, and the main parameters are shown in Table 2. The explosive adopts the Landau explosion model, and the main parameters are shown in Table 3. After blasting, the broken rock blocks will undergo dynamic processes such as collision and accumulation. In this regard, the half-spring-half-edge joint contact collision model (Feng

Table 1 Main parameters of the rock element

Density/ $kg{\cdot}m^{-3}$	Elastic modulus/GPa	Poisson's ratio	Cohesive force/MPa	Tensile strength/MPa	Internal friction angle	Dilatancy angle
2500	50	0.2	14	6	40°	40°

et al., 2014; Feng et al., 2011) is used to simulate the contact collision process of broken rock blocks.

Model parameters and calculation case design

As shown in Fig. 2, the size of the numerical model is set to 10 m× 10 m× 10 m, which is divided into 180,604 tetrahedral elements. Except for the excavation section, the outer surface of the model is set as a non-reflective boundary. The borehole depth of multi-stage cut blasting of vertical shaft in the above-mentioned engineering case is about 5 m, and a good blasting effect has been achieved. On this basis, the borehole depth is further increased, and the CDEM is used to further carry out the numerical simulation study of 6 m deep hole blasting in the vertical shaft and to discuss and optimize the relevant parameter design of the multi-stage cut blasting.

The charge structure of the cut borehole is divided into two stages as shown in Fig. 2. The length of the first stage is l_1, the explosive length is e_1, and the stemming length is b_1. The length of the second stage is l_2, the explosive length is e_2, and the stemming length is b_2. The blasting delay time between the first stage and the second stage is 20 ms. In order to study the influence of the length proportion of the two stages on the blasting effect, the ratio η of the first stage length l_1 to the total length of the borehole (l_1+l_2) is taken as the independent variable, namely, $\eta=l_1/(l_1+l_2)$, which is called the length proportion of the first stage. In addition, in order to ensure the uniqueness of the independent variables, it is necessary to control the total charge length and the linear charge density of each stage in each calculation case to be the same.

In the vertical shaft blasting construction of Shaling Gold Mine, 8 rolls of emulsion explosives are placed in each cut borehole, and the length of a single roll of explosive is 450 mm. It can be seen that the charge length in the cut borehole is 3.6 m, the depth of the borehole is 5.1 m, and the linear charge density of the cut borehole is 0.7. Under such design conditions of charge parameters, vertical shaft cut blasting can obtain better blasting effect. Therefore, in the following numerical simulation research, the same linear charge density as in engineering practice is still used, in order to make the numerical simulation results closer to engineering practice. In all the following numerical simulation cases, the linear charge density of each stage is 0.7, that is, $e_1/l_1= e_2/l_2=0.7$; the total charge length of the borehole is 4.2 m. This paper takes the length proportion of the first stage η as the independent variable and sets up six calculation cases. The specific parameters of the calculation cases are shown in Table 4.

Table 2 Main parameters of the virtual crack between rock element

Normal stiffness per unit area/ $GPa{\cdot}m^{-1}$	Tangential stiffness per unit area/ $GPa{\cdot}m^{-1}$	Cohesive force/ MPa	Tensile strength /MPa	Internal friction angle	Sliding friction angle after rupture
100	100	14	6	40°	22.8°

Numerical simulation analysis for deep hole multi-stage cut blasting of vertical shaft

Morphological characteristic analysis of the blasting cavity

Figure 3 shows the blasting cavity shapes of the six calculation cases. It can be seen that there are significant differences in the blasting cavity shape in different calculation cases. When the length proportion of the first stage η is small (Figs. 3(a), (b)), the blasting cavity shape in the upper region of the cut borehole is "trumpet-shaped," while the blasting cavity shape in the lower region of the cut borehole is more uniform "slender shaped." There is a clear boundary between the upper region and the lower region of the blasting cavity. The rock at this boundary is relatively low in fracture, and there is obvious upper and lower stratification along the cut direction. When the length proportion of the first stage η is large (Figs. 3(d), (e), and (f)), both degree and scope of fragmentation in the upper region of the blasting cavity are significantly reduced, and even the upper end of the stemming for the first stage does not break. From the perspective of the overall fracture state of the blasting cavity of the six calculation cases, the blasting cavity of the case where the length proportion of the first stage η is 0.42 (Fig. 3(c)) is relatively continuous along the cut direction, and the upper region of the cut borehole shows obvious throwing blasting characteristics, and there is no obvious delamination in the cut direction.

Fractal damage analysis of the blasting cavity

The model body is cut to obtain the cross-sectional shape shown in Fig. 4 and Fig. 5. The morphological characteristics

Table 3 Main parameters of the explosive

Density/ $kg{\cdot}m^{-3}$	Detonation velocity/ $m{\cdot}s^{-1}$	Detonation heat/ $MJ{\cdot}kg^{-1}$	Adiabatic index in the initial stage	Adiabatic index in the second stage
1150	4500	3.1	3.0	1.333

of the blasting cavity can be observed in more detail from the cross-sectional view. The morphological characteristics of section XOZ and section YOZ of the same calculation case are basically the same. In addition, in order to further study the influence of the length proportion of the first stage η on the fracture shape of the blasting cavity, combined with the fractal damage theory, the blasting cavity shape distribution and damage characteristics are quantitatively analyzed. There are many specific calculation methods for fractal dimension. Among them, the box-counting dimension is a more commonly used one, which can effectively characterize the fractal characteristics of rock fractures and broken shapes. According to the basic principle of box-counting dimension, the fractal dimension of any non-empty bounded target set can be expressed as (Wang et al., 2020; Ding et al., 2021b; Ding et al., 2021c):

$$D = \lim_{k\to\infty} \frac{\lg N(\delta_k)}{-\lg \delta_k} \tag{1}$$

where D is the fractal dimension, δ_k is the side length of the square box, and $N(\delta_k)$ is the minimum number of square boxes with side length δ_k needed to cover the target geometry.

Figure 6 is a schematic diagram of the principle of image processing and fractal dimension calculation of the blasting cavity section. First, according to the distribution characteristics of the blasting cavity shape, crop the above-mentioned blasting cavity section picture. During the image cropping process, it is necessary to ensure that the aspect ratio of the cropped image is 2:1, and the corresponding size of the cropped image in each calculation case is exactly the same. Then, the obtained image is binarized and the picture pixels are re-assigned. The pixel in the length direction is 1024 px and the pixel in the width direction is 512 px. Finally, the MATLAB program is used to count the number of grids with different side lengths required to cover the blasting cavity, and according to Eq. (1), the fractal dimension fitting straight line of the blasting cavity is obtained for the different calculation cases shown in Fig. 7. Table 5 shows the fractal dimensions of the blasting cavity obtained in different calculation cases.

Based on the fractal dimension of the blasting cavity obtained above, the fractal damage of the blasting cavity can be further analyzed. The corresponding relationship between fractal damage ω and fractal dimension D_t under blasting load is:

$$\omega = \frac{D_t - D_0}{D_t^{\max} - D_0} \tag{2}$$

where ω is the fractal damage; D_t is the fractal dimension of the blasting cavity after blasting; D_0 is the fractal dimension; and $D_t^{\max}$ is the fractal dimension under the condition of complete damage and destruction. For two-dimensional plane

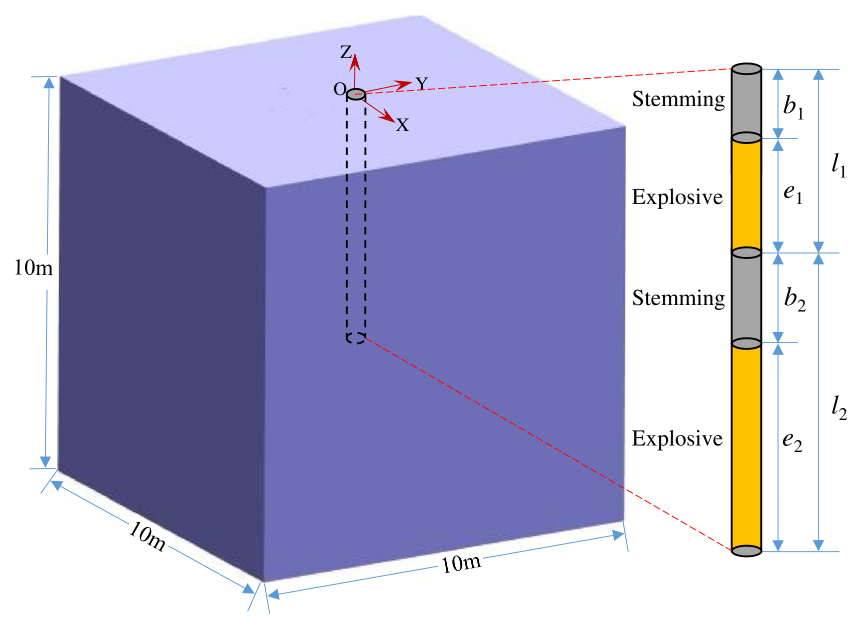

Fig. 2 Schematic diagram of model size and charge structure

Table 4 Parameters of calculation cases for the deep hole multi-stage cut blasting

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
l_1/m	1	2	2.5	3	3.5	4
l_2/m	5	4	3.5	3	2.5	2
e_1/m	0.7	1.4	1.75	2.1	2.45	2.8
e_2/m	3.5	2.8	2.45	2.1	1.75	1.4
b_1/m	0.3	0.6	0.75	0.9	1.05	1.2
b_2/m	1.5	1.2	1.05	0.9	0.75	0.6
η	0.17	0.33	0.42	0.50	0.58	0.67

problems, $D_t^{\max}$ =2; For three-dimensional problems, $D_t^{\max}$ = 3.

For the research in this paper, the rock mass is undamaged before blasting, so D_0=0. Based on this, according to Eq. (2) and the statistical data of the fractal dimension of the blasting cavity in Table 5, the change curve of the fractal damage of the blasting cavity with the length proportion of the first stage shown in Fig. 8 can be obtained. It can be seen from the figure that the fractal damage of the blasting cavity of the section XOZ and the section YOZ both increase first and then decrease as the length proportion of the first stage increases. In all the six calculation cases, when $\eta = 0.42$, the fractal damage of the blasting cavity of the section XOZ and the section YOZ both reach the peak. It can be seen that when η = 0.42, the overall blasting damage of the blasting cavity reaches the maximum.

Analysis of fragmentation characteristics of blasting cavity

In order to quantitatively describe the fracture characteristics of the blasting cavity, degree of element fracture F_e and degree of interface fracture F_i are introduced for analysis. Among them, degree of element fracture F_e is the ratio of the number of plastic deformation and failure elements to the total number of the model; degree of interface fracture F_i is the ratio of the fractured element surface to the total area. Figure 9 shows the change curve of degree of element fracture and degree of interface fracture with time. It can be seen from the figure that when the explosive in the first stage is detonated, the rock in the first stage is broken. The rock fragmentation time in the first stage is about 2 ms, and fracture degree reaches the peak of the first stage blasting. After a delay of 20 ms, the explosive in the second stage is detonated, the rock in the second stage is broken, and the rock fragmentation time in the second stage is also about 2 ms. The blasting cavity formed by the first stage blasting provides a free surface for the second stage blasting, resulting in a significantly greater fracture degree in the second stage than in the first stage, indicating that the effective use of explosive energy in the second stage is more efficient and is more beneficial to rock fragmentation.

Figure 10 shows the change curve of the peak fracture degree after the first stage blasting and the second stage blasting with the length proportion of the first stage. It can be seen from the figure that as the length proportion of the

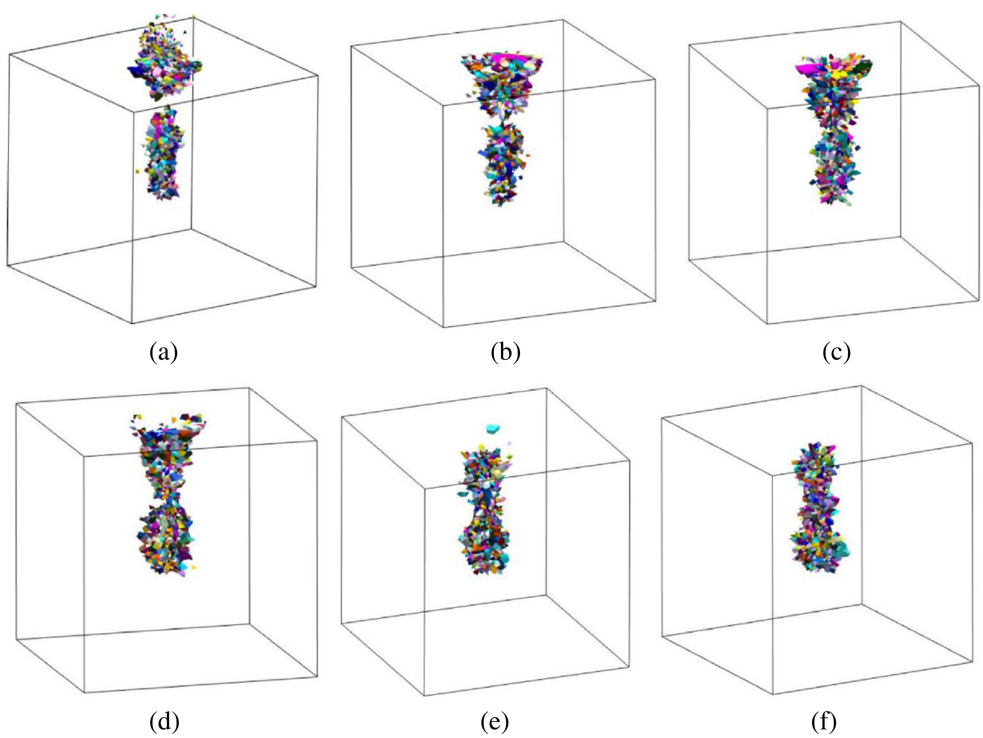

Fig. 3 Blasting cavity shapes of the six calculation cases. (a) η =0.17 (b) $\eta = 0.33$ (c) $\eta = 0.42$ (d) η= 0.50 (e) $\eta = 0.58$ (f) $\eta = 0.67$

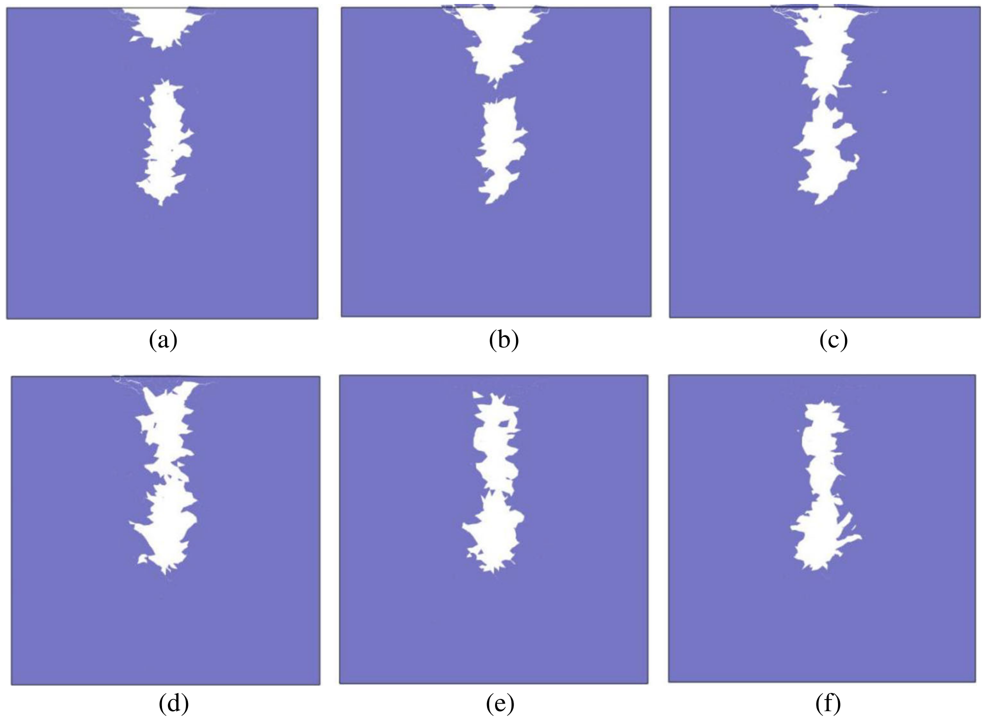

Fig. 4 Morphological characteristics of section XOZ. (a) $\eta = 0.17$. (b) $\eta = 0.33$. (c) $\eta = 0.42$. (d) $\eta = 0.50$. (e) $\eta = 0.58$. (f) $\eta = 0.67$

first stage increases, the charge amount of explosive used to break the rock in the first stage blasting also increases, so that after the first stage blasting, the peak fracture degree of the rock shows a trend of increasing with the increase of the length proportion of the first stage. Partially, in the process of increasing the length proportion of the first stage from 0.42 to 0.58, although the charge amount of explosive in the first stage blasting increases, the fracture degree after the first stage blasting decreases slightly. This is mainly due to the fact that under the condition of maintaining the line charge density at 0.7, as the length proportion of the first stage increases, the stemming length of also increases, resulting

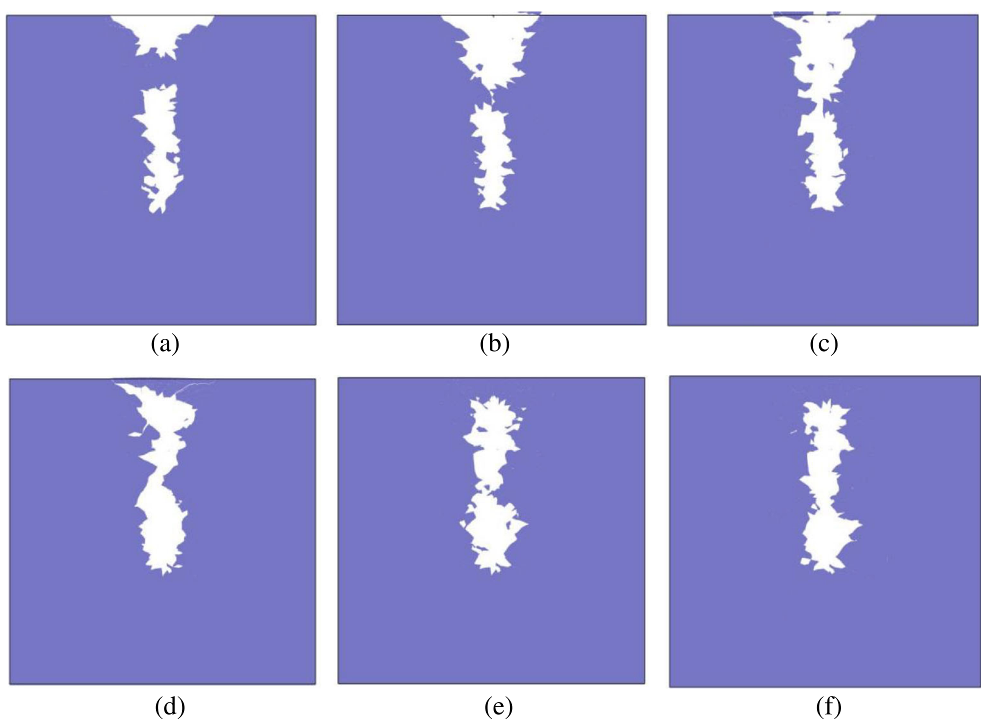

Fig. 5 Morphological characteristics of section YOZ. (a) $\eta = 0.17$. (b) $\eta = 0.33$. (c) $\eta = 0.42$. (d) $\eta = 0.50$. (e) $\eta = 0.58$. (f) $\eta = 0.67$

Table 5 Fractal dimensions of the blasting cavity for different calculation cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Fractal dimension of section XOZ	1.758	1.796	1.801	1.788	1.770	1.752
Fractal dimension of section YOZ	1.765	1.805	1.815	1.783	1.768	1.751

in an increase in the minimum resistance line of the first stage blasting, which is not conducive to rock fragmentation and the formation of blasting cavity in cut blasting. For the first stage blasting, when the charge length and the stemming length increase in the same proportion, the rock fragmentation effect of the cut blasting is determined by these two factors.

After the second stage blasting, the final fracture degree increases first and then decreases with the increase of the length proportion of the first stage. When the length proportion of the first stage is 0.42, the peak fracture degree reaches the maximum. As the length proportion of the first stage increases, the charge amount of explosive of the second stage blasting gradually decreases. In the case that the length of the first stage is relatively large, although the fracture degree after the first stage blasting is also large, the corresponding second stage blasting charge is relatively small, which leads to a significant reduction in the energy used for rock fragmentation in the second stage blasting.

It can be seen that in all six calculation cases, when the length of the first stage accounts for 0.42, the cut blasting can achieve the best fracture effect.

Analysis of fragmentation and volume of blasting cavity

The volume and characteristic size of each fragment after blasting in the above calculation cases are counted, and the fragmentation distribution curve shown in Fig.11 is obtained. In the figure, the characteristic size is the sieve hole diameter, and the calculation equation for the characteristic size L_c of each fragment in the numerical calculation is (Feng et al., 2019):

$$L_c = \left(\sqrt[3]{V_b} + L_{\max}\right)/2 \tag{3}$$

where V_b is the volume of a certain fragment and L_{max} is the maximum distance between the vertices of the fragment.

It can be seen from Fig.11 that when the characteristic size is 0.3 m, the case with the length proportion of the first stage accounting for 0.33 has the largest passing ratio, followed by the case with the length proportion of the first stage accounting for 0.42, and the case the length proportion of the first stage accounting for 0.67 has the smallest passing ratio. When the characteristic size is 0.4 m, the case with the length proportion of the first stage accounting for 0.42 has the largest passing ratio, followed by the case with the length proportion of the first stage accounting for 0.33, and the case the length proportion of the first stage accounting for 0.67 has the smallest passing ratio. Therefore, the calculation case with the length proportion of the first stage accounting for 0.33 and 0.42 can better control the blasting fragmentation, reduce the boulder yield, and ensure the blasting effect.

Figure 12 shows the change curve of the volume of blasting cavity with the length proportion of the first stage. When the

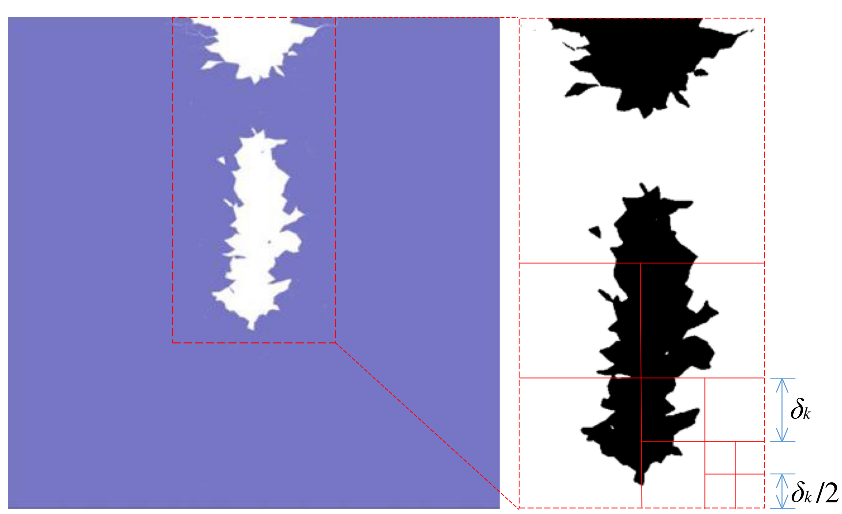

Fig. 6 Schematic diagram of the principle of image processing and fractal dimension calculation of the blasting cavity section. (a) Section XOZ. (b) Section YOZ

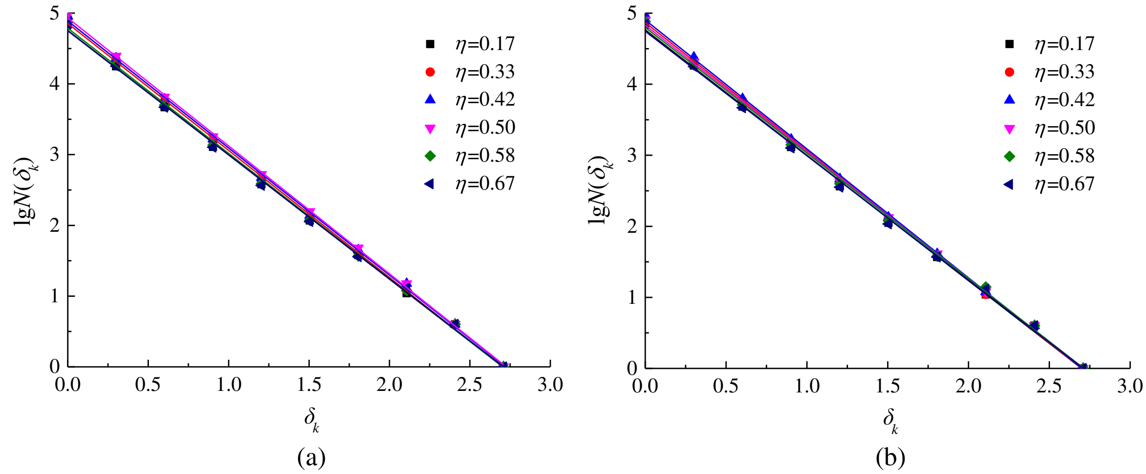

Fig. 7 Fractal dimension fitting straight line of the blasting cavity for different calculation cases

length proportion of the first stage is 0.42, the volume of blasting cavity reaches the maximum value of 8.66 m^3; when the length proportion of the first stage is 0.67, the volume of blasting cavity reaches the minimum value of 5.69 m^3. It can be seen that in all six calculation cases, when the length proportion of the first stage accounts for 0.42, the volume of blasting cavity reaches the maximum, which can create the largest free surface space and is beneficial to the full use of the subsequent blasting energy.

Conclusion

The engineering practice of the air-intake shaft of Shaling Gold Mine shows that multi-stage cut blasting technology can make better use of explosive energy, increase the borehole utilization rate, and increase the single-cycle footage. On this basis, based on the continuum-based discrete element method (CDEM), the fractal damage, fragmentation, and blasting cavity characteristics of deep hole multi-stage cut blasting of vertical shaft are studied and analyzed.

In deep hole multi-stage cut blasting of vertical shaft, when the length proportion of the first stage η is relatively small, there is a clear boundary between the upper region and the lower region of the blasting cavity. The rock at this boundary is less broken, and there is a clear layering phenomenon along the cut direction. When the length proportion of the first stage η is relatively large, the fragmentation degree and the fragmentation range of the upper region of the blasting cavity are significantly reduced, and even the upper end of the stemming does not break.

Characteristic parameters such as fractal damage of blasting cavity, fracture degree of element, and fracture degree of interface show a trend of first increasing and then decreasing as the length proportion of the first stage η increases. In all six calculation cases, when η=0.42, fractal damage of blasting cavity, fracture degree of element, and fracture degree of interface all reach the peak value. This shows that when the length proportion of the first stage is 0.42, the rock fragmentation of the multi-stage cut blasting reaches the maximum value, and the explosive energy is more effectively used. In addition, the analysis of blasting fragmentation and blasting cavity volume shows that when the length proportion of the first stage is 0.42, the blasting fragmentation distribution is more reasonable, the boulder yield is low, and the cavity volume is the largest.

In summary, for the technical application of deep hole multi-stage cut blasting of vertical shaft, there is an optimal range for the length proportion of different stages. Under the conditions of rock parameters, explosive performance and linear charge density set by the numerical simulation in this paper, when the length proportion of the first stage accounts for 0.42, the multi-stage cut blasting of vertical shaft can make better use of explosive energy and achieve the best blasting effect.

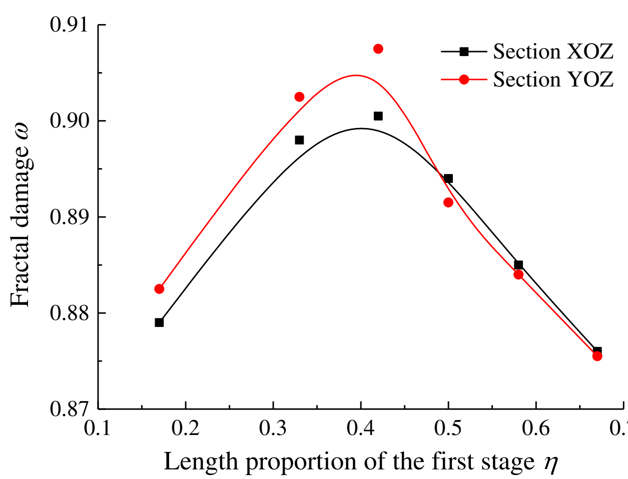

Fig. 8 Change curve of the fractal damage of the blasting cavity with the length proportion of the first stage

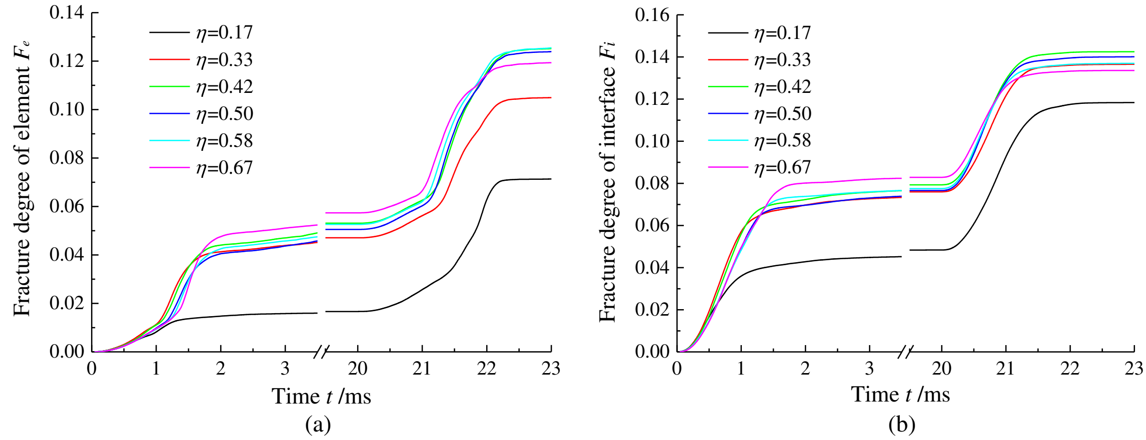

Fig. 9 Change curve of fracture degree with time. (a) Degree of element fracture. (b) Degree of interface fracture

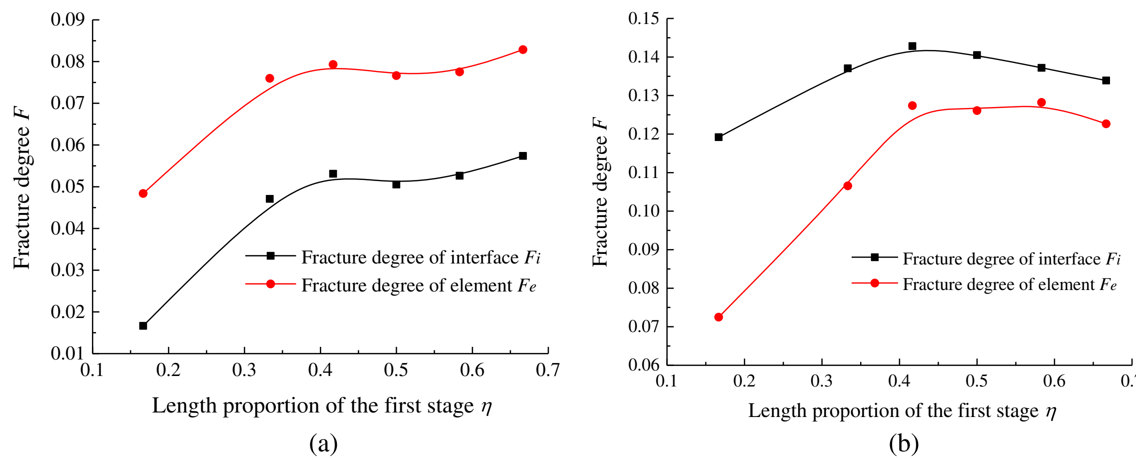

Fig. 10 Change curve of peak fracture degree with the length proportion of the first stage. (**a**) After first stage blasting. (**b**) After second stage blasting

Discussion

This paper analyzes and evaluates the blasting effect of deep hole multi-stage cut blasting of vertical shaft from multiple dimensions such as blasting cavity shape, fractal damage, fracture degree, blasting fragmentation and blasting cavity volume. The comprehensive evaluation points out that among the six calculation cases carried out, the calculation case with the length proportion of the first stage of 0.42 has the best

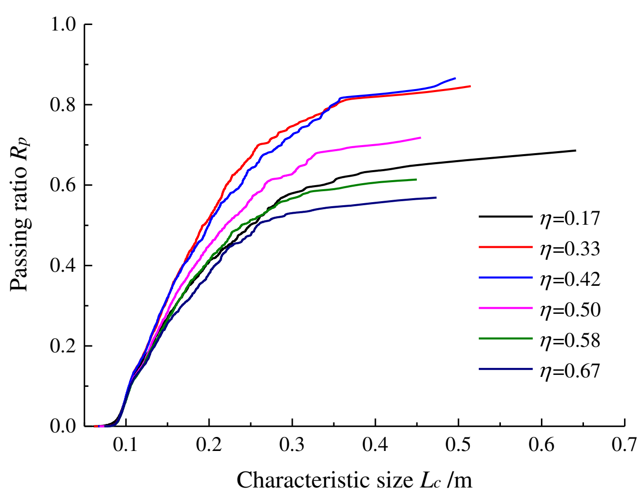

Fig. 11 Fragmentation distribution curve

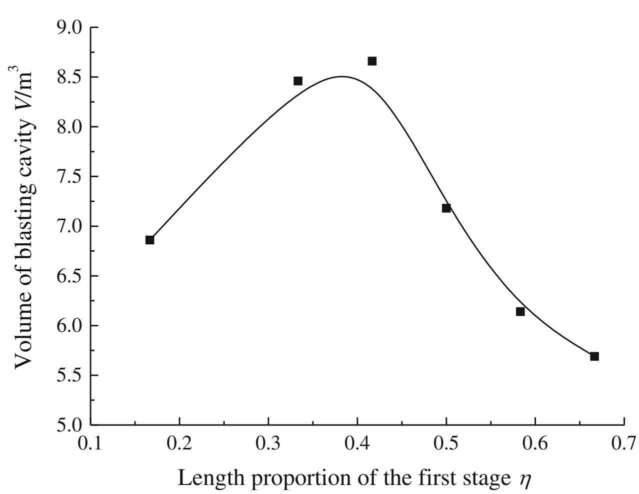

Fig. 12 Change curve of the volume of blasting cavity with the length proportion of the first stage

blasting effect. It should be pointed out that this is a conclusion based on the rock conditions, explosive performance, and linear charge density defined in this paper. In particular, this paper studies the blasting of a single cut borehole. However, in the engineering practice of vertical shaft blasting, the number of cut boreholes is generally 8–10. The interaction of the blasting stress waves between the cut boreholes cannot be ignored. The process of fracture and blasting cavity formation is more complicated, which is different from the numerical simulation research in this paper. The research and analysis in this paper prove that the blasting effect of multi-stage cut blasting of vertical shaft is affected and controlled by the length proportion of the first stage. Under certain engineering conditions, there is an optimal length proportion of the first stage, which can make the explosive energy fully break the rock and obtain a better cut blasting effect.

Funding information This research was supported by (1) Fundamental Research Funds for the Central Universities (FRF-TP-20-044A1), (2) China Postdoctoral Science Foundation (2020 M680354), (3) National Natural Science Foundation of China (51934001, 51974316).

Declarations

Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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