Heliyon 8 (2022) e10992

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Research on structural parameter optimization of elliptical bipolar linear shaped charge based on machine learning

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ARTICLE INFO

Keywords:
Machine learning
Shaped charge
Blasting
Parameter optimization

ABSTRACT

Numerical simulation based on SPH method, compared with laboratory experiments, using the grey correlation theory to analyze the correlation between the parameters of the elliptical bipolar linear shaped charge and the performance of the shaped charge jet. The structure of shaped charge is optimized by machine learning to obtain the optimal structural parameters, and it is compared with the rock crack development of shaped charge blasting in practical application. The results show that the structural parameters of the shaped charge have the same influence on the jet head velocity, and there are certain differences in the impact on the jet length. The fitted curve of the support vector machine (SVM) regression model based on the genetic algorithm (GA) is high prediction accurate. By comparing the optimization results with the actual engineering application of the shaped charge structure, the rock breaking effect has been significantly improved, which has important guiding significance for the actual engineering application.

1. Introduction

By changing the charge structure, shaped charge blasting can accumulate energy in the predetermined direction to form a shaped charge jet with high-density, high-speed, and high-pressure, thereby realizing directional fracture controlled blasting technology. The effect is remarkable, and the application in the field of engineering blasting is also becoming more and more extensive. The design of shaped charge structure directly affects the effect of directional fracture, and the relationship between the structural parameters of shaped charge is also relatively complicated. How to obtain the optimal shaped charge structure is an urgent problem to be solved.

At present, the optimization research on the structural parameters of shaped charge is mainly concentrated in the field of military industry. The study found that the shape of the explosive forming projectile was mainly affected by the shape and material of the liner, the structure of the shaped charge, and the geometric parameters [1, 2]. Ma et al. [3] studied the influence of the shaped charge structure parameters on the formation of linear explosively formed projectiles, and it was found that the velocity, length-diameter ratio and specific kinetic energy of the linear explosive forming projectile were closely related to the structural parameters of the shaped charge. Murphy et al. [4, 5] used experimental and numerical methods to study the penetration of concrete target by shaped charge, and compared the effects of liner material, cone angle, wall thickness and blasting height on the penetration effect. Huerta [6] studied the structure design and optimization of the single-cone shaped charge through numerical simulation, and carried out experiments to verify the reliability of the results. Ning et al. [7, 8] studied the effect of jet formation and shaped charge structure parameters on penetration through experiments and numerical simulation. Fu et al. [9] used the orthogonal design test method to optimize the structure of the annular shaped charge, and studied the influence of different charge structure parameters on the ability of the annular shaped charge to penetrate the target. Wang [10] systematically carried out experiments for penetration into concrete by shaped charge with different liner material, different cone angle, different liner thickness at different standoff, and analyzed the influence of liner material, cone angle, liner thickness and standoff on crater diameter, hole diameter, crater depth and penetration depth.

In recent years, the application of shaped charge blasting in engineering construction has become more and more extensive. Luo et al. [11, 12] designed the structure of the linear shaped charge, carried out the formation of guided crack in the shaped charge blasting, the initiation, propagation and penetration of rock crack, and verified the practicality of the shaped charge in the directional blasting of rock. Guo et al.

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https://doi.org/10.1016/j.heliyon.2022.e10992
Received 27 June 2022; Received in revised form 20 August 2022; Accepted 4 October 2022

[13, 14] applied the directional blasting technology of shaped charge in coal seam crack propagation and permeability increasing, investigated the forming mechanism of shaped charge jet, the propagation characteristics of stress wave and detonation wave, the stress distribution characteristics of coal elements, and the mechanism of crack extension under shaped charge blasting by theoretical analysis and numerical simulation. Yin et al. [15] theoretically analyzed the breaking mechanism of rock blasting using the general cylindrical bilateral-groove shaped charge approach. Several cases with different energy gathering forms using rock drilling and blasting method were tested by numerical modeling, and then an innovative approach of bilateral-groove shaped charge was determined through comprehensive comparative analyses. Wu et al. [16, 17, 18] conducted a preliminary study on the development and evolution of rock crack in elliptical linear shaped charge blasting. However, how to design the structure of the shaped charge to improve the effect of directional rock fracture in the field of underground engineering is a problem worthy of study.

In this paper, for the elliptical bipolar linear shaped charge structure, a method for analyzing the structural parameters of the shaped charge by using the grey correlation theory was proposed, the correlation degree between the parameters of the shaped charge and the shaped charge jet molding was obtained, and analyzed of the primary and secondary relationship between the parameters affecting the shaped charge jet performance. The SVM network regression models based on the parameter optimization algorithm method of GA were then used to parameter optimization and obtain the best structure parameters of the shaped charge. Compared with the actual engineering application of the rock breaking ability of the shaped charge structure before optimization, it verified the rock breaking ability of the optimized shaped charge structure has been significantly improved.

2. Orthogonal experimental design and results

2.1. Analysis of influencing factors of shaped jet molding

The elliptical bipolar linear shaped charge structure is composed of three parts: explosive, charge liner and charge shell. The geometric model is shown in Figure 1(a). The main factors affecting the shaped charge jet molding are the explosive parameters and the shaped charge structural parameters. Three structural parameters, namely charge shell thickness d, charge liner cone angle α, and charge liner thickness δ are selected for grey correlation analysis, and use the SPH method in LS-DYNA for simulation calculation. The SPH model is shown in Figure 1(b), and the influence relationship of various factors on the shaped charge jet performance is obtained, which provides a reference for subsequent structural optimization.

2.2. Analysis and verification of SPH method

Based on the model test in the literature [19], the same geometric parameter model as in the literature [20] is adopted, and the geometric parameter model is shown in Figure 2. The simulation calculation is carried out based on SPH method, and the SPH particle spacing is set to 0.008–0.01cm. The model after SPH particle discretization is shown in Figure 3.

The shaped charge jet and velocity distribution at different times during the forming process of the shaped charge jet are shown in Figure 4. It can be seen from the figure that the shaped charge jet obtained based on SPH method is basically consistent with the shaped charge jet realized by the self-programming of the Gaussian smooth kernel function of Yang et al. [20].

Figure 4(a) is the velocity cloud diagram of the shaped charge jet at 6.5 μs. At this moment, the average maximum velocity of the jet head reaches 3554 m/s, which is basically consistent with the maximum average velocity of the jet head measured by Ayisit [21] through the electromagnetic coil of 3520 m/s. The average peak velocity of the jet head measured by Ayisit [21] through X-ray technology is 3300–3500 m/s, and the average peak velocity of the jet head obtained by the SPH method in this paper is 3295 m/s after the shaped charge jet is formed

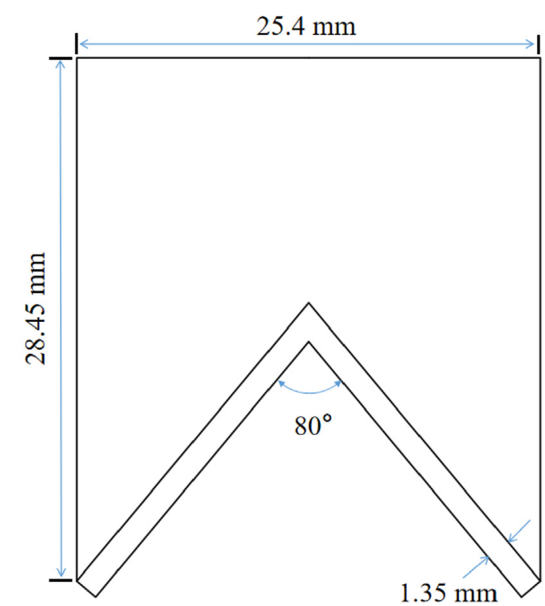

Figure 2. Numerical model.

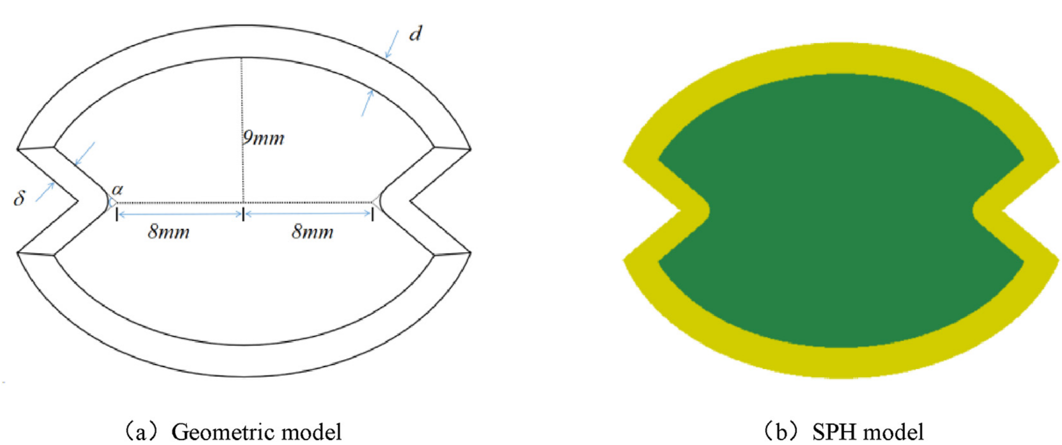

Figure 1. Elliptically bipolar linear shaped charge model.

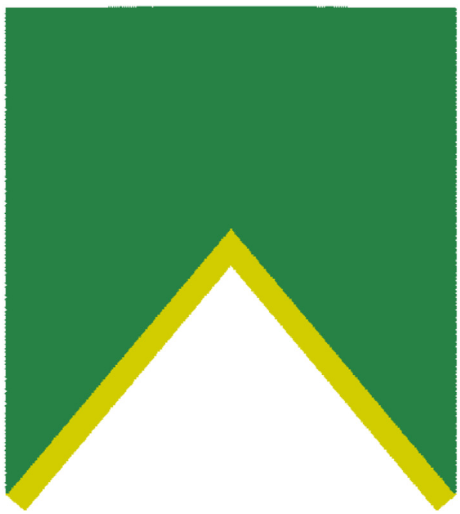

Figure 3. SPH discretization model.

and stabilized, as shown in Figure 4 (b). The results obtained by SPH method are basically consistent with the existing model test results and numerical simulation results, which can prove the effectiveness of SPH method in this paper.

2.3. Orthogonal design

Select the charge shell thickness d, charge liner cone angle α, and charge liner thickness δ as the three factors of the orthogonal design test. The corresponding values of these factors are based on a reasonable range according to the existing data and considering the actual needs and processing requirements. The jet head velocity (v) and jet length (L) are taken as the evaluation indexes of the jet performance. The factors of charge structure and their values are shown in Table 1.

2.4. Simulation result

The simulation calculation uses a single point detonation method, the detonation point is located at the center of the geometric model, and the solution time is 30 μs. The simulation process is illustrated by the results of the No. 1 orthogonal test, as shown in Figure 5. The detonation wave propagates to the top of the charge liner at 2.5 μs after the detonation of the explosive. As the detonation continues, the charge liner began to collapse under the action of the strong impact, and the detonation products drive the micro elements of the liner to converge towards the axis of the liner, producing high-speed, high-temperature and high-pressure particles at the convergence. At 5.0 μs, the shaped charge jet forms a high-speed jet head and a low-speed slug. At this time, the maximum velocity of the jet head is 2591 m/s. Due to the great difference between the velocities of the jet head and the slug, the jet is constantly stretched. At 10.0 μs, the contact part between the charge liner and the charge shell begins to break, and the explosive particles lose their restraint and continue to overflow from the fracture. At 14 μs, the jet head velocity tends to be stable.

The test schemes in Table 1 were simulated respectively to obtain the average velocity v of the jet head and the jet length L at 14.0 μs of each test scheme. The simulation results of each experiment are shown in Table 2.

3. Grey correlation analysis

The grey correlation theory is used to analyze the orthogonal test data, the correlation degree between the structural parameters and the performance of the shaped charge jet is obtained, and the primary and secondary relationship between the structural parameters and the performance of the shaped charge jet is analyzed.

3.1. Dimensionless processing

Before the grey correlation analysis, the data needs to be processed. The performance of the shaped charge jet is mainly evaluated by the jet head velocity and jet length. Therefore, the jet head velocity v and jet length L obtained by the simulation calculation are used as the reference series, and the charge shell thickness d, charge liner cone angle α, and charge liner thickness δ are used as the comparison sequence. Before the grey correlation calculation, the data in Table 2 needs to be averaged and transformed to ensure that the data has a uniform dimension and a comparable order of magnitude. The results of the dimensionless processing of each sequence are shown in Table 3.

Table 1. Horizontal design values of each factor of shaped charge structure.

No.	d/mm	α/(°)	δ/mm
1	1.0	60	0.8
2	1.3	70	1.1
3	1.6	80	1.4
4	1.9	90	1.7
5	2.2	100	2.0

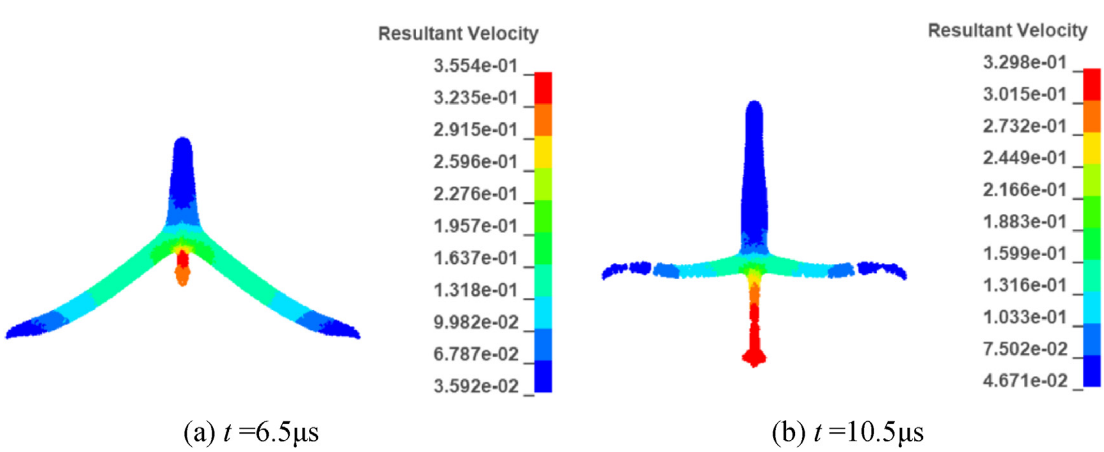

Figure 4. Cloud chart of velocity at different time of jet formation (Unit: 104 m/s).

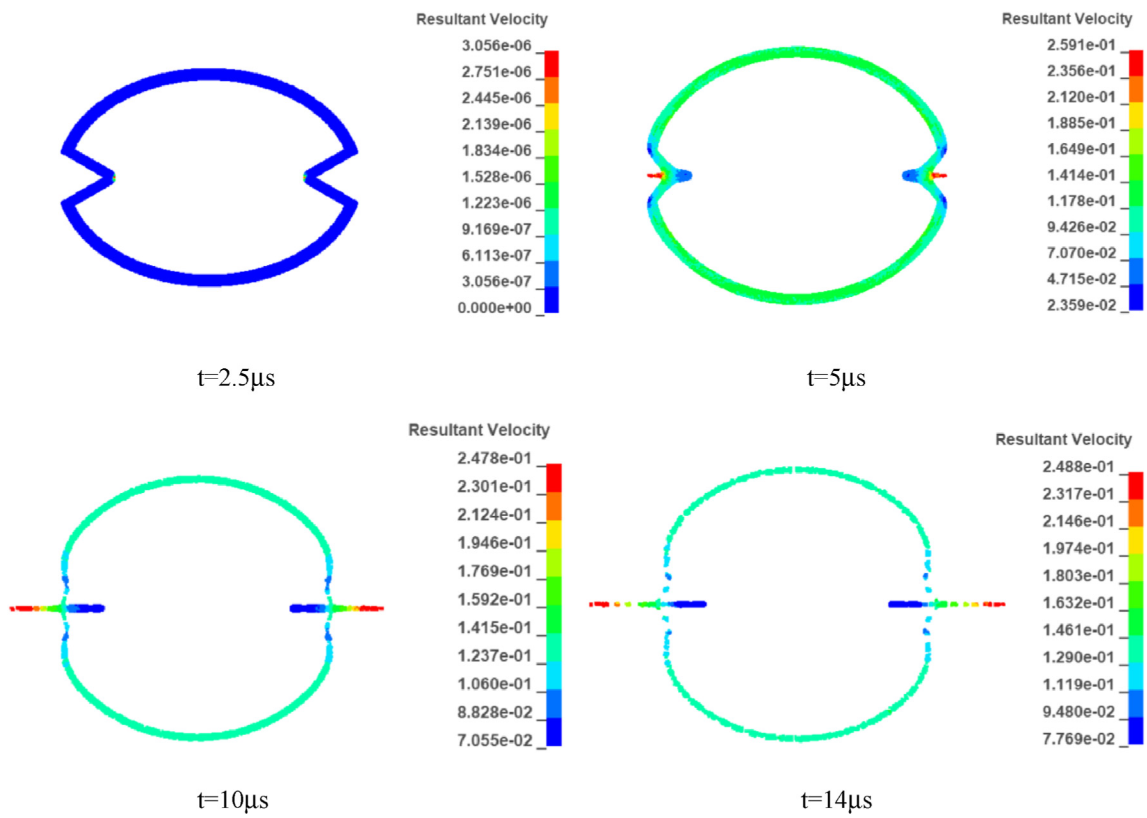

Figure 5. Jet molding at different times.

Table 2. Simulation results.

No.	d/mm	α/(°)	δ/mm	v/(m·s^{-1})	L/mm
1	1.0	60	0.8	2450	19.78
2	1.0	70	1.1	2340	18.43
3	1.0	80	1.4	2290	17.72
4	1.0	90	1.7	2080	15.67
5	1.0	100	2.0	1800	12.82
6	1.3	60	1.1	2475	20.8
7	1.3	70	1.4	2340	19.32
8	1.3	80	1.7	2285	18.33
9	1.3	90	2.0	2090	16.26
10	1.3	100	0.8	1865	9.36
11	1.6	60	1.4	2655	22.87
12	1.6	70	1.7	2460	20.73
13	1.6	80	2.0	2200	18.10
14	1.6	90	0.8	1995	11.65
15	1.6	100	1.1	1780	10.00
16	1.9	60	1.7	2660	23.34
17	1.9	70	2.0	2435	20.80
18	1.9	80	0.8	2140	14.17
19	1.9	90	1.1	1980	13.06
20	1.9	100	1.4	1680	10.66
21	2.2	60	2.0	2530	22.30
22	2.2	70	0.8	2350	17.95
23	2.2	80	1.1	2315	17.52
24	2.2	90	1.4	2015	14.66
25	2.2	100	1.7	1740	11.86

Table 3. Dimensionless processing results of each sequence.

No.	d	α	δ	v	L
1	0.6250	0.7500	0.5714	1.1146	1.1826
2	0.6250	0.8750	0.7857	1.0646	1.1019
3	0.6250	1.000	1.000	1.0419	1.0594
4	0.6250	1.1250	1.2143	0.9463	0.9369
5	0.8125	1.2500	1.4286	0.8189	0.7665
6	0.8125	0.7500	0.7857	1.1260	1.2435
7	0.8125	0.8750	1.000	1.0646	1.1551
8	0.8125	1.000	1.2143	1.0396	1.0959
9	0.8125	1.1250	1.4286	0.9509	0.9721
10	0.8125	1.2500	0.5714	0.8485	0.5596
11	1.000	0.7500	1.000	1.2079	1.3673
12	1.000	0.8750	1.2143	1.1192	1.2394
13	1.000	1.000	1.4286	1.0009	1.0821
14	1.000	1.1250	0.5714	0.9076	0.6965
15	1.000	1.2500	0.7857	0.8098	0.5979
16	1.1875	0.7500	1.2143	1.2102	1.3954
17	1.1875	0.8750	1.4286	1.1078	1.2435
18	1.1875	1.000	0.5714	0.9736	0.8472
19	1.1875	1.1250	0.7857	0.9008	0.7808
20	1.1875	1.2500	1.0000	0.7643	0.6373
21	1.3750	0.7500	1.4286	1.1510	1.3332
22	1.3750	0.8750	0.5714	1.0692	1.0732
23	1.3750	1.000	0.7857	1.0532	1.0474
24	1.3750	1.1250	1.0000	0.9167	0.8765
25	1.3750	1.2500	1.2143	0.7916	0.7091

3.2. Simulation results and analysis

Combined with the grey correlation theory, in order to study the correlation degree between the evaluation indexes v and L and the test factors d, α, δ, firstly calculate the correlation coefficient between each test factor and the evaluation index in different test groups, and then the correlation degree between the test factor and the evaluation index was obtained by the average method. The results are shown in Table 4.

It can be seen from Table 4 that the correlation between charge shell thickness and jet head velocity is the largest, and the correlation between charge liner thickness and jet head velocity is the smallest. Since the correlation between the three test factors and the jet head velocity is not much different, it can be considered that the three factors have the same effect on the jet head velocity. The correlation between liner thickness and jet length is the largest, and the correlation between charge liner cone angle and jet length is the smallest, that is, the effects of the three factors on the jet length are different to a certain extent.

In order to study the best combination of test factor parameters for the evaluation indexes v and L, firstly, the correlation coefficient between each evaluation index and test factor in different test groups is calculated, and then the correlation degree between the evaluation index and each group of test factor parameter combination is calculated respectively. For the jet head velocity, the 13th group is the best parameter combination, and the maximum grey correlation value is 0.8058. The minimum grey correlation degree of group 25 was 0.3883, and the results were quite different. For the jet length, the 13th group is the best parameter combination, and the maximum grey correlation value is 0.7148. The minimum grey correlation degree of group 25 is 0.3842, and the results are also quite different. When considering the jet head velocity and jet length comprehensively, the group 3 is the best parameter combination, and the maximum grey correlation value is 0.7278. The minimum value of grey correlation degree in group 25 is 0.3863, and the results are quite different. The results show that the selection of structural parameters of shaped charge is very important to the formation of shaped charge jet.

4. Parameter optimization of shaped charge based on machine learning

Through the SVM network regression model based on the parameter optimization algorithm method of GA to optimize the parameters of the elliptical bipolar linear shaped charge, so as to realize the elliptical bipolar linear shaped charge jet performance prediction.

4.1. Forecast based on GA-SVM model

The GA algorithm is used to optimize the SVM parameters, the penalty function, the kernel function parameters and the epsilon parameters are genetically coded, the fitness function selects the smallest mean square error, and the best structural parameters are obtained through continuous iterative evolution. For 25 sets of data, the first 20 sets of data are selected for the training set, and the remaining 5 sets of data for the test set. The selected experimental data are shown in Table 5.

The data set is brought into the GA-SVM optimization program written in MATLAB. The program first normalizes the data, then optimizes the parameters C, g, and epsilon of the SVM, then sets the optimal SVM parameters to the data set training, and finally perform regression prediction on the original data. Regression prediction of the jet head velocity, the optimized parameters are: penalty factor C is 35.9312, g is 0.0229, epsilon is 0.0100, minimum root mean square error MSE is 0.0076, square correlation coefficient is 0.9826. The comparison between the original data and the regression prediction data is shown in Figure 6.

It can be seen from Figure 6 that the GA has a better optimization effect on the parameters of the SVM, and can correctly establish the relationship model between the structure parameters of the elliptical linear shaped charge and the jet performance. The specified charge structure parameters can predict the jet performance under certain conditions with high accuracy, so as to better assist the actual design work.

Table 4. Grey correlation calculation results based on evaluation indexes and the comparison sequence factors.

Factor	Correlation to v	Correlation to L
d	0.5918	0.5530
α	0.5894	0.5445
δ	0.5810	0.6258

Table 5. Training and test sets.

No.	d/mm	α/(°)	δ/mm	v/(m·s^{-1})	L/mm
1	1.0	60	0.8	2450	19.78
2	1.0	70	1.1	2340	18.43
3	1.0	80	1.4	2290	17.72
4	1.0	90	1.7	2080	15.67
5	1.0	100	2.0	1800	12.82
6	1.3	60	1.1	2475	20.8
7	1.3	70	1.4	2340	19.32
8	1.3	80	1.7	2285	18.33
9	1.3	90	2.0	2090	1.6.26
10	1.3	100	0.8	1865	9.36
11	1.6	60	1.4	2655	22.87
12	1.6	70	1.7	2460	20.73
13	1.6	80	2.0	2200	18.10
14	1.6	90	0.8	1995	11.65
15	1.6	100	1.1	1780	10.00
16	1.9	60	1.7	2660	23.34
17	1.9	70	2.0	2435	20.80
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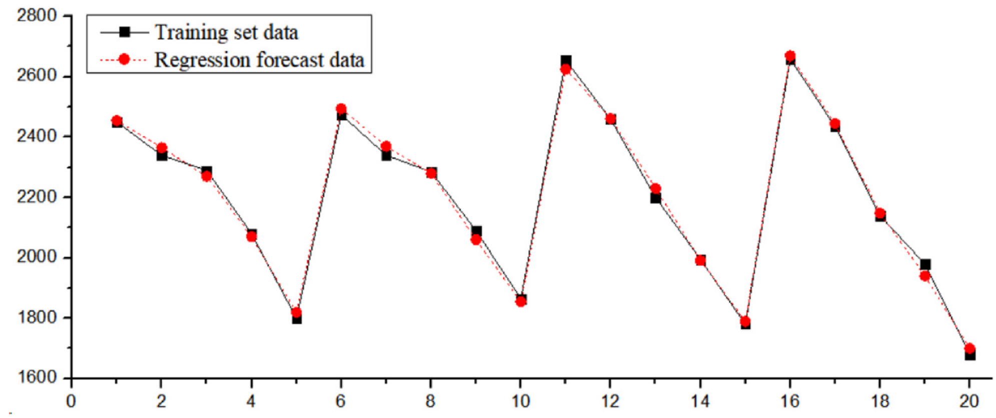
23	2.2	80	1.1	2315	17.52
24	2.2	90	1.4	2015	14.66
25	2.2	100	1.7	1740	11.86

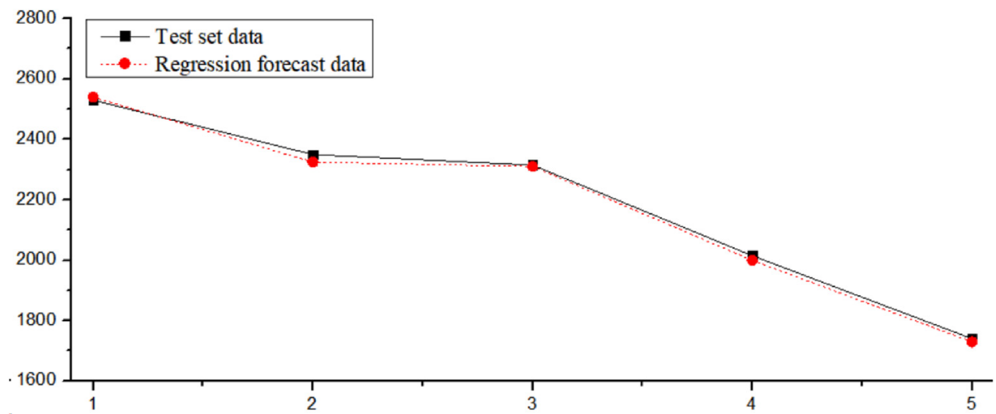
4.2. Parameters optimization of elliptical bipolar linear shaped charge

The GA has a strong ability in parameters optimization. In order to improve the jet performance and find the best charge structure parameters, the GA is used to optimize the parameters. The optimization parameters are the charge shell thickness, charge liner cone angle, and charge liner thickness. Therefore, the length of the individual is 3. The population size of the GA is set to 20, the evolutionary algebra is 500, and the crossover probability is 0.9. The greater the head speed, the better the individual. After the parameter optimization process is over, the parameter corresponding to the best individual fitness value is the optimal structural parameter at this time.

In the GA optimization process, the search set is set for the optimization parameters respectively, the charge shell thickness is set to [1.0, 2.2], the charge liner cone angle is set to [60, 100], and the charge liner thickness is set to [0.8, 2.0]. Using MATLAB to write algorithm code to optimize the charge structure parameters, the optimal charge structure parameters and the predicted maximum jet head velocity are the results of #1 in Table 6. Combined with practical applications, the charge shell thickness search set is set to [1.8, 2.2], the optimal charge structure parameters and the predicted maximum jet head velocity are obtained as the result of #2 in Table 6.



(a)



(b)

Figure 6. Comparison of jet head velocity data.

Table 6. Results of parameter optimization of shaped charge.

No.	d/mm	α/(°)	δ/mm	optimization result $v/(m{\cdot}s^{-1})$	simulation result $v/(m{\cdot}s^{-1})$
#1	1.64	60.00	1.93	2698	2683
#2	1.93	62.64	1.84	2681	2668

In order to verify the optimization results of shaped charge parameters, the obtained optimal structural parameters are used for simulation verification, as shown in Figures 7 and 8. The simulation calculation results are compared with the optimization prediction results, as shown in Table 6, and the error degree is used for evaluation. The optimization prediction results are very close to the simulation calculation results, and the error degree is no more than 1%. This shows that the accuracy of GA optimization is very high, and it is very suitable for the optimization problem of multivariate nonlinear targets.

4.3. Rock crack development

Considering that the increase of the charge shell thickness can reduce the damage in the non-concentrated energy direction, combined with the obtained optimization parameters, the structural parameters of the charge shell thickness of 2 mm, the charge liner cone angle of 62°, and the charge liner thickness of 1.8 mm are selected for rock crack comparative analysis with the shaped charge structure in practical engineering application. The structure parameters of the shaped charge used in practical engineering are mostly the charge shell thickness of 2 mm, the charge liner cone angle of 70°, and the charge liner thickness of 2 mm. The development of rock cracks in two types of shape charge blasting are shown in Figures 9 and 10, and the selection of material parameters is consistent with the literature [16].

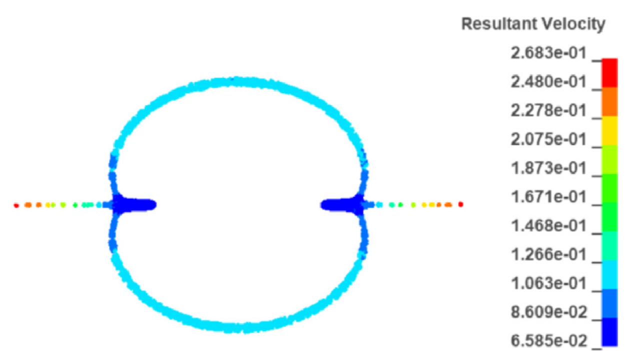


Figure 7. Structural parameter simulation results of #1.

Figure 9 shows the rock crack development of shaped charge blasting applied in practical engineering, and Figure 10 shows the crack development of shaped charge blasting after optimization. The average length of main crack before optimization is 35.72 cm, the average length of main crack after optimization is 38.11 cm, the length of main crack increases significantly, and the length of secondary crack decreases significantly compared with that before optimization. After optimization, the rock breaking performance of shaped charge has been significantly improved.

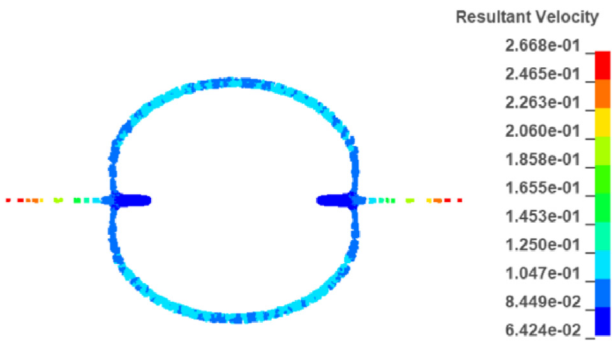


Figure 8. Structural parameter simulation results of #2.

5. Discussion

For shaped charge, when the explosive is detonated, due to the sparse wave and lateral expansion effect, the detonation velocity and the strength of the wave front are reduced, and the pressure acting on the charge liner is weakened. The existence of charge shell prolongs the time of detonation products acting on the charge liner, and more energy is used to crush the charge liner. According to the related theory of explosive dynamics and the process of crushing of the charge liner, charge liner cone angle determines the pressure of the detonation effect on the surface of the charge liner. When the charge liner cone angle increases, the tangent angle between the detonation front and the charge liner surface also increases, and the crushing effect of the charge liner towards the charge center decreases. If the cone angle increases to 180°, it is equivalent to that the detonation wave acts directly on the plate without energy accumulation effect. For the charge shell thickness, the jet performance is related to the velocity and mass of the jet head. According to the kinetic energy theorem, the kinetic energy is directly proportional to the second power of the velocity and the first power of the mass. It can be seen that the jet head velocity plays a leading role in the jet performance. The three structural parameters of elliptical bipolar linear shaped charge have a certain influence on the formation of shaped charge jet. For solving the problem of how to combine the parameters to obtain the best shaped charge structure, it is a good choice to use machine learning method for structural optimization.

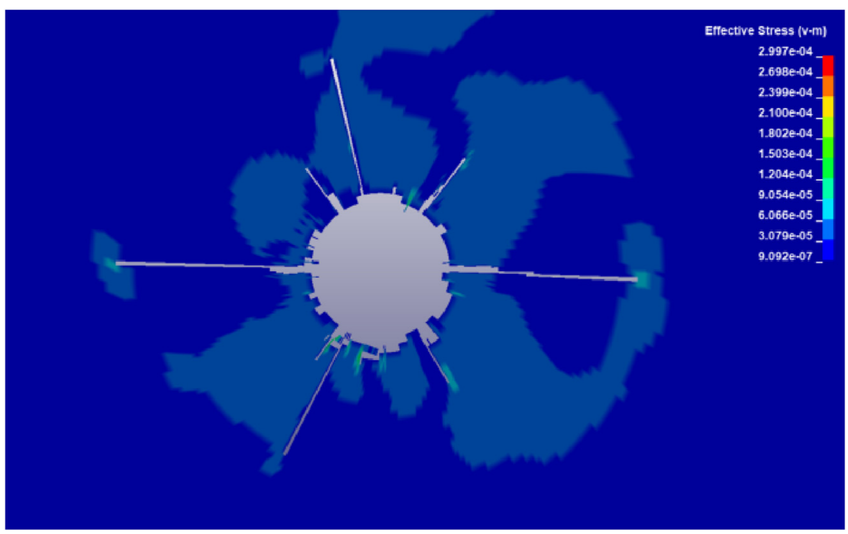


Figure 9. Crack development of shaped charge blasting before optimization.

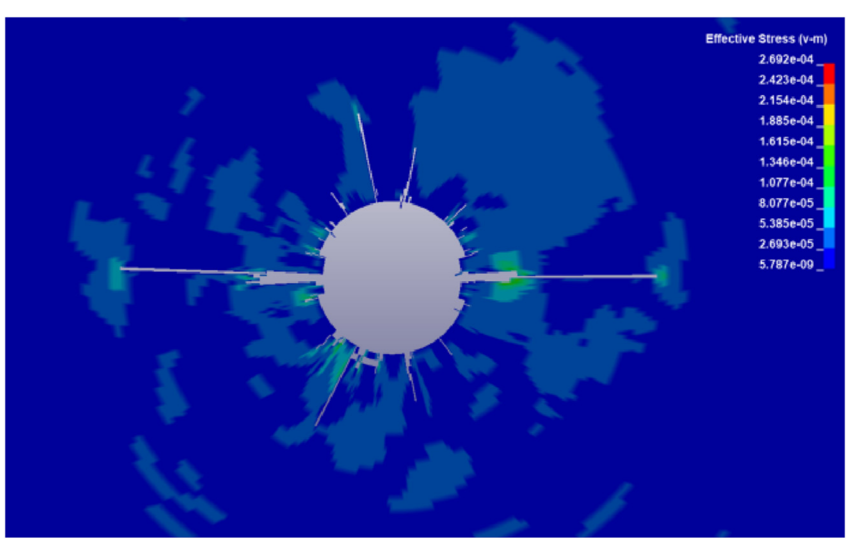


Figure 10. Crack development of shaped charge blasting after optimization.

6. Conclusions

(1) The structural parameters of elliptical bipolar linear shaped charge have a considerable influence on the jet head velocity and have a certain difference on the jet length. The selection of structural parameters of shaped charge is very important to the performance of shaped charge jet.
(2) Through the SVM network regression model, combined with the GA to optimize the parameters of the elliptical bipolar linear shaped charge can correctly establish the relationship model between the structural parameters of elliptical linear shaped charge and jet performance. The prediction accuracy is high, and can well assist the structural design of shaped charge.
(3) Compared with the structural parameters of shaped charge commonly used in practical engineering, the structural parameters obtained through optimization have significantly improved rock breaking performance. At the same time, the damage to the rock in the non-concentrated energy direction is reduced, and the optimization of shaped charge has been significantly improved, which has important guiding significance for practical engineering application.

Declarations

Author contribution statement

Bo Wu: Analyzed and interpreted the data; Wrote the paper.
Shixiang Xu: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Guowang Meng, Yaozhong Cui: Analyzed and interpreted the data.

Funding statement

Bo Wu was supported by National Natural Science Foundation of China [No. 52168055, No. 51678164].

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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