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Safety distance for secondary shotcrete subjected to blasting vibration in Jinping-II deep-buried tunnels

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ABSTRACT

Performance and quality of secondary shotcrete is vital to the stability and safety of tunnels. It is required to determine a safety distance away from blasting work faces where the support of the secondary shotcrete can be executed to avoid damage from blasting vibration. For the case of the Jinping-II diversion tunnel, characteristics of the blast-induced vibration under high in situ stress are firstly investigated by site monitoring and numerical modelling. The results show that in the highly-stressed rock masses, the transient release of in situ stress on excavation faces accompanying rock breakage by blasting is another important excitation for the blast-induced vibration. If it is left out of consideration in the impact assessment of the blast-induced vibration, the implementation of the secondary shotcrete takes place at a distance close to the blasting work face, and the vibration-induced failure of the shotcrete occurs. Based on the numerical simulation, influences of the blast-induced vibration on the shotcrete with different ages are evaluated with the maximum tensile stress criterion and the Mohr–Coulomb criterion. It is concluded that under the high in situ stress, the major failure mechanism of the shotcrete subjected to blast-induced vibration is loss of adhesion at the shotcrete–rock interface due to shear failure. According to the maximum extent of failure, it is suggested that in the Jinping-II diversion tunnel project the secondary shotcrete is to be constructed behind the blasting work face at least 24.0 m to avoid the vibration-induced failure.

1. Introduction

Tunnelling construction disturbs the initial equilibrium state of rock masses, resulting in redistribution of stress, deformation of surrounding rock masses and even collapse of rock blocks. To provide a safe construction environment for workers and machines, and to guarantee a safe operation environment for the tunnel itself, rock support is essential to help the rock carry its inherent loads. Shotcrete, i.e. pneumatically sprayed concrete, is considered as one of the most important supporting materials, and is widely used in tunneling, mining and other construction industries. The shotcrete serves a number of functions. Generally, it supports rock blocks around a tunnel excavation surface, induces an arching effect around a tunnel face, generates internal pressure by convergence control, prevents rock masses from losing strength, distributes stress acting on the shotcrete itself and transfers the stress induced by excavations to a steel rib or rockbolt (Song and Cho, 2009). Therefore, the good performance and quality of the shotcrete is vital for the safety of the workers and the function of the tunnels.

The method of drill and blast remains an economical and efficient excavation technique of rock masses in tunnelling. The striving for a more time-efficient construction process in tunneling naturally focuses on possibilities of reducing the time period of waiting between construction stages. Therefore, the shotcrete and the blasting constructions are usually operated by turns. After a blast operation is completed, the primary shotcrete construction follows the blasting work face closely as soon as possible to form a flexible thin layer to control deformation of surrounding rock masses, as shown in Fig. 1. This means that the primary shotcrete is inevitably subjected to vibration induced by next blasts. As a temporary support, the failure of the primary shotcrete occurring at close proximity to the blasting work face is tolerated. In order to improve the shotcrete performance and further guarantee rock mass stability, a concrete layer is sprayed again on the basis of the primary shotcrete. This is secondary shotcrete. The secondary shotcrete serves as a permanent support and does not allow any

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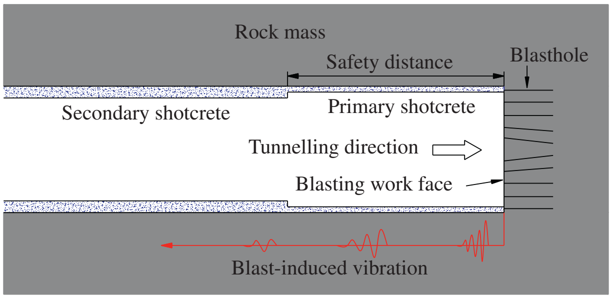

Fig. 1. Schema of the relationship between shotcrete and blasting site in a tunnel.

failure occurring due to the blast-induced vibration. But if the secondary shotcrete is very close to the blasting work face during the early age when it is still in the process of curing, the strength and the deformation property of the cured concrete may be threatened (Ansell, 2004). Although it may be applied well initially on a tunnel surface, spalling may be created due to the superposition of reflected tensile waves (Grady, 1988; Ohtsu et al., 2007), and the cured secondary shotcrete may debond from the tunnel surface, inducing corrosion, buckling, fracturing and internal voids over time (Barret and Mccreath, 1995; Song and Cho, 2009). Such conditions will cause severe tunnel stability problems. Therefore, investigating the effects of the blast-induced vibration on the secondary shotcrete, and determining a safety distance away from the blasting work face where the secondary shotcrete construction can take place, will be of great significance to safe and economical tunnelling projects.

In this regard, studies are well documented by many researchers globally. Malmgren and Nordlund (2006), by developing a single-degree-of-freedom (SDOF) model, evaluated the influence of the production blasting induced stress waves on the performance of shotcrete support for a rock wedge. Yi et al. (2009) derived the stress and deformation of the concrete lining in a circular tunnel by using the method of wave function expansion. Because some parameters change drastically associated with space and time during blasting, the analytical solutions are available only in extremely simplified cases. Interesting work has, however, been published on in situ or laboratory tests, where young or fully cured shotcrete on a rock surface was subjected to blast-induced vibration. Kendorski et al. (1973) carried out in situ tests to determine how a shotcrete lining was affected by standard drift blasts at various distances from the lining. A standard blast consisted of 409 kg premixed ammonium and fuel oil (ANFO). The tests revealed that cracks started to appear in the shotcrete when the detonations occurred at a distance of 16.5 m, and the function of the lining was considerably reduced when detonating from 12.2 m. Tests performed by Nakano et al. (1993) during the construction of parallel tunnels implied that cracks of the shotcrete occurred when the particle velocity exceeded 70 cm/s. Based on the vibration tests conducted in the waterway system in the Gotvand Dam, Iran, studies of Nateghi (2012) showed that the critical distance from the blasting source was about 13 m and the maximum charge per each delay could not be more than 22 kg for the initiation of damage in the concrete lining. Ansell and his team (Ansell, 2004; Ahmed and Ansell, 2012a) have done considerable research on the young shotcrete subjected to blasting vibration. Their studies reveal that the young shotcrete without reinforcement can also survive high vibration levels without being seriously damaged even when the rock material is fragmented and ejected. Further experimental research conducted by Shin and Lee (2001), and Zhang et al. (2005) indicates that the blast-induced vibration has negative and positive effects on the young shotcrete, which depends on the vibration amplitude and the curing time. Vibration below 2.5 cm/s can increase the strength of the young shotcrete within the first 1–2 days, but in excess of the critical vibration amplitude or after the critical age of the shotcrete, the vibration will cause cracks in the young shotcrete and reduce its strength. The effect of blasting vibration on the shotcrete has also been studied through numerical modelling. The early studies investigated the propagation of elastic stress waves in a one-dimensional model of the shotcrete on a rock surface. Then, based on the modelling concepts of the structural dynamics and the stress wave theory, elastic–plastic models, continuum damage models were used to study dynamic responses of the shotcrete under blasting vibration (Wang et al., 2007; Zhou et al., 2008; Ahmed and Ansell, 2012b; Buonsanti and Leonardi, 2013).

A large number of huge hydropower projects such as Xiaowan, Xiluodu, Jinping and Longpan are being built or to be built in China and all require large-scale and high-intensity rock excavation of long and deep-buried tunnels under complex geological conditions. The depths of some tunnels reach up to several kilometers, and thus, the surrounding rock masses of these tunnels always withstand high in situ stress due to self-weights and tectonic movements. Some new mechanical phenomena have been observed when the high-stress rock masses are excavated by using the drill and blast method. One of them is that, accompanying explosive detonation and secession of rock fragments from their initial locations, the in situ stress in the close vicinity of the newly-formed excavation boundaries is suddenly released (Carter and Booker, 1990; Cai, 2008). While at a distance slightly far away from the excavation faces, the stress release will last a longer time due to the time effect of rock deformation and failure, which is a quasi- static process. Lu et al. (2012) termed the former instantaneous mechanical process transient release of in situ stress. This unloading disturbance is propagated outside in the form of elastic waves and induces vibration in surrounding rock masses (He et al., 2010; Yang et al., 2013). To be more exact, in the highly-stressed rock masses, blast-induced vibration is attributed to a combined action of the explosion and the transient release of in situ stress on excavation faces. The vibration induced by the transient release of in situ stress overlaps with the explosion-induced vibration, and will aggravate the vibrational failure of the shotcrete. Unfortunately, previous studies on the shotcrete subjected to blast-induced vibration have only been directed towards explosion, and the vibration induced by the transient release of the in situ stress on excavation faces was ignored or confused with the explosion-induced vibration. Furthermore, the initial static stress in the shotcrete subjected to blast-induced vibration attracts relatively little attention.

In this paper, for a case study of a deep-buried tunnel construction project, site blasting vibration tests are firstly presented to study the characteristics of blast-induced vibration under high in situ stress. Related numerical simulations are then conducted. Based on the site monitoring and the numerical simulation, vibrational failure characteristics of the secondary shotcrete are investigated, and a specific safety distance away from the blasting work face is suggested to prevent the failure of the secondary shotcrete during blasting. Here it needs to be stated that the shotcrete studied in this paper refers to the secondary shotcrete.

2. Site description and field tests

2.1. General

The Jinping-II Hydropower Station at the upstream of the Yalong River is located in Sichuan Province, Southwest of China, as shown in Fig. 2 (Li et al., 2012). The installed capacity of this project is 4800 MW. It is mainly composed of a headwork sluice dam,