Dynamic Simulation Study on Protective Coal Pillar Width on Floor Roadway

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Research Article

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Posted Date: March 11th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-213686/v1

Dynamic simulation study on protective coal pillar width on floor roadway

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Abstract: Determination of reasonable protective coal pillar width has a great significance for the safety and stability of the coal seam working face and the surrounding structures and facilities. For studying the reasonable width of protective coal pillar, based on the platform of ABAQUS, program with the PYTHON language to make dynamic model which can simulate the dynamic changes of different width. Then the deformation law of floor roadway under different protection coal pillar width is analyzed. The finite element optimization analysis program is compiled based on MATLAB, and the minimum deformation of roadway and protective coal pillar is used as the optimization goal to make calculation for the dynamic model, and the reasonable width of protective coal pillar is proposed. Through the comparison between the simulation result and the field monitoring data, validity of the calculation result and rationality of the method are verified. The research results provide the reference for the setting of protective coal pillar for similar mining conditions.

Key word: Floor roadway; Protective coal pillar; Dynamic optimization

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1 Introduction

Reasonable width of protective coal pillar is very important for maintaining the stability of roadway and working face and improving the mining rate of coal resources. At present, many coal mines in China still adopt the traditional method of retaining coal pillar width, that is, to rely on experience to determine the coal pillar width. Generally, a larger size of protecting coal pillar is reserved in the principle of regardless of the cost. Although it plays a role in protecting the overlying surrounding rock and roadway, it causes a large amount of waste of coal resources. Therefore, reasonable coal pillar width by considering both coal mining rate and roadway stability has always been the focus of many scholars.

Wang et al. (Wang et al., 2020) established a mechanical model based on the failure form of the main roof breaks above the protective coal pillar and applied in the protective coal pillar of the recovery room of the longwall panels in Hongliulin Coal Mine for evaluating the width of protective coal pillar. Sun et al. (Sun et al., 2020) used DFOS technology and FLAC^{3D} numerical simulation to determine the reasonable size of protective coal and rock pillar of the working face 1231(1) in a mine in Huainan. Xi et al. (Xi et al., 2008) set up four calculation models with different coal pillar widths (3m, 6m, 8m and 12m respectively) to carry out simulation study on the stress and deformation of surrounding rock, and put forward reasonable suggestions for the reserved coal pillar width in Shitanjing mine. Tu et al. (Tu et al., 2013) used theoretical analysis, numerical simulations, and field measurements to analyze the distortion and stability of a coal pillar located in a steep mining face and obtained the reasonable size of coal pillar to ensure the stability of coal pillar and goaf roof in the Xintie mine of the Long Mine group. Yan et al. (Yan et al., 2012) established 6 kinds of calculation models (designed width of coal pillar is 4, 6, 8, 10, 14 and 20 m) to make numerical simulation and obtain the relationship between pillar width and gateroad stability. Zhang et al. (Zhang et al., 2011) calculated the model when the coal pillar width is 3m, 4m, 5m, 6m, 8m, 10m, 12m, 15m and 20 m, respectively, and finally determined the protective coal pillar width for 7113 return air roadway. Yu et al. (Yu et al., 2015) studied the stress evolution law, elastic-plastic region variation, and the roadways deformation law of 5 different coal pillar width of 4 m，6 m，8 m，10 m and 12 m by numerical simulation, and determined the reasonable width of double tunneling pillar between roadways in large mining height face considering safety production and resources recovery. Zhang et al. (Zhang et al., 2013) analyzed the stress distributions and the failure characteristics of the surrounding rocks of large coal pillars with different widths by FLAC based on the engineering geological conditions in Hexi coal mine of Fenxi mining group, and got the optimal size of coal pillar between panels is 26m. Han et al. (Han et al., 2007) obtained the variation range of plastic area of 4 different coal pillar widths and the results show that the destruction of a small coal pillar is greatly affected by its width.

Based on the above analysis, two influencing factors are mainly considered in the research on the optimization of the reasonable size of protective coal pillar: (1) the self-stability of the coal pillar; (2) stability of surrounding facilities (such as mining roadway, transportation roadway, etc.) (Zhang et al., 2017; Li and Cao, 2005; Yu and Tu, 2006; Wang et al., 2014; Liu et al., 2012; Wang et al., 2013). However, when the distance between coal seam and floor roadway is small, it is relatively one-sided to consider one factor to determine the reasonable width of protective coal pillar. Meanwhile, in the process of numerical simulation research, the scheme comparison method is widely used, that is, the analysis model under different schemes is established, the calculation results are compared, the influence law of different protective coal pillar width on roadway stability is found out, and the reasonable width is finally determined. During numerical analysis, there must be existed the problems repetitive modeling and scheme comparison, which greatly reduce the efficiency of analysis. And it is impossible to establish all schemes in the process of model building, so the optimal scheme is easily ignored (Wang et al., 2016, 2020). Therefore, this paper takes the mining of 42010 working face near floor roadway in a coal mine as an example, and puts forward a dynamic optimization method for the width of protective coal pillar considering the above two influencing factors comprehensively, which provides a reference for determining the reasonable size of protective coal pillar.

2 Project background

The floor strata of the 42010 working face of a coal mine project are mainly siltstone, and the floor roadway is 26m below the coal seam with a buried depth of 610m. The cross-section of the roadway is a semicircular arch, with clear width and height of 5m and 6.8m, respectively. The supporting measure of the roadway is bolt-shotcrete support and the thickness of shotcrete is 0.2m. In roadway construction, anchor cable support parameters are ϕ22 mm×7500 mm, and the interval and row spacing are 1200 mm×1200 mm. The floor is supported by ϕ22 mm×8300 mm high-strength steel strand anchor cable, and the interval and row spacing are 1300 mm×1300 mm.

The layout and thickness of the rock strata are shown in Fig. 1 and the pattern of roadway support with bolt-shotcrete support in the roadway cross-section are shown in Fig. 2.

3 Determination method for reasonable coal pillar width

3.1 Numerical modeling

In the process of using numerical simulation to determine the reasonable coal pillar width, researchers in the past often set up models for calculation under different coal pillar conditions, and then make comparative analysis of the results to determine the final scheme. However, the repeated modeling process will consume a lot of time and energy. In order to solve the problem, this paper uses a parameterized design method for research, which can realize the calculation and analysis of models under different schemes only by changing the parameters in the calculation process. The process of parameterized design method is shown in Literature (Wang et al., 2014). A dynamic parameterized model (as shown in Fig. 3) capable of simulating different protective coal pillar widths was developed by Python, the standard design language of ABAQUS. In Fig. 3, coal pillar width (L) is a variable parameter, and its change can be determined by the interactive GUI (as shown in Fig. 4). When different value of “Coalwidth” is input, L in the model will change accordingly, so as to obtain the calculation model with the corresponding protective coal pillar width.

In order to reduce the boundary effect and improve the reliability of numerical simulation, the height and width of the model are set to be 150m and 250m respectively. Horizontal constraints are imposed on the left and right boundary of the model, while vertical constraints are imposed on the bottom boundary. The gravity stress is applied to the whole model, and a pressure stress of 10.50MPa is applied to the top boundary of the model according to the in-situ geostress test. According to the field construction planning, the width of the protective coal pillar is in the range of 20m to 60m.The finite element models with different protective coal pillar widths are shown in Fig. 5 (taken the four cases of L=20m, 30m, 40m and 60m as examples).

The mechanical properties of rock strata are simulated by Drucker-Prager criterion during the numerical simulation. According to field engineering investigation data and rock mass mechanical test report, the values of mechanical parameters of surrounding rock in simulation calculation are determined in Table 1.

3.2 Calculation results analysis

After roadway support in coal seam floor, the stability of surrounding rock is greatly affected by the change of overlying coal seam working face. Different width of protective coal pillar has different influences on the stability of roadway surrounding rock and the supporting effect of coal pillar (Li, 2020; Sinha and Walton, 2020; Gao et al., 2019).

3.2.1 Deformation characteristics of roadway

Python language is used to write a post-processing program that can automatically analyze the calculation results, extract the displacement of key points of surrounding rock of roadway under different protective coal pillars width, and obtain the deformation law of roadway, as shown in Fig. 6. It can be found that with the increase of the width of the protective coal pillar, the convergence value of both side walls of the roadway gradually decreases from 0.031m to 0.026m, while the convergence between roof and floor increases from 0.001m to 0.008m. Through overall deformation of the roadway, the convergence of the two side walls is much greater than that of the roof and floor.

3.2.2 Study of protective coal pillar stability

Coal seam mining causes disturbance to protective coal pillar, and its two ends are in a state of plastic failure in a certain depth range. In general, the protective coal pillar can be divided into two parts: the yield zone and the elastic core zone. The plastic zone is in a state of destruction and its supporting capacity is relatively low. However, the elastic core zone is less disturbed, and its integrity and strength are higher. Meanwhile, the core zone is constrained by two-side yield zones, and its strength will increase. With the increase of the width of the protective coal pillar, the range of the core area will also increase, the supporting capacity of the coal pillar will increase, and the influence of the working face on the floor roadway will decrease gradually.

Fig. 7 shows the changing rule of the maximum deformation at both ends of the protective coal pillar with the width. It can be found that with the increase of the width of the protective coal pillar, the deformation at both ends of the coal pillar decreases gradually. When the coal pillar size is less than 35m, the reduction degree of deformation value is larger. When the width of coal pillar is larger than 35m, the influence of the width on the deformation at both ends of coal pillar decreases gradually.

Fig. 8 shows the plastic zone distribution of protective coal pillar with different width. It can be found that the maximum value of equivalent plastic strain is located at both ends of the coal pillar and gradually decreases towards the inside of the coal pillar. When the width is less than 35m, the whole coal pillar is basically in the plastic state, but with the increase of the width, part of the coal in the inner position of the coal pillar does not enter the plastic state. It shows that with the increase of the coal pillar width, the elastic core zone is gradually formed inside the coal pillar, which makes the coal body get better protection and better stability.

Fig. 9 shows the changing rule of the plastic zone thickness of protective coal pillar with width. When the width of protective coal pillar is less than 37m, the thickness of plastic zone is equal to the width of coal pillar, indicating that the whole coal pillar has entered the plastic state completely. When the width of protective coal pillar exceeds 37m, the change of plastic zone thickness tends to be stable.

Through the above research, it can be seen that with the increase of the width of the protective coal pillar, the overall deformation of the roadway decreases gradually, and the convergence of the two side walls of the roadway is greater than that of the roof and floor. When the width of coal pillar is larger than 35m, the deformation at both ends of coal pillar tends to be stable, and when the width is larger than 37m, the change of plastic zone thickness tends to be stable.

4 Dynamic simulation study of protective coal pillar width

4.1 Establishment of optimization model of protective coal pillar

In the process of coal seam mining, the surrounding rock of floor roadway is disturbed, leading to the influence to the roadway stability. Meanwhile, when the protective coal pillar is reserved, its own stability is the basis to ensure the normal operation of the working face. Therefore, the safety and stability of coal pillar and roadway should be taken into consideration when optimizing the width of protective coal pillar (L). Based on this principle, a dynamic multi-objective optimization program based on finite element parameterized design is developed in this paper. Its basic principle is as follows: when the width of the protective coal pillar is calculated within its value range, the objective function is automatically analyzed according to the calculation results, and when the objective function tends to be minimal, the obtained width of the protective coal pillar is the optimal scheme.

According to Section 3.2, the deformation of the floor roadway and the protective coal pillar can be obtained when the finite element parameterized model is calculated under different protective coal pillar width (L), which can be expressed as:

$$U_i=f(L),\ i=1,\ 2,\ 3 \tag{1}$$

where, i is the i'th deformation value to be considered. And U_1 and U_2 are the convergence of the two side walls and convergence between roof and floor of roadway, respectively. U_3 is the maximum deformation at both ends of protective coal pillar.

It can be seen from Eq. (1) that U_i is the function of the width (L) of the protective coal pillar. When L changes, the deformation of the floor roadway and the protective coal pillar will also change. Considering the principle of economy when coal pillar is reserved, the width of coal pillar should not be too large. Therefore, in the optimization process, the total objective function can be expressed as:

$$U=\sum_{1}^{n}\frac{U_i}{U_{i\max}}+\frac{L}{L_{\max}} \tag{2}$$

where, U is the total objective function. n is the number of single objective function and U_i is the corresponding single objective function. U_{imax} is the maximum value of a single objective function calculated within the range of optimization parameters. L_{max} is the maximum value of protective coal pillar in the optimization process.

The constraint condition of the width (L) of the protective coal pillar can be expressed as:

$$L_{\min}\le L\le L_{\max} \tag{3}$$

where, $L_{\min}$ and $L_{\max}$ is the optimization range of protective coal pillar width. According to the engineering conditions, the geological survey report and the analysis of the calculation results in Section 3.2, $L_{\min}$ and $L_{\max}$ are set to 30m and 50m, respectively. The optimization process is to find a reasonable width of protective coal pillar within its range so that the total objective function U tends to minimize.

4.2 Program implementation

In order to realize the above optimization method, a program (Disp.py) is written by PYTHON language to read the deformation of key points of roadway and coal pillar automatically. Then, the optimization analysis program (COALwidthOP.M) based on genetic algorithm is developed through MATLAB, and combined with the dynamic parameterized model program which can simulate different coal pillar widths, the automatic optimization of protective coal pillar width is realized. The implementation steps are as follows:

(1) The dynamic parameterized model program is called, and then the width of the protective coal pillar (L) is modified to carry out the finite element calculation, and the calculation result file is output.

(2) The post-processing program (Disp.py) is used to read the deformation of key points in the calculation results and calculate the total objective function U.

(3) The optimization analysis program (CoalwidthOp.m) is used to optimize the total objective function U.

(4) When the termination condition of the optimization iteration calculation is satisfied, the optimization result will be output. If not, return to Step (1) and modify the design parameter to continue the calculation until the termination condition is met.

The optimization process of protective coal pillar width (L) is shown in Fig. 10.

4.3 Analysis of optimization results

According to the project planning scheme, the initial designed scheme of protective coal pillar width (L) is set as 46m. According to the optimization method proposed in this paper, the width of the protective coal pillar is optimized by considering the convergence of the two side walls of the roadway, the convergence of the roof and floor, and the deformation of the protective coal pillar. The optimization program calls ABAQUS to carry out finite element calculation for 126 times, and the calculation process ends. Finally, the width of protective coal pillar (L) is determined to be 37.65m.

In the optimization process, the value of the total objective function U in the iterative step is calculated according to Eq. (2), and the changing rules of total objective function values U with iterative step is obtained, as shown in Fig. 11. It can be found that through the first 96 steps of iterative calculation, the total objective function (U) has been basically close to the optimal solution of the problem, and then converges to the optimal solution as the optimization calculation continues. Finally, the total objective function U obtained from the optimization value is 1.223, which is about 10.5% lower than the result from the design value. Table 2 is the comparison of the calculated results between the designed value and the optimization value of protective coal pillar width. Through comparison, it can be found that the width of the protective coal pillar decreases by about 18% after optimization, although the convergence of the two side walls of roadway and the maximum deformation of coal pillar increase slightly. Therefore, on the premise of considering the overall stability of roadway and coal pillar, the reasonable size of protective coal pillar suitable for engineering construction is obtained through optimization analysis.

5 Field monitoring results analysis

5.1 Roadway deformation monitoring

According to the optimization analysis and calculation result and the field construction situation, the width of protective coal pillar is set as 38.5m. In order to further study the influence of protective coal pillar on the stability of floor roadway, the roadway deformation monitoring was carried out. The multi-point displacement meter is arranged on both side walls of the roadway to monitor the deformation of both side walls. Displacement detectors are arranged in the middle position of roadway roof and floor to monitor the convergence between roof and floor.

From Fig. 12, it can be found that after coal seam mining for 5 days, the deformation of the roadway gradually tends to be stable, and the convergences of the two side walls and roof to floor are about 27.2mm and 2.6mm respectively. By comparing the calculation results (see in Fig. 6) of the numerical simulation model consistent with the construction parameter, it can be found that the numerical simulation results are in agreement with the field measured data, which also verifies the correctness of the numerical calculation results and the effectiveness of the optimization method.

5.2 Analysis of support effect of protective coal pillar width

The mining of coal seam disturbs the protective pillar, and the protective coal pillar can be divided into two parts: the yield zone and the elastic core zone. The yield zone is in the plastic failure stage and the supporting force is relatively small. Therefore, the elastic core zone plays a major supporting effect. The compressive stress distribution of surrounding rock is shown in Fig. 13. In the middle part of the coal pillar, the compressive stress concentration is very obvious and the compressive stress value is in the range of 18.4MPa to 19.8MPa. The compressive stress in the coal pillar presents a symmetrical distribution state. With the increase of the depth, the compressive stress gradually increases, and the maximum value (19.8MPa) is located at 12m depth position of the coal pillar. When the depth is greater than 12m, the compressive stress decreases slightly.

Drill cuttings method is used to drill holes in the protective coal pillar, and the position of the maximum support pressure in the protective coal pillar can be determined according to the amount of coal powder in different positions of the drilling hole (Wang et al., 2020; Wang et al., 2020). During the field test, a coal electric drill and a twist drill pipe with a diameter of 42mm were used, and a mark was made on each 1m of the drill pipe. The thrust should be uniform during drilling, and the coal powder should be collected, weighed and recorded after every 1m drilled. The distribution of coal-powder weight in different drilling depth of protective coal pillar is shown in Fig.14. The maximum weight of coal powder in the borehole is 3220 g, which occurs within the borehole depth range of 12~13m. Therefore, the maximum support pressure in the protective coal pillar is located at a depth of 12~13m, which is basically consistent with the numerical simulation results (see in Fig. 13).

6 Conclusions

Reasonable protective coal pillar width is the premise of ensuring the safety and stability of coal seam working face and surrounding structures and facilities. In this paper, based on the project construction, the study of protective coal pillar width is carried out. A series of conclusions are made as follow:

(1) Based on ABAQUS platform, this paper uses Python language programming to establish dynamic parameterized model that can simulate different width of protective coal pillar. Then, the deformation law of floor roadway under different width of protective coal pillar is analyzed, and the results show that different coal pillar widths have different effects on the convergence of two side walls and roof to floor. Meanwhile, the stability of protective coal pillar is also evaluated.

(2) The finite element optimization analysis program based on MATLAB language was developed, and the dynamic parameterized model was calculated with the minimum deformation of roadway and protective coal pillar as the optimization objective. Finally, the reasonable width of the protective coal pillar is obtained, and the optimization result was compared with the designed scheme to verify its rationality.

(3) The optimization result was used in field construction. The correctness of the numerical calculation results and the effectiveness of the optimization method are verified by comparing the results of numerical simulation and the monitoring data of the project site. Meanwhile, the research method in this paper provides an effective way for using finite element to optimize similar projects.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (nos. 51409154 and 51804182), the Plan for Outstanding Youth Innovation Teams in College and University of Shandong Province, China (no. 2019KJG007), the Shandong Provincial Natural Science Foundation, China (no. ZR2020ME097).

Conflict of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Figures

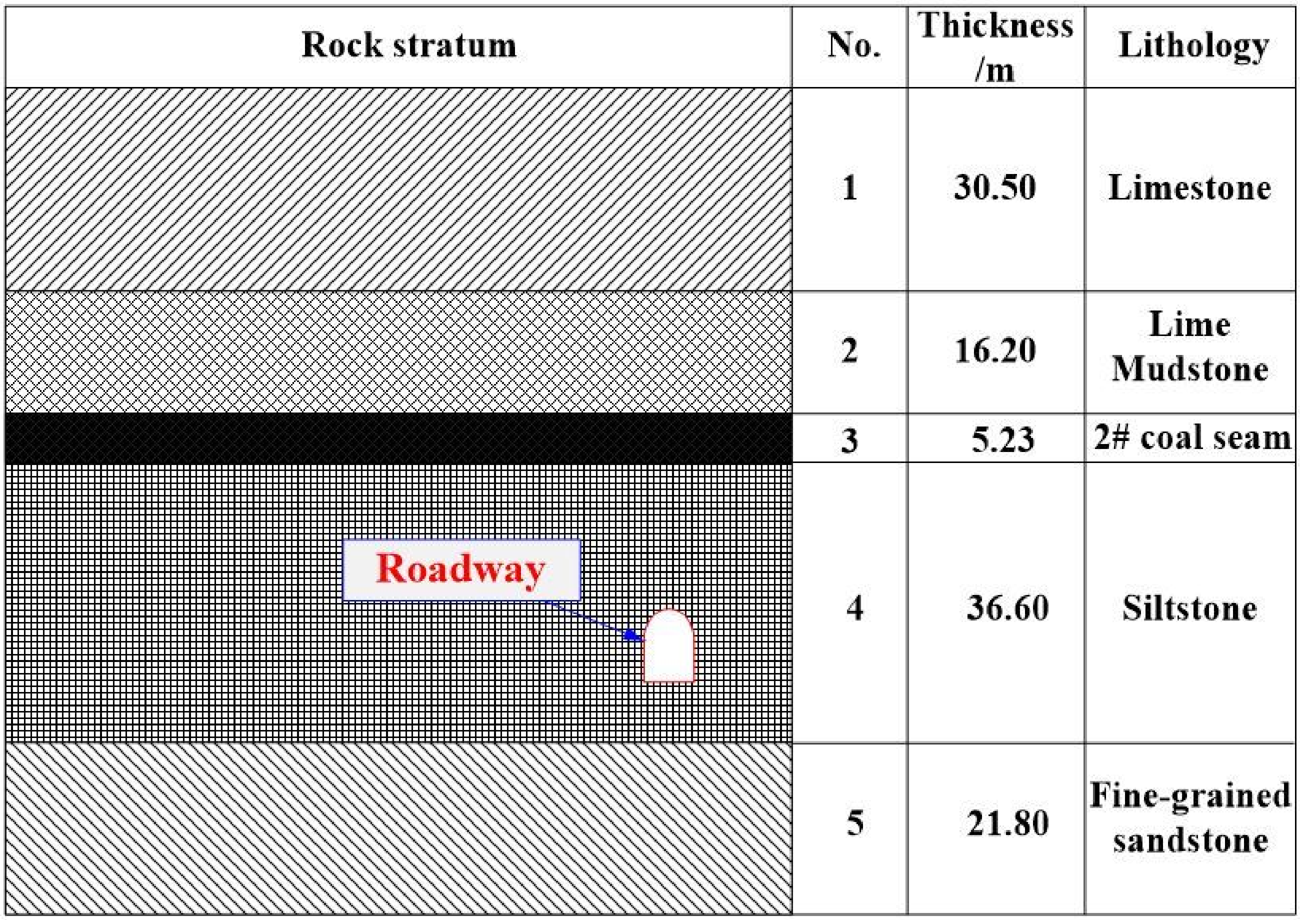


Figure 1

Rock stratum histogram.

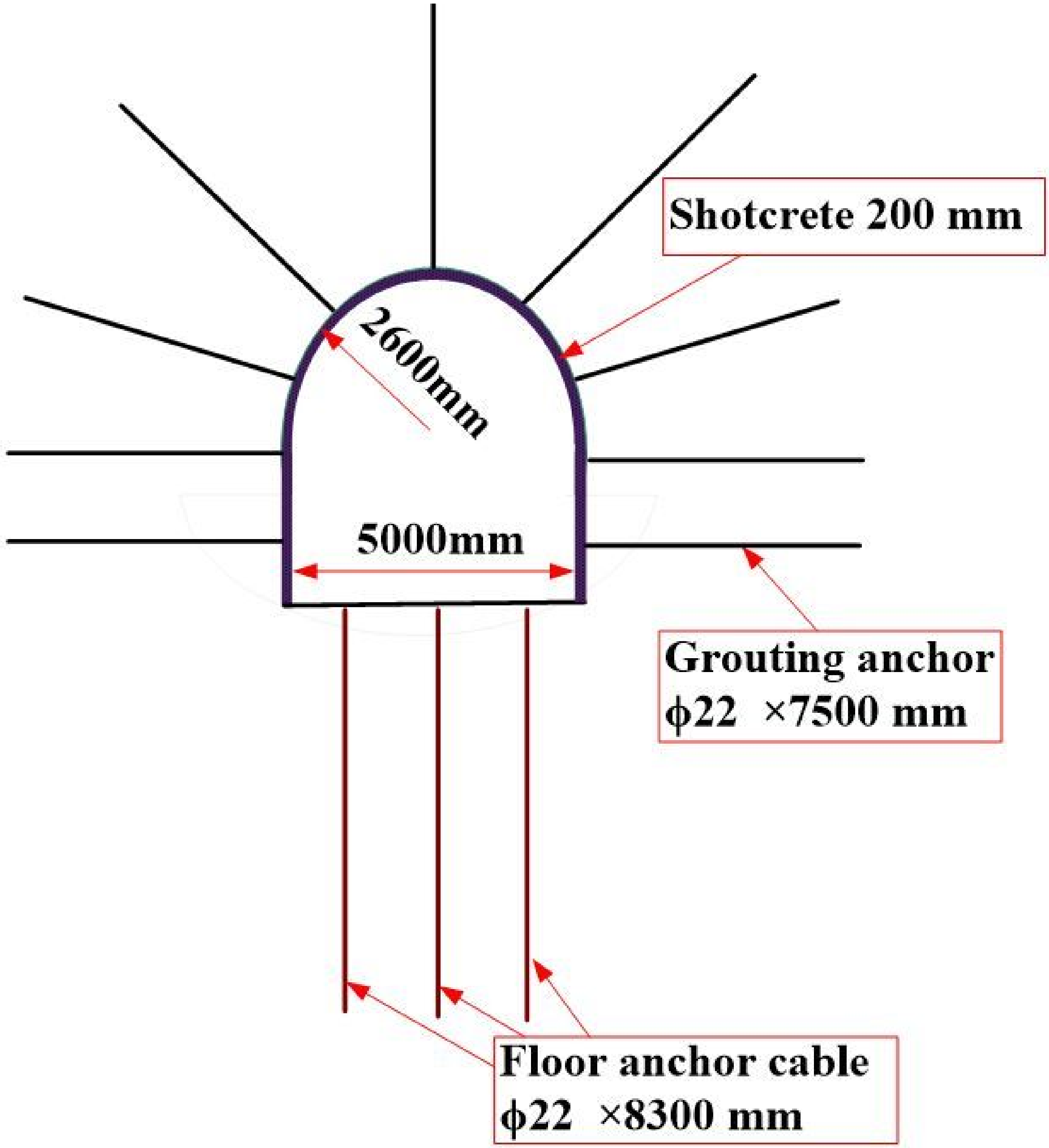


Figure 2

Support section of roadway.

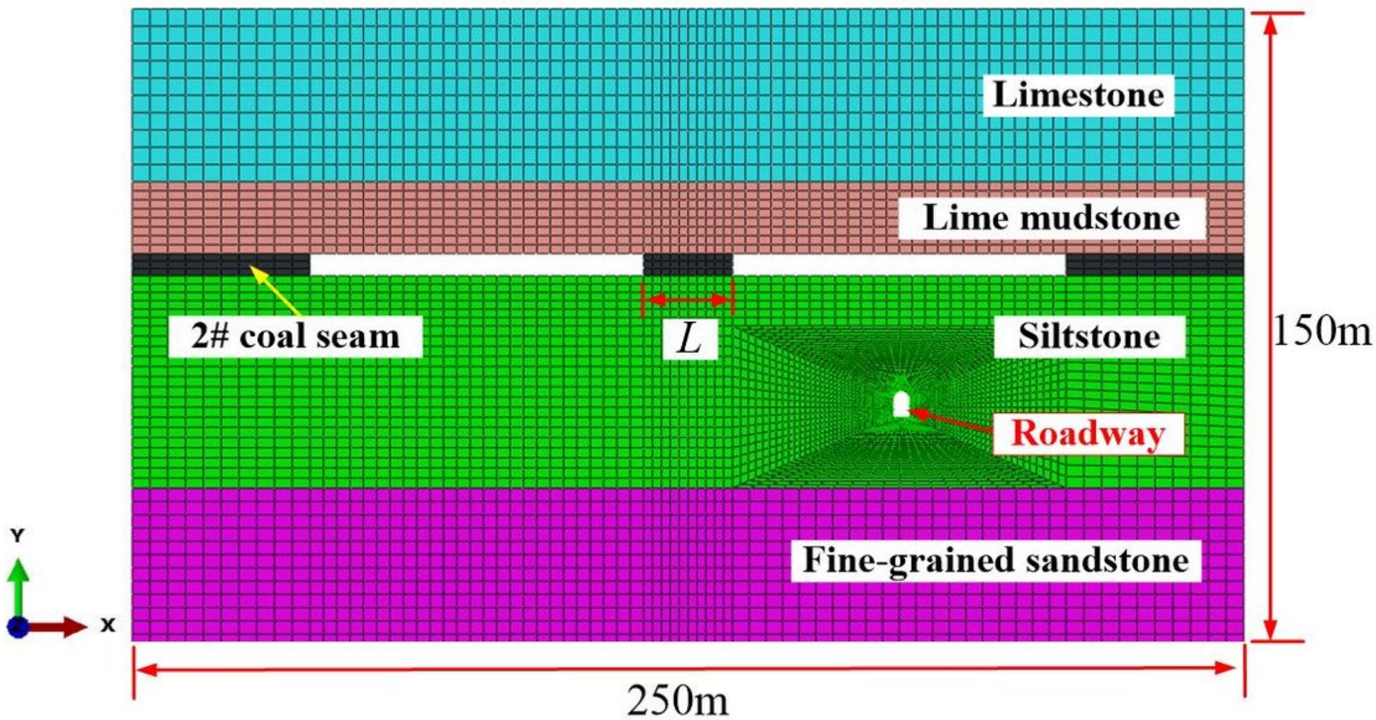


Figure 3

Dynamic parameterized model.

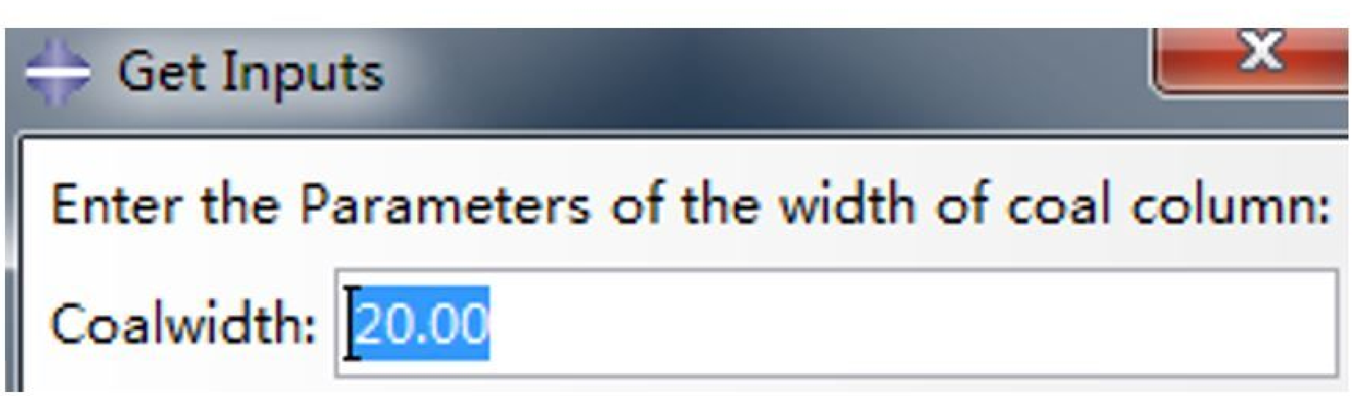


Figure 4

Interactive GUI for the input of protective coal pillar width.

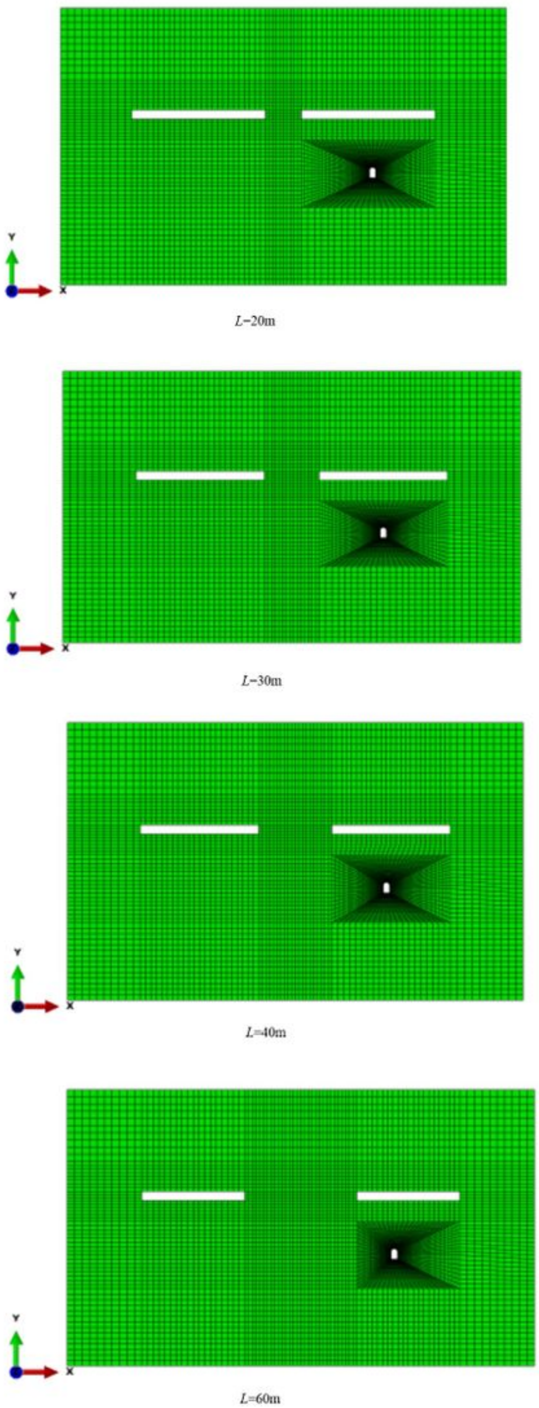
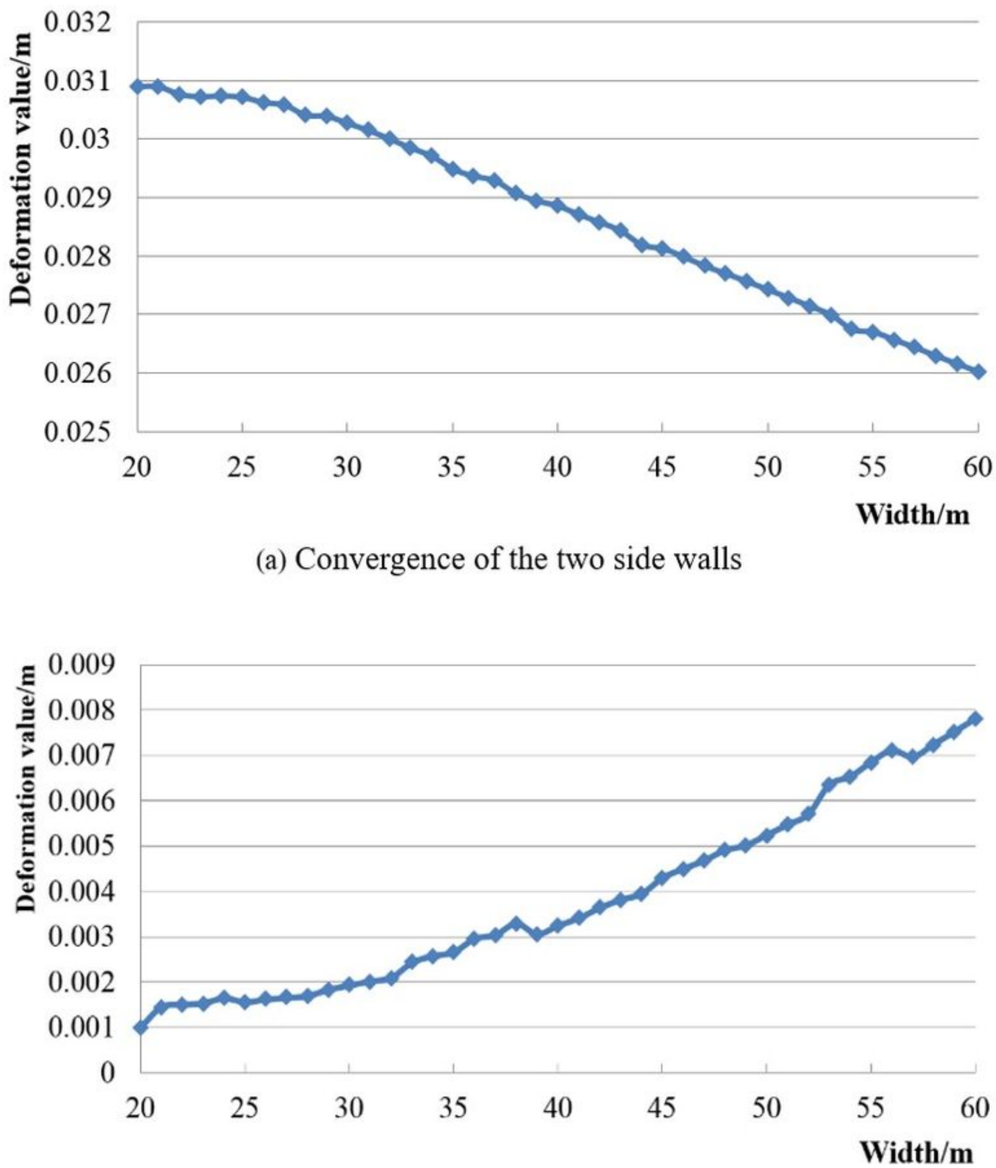


Figure 5

Finite element model of different protective coal pillar width.



(a) Convergence of the two side walls

(b) Convergence between roof and floor

Figure 6

Deformation law of roadway surrounding rock under different protective coal pillar width.

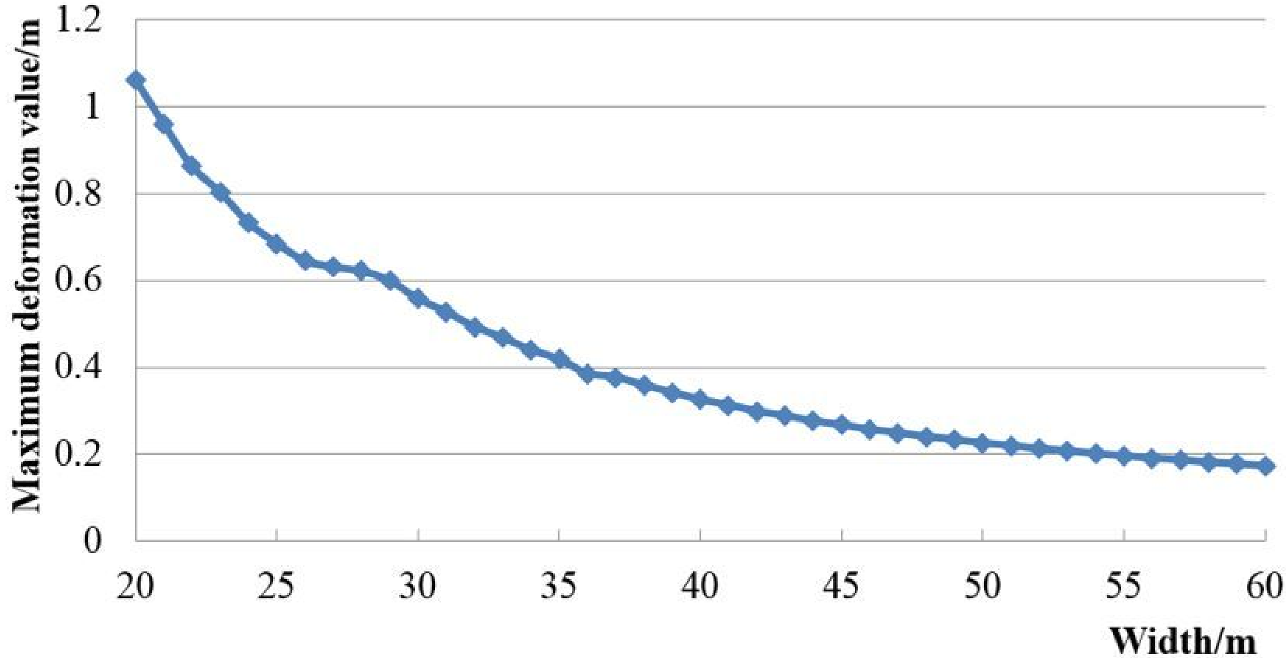


Figure 7

Changing rule of the maximum deformation at both ends of protective coal pillar with width.

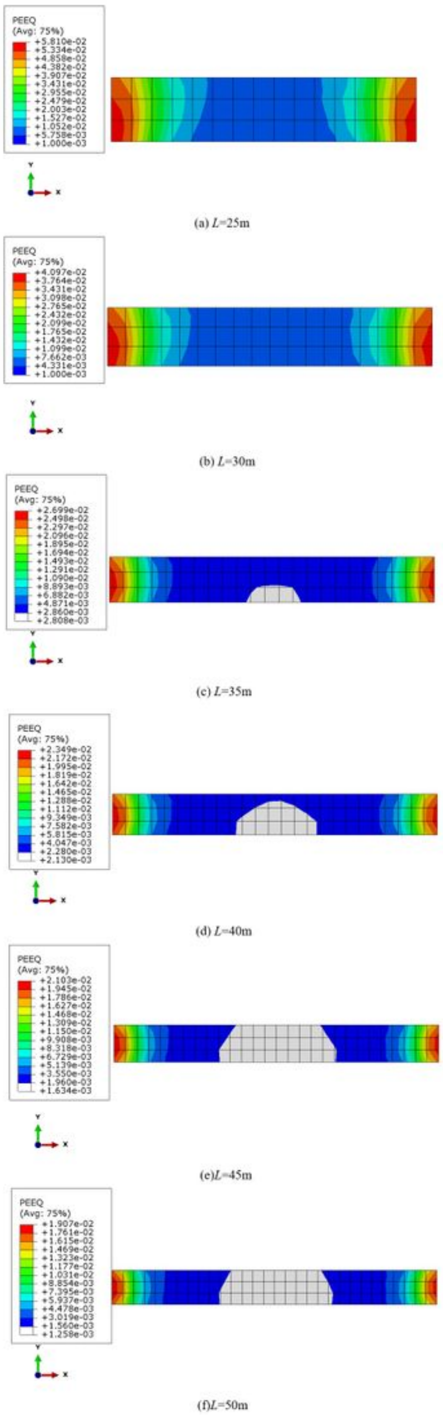


Figure 8

The plastic zone distribution of protective coal pillar with different width (L).

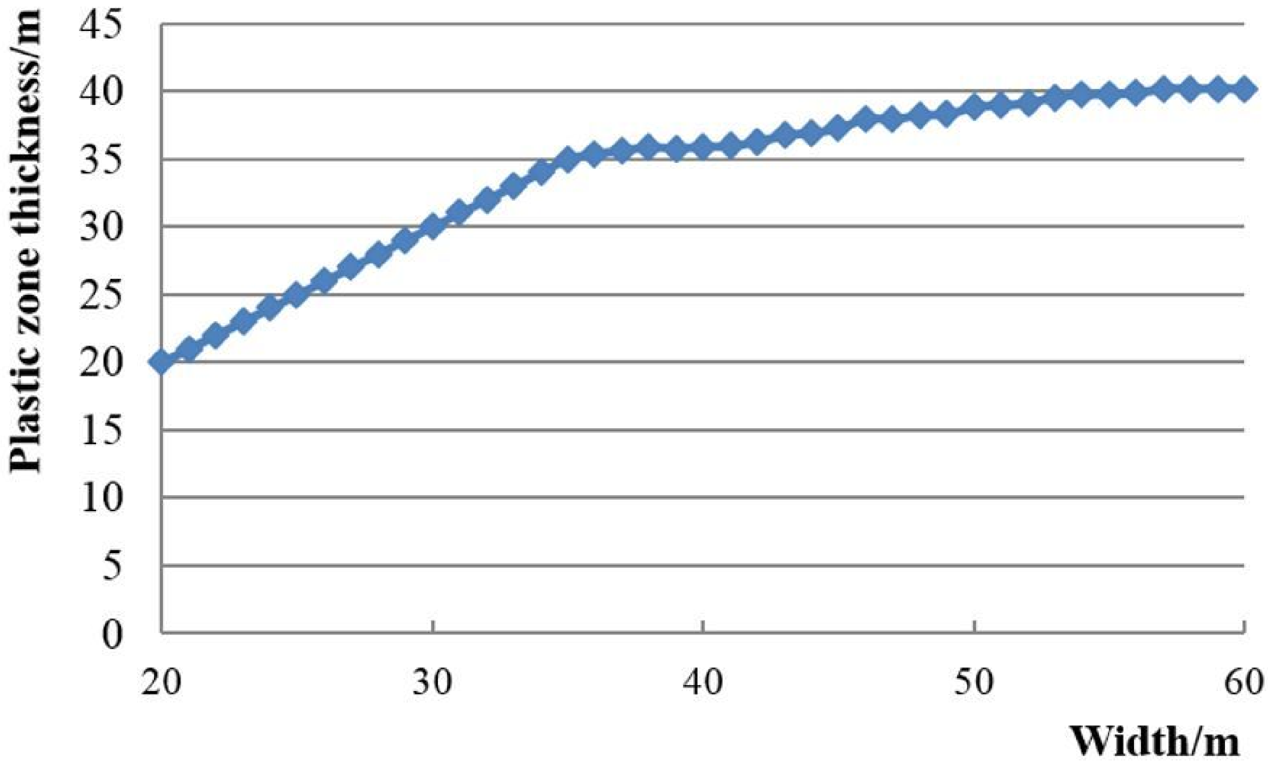


Figure 9

Changing rule of the plastic zone thickness of protective coal pillar with width.

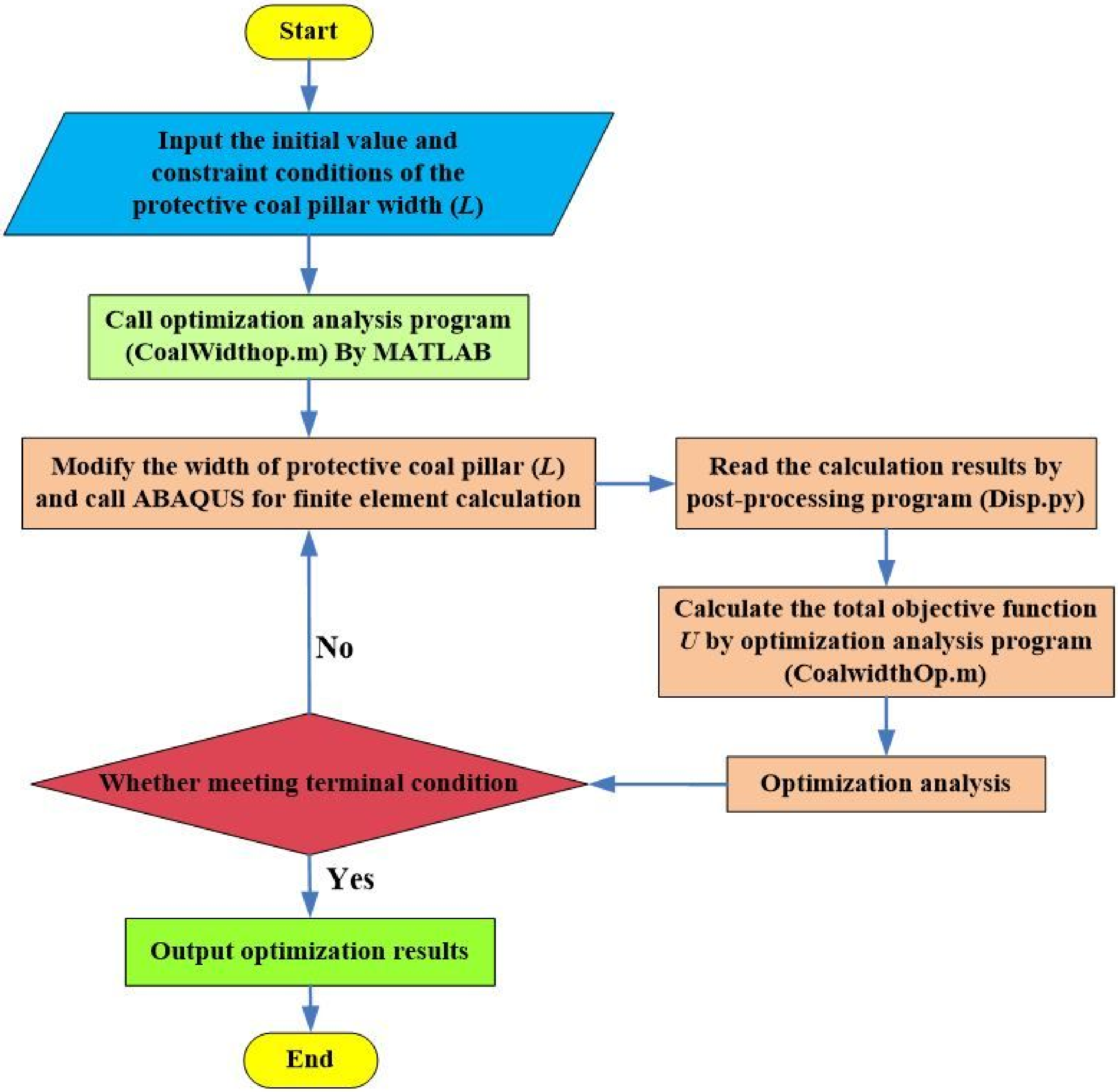


Figure 10

Optimization process of protective coal pillar width (L).

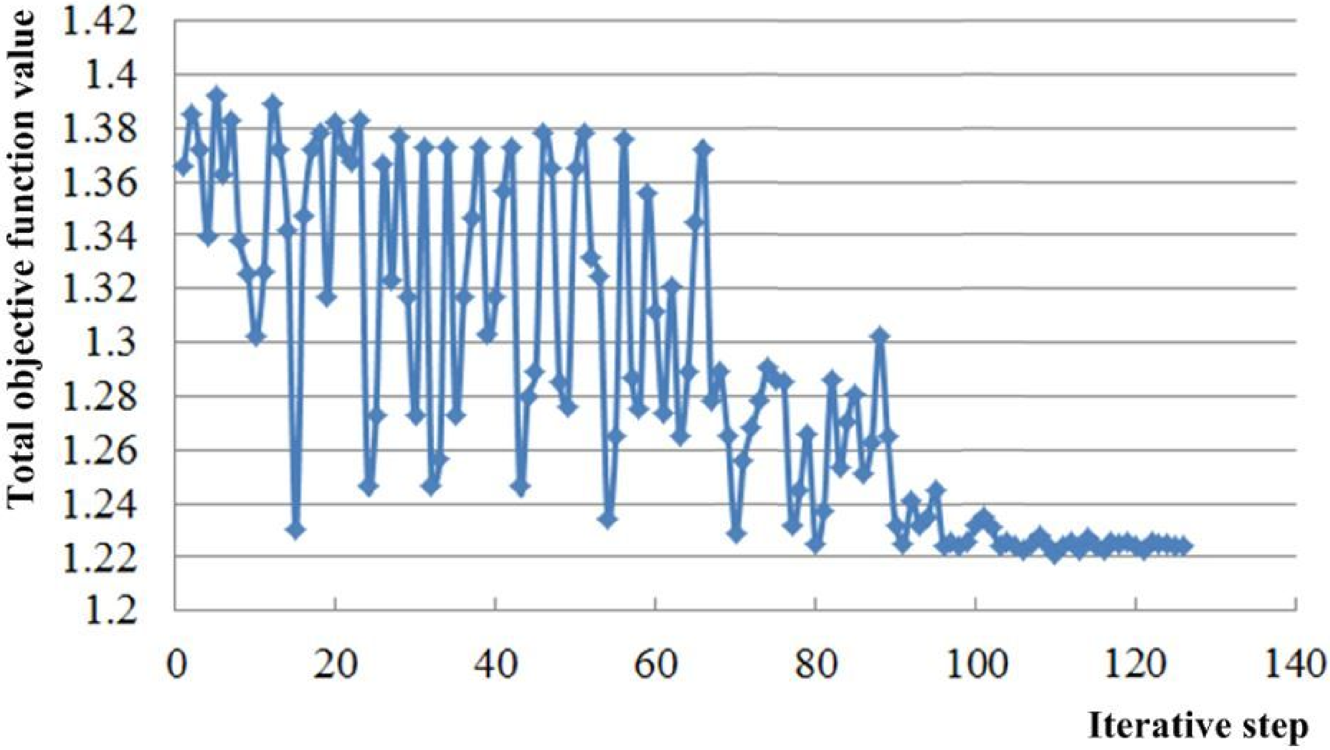


Figure 11

Changing rules of total objective function values U with iterative step.

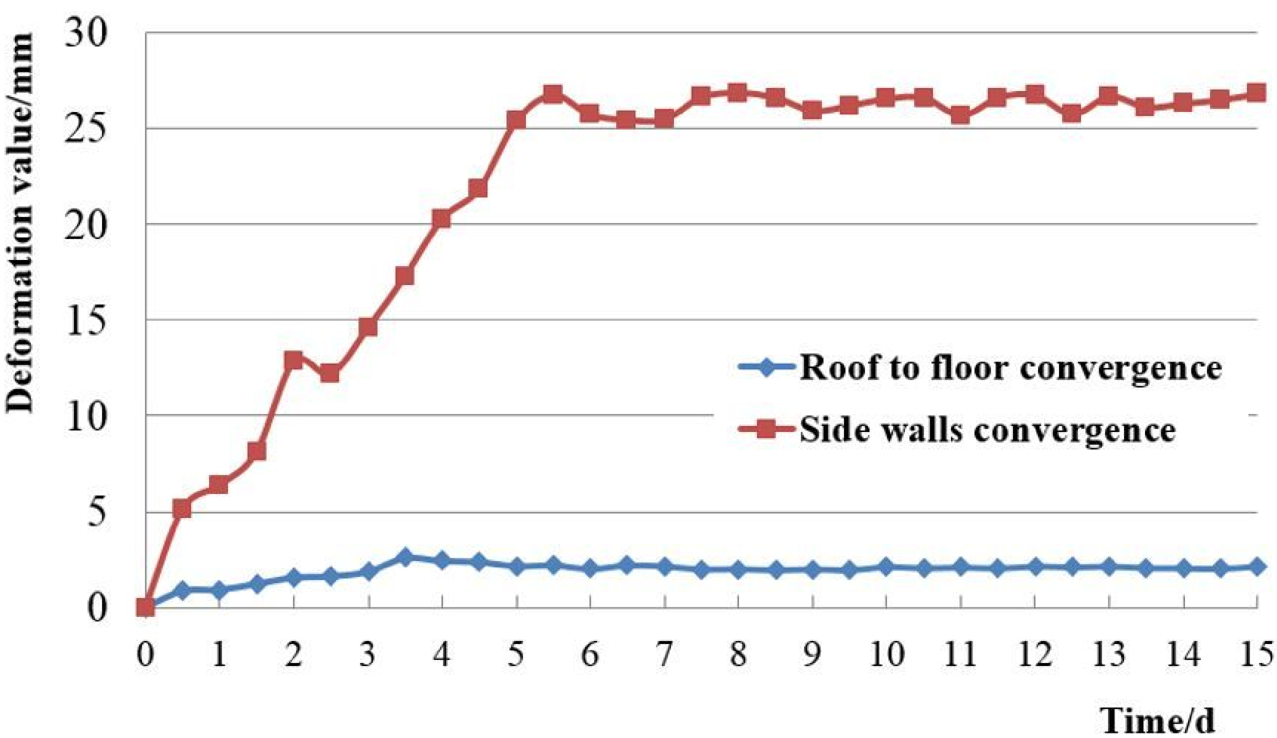


Figure 12

Changing rule of the field monitoring deformation of roadway with time.

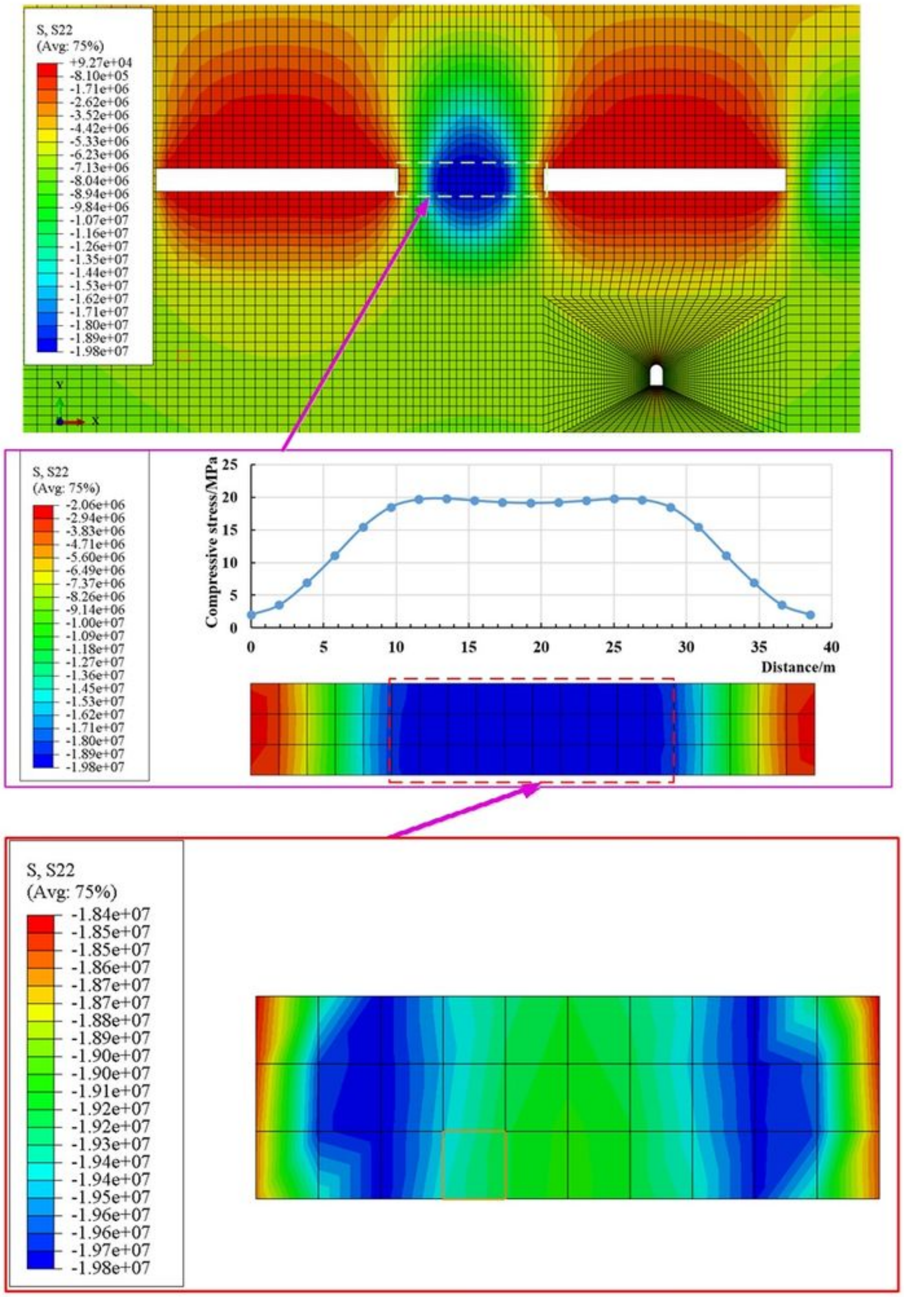


Figure 13

Compressive stress distribution of surrounding rock and protective coal pillar.

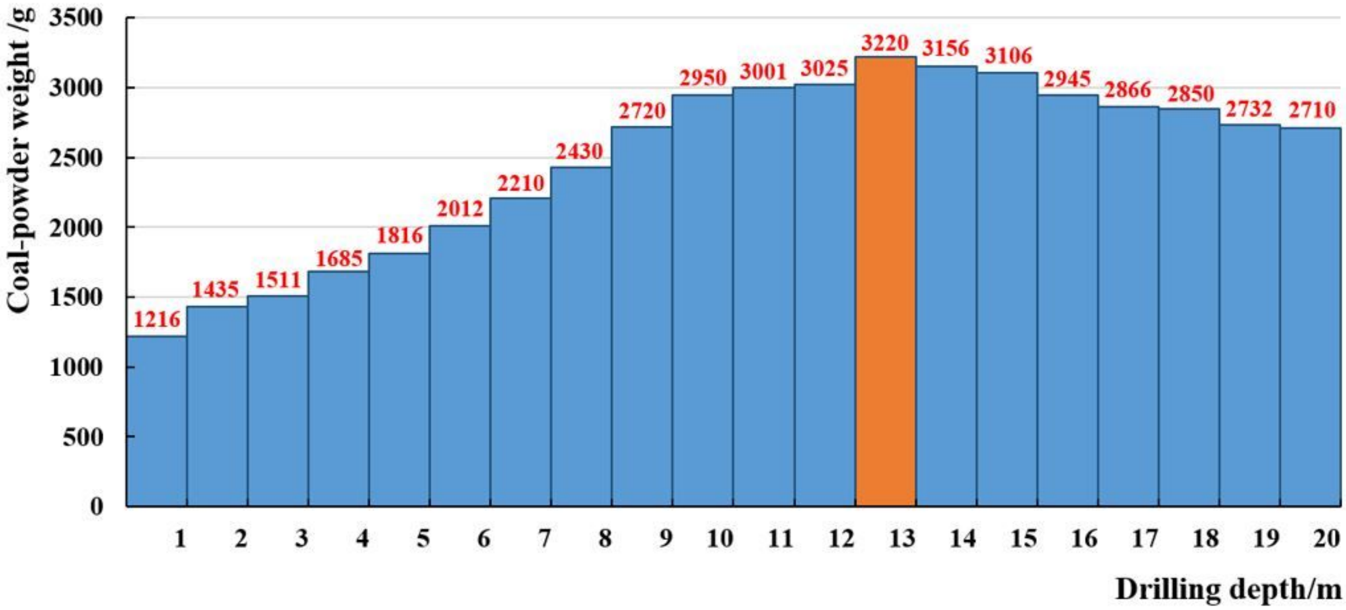


Figure 14

Distribution of coal-powder weight in different drilling depth of protective coal pillar.