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Influence of tunneling methods on the strainburst characteristics during the excavation of deep rock masses

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ABSTRACT

It is widely known that blasting and TBM are the general methods for the deep rock mass excavation, and can respectively induce transient release of in-situ stress (TRIS) and quasi-static unloading of in-situ stress (QSUIS) on the excavation boundary. As one of the most important triggers, the unloading of in-situ stress caused by excavation frequently induces strainbursts. However, little attention has been focused on the influence of the tunneling methods on the strainburst characteristics. In this paper, the cracking of surrounding rock masses and associated energy dissipation under the different tunneling methods was analyzed. The influence of different tunneling methods on the evolution characteristics of strainburst was also discussed. Results show that, compared with the TBM excavation, the blasting excavation aggravates the cracking of surrounding rock masses, and enlarges the energy dissipation during the cracking process. During the unloading process of in-situ stress, the total energy and the releasable strain energy for the case of blasting excavation are much higher than that for the TBM excavation, this makes that the intensity and frequency of immediate strainbursts induced by blasting excavation are much greater than that caused by TBM excavation. While after the unloading of in-situ stress, as the surrounding rock masses dissipate larger energy during its cracking process, the releasable strain energy for the case of blasting excavation is lower than that for the TBM excavation. This brings down the risk of time delayed strainbursts for the blasting excavation. In addition, a case study at diversion tunnels in Jinping II hydropower project was presented as a verification.

1. Introduction

With the development of the Chinese economy, more and more underground projects are being built to meet the large energy demands, such as underground openings of hydropower stations, deep mines and geological storage of nuclear wastes. All these underground projects require large-scale excavation of deep rock masses under the high in-situ stress. The excavation alters the geometry of original rock masses and unloads the in-situ stress on excavation boundary which will lead to the redistribution of stress and the change of strain energy in surrounding rock masses. If the excavation-induced stress and energy accumulation exceed the limit values which the brittle rock masses can bear, a sudden and violent rock mass failure may occur accompanying with a large energy release (Salamon, 1983; Hua and You, 2001; Jiang et al., 2010; Cai and Champaigne, 2012; He et al., 2012b). As a human-excavation induced geologic hazard, rockburst not only threatens the stability and safety of the surrounding structures, but also endangers the lives of nearby workers. Therefore, it is important to understand and manage the rockburst with a positive attitude.

Rockbursts can be divided into three types: pillar burst, fault slip burst and strainburst (Hedley, 1992). As the strainburst occurs frequently near the excavation boundary and often threatens the safety of workers and construction equipment, a better understanding of strainburst is particularly important. Many meritorious studies have shown that the strainburst is a sudden and violent rock failure phenomenon which depends on the accumulation of strain energy during the loading and release of strain energy upon failure (Cook, 1965; Singh, 1988; Ortlepp and Stacey, 1994; Kaiser et al., 1996; Wang and Park, 2001; Zhu et al., 2010; He et al., 2012a; Chen et al., 2015). To find out the triggers of strainbursts, microseismic monitoring techniques have been employed during the excavation of deep rock masses (Kaiser et al., 2005; Tang et al., 2010; Feng et al., 2012; Li et al., 2012), and strainburst tests have been performed in laboratory to study the strainburst behaviors under true-triaxial unloading conditions (He et al., 2010, 2012b, 2015; Gong et al., 2012). In addition, numerical simulation methods have been used to study the evolution mechanism of strainburst and its influence factors (Tang and Kaiser, 1998; Huang and Wang, 1999; Wang et al., 2006; Jiang et al., 2010; Zhu et al., 2010). All above studies have indicated that the accumulation and release of strain energy in the rock masses is the main internal trigger of strainbursts, and the dynamic disturbances such as explosion, vibration,

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unloading of in-situ stress are the very important external causes of strainbursts.

As one of the most important triggers, the unloading of in-situ stress caused by excavation frequently induces strainbursts. A high excavation rate can result in a large unloading rate of in-situ stress, and causes great ratio of the released energy transforming into the form of seismic energy (Salamon, 1974). Different from excavation at shallow depth, tunneling at large depth could cause the reduction and increase of stress in surrounding rock masses and this dynamic change of stress is the major trigger of strainbursts (Ortlepp, 2001). The change rate of time-dependent stress which is determined by the stress magnitude and duration time of stress change is the most important factor to the occurrence of strainbursts, and the high change rate of time-dependent stress could bring about the greater influence on the strainburst (Zhu et al., 2010). Under the different unloading rate, a series of experimental tests performed by Zhao et al. (2014) indicated that the strainburst intensity and the associated acoustic emission (AE) energy release are dependent on the unloading rate, and a higher unloading rate means a stronger strainburst.

It is widely known that blasting and TBM (tunnel-boring machine) are the general methods for deep rock mass excavation. Different excavation methods can produce distinct unloading paths of in-situ stress. For the blasting excavation at large depth, the release of in-situ stress is a transient process. While for the TBM excavation, the unloading of in-situ stress is a quasi-static process (Yan et al., 2009; Lu et al., 2012; Li et al., 2014; Zhu et al., 2014). Different unloading paths of in-situ stress mean different unloading rates and will have a great influence on the strainburst characteristics. However, the above-mentioned studies about strainburst ignore the influence of the unloading stress paths associated with excavation methods on the failure characteristics during the strainburst.

The purpose of this paper is to study the strainburst characteristics under the different tunneling methods (blasting and TBM). In the following discussion, the evolution mechanism of strainburst is firstly explained from the perspective of energy, and then influence of excavation methods on the cracking of surrounding rock masses and associated energy dissipation is analyzed. Subsequently, the influence of different tunneling methods on strainburst characteristics is studied, and statistics results of rockbursts occurred in No.1 diversion tunnel excavated by TBM and No.2 diversion tunnel excavated by blasting at Jinping II hydropower project are presented as a verification. Finally, a method to calculate the jection speed of rock mass fragments during strainburst is introduced and discussed. The analysis results can be helpful to understand and assess the strainburst hazard during the deep rock mass excavation by different tunneling methods.

2. Evolution mechanism of strainburst

During the evolution process of strainburst, the initiation, growth, opening and closure of crack observed by the digital panoramic borehole camera system shows that the evolution process of strainburst is often accompanied with the cracking of rock masses (Feng et al., 2012). Considering a unit volume rock mass element which is a linearly elastic, homogeneous and isotropic material, the unit volume rock mass element will produce deformation under the action of external force. At the same time, the stress–strain and strain energy of the unit volume rock mass element will be altered as shown in Fig. 1. From state A to B, elastic deformation is produced under the action of external force, and all the work done by external force is transferred into the strain energy of the unit volume rock mass element; from state B to C, inelastic deformation is generated, some energy is dissipated and the rest energy is still stored in the form of releasable strain energy in the unit volume rock mass element; when the releasable strain energy in the unit volume rock mass element exceeds the limit value which the rock mass element can store, the rock mass element will be destroyed like the state D accompanying with a large energy release (as shown in

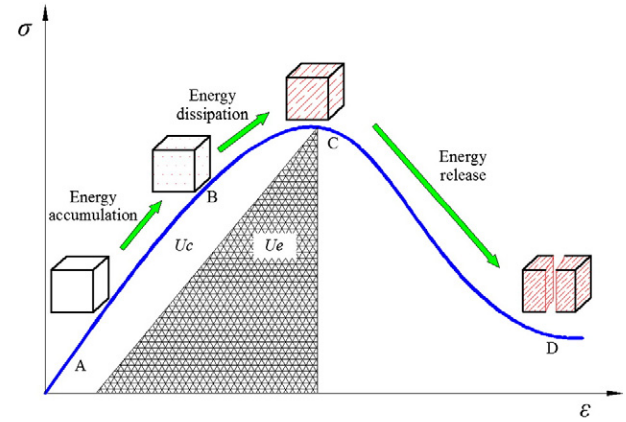

Fig. 1. Relationship between energy change and stress–strain state of unit volume rock mass element.

Fig. 1). During the deformation and failure of this unit volume rock mass element, the energy balance can be described by the following formula:

$$U = U_c + U_e \tag{1}$$

where, U represents the total energy density imported by the external force doing work, unit: kJ/m^3; U_c represents the dissipation energy density during the process of inelastic deformation, unit: kJ/m^3; U_e represents the releasable strain energy density stored in the unit volume rock mass element, unit: kJ/m^3.

During the above process of inelastic deformation, the part of the total energy is dissipated in the forms of surface energy and frictional energy to promote the initiation, growth, opening and closure of cracks, and the rock mass will be cut into fragments by these cracks. Then the rest part of the total energy will be released in the form of kinetic energy, and the rock mass fragments will be thrown. If the kinetic energy is large enough, the rock mass fragments will be ejected at a high speed and the strainburst happens.

For the deep rock masses, the large in-situ stress endows the rock masses with high strain energy, and the excavation would also enlarge the strain energy of rock masses. During the deformation and failure of surrounding rock masses, part of the accumulated energy is dissipated in the irreversible forms and causes the cracking of surrounding rock masses. The rest of the accumulated energy is still stored in the rock masses in the form of the releasable strain energy. If the releasable strain energy exceeds the limit value that the rock masses can bear, this energy will be quickly released and may induce strainbursts in surrounding rock masses. It is widely accepted that TBM excavation and blasting excavation could induce the quasi-static unloading of in-situ stress (QSUIS) and transient release of in-situ stress (TRIS) on the excavation boundary, respectively (Yan et al., 2009; Lu et al., 2012; Li et al., 2014; Zhu et al., 2014). Different unloading stress paths would cause the different adjustment process of stress in surrounding rock masses and induce the different deformation around the excavation boundary. This will inevitably affect the energy change and influence the failure characteristics of strainburst.

3. Influence of tunneling methods on the cracking of surrounding rock masses

Studies by Feng et al. (2012) have shown that the strainburst often occurs with the cracking of rock masses. Therefore, to study the influence of tunneling methods on the failure characteristics of strainburst, the cracking of surrounding rock masses under different excavation methods needs to be analyzed at first.