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Technical Note

Observation of rock fragment ejection in post-failure response

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1. Introduction

Rockburst is a dynamic energy phenomenon accompanying the failure of hard rock in the form of brittle fractures [1–3]. Surplus energy is released when the accumulated elastic strain energy of rock is greater than the consumptive energy required for fracturing during its quick post-failure. This freed energy often takes radiant forms, such as acoustic energy, electromagnetic energy, and thermal energy [2,4,5], as well as physical forms, such as fragments being thrown in the laboratory, or an ejective rockburst in the field [6–11]. Of these types of releases, the fragments with kinetic energy always result in dangerous engineering accidents due to their abrupt impacts at high speeds [12–17].

To reduce bursting disasters in underground engineering, a great deal of effort has been put forth to explain the rockburst mechanism, predict ejection behavior, and design corresponding protective support techniques, etc. [18–24]. Conventional wisdom indicated that knowledge of the ejection velocity of the burst rock fragments is the key to further predicting rockburst risks and designing a corresponding protective support system [25–28]. For example, Kaiser and Cai underlined that rock ejection with a velocity of up to 3 m/s required a specially integrated yielding support system [28]. Simulated rockburst experiments in an underground tunnel in South Africa were successfully conducted to measure the ejection velocity of rock fragments directly. The results indicated that the in situ rock fragments were ejected from the tunnel wall with velocities in the range of 0.6 m/s to 2.5 m/s, thereby providing useful clues for rockburst's prevention technique in deep mining [29,30].

As expected, high experimental costs, rigorous site requirements (i.e., hard rock and high geostress) and complicated preparatory work for such field experiments have limited the application of in-situ rockburst measurements. Laboratory observations of rock ejections serve as a convenient and reasonable alternative method [31–33]. Petukhov noted that violent fracture of rock specimen in a compression machine could represent a laboratory simulation for dynamic rock failure during a burst in the field [32,34]. Visual observations of fragment ejection velocity in a laboratory are important not only to understand further the outbreak behavior of fragments in post-failure of hard rock but also to assess the bursting properties of rock in actual engineering.

High-speed filming, which records instantaneous behavior by taking successive photographs over a short time interval, has been used in dynamically mechanical experiments as an accurate tool for observing impact failure [33,35,36]. Unfortunately, the high-speed camera has few applications in the documentation of ejection performance rock specimens under quasi-steady compression conditions. As a result, these filming methods warrant further research.

In this article, we present a method to observe the ejection velocity of rock fragments under laboratory uniaxial compression tests with the help of a high-speed camera. Also shown in this article is an algorithmic program developed to calculate the initial speed and throwing angle of ejected rock fragments. This work

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makes use of the ejection responses for three types of hard rock in post-failure. These responses of fragments include flight tracks, initial speed and angle, flake size, and a positive correlation between the ejection speed and the elastic modulus of the specimens. The experimental technique and observed results could further develop our skill in reliably estimating rockburst and enable better understanding brittle failure of hard rock.

2. Observation methods

Because the ejection process is very transient and the ejection velocity of fragments is high during post-failure of hard rock, a high-speed recording device, such as a high-speed camera, is needed to track the motion trail of the fragment automatically. Here, an intact observing scheme, including a high-speed camera, is used to catching the flying trail of the ejected rock fragments. Corresponding algorithm is also introduced for estimating the fragment's initial ejecting speed and initial throwing angle.

2.1. Technical scheme

The observation scheme, as shown in Fig. 1, consisted of a high-speed camera, a testing machine, a control computer, two limiting steel plates, a scale plate and several floodlights. The rock specimen was placed at the base of the compressive testing machine and the height of the high-speed camera was set level with the specimen. Two pieces of limiting steel plates were installed in front of the specimen to screen the fragments into a narrow throwing range. The scale plate was placed parallel to the ejected fragments, and its plane was vertical to the optical axes of the high-speed camera. By the control of the limiting steel plates, only the fragments that flew with trace vectors nearly parallel to the scale plate were recorded by the high-speed camera. The scale plate was marked with points at certain intervals (e.g., 0.2 m) and was used as a reference for calculating the spatial position of fragments at different times. Several floodlights were placed at varying locations and heights for adequate lighting in the filming zone. This approach also ensured multiple viewing points and enabled clear photography.

The servo-controlled testing machine was used to create conceivable throwing fragments, and the corresponding trajectories were recorded using the high-speed camera. In this experiment, the compressive loading pattern of the testing machine was often set as a displacement control at a low loading rate with the goal of obtaining quasi-steady compression [37–39]. The testing machine acquired data automatically with time intervals ranging from 0.01 to 1.0 s. The high-speed device was an improved 'Giga-View' camera. The digital memory cell allowed for cyclic and automatic frame data storage at rates between 30 to 17,045 Hz. This means that a recorded video of 1280 × 1024 pixels is approximately 20 s long at a filming rate of 400 frames per second profiting from its large memory cell. This length of recording time was adequate because post-failure of the rock specimen typically occurs only over several seconds.

The system was set up as follows: first, the deformational sensors were installed; second, the servo-controlled testing machine was started to compress the specimen; last, the installed high-speed camera was used for filming according to the specified observation scheme. It was crucial that the high-speed camera be stopped in several seconds after the failure accompanying with the ejection behaviors and broken sound during the compression experiment. With these operating instructions, the ejection tracks of fragments can be captured, as shown in Fig. 2.

2.2. Algorithm for velocity estimation

The velocity of fragments cannot simply be calculated using the increased displacement and relevant time intervals on the recorded video pictures, even though filming was performed by a high-speed camera. The reason is that each fragment on the scale plate is projecting its shadow and is affected by the viewing angle of the camera lens (as shown in Fig. 3). When the fragment is thrown from position 'A' to position 'B' in Fig. 3, the real flying distance (Δl, i.e., $(\Delta x, \Delta y)$) of the fragment is not equal to the shadow displacement ($\Delta l'$, i.e., $\Delta x', \Delta y'$) on the scale plate. The relationship of the increased displacement is $\Delta l = a/(a+b) \cdot \Delta l'$. Therefore, the speed of any given fragment, which is calculated by measuring the space between two fragments' shadows on the different frames in time series, is inaccurate and needs a detailed mathematical conversion.

There are two key stages in estimating the velocity of a fragment. The first stage consists of calculating the spatial trace of a flying fragment based on the recorded time-series frames by the high-speed camera. The second stage involves the matching of the fragment's velocity according to the calculated trace of the fragment.

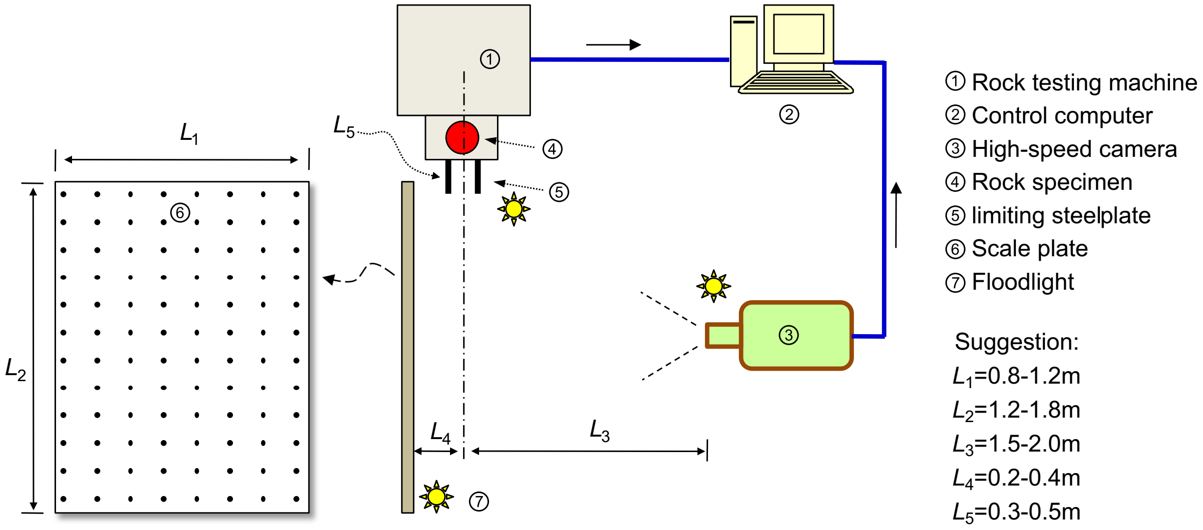

Fig. 1. Observation scheme for rock fragment ejection in post-failure.