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Short communication

Rock mass failure mechanisms during the evolution process of rockbursts in tunnels

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1. Introduction

A rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event.[1] Rockburst is a common and serious form of engineering disaster that may happen during excavation of deeply-buried tunnels. As the depths of excavations have progressively increased, more and more cases of rockbursts in tunnels have been reported. Rockbursts can cause mechanical damage, delays to projects, and economic loss. As an example, hundreds of rockbursts occurred during the construction of the extra-long seven tunnels in the Jinping II hydropower station in China. On 28 November 2009, an extremely serious rockburst caused seven deaths and one injury, as well as the total destruction of a tunnel boring machine (TBM).

The study of rockburst evolution mechanisms is the foundation for developing theoretical and numerical models to warn of, and control, rockbursts. There has been a great amount of research carried out on the mechanisms underlying rockbursts in tunnels, including case records and laboratory tests. Ortlepp and Stacey used case records to make a significant improvement to our understanding of rockbursts and stated that strain bursts are the main form.[2,3] An on-the-spot survey of rockbursts and the failure modes of ejected rock blocks examined using a scanning electron microscope revealed that the processes causing a rockburst can be summarized as: compression cracking, compression shear cracking, bending, and breaking.[4] Early biaxial mechanical testing studies suggested that the damage produced is shear-based.[5] However, based on true triaxial laboratory tests, it was found that both tensile and shear failure can occur during rockburst evolution.[6–8] In fact, rockbursts are extremely complex phenomena influenced by several factors, *e.g.* geological conditions, the presence of groundwater, rock lithology, and the tunnel excavation itself. It is difficult to realize the actual stress path involved in the development process of rockbursts and to simulate rockburst of different types through laboratory testing. In addition, existing case studies focus on the mechanisms of rockburst occurrences. Thus, how to obtain direct evidence on the evolution mechanisms behind rockbursts remains an unresolved problem.

Microseismic (MS) monitoring is important for understanding the *in situ* process of rock mass failure associated with rockbursts.[9,10] The process of rockburst evolution can be seen as a series of rock mass failure events related to MS events. This means that if we can identify the types of rock mass failure events involved in the process of development of rockbursts (tensile, mixed, or shear), the rockburst evolution mechanisms can be obtained directly. Based on such MS information, methods involving energy ratios and moment tensor analysis have been widely used to judge the type of rock mass failure occurring. A large number of MS monitoring results have indicated that the energy ratios of tensile failure events are much smaller than those for shear failure events.[11–14] To study the characteristics of the type and crack plane

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of rock mass failure, the moment tensor analysis method was introduced and later improved.[15,16] However, the applicability of these two methods still required verification using real-time MS monitoring of tunnel engineering projects.

The aim of the study reported here is to explore the evolution mechanisms of rockbursts in tunnels. For this purpose, a comprehensive method of judging the type of rock mass failure occurring during rockburst evolution is proposed based on real-time MS information. The features and evolution mechanisms behind a series of rockburst cases of different types are presented. At the same time, the effect of stiff structure on the rockburst evolution process is also discussed.

2. Microseismic monitoring of rockburst evolution processes in tunnels

2.1. Microseismic monitoring in the tunnels of Jinping II

In situ MS monitoring was conducted in the four headrace tunnels and a drainage tunnel of the Jinping II hydropower station in China (with a total length of 12.4 km) to study the rockburst evolution process and warn of rockburst risk. The diameters of the headrace and drainage tunnels are 13 and 7.3 m, respectively. The burial depth of these tunnels varies from 1900 to 2525 m. Detailed information on the MS monitoring zone, cross sections, and geology of the Jinping II tunnels can be found elsewhere in the literature.[9,17] Several working faces were setup in these tunnels to speed up the construction process and one or two six-channel MS acquisition units were placed at each working face (see Fig. 1). Two groups of sensors were installed behind each workface and these were moved forward progressively as the tunnel face advanced. The monitoring program and related sensor layout have already been reported by Chen et al.[18]

In contrast to large-scale MS monitoring in mines, MS monitoring in tunnels presents two obvious differences: (i) as the sensors are repeatedly moved forwards, the distance between the MS sources and sensors is usually small (less than 150 m). This means that most failure events can only be recorded by the sensors near to where an event occurs (referred to as ‘near sensors’) and cannot trigger sensors in other tunnels (referred to as ‘far sensors’), as shown in Fig. 1. For example, 354 of the 471 MS events occurring in April 2011 were just recorded by near sensors. (ii) The failure events are basically outside the sensor array.

2.2. Description of rockbursts in tunnels

In terms of development mechanism and effect of geological structure, there are two main types of rockbursts during tunnel excavation: strain bursts and strain–structure slip rockbursts.[9,10] The main factor controlling both of these rockbursts is the same: high geo-stress. The latter is also commonly affected by the presence of stiff structures. Typically, strain bursts occur in regions with hard rock masses that are intact and with few discontinuities. The rock faces of the explosion pits generated by strain bursts are typically fresh. The shapes of the explosion pits are often nested, or V-shaped (see Fig. 2a). Strain–structure slip rockbursts occur in zones with hard rock masses containing sporadic stiff structures. Most of these stiff structures are closed, dry, without filling, and of low ductility. At the same time, the number of stiff structures is usually not greater than two (or two sets), as shown in Fig. 2b and c.

The rockburst cases considered here derive from the headrace tunnels of the Jinping II hydropower station in China. The selected rockburst cases satisfy the following three requirements: (i) the rockburst grade is moderate or intense; (ii) continuous MS information is available throughout the rockburst development process; and (iii) clear photographs were taken of the resulting explosion pit. The grade of the rockburst is determined according to the depth of the explosion pit: for a moderate rockburst this is 0.5–1 m and for an intense one it is 1–3 m.

According to the type of rockburst and number of stiff structures in the rockburst zone, three different kinds of rockbursts can be identified: (1) strain bursts, (2) strain–structure slip rockbursts with the development of a single stiff structure (or a single set thereof), and (3) strain–structure slip rockbursts with the development of two stiff structures (or two sets thereof). The numbers of these three different kinds of rockburst cases is 6, 7, and 5, respectively, based on the aforementioned selection principles.

3. Methods of evolution mechanism analysis for rockbursts in tunnels

3.1. The energy ratio method

In this method, the radiated MS energies of rock mass failure events are calculated using seismogram processing software provided by Integrated Seismic System (ISS). The calculation follows that of Mendecki et al.[19] by use of the formula:

$$E_{P,S}=\frac{8}{5}\pi\rho v_{P,S}R^2\int_0^{t_s}\dot{u}^2_{corr}(t)dt \tag{1}$$

where $E_{P,S}$ is the P- or S-wave energy, ρ is the rock density, $v_{P,S}$ is the P- or S-wave velocity, R is the distance from the source, t_s is the duration, and $\dot{u}^2_{corr}(t)$ is the square of the far-field-corrected radiation pattern of the velocity pulse.

The ratio of the S- and P-wave energies (E_S/E_P) can be used to judge the type of focal mechanism responsible for generation of an MS event. It is generally accepted that E_S/E_P values associated with rock mass failure events involving tensile failure are less than 10.[11,12] If the rock mass failure process can be viewed as involving shear failure, then E_S/E_P is greater than 20.[13,14] Thus, the energy ratio criteria can be summarized as:

$$\begin{cases} E_S/E_P<10 & \text{Tensile failure} \\ 10\leq E_S/E_P\leq 20 & \text{Mixed failure} \\ E_S/E_P>20 & \text{Shear failure} \end{cases} \tag{2}$$

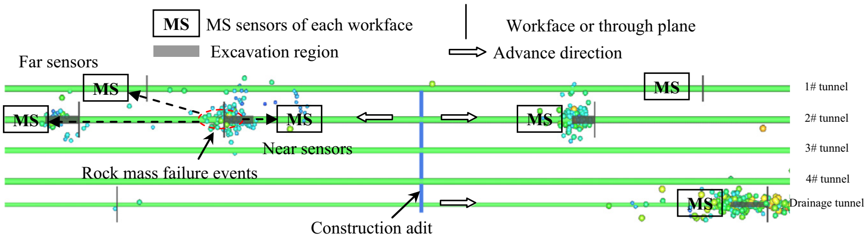

Fig. 1. Schematic representation of the microseismic monitoring system used in the headrace tunnels at the Jinping II hydropower station in China.