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Analysis of tunnel support design to withstand spalling induced by blasting

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ABSTRACT

This paper presents modeling of rock spalling induced by a dynamic pulse using the finite-discrete element method, for the purpose of tunnel support design to withstand blasting. 1D and 2D model results are compared to analytical spalling equations and field test findings. It was found that only the 2D models are suitable for support design. A distinction between heavy spalling and light rockfall is made based on an estimation of the ratio of the peak stress of the arriving wave to the rock tensile strength. Accordingly, different design approaches are suggested: for heavy spalling a low impedance isolating layer between the tunnel liner and surrounding rock is recommended. For light rockfall, a simplified static FEM analysis procedure is presented.

1. Introduction

A blast coupled in rock imposes extremely high pressures that cause complex fracturing mechanisms to occur. The close field response of the rock has been studied by many researchers: Grady and Kipp (1980) proposed a continuum based damage model to investigate oil shale fracturing; Donze et al. (1997) investigated the influence of different parameters on the size of the crushed zone and length of the radial cracks; Zhu et al. (2008) studied fragmentation mechanisms around a borehole loaded with explosives using the continuum code AUTODYN in the context of mining and quarrying.

Design of a tunnel support system to withstand the close field blasting impact would be impracticable (EM 1110-345-432, 1962). Therefore, this paper focuses on the far field response of a tunnel to an explosive blast, where the reflection of the blast wave from the tunnel boundary can cause rock fragments to fly into the tunnel (spalling). Tunnel support systems that have been designed to carry static loading may not be sufficient to withstand these additional loads. Limited guidelines exist for the engineer tasked with designing tunnel support to withstand blast loads or evaluating the performance of an existing support system.

The most extensive tests of damage to tunnels from blasting took place between the years 1948–1952, conducted by Engineering Research Associates together with the US Army Corps of Engineers (COE) and the US Bureau of Mines (ERA, 1953). Measurements of the amount of broken rock and the velocity of the rock ejection into the tunnel were made as part of those tests, so that tunnel support could be designed accordingly (note that those tests were performed for unsupported tunnels). Although the ERA tests serve as an invaluable database for assessing blast damage, using those to draw conclusions for proper support is not a straightforward process.

Field tests to investigate tunnel support performance under blast loads have been conducted by various authors. Most commonly, peak particle velocity (PPV) is used as a damage threshold. Kendorski et al. (1973) tested bolted and lined tunnels in heavily jointed schist using ANFO as an explosive and found that hairline cracks formed in the liners under PPVs of 900 mm/s and that displacement of the cracks was associated with PPVs of 1200 mm/s. Wood and Tannant (1994) found that the reinforced shotcrete can maintain its functionality even when the PPV was up to 1500–2000 mm/s.

Different authors have used numerical methods to simulate the response of tunnel support to blast loads (Wu et al., 2011; Deng et al., 2014). Mitelman and Elmo (2014) validated a hybrid FEM/DEM (FDEM) approach to explicitly simulate damage to tunnels induced by blast loads. In this paper, a similar approach is further applied to investigate the adequate protective support required to prevent blast induced damage. In general, numerical modeling is a rigorous process that requires several inputs and assumptions, and intensive computational capabilities. Hence, there is an incentive to simplify the problem and analysis methods. This paper discusses the validity and limitations of different approaches of tunnel support design to withstand blasting.

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Rockbursts are another form of dynamic loading that may be imposed on a tunnel. Rock bursting into the tunnel occurs as a result of high stresses in deep mines or tunnels. Kaiser and Cai (2012) discusses the rockburst phenomenon and lays out general guidelines for dynamic support. Although blast induced damage and rockbursting are triggered by different mechanisms, the two share similarities in terms of the manner of how they impact support; both are manifested by a series of small impacts, with velocities ranging from 3 to 10 m/s. It is the authors' opinion that work related to rockburst support and blast load support can shed light on each other, as currently both subjects are far from being fully developed.

2. 1D spalling

2.1. Analytical equations

A comprehensive discussion on tunnel dynamic support design based on the findings of the ERA tests can be found in the COE manual (EM 1110-345-432, 1962). The spalling damage to the tunnels is explained using a 1D simplification. The theory is backed by laboratory experiments on steel bars subjected to explosive pulses. Understanding of the spalling phenomenon (Fig. 1) and proper prediction of the extent and velocity of spalling is essential for assessment of the load that will act upon the tunnel liner.

Ahmed and Ansell (2012) compared simplified 1D and 2D models of rock and shotcrete liner subjected to blast loads and found that results are comparable. Zhao et al. (2010) proposed a simplified decoupled method of dynamic liner design based on the 1D idealization to estimate the load on the tunnel liner. The same author idealized a support system of liner and rock bolts to behave as a beam on two springs with a span equal to the bolt spacing. This beam is further simplified to an equivalent Single Degree of Freedom (SDOF) system. The load from the 1D analysis is subsequently used as an input to compute the displacements and stresses that develop in the liner.

Analytical equations for the first spall thickness and first spall velocity were derived by Zhao et al. (2010) based on the geometry presented in Fig. 1. According to the notation used in the figure, the first spall will form when:

$$\sigma_m - \sigma_x = \sigma_t \tag{1}$$

where σ_m is the peak stress of the wave, σ_t is the tensile strength of the rock material, and σ_x is the compressive stress of the incident wave at the point of the first spall. With the knowledge of the wave velocity c of a material, the above equation can be rearranged to find the thickness of the first spall h as:

$$h = \frac{ct_2\sigma_t}{2\sigma_m} \tag{2}$$

where t_2 is the time of the descending part of the wave. Note that the rise time of the wave does not affect results. The PPV of tensile waves are opposed to the direction of their propagation and therefore the velocity of the first spall is the PPV contribution from both the incident wave and the reflected wave. The PPV is equal to the product of stress and the materials impedance ρc. Using this relationship the velocity of the first spall V_o is given by:

$$V_o = \frac{(\sigma_m + \sigma_x)}{\rho c} = \frac{2\sigma_m}{\rho c}\left(1 - \frac{\Delta t}{t_2}\right) \tag{3}$$

where Δt is the time interval from the time when the peak stress reaches the free surface to the time of the first spall.

Subsequent to the detachment of the first spall a new free face is formed and the remainder of the compressive pulse, now with a peak stress of σ_x, will reflect from the newly formed free face. The second spall will occur if the tensile stress will once again exceed the strength of the rock. The number of the spalled layers will be given by the integer number smaller than the ratio σ_m/σ_t (EM 1110-345-432, 1962).

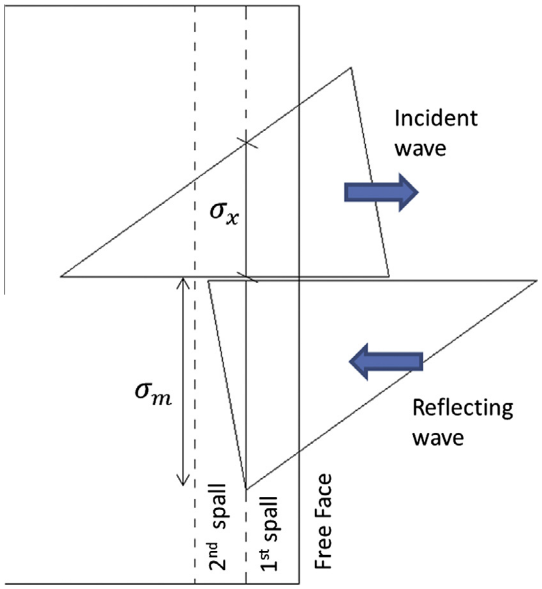

Fig. 1. Spalling process due to a compressive pulse reflecting from a free face. σ_m is the peak stress of the wave and σ_x is the compressive stress of the incident wave at the point of the first spall.

2.2. 1D Numerical models

Numerical models of bars subjected to a dynamic 1D load are set up in order to compare results of spalling to the analytical equations. Modeling is undertaken using the code ELFEN, a hybrid Finite-Discrete Element (FDEM) code that incorporates fracture-mechanics principles to allow for the realistic simulation of brittle fracture-driven processes (Hamdi et al., 2014). As the spalling phenomenon is a tensile failure process, the Rankine rotating crack is used as a failure criterion. This failure criterion is based on the concept of Mode 1 fracturing studied in fracture mechanics. Once the maximum principal stress reaches the tensile strength limit, tensile softening is initiated and the elastic modulus is degraded in the direction of the major principal stress invariant (Rockfield, 2005).

Four models are set up as shown as illustrated in Fig. 2. The material properties are listed in Table 1, where only the tensile strength σ_t varies while all other parameters are kept constant.

The model geometry consists of a bar in the dimensions of 0.5 × 5.0 m. The right end of the bar is constrained in both vertical and horizontal directions, and the horizontal boundaries of the bar are constrained in the vertical direction to maintain the one-dimensionality nature of the problem. The results presented hereafter refer to a face load with a triangular shaped curve with a peak of 10 MPa and a time period of 0.8 ms applied to the left side of the bar. No damping is used in the models, as the purpose of these models is to compare results to the analytical equations, which do not account for wave attenuation. A preliminary numerical investigation conducted by the authors found that the effect of damping on spall thickness and velocity can be neglected for these high frequencies and distances.