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Stability analysis of the blast-induced damage zone by continuum and coupled continuum–discontinuum methods

David Saiang

Division of Mining and Geotechnical Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden

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ABSTRACT

The presence of a blast-induced damage zone (BIDZ) around a tunnel boundary is of significant concern mainly with regard to safety, stability, costs and the overall performance of the tunnel. The BIDZ is essentially characterized by reduction in strength and stiffness, and increase in permeability. Guidelines have been developed based on perimeter blasting experiences and overbreak characterization to regulate damage due to blasting. Although the over-break approach of assessing the degree of blast-induced damage is practical, the method does not provide a measure of the competency of the damaged rock. Very often it is important to know how the damaged rock mass will behave under any given conditions. In this paper a series of numerical analyses was performed using continuum and coupled continuum–discontinuum methods to study the behaviour of the blast-induced damage zone. In the coupled continuum–discontinuum method FLAC and PFC^{2D} were coupled together. The inner segment of the model was simulated using PFC^{2D}, while the outer segment was simulated using FLAC. This enabled the tracking of failure and fallout from the PFC^{2D} model. The tunnel was excavated within the PFC^{2D} segment. Blast-induced radial cracks were traced and individually implemented in the models. Models were also run independently in FLAC and $Phase^2$ and the results were compared to those of the coupled models. The results show that the failure around the tunnel was confined in most parts to the damaged zone at shallow depths, but not in deep excavations. The failures and fallouts mapped with the coupled models were consistent with practical observations. Since the continuum models cannot simulate failure, results from the coupled model were used to identify indicators for failure in the continuum models. It was seen that yielding due to volumetric straining (in FLAC) and 100% yielded elements (in $Phase^2$) were consistent with the failures mapped in the coupled models for shallow excavations, but was less consistent for deep excavations.

1. Introduction

The most cost effective method for excavating tunnels in massive hard rock masses, where the uniaxial compressive strength very often exceeds 200 MPa, is by drilling and blasting. A very important concern often arises with this method: unwanted damage induced by blasting beyond the desired perimeter of the tunnel. The significance and importance of this damage have been deliberated by among others; Oriad (1982), MacKown (1986), Ricketts (1988), Plis et al. (1991), Andersson (1992), Forsyth (1993), Persson et al. (1996) Raina et al. (2000) and Warneke et al. (2007). To minimize this damage perimeter blasting techniques, such as smooth blasting (e.g. Holmberg and Persson, 1980) are commonly used, complemented by theoretical blast damage tables and charts (e.g. AnläggningsAMA-98, 1999). In spite of these precautionary measures blast damage is still inevitable and the conceived consequences are evidenced in the form of increased support cost and requirements, slow tunnel advance, unforeseen stability problems originating from blast damage, conduit for water flow, reduction in tunnel life, etc.

Although the blast-induced damage guidelines, mentioned above, are useful in tunnelling and drifting works, it is still unclear how, when and to what degree the damaged zone affects the stability of an excavation. The construction of a tunnel for example can either speed up or slow down if the effects of the damaged zone are understood at a reasonable level so that the blast-induced damage can be controlled optimally without making too many sacrifices. Cautious blasting is costly and time consuming. If it can be eliminated in some cases then it will save cost and time for clients and contractors alike. On the other hand if no such controls are in place then the excavation can be in danger of uncontrolled blasting, which will lead to instability problems and unsafe working environment, bad tunnel geometry, and additional material to remove.

In order to understand the effect of the BIDZ on the stability and performance of an excavation, an understanding of how the zone behaves under certain scenarios is essential. This was the focus of a paper by Saiang and Nordlund (2008). This paper (i.e. Saiang and

E-mail address: david.saiang@ltu.se.

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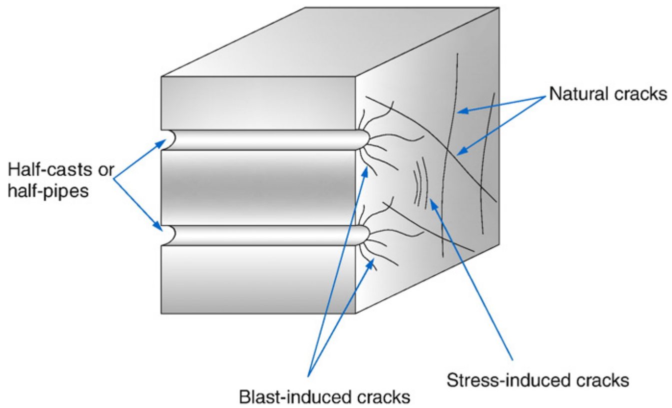

Fig. 1. Blast-induced cracks originate from the half-casts while stress-induced and natural cracks do not (modified after Olsson et al., 2004).

Fig. 2. Radial cracks observed around (Ø64 mm blast-holes from a bench blast and 0.5 m by 0.5 m burden and spacing respectively. The explosive used was Kumulux with 22 mm cylindrical column charge, with the holes blasted instantaneously (Olsson and Bergqvist, 1995).

Nordlund, 2008) also revealed the need for detailed modelling of the blast-induced damage zone, in order to gain a proper understanding of its behaviour. Hence, in the present paper the damaged zone was studied after coupling FLAC (Itasca, 2005) and PFC^{2D} (Itasca, 2008) to create a continuum–discontinuum coupled model. In the coupled model the inner segment of the model was simulated using PFC^{2D}, while the outer segment was simulated using FLAC. This enabled the tracking of failure and fallout within the PFC^{2D} segment where the tunnel was excavated. Blast-induced radial cracks were individually implemented in the model. Models were also run independently in continuum based codes, FLAC and Phase^2. The results of these models were compared to the coupled models. Since continuum models cannot simulate failure, results from the coupled model were used to identify indicators for failure in the continuum models, i.e. in the FLAC and Phase^2 models. It must be noted that the numerical analyses presented in this paper do not concern the actual blasting process, but the effects and behaviour of the damage created by blasting.

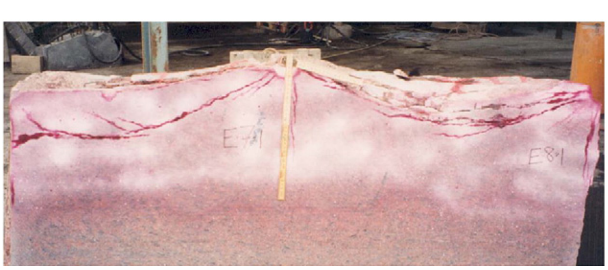

Fig. 3. Tangential cracks observed around (Ø64 mm blast-holes from bench a blast with 1.0 m by 0.8 m burden and spacing respectively. The explosive used is Gurit with 22 mm cylindrical column charge and blasted instantaneously (Olsson and Bergqvist, 1995).

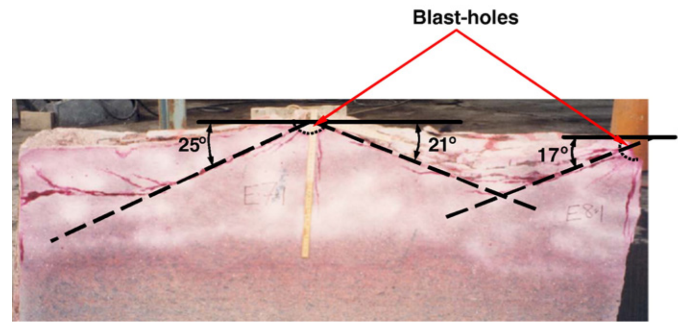

Fig. 4. Estimation of intersecting cracks from adjacent blast-holes. Cracks with orientation angles up to 25° from the blast-hole row intersect each other, while those greater than 25° do not intersect.

SveBeFo (Swedish Rock Engineering Research) has performed an extensive investigation into damage caused by blasting for over a decade, starting in the early 1990's (Olsson, 1992; Olsson and Bergqvist, 1993, 1995, 1997; Ouchterlony, 1997; Nyberg et al., 2000; Ouchterlony et al., 2001; Nyberg and Fjellborg, 2002; Olsson and Ouchterlony, 2003; Olsson et al., 2004). Results from these investigations were used as a basis to develop computer models in this paper.

2. Background

2.1. Blast-induced fracture characterization

In order to make an educated judgement on the failure processes and expected effects, the understanding of the characteristics of the BIDZ is important. The blast-induced damage can generally be defined as any damage that originates from blasting. SveBeFo developed a simple methodology to differentiate between blast-induced damages (or cracks according to SveBeFo) and those that originate from other sources. This is illustrated in Fig. 1. Cracks that originate from the half-pipes are considered as blast-induced and those not originating from the half-pipes are considered to be from other sources, either natural or stress-induced. The SveBeFo investigations revealed that the maximum depth of damage (i.e. in terms of crack length) resulting from controlled blasting usually extends to about 0.7 m and in less controlled conditions can reach 1.2 m. The average depth of these crack lengths was about 0.3 m.

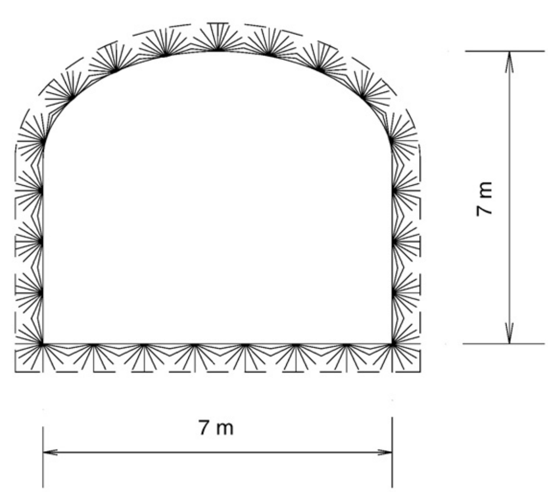

Fig. 5. Radial cracks generated within the PFC and Phase^2 models as per observations in Figs. 2 and 3. The spacing between the blast-holes is 1.0 m and the tunnel dimension is 7 m×7 m.