Experimental Study on Instability and Load Transfer Mechanism within Multi-Pillar System

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Abstract. In order to study the instability and load transfer mechanism among multiple parallel pillars during underground mining, compressive tests on single- and treble-pillar specimens were conducted under soft loading condition with adjustable stiffness. Disc spring group was used to realize the adjustable stiffness of the test machine. Experimental results showed that the instability of rock specimen was determined by the stiffness of test machine, where the sudden jump displacement $Δd$ exponentially decreases with the increase of loading stiffness. The load transfer behavior of treble-pillar specimen could only be reproduced under this soft loading condition. Under the soft loading condition, the failure of single pillar in multi-pillar system induces the sudden increase of cumulative AE counts not only in itself, but also in adjacent pillars, which indicates the accelerated damage in adjacent pillars accelerated by load transfer effect. Finally, it was concluded that the soft loading condition was the necessary condition for the load transfer of multi-pillar system. Results of this study may contribute to the better understanding of load transfer mechanism and to optimizing the design of room-and-pillar stopes during underground mining.

1. Introduction

In the mining with room-and-pillar method, many pillars with different sizes and shapes were left behind as a temporary or permanent support, these pillars work with the surrounding rockmass to stabilize the underground stopes [1-3]. However, the unstable pillar failure may widespread in underground mines and seriously threatens the safety of workers and equipment. Pillars may fail in different manner, depending on the mechanical behavior of pillars and mining layout. In some cases, only a few tens of pillars fail; however, in extreme cases, hundreds, even thousands of pillars can fail [4-9]. Swanson and Boler [10] coined the term “cascading pillar failure” to describe the collapses of pillars. Cascading pillar failure in room-and-pillar mines can also be termed as “progressive pillar failure”, “massive roof collapse”, “domino-type failure”, or “pillar run” [9].

Many efforts have been devoted to study the failure mechanism of pillars, which is closely related to the transferred load from collapsing pillars to adjacent pillars [11-15]. In other words, the failure of one critical pillar could possibly trigger the collapse of a large areas of the mine when transferred load exceeds the bearing capacities of adjacent pillars [2, 16-18]. Zhou, Chen [17] gave experimental and numerical results on the failure process of double-pillar specimen, and found that the pillar with higher elastic modulus or lower strength would lose its bearing capacity firstly. In this respect, an individual pillar with higher elastic modulus or lower strength was the weak link of a group of pillars. Zhou, Zhao, et al. [19] also studied the collapse of mined-out areas triggered by residual pillar extraction.
and they concluded that the magnitude of the dynamic disturbance was closely related to extraction time of the residual pillar. Moreover, the load transfer and collapse of pillars were not only related to the mechanical properties of the pillar itself, but also greatly affected by the stiffness of the surrounding rockmass [20-23]. Wang, Sloan [22] carried out numerical analysis on the failure mechanism of multi-pillar system, and revealed that the stiffness and uniaxial compressive strength (UCS) of pillar played important roles in controlling the failure process of multi-pillar system. Kaiser and Tang [20] studied the effect of elastic rebound of roof and floor on the failure mode of single pillar specimen by using RFPA2D and confirm that soft loading system promotes unstable failure or collapse of pillars. These studies have given us good understanding of the failure behavior of multi-pillar system.

However, the physical essence of cascading pillar failure lies in the interaction among these pillars, in this respect, the associated load transfer mechanism among pillars is still unclear. Moreover, the existing experiments were not effective in quantifying the elastic energy storage and release in roof and floor. Thus, the mechanism associated with the load transfer behavior during the cascading pillar failure and accompanying elastic rebound of surrounding rockmass should be examined further in order to understand the instability mechanism of cascading pillar failure.

2. Experimental Preparation

2.1. Experimental apparatus

A physical model composed of pillar (s) and surrounding rockmass was proposed, as shown in Fig. 1b. It consists of parallel pillars and near-field surrounding rockmass, and the stress from the far-field surrounding rockmass is applied as a boundary condition. The near-field surrounding rockmass can store a large amount of elastic deformation energy under compression; it has a major effect on the load transfer and instability of pillars [23, 24].

Fig. 1 Schematic diagram of physical model and experimental method. (a) Schematic diagram of testing apparatus, (b) Physical model of pillars-surrounding rockmass system, (c) Experimental setup of single- and treble-pillar specimen.

The experimental apparatus as shown in Fig. 1a and 1c are designed. By comparing Fig. 1a with Fig. 1b, the far-field surrounding rockmass is represented as the stress boundary condition with a constant loading rate through the movement of piston of test machine; while the near-field surrounding rockmass...
rockmass is simulated with disk spring group, which may deform elastically with adjustable stiffness $K$ and realize the soft loading condition. The single- and treble-pillar specimen is used to simulate the parallel pillar ($s$). Fig. 1a shows the rigid servo-control test machine, with a maximum axial load of 300 t. The displacement measurement range is 0–100 mm, the minimum loading rate is 0.001 mm/s and the steel frame stiffness is about 5 GN/m. The stiffness of disc spring group $K$ can be adjusted by changing the number $N$ of disc spring. The disc spring group is in elastic state during the whole compressive tests. In addition, there was no obvious deflection happened to the upper plate and rigid platform when one side of the pillars in treble-pillar specimen failed; and monitoring data showed that the amount of deflection during the whole loading process was smaller than the minimum jump value of pillar group-surrounding rock mass system. Therefore, the effect of loading platform deflection on CPF of treble-pillar specimen can be ignored.

2.2. Experimental Scheme

The uniaxial load was applied with displacement-control model (0.003 mm/s). Three load sensors were used to monitor the load of each pillar specimen; and three ball-and-socket devices were used to adjust the load from test machine so that each pillar specimen was under uniaxial compression. Two laser displacement sensors were used to measure the displacement of treble-pillar specimen ($d_p$) and the displacement of the test machine ($d_m$), respectively. In order to obtain the whole load-displacement curve of the specimen, the high-frequency laser displacement sensor and load sensor are connected to the high speed data-acquisition instrument (sampling frequency 2 kHz), and then the complete displacement and load data of specimen can be extracted. The failure of the treble-pillar specimen was monitored with the acoustic emission (AE) equipment of Physical Acoustics Corporation (PAC). Each pillar specimen was pasted with two AE sensors. The frequency range of the sensors was 125 Hz to 750 kHz. The pre-amplification was set as 40 dB; and AE signals whose amplitude exceeds 40 dB were collected. As shown in Table 1, three kinds of sandstone specimens with different mechanical properties were tested, e.g., elastic modulus ($E$), uniaxial compression strength (UCS), cohesion ($c$), tensile strength ($\sigma_t$), internal friction angle ($\phi$), Poisson’s ratio ($\nu$), pre-peak stiffness ($k$) and post-peak stiffness ($k_p$). Letters W, Y and R represent white, yellow and red sandstones, respectively. The sandstone specimens were retrieved from Zigong City, Sichuan, China, showing good homogeneity. The size of the specimens is $\phi50 \text{ mm} \times 100 \text{ mm}$.

| Rock type                 | $E$ (GPa) | UCS (MPa) | $\sigma_t$ (MPa) | $c$ (MPa) | $\phi$ (°) | $\nu$ | $k$ (kN/mm) | $k_p$ (kN/mm) |
|---------------------------|-----------|-----------|------------------|-----------|-----------|------|-------------|---------------|
| White sandstone (W)       | 5.75      | 49.06     | 4.85             | 8.44      | 45.18     | 0.186| 112.81      | 843.01        |
| Yellow sandstone (Y)      | 2.52      | 43.65     | 2.78             | 10.56     | 38.56     | 0.173| 49.45       | 532.11        |
| Red sandstone (R)         | 3.27      | 24.85     | 1.62             | 3.27      | 54.3      | 0.215| 64.16       | 332.25        |

The experimental schemes were listed in Table 2. Specimens from 1-a-1 to 1-a-5 were tested under different loading stiffnesses, e.g., 55 kN/mm, 110 kN/mm, 165 kN/mm, 220 kN/mm and 275 kN/mm, respectively. The treble-pillar specimen 1-b was used to study the cascading pillar failure and load transfer behavior of treble-pillar specimen. The treble-pillar specimen named as W-Y-R in Table 2 was tested under soft loading condition with loading stiffness of 550 kN/mm.

| Specimen No. | Single-pillar | Treble-pillar |
|--------------|---------------|---------------|
| 1-a-1        | 1-a-2         | 1-a-3         |
| 1-a-4        | 1-a-5         | 1-b           |
3. Experimental Results

3.1. Single-Pillar Specimen

Fig. 2 shows the test results of single-pillar specimens (1-a-1, 1-a-2, 1-a-3, 1-a-4 and 1-a-5) under various loading stiffness, where the axial load, pillar deformation and cumulative AE counts versus time were shown. The loading stiffnesses of 1-a-1, 1-a-2, 1-a-3, 1-a-4 and 1-a-5 are 55.17 kN/mm, 110.34 kN/mm, 165.51 kN/mm, 220.68 kN/mm and 275.85 kN/mm, respectively.
As seen in Fig. 2a ~ e, the load-time curves of soft loading conditions experience a violent drop after the peak strength point. The cumulative AE counts-time curves of all the specimen increased significantly in the early stage, and then entered the stable stage with a slow increase. However, the cumulative AE counts-time curves of soft loading conditions in Fig. 2a~ e increased rapidly after the peak strength point due to the sudden jump of disc spring group. The more cumulative AE counts in the early stage was due to the compaction process of the sandstone specimen.

As shown in Fig. 2a ~ e, the deformation-time curves of soft loading conditions experienced a sudden jump \( \Delta d \) owing to the violent elastic deformation recovery of disc spring group. As shown in Fig. 2f, the sudden jump \( \Delta d \) exponentially decrease with the increase of loading stiffness. Therefore, it was concluded that the larger the stiffness of disc spring group, the less violent degree of rock failure instability. When the stiffness of the disc spring group is large enough (that is close to stiff loading condition), steady and progressive failure of rock may happen.

3.2. Treble-Pillar Specimen
Fig. 3 shows the experimental result of W-Y-R specimen under soft loading condition. Pillar R, Pillar W and Pillar Y fail in order at 828.02 s, 898.52 s and 942.10 s, respectively. (1) Pillar R fails first with a load drop (66.44 kN), resulting in the sudden increases of load (which is called the load transfer) in Pillar W (17.52 kN) and Pillar Y (10.77 kN), as shown in Fig. 3(a). The failure of Pillar R causes the elastic rebound (0.18 mm) and elastic energy release (3.61 J) of disc spring group; and the elastic energies of Pillar W and Pillar Y respectively increases by 1.75 J and 0.66 J due to the elastic rebound of disc spring group, as shown in Fig. 3(b) and (c). Therefore, the elastic energy transfer ratio from disc spring group to treble-pillar specimen is defined as: \( 1.75 J + 0.66 J / 3.61 J \approx 66.76 \% \). (2) Pillar W fails subsequently with a load drop (104.26 kN), resulting in the sudden increase of load (or load transfer) in Pillar Y (24.93 kN), as shown in Fig. 3(a). The failure of Pillar W causes the elastic rebound (0.68 mm) and elastic energy release (26.13 J) of disc spring group; and the elastic energy of Pillar Y increases by 8.51 J due to the elastic rebound of disc spring group, as shown in Fig. 3(b) and (c). Therefore, the elastic energy transfer ratio from disc spring group to treble-pillar specimen is calculated as: \( 8.51 J / 26.13 J = 32.57 \% \). (3) Pillar Y fails finally with a load drop (84.61 kN), causing the elastic rebound (1.06 mm) and elastic energy release (33.74 J) of disc spring group, as shown in Fig. 3(a), (b) and (c).
Fig. 3 Experimental results of W-Y-R specimen under soft loading condition. (a) Load and cumulative AE counts versus time; (b) Load and displacement versus time; (c) Load-displacement curves of pillars and disc spring group; (d) Failure patterns.

From Fig. 3(a), the failure of single pillar in W-Y-R specimen under soft loading condition induces the sudden increase of cumulative AE counts not only in itself, but also in adjacent pillars by load transfer. For example, Pillar Y experienced three sudden increases of cumulative AE counts. The first sudden increase was resulted from the failure of Pillar R; the second was resulted from the failure of Pillar W; and the third one indicated the failure of Pillar Y itself. Fig. 3(d) shows the failure patterns of W-Y-R specimen under soft loading condition, where Pillar R, Pillar W and Pillar Y fails abruptly at 828.02 s, 898.52 s and 942.10 s with loud noise due to the violent elastic rebound of disc spring group. Rock debris ejects from the lower right corner of Pillar R. A shear band forms at an orientation of 60° ~ 65° from the top left corner to the lower right corner in Pillar W. Multiple splitting fractures form along the axial direction in Pillar Y.

4. Conclusions

In this study, the instability of single-pillar specimen and load transfer behavior of treble-pillar specimen were investigated based on laboratory tests. The following conclusions can be drawn:

(1). The soft loading condition is the necessity for the load transfer within multiple pillars; and the rapid elastic rebound of near-field surrounding rockmass (simulated with disc spring group) is the physical essence that induces the load transfer behavior. No load transfer will happen under the stiff loading condition due to lack of elastic rebound of near-field surrounding rockmass.

(2). The loading stiffness has little effect on the pre-peak mechanical properties of rock specimens. The loading stiffness mainly affects the unstable failure process of specimen. Sudden displacement jump $\Delta d$ increases with the decreased stiffness, resulting in more severe unstable failure behavior of rock specimen.

(3). The soft loading condition has major effect on the load and elastic energy transfer within the multi-pillar system. Domino failure behavior of multi-pillar system may happen when the transferred load exceeds the bear capacity of adjacent pillars.

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5. References

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