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Numerical Simulation Investigation of Seismic Dynamic Response of Pillars in Underground Goaf

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Abstract: In order to obtain the dynamic response law of pillars in underground goafs under the action of seismic wave, the acceleration response and dynamic displacement response law of pillars were studied by using the MIDAS-GTS/NX finite element simulation software based on a mine. Results are shown as follows: (1) the response of the top acceleration and displacement of the pillar and roof of goaf is larger than that of the bottom. (2) The cross-sectional area of pillars has a significant effect on the dynamic response of pillars in underground goafs. The stability of pillars with large cross-sectional area is generally better. (3) The position of pillars has a significant effect on the dynamic response of pillars. The dynamic response of pillars in the center of goaf is the strongest. However, the dynamic response of pillars in the edge of goaf is smallest. (4) The laws of acceleration and displacement response of pillars in goafs under horizontal seismic wave are revealed, which provides reference for mining design and earthquake damage prevention.

Keywords: Mining Engineering, Earthquake Engineering, Underground Goaf, Dynamic Response, Numerical Simulation

1. Introduction

The western part of China lies at the intersection of the Indian plate and the Eurasian plate. The collision and compression of the Indian plate resulted in the strong uplift of the western part of the mainland of China and the formation of the world roof-Qinghai-Tibet Plateau, which led to frequent earthquakes in the western part of China. For example, the 2001 Kunlun Mountain Pass West M8.1 earthquake in Qinghai, the 2008 Wenchuan M8.0 earthquake, the Lushan M7.0 earthquake in Sichuan in 2013, the Yingjiang M6.1 earthquake in Yunnan in 2015 and the Jiuzhaigou M7.0 earthquake in Sichuan in 2017. The western region is the main area where earthquakes occur.

There are a large number of mineral resources in Western China, some of which occur in mountain bodies. In order to protect the local natural environment, well mining is generally used. After many years of mining, because of historical reasons, many goafs did not fill in time, forming a large area of goaf group. The goaf group has the characteristics of large area, poor overall stability and obvious ground pressure activity. Therefore, the seismic stability of underground goaf is an urgent problem for scientific researchers. The stability of underground goaf is directly related to the remaining pillars. The pillars support the upper roof of the goaf to maintain the stability of the goaf.

At present, more research work has been done on seismic problems in tunnels [1-3], underground metro stations [4-6], civil air defense projects [7-8] and underground pipeline corridors [9-10]. There are few studies on seismic dynamic response and seismic fortification of pillars in underground super-large goafs. Few related literatures have been reported. Wei et al. [11] by analyzing the catastrophic behavior of coal mine goaf under the action of seismic force, summarized the key safety problems in the seismic safety protection design of coal mine goaf. Cui et al. [12] summarized the research progress of catastrophic behavior of large underground caverns under earthquake fluctuation, and put forward the existing problems and future development direction. Liu et al. [13] based on the principles of seismic engineering and mining subsidence, established a coupling model of mining damage and seismic damage in coal mine, and quantitatively analyzed the damage degree of earthquake to underground goaf. Tang et al. [14] used the finite difference software FLAC3D to simulate the dynamic action of a typical stope in a copper mine when it was subjected to side collapse of surrounding mining blasting. Through the analysis of the simulation results, the dynamic response characteristics of the stope were obtained. Zhang et al. [15] used three-dimensional numerical simulation software, established three-dimensional numerical analysis model under different conditions, and studied the surface seismic response of a coal mine in the underlying goaf. It is concluded that under the action of seismic wave, the dynamic response characteristics of the ground surface in the underlying goaf are affected by the existing underground goaf.

The seismic stability of the underground super-large goaf is poor, and the pillars in the goaf play a key role in maintaining the stability of the goaf. It is important to study the response law of the pillars in the goaf under seismic action to prevent earthquake damage. Based on the research background of a specific mine, a three-dimensional numerical model of mine-goaf-pillar is established by using MIDAS-GTS/NX numerical simulation software. The response laws of acceleration and dynamic displacement of pillar under seismic wave are studied by using Darui artificial wave as loading wave. The research results have promoted the understanding of dynamic characteristics of underground goaf under earthquake wave.

2. General Situation of Mine

2.1. Mine Geology

A copper mine in Western China belongs to underground mining. The copper deposit has simple geological conditions. The ore body is thin-bedded and occurs in the middle of the dolomite of Maidiping section of the Dengying Formation of the upper Sinian. The lithological characteristics of the ore-bearing horizon are as follows: gray-white thin to medium-thick layered copper-bearing sandstone-clastic dolomite-siltstone in the upper and lower parts, and copper-bearing massive rock in the middle part. The ore beds are layered and stable. The thickness of the orebody is 4.75~5.2m, with an average 5m thickness. The tendency is 98~175°. The inclination angle is 3~7°. The floor of the ore bed is grayish-white thin to medium-thick layered dolomite, and the roof is grayish-white thin to medium-thick layered dolomite. The ore bed is copper-bearing block rock, and the thickness of surface and deep ore bed is not obvious, and the ore bed is stable. The surrounding rock of the ore bed is mainly copper-bearing dolomite with clear boundaries with the orebody. The surface condition is relatively thick in the north and South and thin in the middle. The hydrogeological conditions in the mining area are simple.

2.2. Goaf Situation

At present, most of the goafs have not been filled. The total volume is 3.8×104m^3. Some pillars in goafs appear waist shrinkage, slip and cracking. However, the overall stability is good. The depth of goafs is 90~152m. The average height of pillars is 5 m. The diameter of pillars is 4.2~7.5m. The distribution of pillars in goafs is irregular.

The stability of pillars in goaf plays an important role in goaf safety. The pillar maintains the stability of goaf. Under the pressure of the upper mountain, the pillar collapses and collapses. This phenomenon is produced by static force. Whether the pillar can keep stable under the dynamic action of earthquake or blasting mining has a great influence on the safety production of the mine. Therefore, the dynamic stability of pillars needs to be studied urgently.

3. Numerical Simulation

3.1. Selection of Parameters

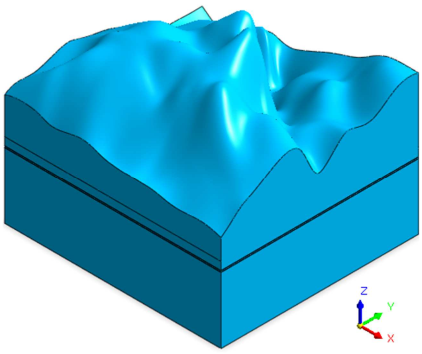
According to indoor rock mechanics test and specification [16], rock mechanics parameters of orebody and surrounding rock are selected as shown in Table 1.

Table 1. *Parameters of surrounding rock.*

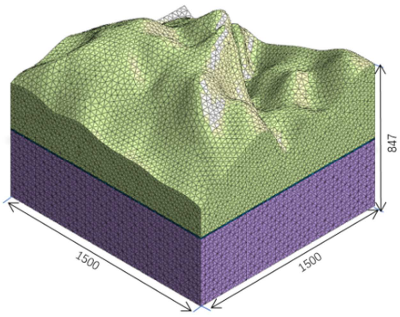
Materials	Elastic modulus E (GPa)	Poisson ratio μ	Bulk density γ (kN/m^3)	Internal friction angle Φ (°)	Cohesion C (kPa)
Dolomite	14.96	0.24	27.4	38	1200
Orebody	9.89	0.25	27.8	35	800

3.2. Establishment of Model

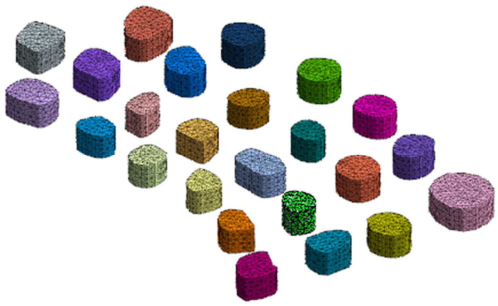
When excavating a goaf in an infinite area of rock mass, the stress and displacement fields around the goafs are changed due to the release of loads. In order to make the numerical model more in line with the actual situation, the size of the model is 3~5 times of the actual size of the goaf [17-18]. The calculation model length and width are 1500 m, and the height is 847m. In order to accurately simulate the propagation of seismic waves in the three-dimensional model, the size of the divided model unit must be less than or equal to the wavelength determined by the highest frequency part of the input wave of 1/10 to 1/8 times. Tetrahedral elements are used to divide the three-dimensional model, and solid elements are used to simulate pillars and surrounding rocks. The total number of nodes is 31483. The total number of elements is 141810. The model is a linear elastic-plastic rock and soil body with isotropic and homogeneous ideal. The Mohr-Coulomb constitutive model is adopted. The fixed boundary is used at the bottom of the model. The free field boundary is used around it and free surface is used at the top. The three-dimensional model is divided into three layers. The upper layer is dolomite surrounding rock. The middle part is ore body containing goaf. The lower layer is the same rock mass as the upper layer. There are 24 pillars in the selected goaf, and the distribution of pillars has certain regularity. The specific three-dimensional numerical analysis model is shown in Figure 1.



(a) Overall model



(b) Three-dimensional mesh



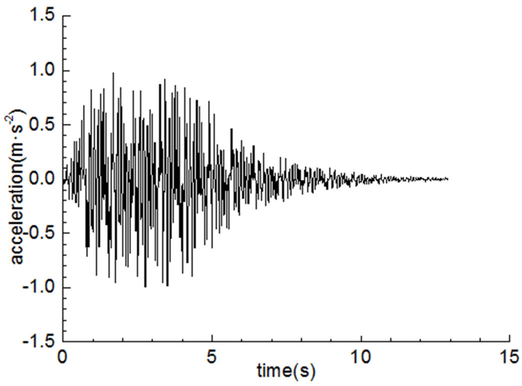
(c) Pillar model

Figure 1. *Numerical simulation model (unit: m).*

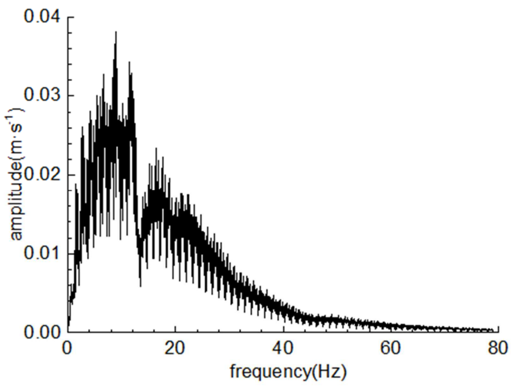
3.3. Seismic Wave and Measuring Points

Darui artificial wave is selected as the loading seismic wave. The loading time is 8s, and the loading peak value is 0.1g. The seismic wave is loaded along the horizontal direction (X-direction). The time history curve and Fourier spectrum of seismic wave acceleration are shown in Figure 2. The excellent frequency of Darui artificial wave is 14~18Hz.

According to the research purpose, 24 pillars are numbered, from left to right, as column A, column B, column C and column D. Column A is A1~A5 from top to bottom, column B is B1~B6 from top to bottom, column C is C1~C7 from top to bottom, and column D is D1~D6 from top to bottom, as shown in Figure 3. Six measuring points are arranged at the top, middle and lower parts of each pillar, and the "+" sign indicates the location of the measuring point. For example, the side measuring points of D1 pillar are numbered from bottom to top as D1V1~D1V6, as shown in Figure 4.



(a) Time history curve



(b) Fourier spectrum

Figure 2. *Time history curve and Fourier spectrum of seismic wave acceleration.*

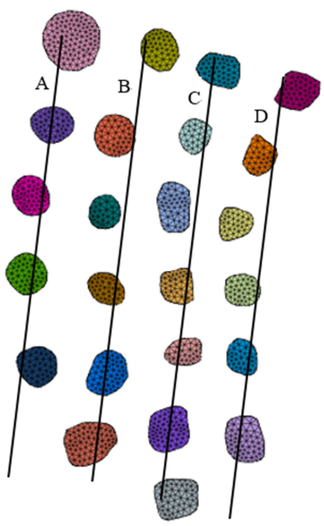


Figure 3. *Pillars number.*

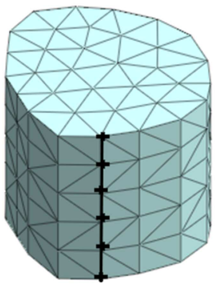


Figure 4. *Pillars measuring point.*

4. Analysis of Numerical Simulation

4.1. Acceleration Response Law of Pillars

Acceleration amplification factor is used to describe the law of acceleration response of pillar in goafs. The acceleration amplification factor γ is defined as the ratio of the absolute value of the peak response of the measuring point to the absolute value of the peak load seismic wave. The acceleration amplification factor can be obtained by formula (1).

$$\gamma = |a_i|_{max}/|a_0|_{max} \tag{1}$$

Where, $|a_i|_{max}$ is the peak value of acceleration response, and *i* is the number of the measuring point.$|a_0|_{max}$ is the peak of load seismic wave.

Under the action of 0.1g Darui seismic wave, the response time-history curve of measuring point B4V6 is shown in Figure 5. The response law of pillar acceleration in each row of goaf is shown in Figure 6.

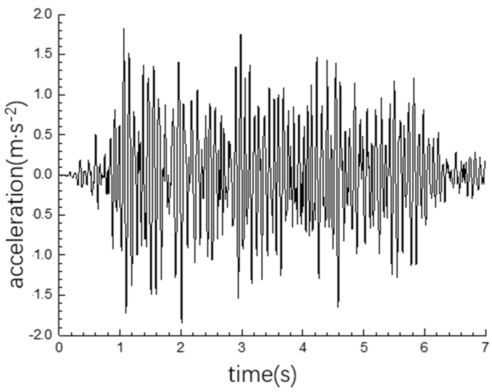
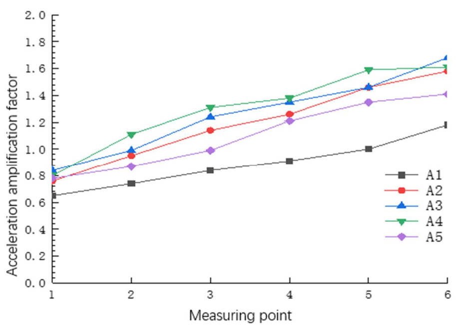
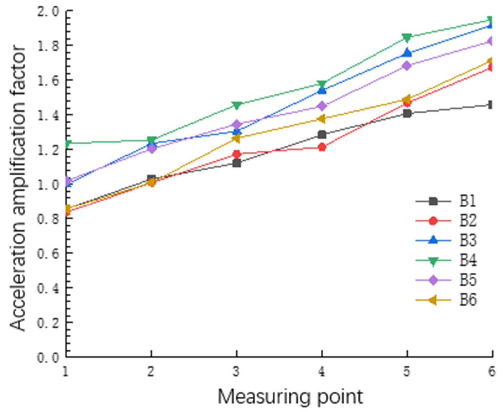


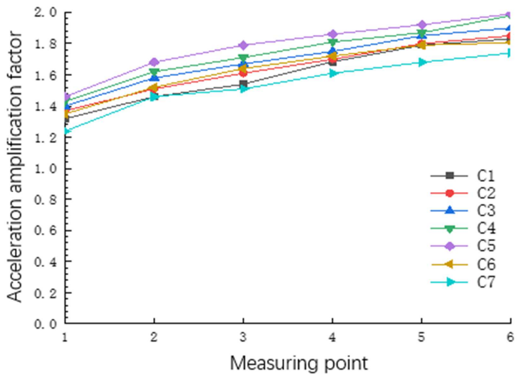
Figure 5. *Response time history of B4V6.*



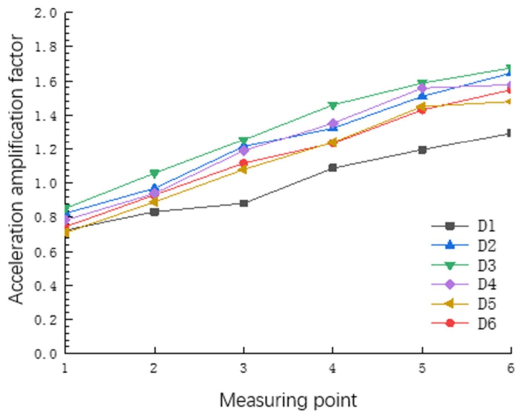
(a) Column A



(b) Column B



(c) Column C



(d) Column D

Figure 6. *Acceleration response of each column pillar.*

From Figure 6 (a), it can be seen that the maximum acceleration amplification factor of column A in goafs is generated at the top measuring point 6, the maximum is 1.7. The minimum acceleration amplification factor is generated at the low measuring point 1 of the pillar, the minimum is 0.75. The average height of pillars in goafs is 5 m. The top of pillars is connected with the roof, and the bottom is connected with the floor. This shows that the dynamic response of the roof is greater than that of the floor under the action of seismic wave. The pillars floor in goafs are the bedrock. The dynamic response of the pillar floor is smaller under the action of seismic wave, while the dynamic response of the roof is larger.

The acceleration amplification factor of the top measuring point is larger and the bottom is smaller.

Taking the measuring point 6 of each pillar as the reference point, it can be seen from the figure that the acceleration amplification coefficients of A1 and A5 are relatively small, while those of A2, A3 and A4 are relatively large. From the above rules, the acceleration response at the middle position of A pillar is relatively strong. The pillars near the edge of goaf have the protection of surrounding rock under the action of seismic wave, and the seismic dynamic effect is small, while the pillars far from the edge of goaf have strong acceleration response.

Figure 3 shows that the section area of A1 pillar is larger than that of other pillars in column A. In Figure 6 (a), it can be seen that the acceleration response of A1 pillar is about 40% smaller than that of other pillars. It can be concluded that the cross-section area of the pillar has a great influence on the acceleration response of the pillar. The stability of pillars with large cross-section area is generally good, and they can withstand strong dynamic action under the action of seismic wave.

As shown in Figure 6 (b), the maximum acceleration amplification factor of column B is 1.95. The minimum is 0.8. The acceleration response of each pillar is similar to that of column A. According to Figure 6 (c), the maximum acceleration amplification factor of column C is 2.0. The minimum is 1.22. The acceleration response of each pillar is similar to that of column A. As shown in Figure 6 (d), the maximum acceleration amplification factor of column D is 1.6. The minimum is 0.7. The acceleration response of each pillar is similar to that of column A.

By comparing the four figures in Figure 6, the acceleration response of pillars in column B and C is the strongest, which is 10%~45% higher than that in column A and D. From Figure 4, it can be seen that columns C and D are located in the central part of the goaf, and pillars B4 and C4 are located in the central part of the goaf. From Figure 6 (b) and (c), the acceleration magnification coefficients of pillars B4 and C4 are the largest. The main reasons are as follows: (1) The pillar in the central position of the goaf is far from the surrounding rock of the edge of the goaf. (2) Under the action of seismic waves, seismic waves form complex reflection waves in the goaf, and these waves gather in the goaf. It can be seen that the position of the pillar has a significant effect on the dynamic response of the pillar.

Through the acceleration analysis of pillars in goaf, some useful rules are obtained. Through the effective understanding of the law, the paper puts forward the corresponding protective measures to prevent the destruction of mine goaf caused by earthquake. For example, the pillars located in the center of the goaf should be strengthened by enlarging the cross-section area as much as possible.

4.2. Pillar Displacement Response Law

The maximum displacement value is used to describe the displacement response law of pillars in goaf. Section 4.1 shows that the dynamic response of column C is the strongest under the action of seismic wave, and only the dynamic displacement of column C is studied in limited space. The dynamic displacement response of column C is shown in Figure 7.

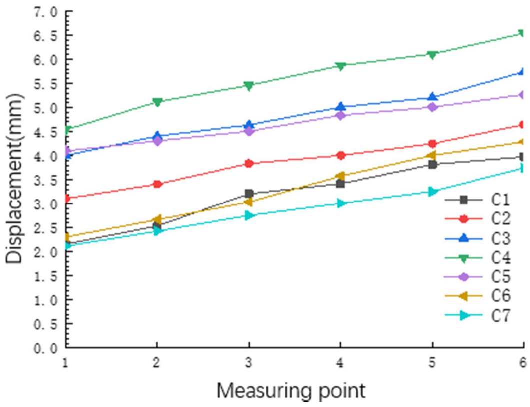


Figure 7. *Pillars of C column.*

From Figure 7, it can be seen that the displacement of measuring points 1 to 6 increases gradually, approximately linearly. At the same measuring point, the displacement of pillar C1~C7 increases first and then decreases. The displacement of pillar C4 is the largest. Pillar C4 is located in the center of goaf, and its dynamic response is strong. The adjacent pillars have an effect on pillar C4.

From Figure 7, it can be seen that the dynamic displacement at the top of each pillar reaches the maximum. In order to obtain the dynamic displacement response law of each pillar, the dynamic displacement response of pillar in goaf is analyzed with the top measuring point of each pillar as the reference point, as shown in Figure 8.

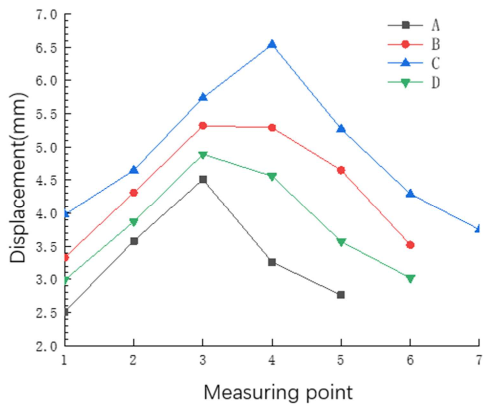


Figure 8. *Dynamic displacement response of pillars.*

From Figure 8, it can be seen that for the same measuring point, the dynamic displacement responses of each column in goaf are in sequence C, B, D and A from large to small. In each row of pillars, the dynamic displacement response of pillars in the middle position is the largest. This is similar to the acceleration response of section 4.1.

4.3. Disaster Prevention in Goaf

The main reason of large area ground pressure disaster is that the treatment of goaf is not timely and the pillar is not enough in this mine. The essence of goaf treatment is to transfer the stress concentration position, ease the stress concentration degree of rock mass, and make the stress reach a new relative balance, so as to control and manage the ground pressure and ensure the safety of mine production.

This phosphate mine is an old phosphate mine enterprise that has been exploited for many years, and the goaf is large. In the actual governance process of the goaf, the comprehensive application of measures from the mining technology, monitoring technology, comprehensive management and other aspects can achieve comprehensive governance, prevention and control.

The waste rock is used to block and isolate the goaf without large well shaped pillars. The working face and the goaf are separated every 50m. In the process of plugging construction, the combination of dry masonry and mortar masonry is emphasized. The sealed insulator is more than 5m thick. The isolation belt can also block the shock wave, especially along the entrance and exit of the mine.

5. Conclusion

The MIDAS-GTS/NX finite element simulation software was used to study the acceleration response and dynamic displacement response of pillars in underground goafs. The following main conclusions were obtained:

(1) Acceleration amplification factor and dynamic displacement of the top measuring point of pillar in goafs are the largest, while that of the bottom measuring point is the smallest. The dynamic response of the roof of a goaf is larger than that of the floor.

(2) The cross-sectional area of pillars in goafs has a significant effect on the acceleration response of pillars. The stability of pillars with large cross-section area is generally good.

(3) The position of the pillar in goafs has a significant effect on the dynamic response of the pillar. The dynamic response of the pillar in the center of a goaf is the strongest, while the dynamic response of the pillar in the edge of a goaf is smallest.

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