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Numerical modelling of observed fallouts in hard rock masses using an instantaneous cohesion-softening friction-hardening model

Catrin Edelbro *

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

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ABSTRACT

The work presented in this paper focuses on compressive stress-induced brittle fallouts in hard rock masses, which are massive or sparsely fractured and subjected to intermediate to high in situ stresses. The results of numerical modelling, using a linear-elastic, brittle plastic material model with cohesion-softening friction-hardening (*CSFH*) behaviour, were compared with observed fallouts for six cases. The objective was to study how well the results of a *CSFH* model agrees with observed fallouts with respect to location, depth, and shape. All six cases were well documented with respect to virgin stresses, fallout characteristics, rock mass properties, and rock behaviour. The modelling results showed that shear strain localization (shear bands) developed for all cases. The depth of the intersected shear bands were used as a fallout indicator. Furthermore, the location and shape of the observed fallouts could be predicted fairly accurately. The predicted fallout depth was in good agreement with observed fallouts for three of the cases. Using both yielded elements and intersecting shear bands as fallout indicators results in a better prediction of fallout than using just one indicator.

1. Introduction

Fallout is defined as the complete detachment of rock slabs from the rock mass and often constitutes a problem for the use of an underground opening. For openings at great depth, and in competent massive or sparsely fractured rock masses, the predominant type of fallout is that of compressive stress-induced (Martin and Christiansson, 2008). These fallouts can be caused by both spalling (initially) and shear failure (subsequently) and it can be difficult to judge the exact cause of a fallout in the field (that has already occurred). For a compressive stress-induced failure, different stages of the failure process can be identified. This includes fracture initiation, propagation, and interaction. The fractures developed during the fracture initiation and propagation phase are referred to as stable fractures, since an increase in stress is required to induce new fractures or to propagate existing ones. Increases in stress at this point lead to accumulation and the growth of fractures. Further increases in stress can result in fracture interaction. Once fractures are formed, the rock can be said to be damaged, and the strength is thus usually reduced. Hence, stress concentrations transfer farther into the rock mass and new fractures are initiated at a larger distance from the boundary. For spalling failure (see e.g. Martin, 1997; Andersson, 2007; Diederichs, 2007; Martin and Christiansson, 2008) thin rock slabs (one to several centimeters thick) parallel to the surface are formed. Fallout can occur once fractures connect to the excavation boundary. Often, slabs fail at the outer ends through shear propagation, or in the middle through tension (buckling). However, shear failure is likely to occur in the final process during the formation of a fallout, see Fig. 1.

Often when one slab has fallen out (or been scaled), new slabs are formed. The spalling of the rock is thus a gradual process that ends up in a final form that is most often drop- or v-notch shaped. The stabilisation of the underground opening by the new geometry created by the fallout is explained by an increase in confinement at the notch apex, together with a decrease in induced damage (Hajiabdolmajid et al., 2002). Since shear often occurs in the outer ends of the slabs, the final shape of the fallout may be captured by studying shear bands (shear strain localisation) and yielded elements failed in shear.

Relatively few studies have been published that deal with field scale behaviour and well-described failures and fallouts of hard rock in underground constructions. One reason might be that the crack initiation and propagation of the surface parallel fractures is not possible to observe from the tunnel surface and can only be noticed through monitoring cross-cuts or borehole observations. Once a fallout occurs, at least in civil engineering constructions, additional rock reinforcement is installed, and detailed documentation of the fallout may not be conducted. Fallouts in mines might not always be re-habilitated and can be documented, but detailed descriptions of the sequence of events leading up to a

* Tel.: +46 920 49 13 38; fax: +46 920 49 19 35.
E-mail address: catrin.edelbro@ltu.se

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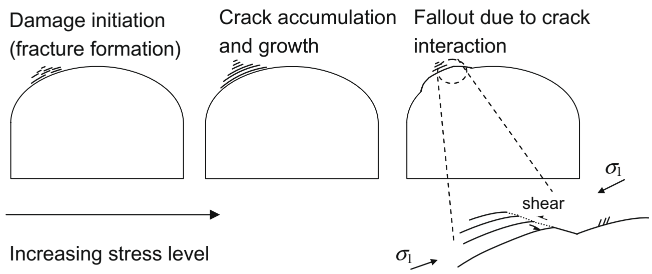

Fig. 1. Schematic picture of different stages of the failure process.

fallout (initiation and progression) may be lacking. Another reason for the scarcity of published information might be lack of high-quality input data for analysis e.g., performed stress measurement, rock properties, etc.

Different methods of how to model failure of brittle and hard rock masses have been proposed by e.g. Hoek et al. (1995), Martin (1997), Hajiabdolmajid et al. (2002) and Diederichs (2007). As suggested by Hoek et al. (1995), an elastic-brittle material model, with low residual values of cohesion and friction angle, should be best suited to represent brittle fallout. The application of the strength parameters in the Hoek–Brown criterion by Martin et al. (1999) resulted in a suggestion that the location and depth of failure (but not the shape and extent) could be predicted fairly well using a value of m_b close, or equal, to zero, and $s = 0.112$ in an elastic analysis (this represents failure initiation at $0.3 \cdot \sigma_c$). Similar findings of low confinement dependency were presented by Diederichs et al. (2004), who summarised research of back-analyses of brittle failure on damage initiation. According to Hajiabdolmajid et al. (2002) a strain dependent model should be used to simulate brittle fallouts. The strain dependent model was suggested to be cohesion-weakening and friction-strengthening and the calculated yielded elements failed in shear resulted in good agreement with fallout observations from the Underground Research Laboratory experiment in Canada. The suggested model is in line with research by Schmertmann and Osterberg (1960), who showed that the friction term is active only if movement between particles exists. Cohesion loss between particles implies the occurrence of such movement. For small plastic strains the frictional term has almost no influence but as the strains accumulate, the cohesion drops and the significance of the friction angle increases. However, for this kind of strain softening models, the required input data, in the form of softening strains for the rock mass, are difficult to obtain. The methodology suggested by Diederichs (2007) was based on determination of the thresholds for damage initiation and systematic damage initiation. Both should preferably be estimated from acoustic emission data, and a reliable estimate of the tensile strength is also required. The equivalent Mohr–Coulomb parameters, used in the simulations performed by Diederichs (2007), were cohesion-softening, friction-hardening. In Diederichs (2007) the predicted depth of the fallout was evaluated through shear band localisations and yielded elements, which coincided with the observed failures.

Different commonly used methods to model failure of brittle and hard rock masses were evaluated by Edelbro (2008a), by comparing the results from finite element analyses with observed fallouts in two hard rock mass cases. The objective was to study which model that best captured the actual rock behaviour and to study the relative importance of different strength parameters and their significance to the predicted results. The result from the instantaneous cohesion-softening friction-hardening (*CSFH*) model seemed to capture the rock behaviour most successfully, as the results showed a "v-notch shape" with a better agreement with observed fallouts, compared to the other models.

In this paper, six cases of observed fallouts are compared with results from finite element analysis using the *CSFH* material model. The objective is to improve the understanding of the failure process and the fallout characteristics, and to study how well the results in the form of maximum shear strain localizations from a *CSFH* model agree with observed fallouts with respect to location, depth and shape. A perfect agreement is not expected since there is variability and uncertainty in e.g., measured stresses and the rock mass strength parameters. However, a model that captures the rock mass behaviour when predicting compressive stress-induced fallouts is desired.

The work presented in this paper is limited to compressive stress-induced brittle fallouts in hard rock masses which are massive or sparsely fractured and subjected to intermediate to high in situ stresses. The primary failure mechanisms considered are spalling and/or shearing where the rock beyond the zone that has fallen out is stable (if no stress changes occur). The considered fallouts in this paper are "initial", i.e., small in volume (the time-dependency is not considered) and consisting of detached rock pieces from the roof or wall of a tunnel or drift. Obviously, a precise limit in initial fallout cannot be established. In this work, a total fallout depth of about 0.02 to 0.4 m represents the initial fallouts. Fallouts caused by stress relaxation or related to dynamic loading (e.g., blasting, rock bursting or earthquakes) are not within the scope of this paper.

2. Numerical modelling

Observed fallouts were compared with the predicted fallouts from numerical models using the stress analysis program *Phase²* (Rocscience Inc., 2008). This program was chosen since it is easily applied to use and widely used within the mining and geo-engineering fields. The program is used for the calculation of stresses and displacements around underground and surface excavations in rock. *Phase²* is an elasto-plastic finite element stress analysis program, in which the material can yield and exhibit non-linear stress-strain behaviour if treated as plastic. If the peak strength is exceeded, residual strength values can be applied by using either an elastic-perfectly plastic material model or, as was done in this work, an elastic-brittle plastic (instantaneous softening) material model.

In the analysis, the maximum shear strains and yielded elements were used as fallout indicators. The evolution of damage can be represented by irreversible/plastic strains in the rock. The maximum shear strain is evaluated, as it indicates where shear occurs within the material. In particular, the developed shear bands (narrow zones of intense straining) are studied. Fallout, caused by shear, is assumed to occur when two shear bands intersect or form a coherent arch. If the shear bands are connected with the excavation boundary, the area in between is assumed to fall out (see e.g. Sjöberg, 1999, and Sandström, 2003). According to e.g. Lau and Chandler (2004) and Eberhardt et al. (1998), the initiation and unstable crack propagation in a brittle intact rock can be predicted by studying the volumetric strain. Unstable crack growth occurs at the point of reversal in the volumetric strain curve, indicating that the formation and growth of cracks exceeds the elastic strength of the rock. Wang (2007) conducted numerical simulations of intact rock samples and showed that the contour map of shear bands and the volumetric strain localization was similar. Edelbro (2008a) also showed that the contour map of shear bands and the volumetric strain localization was similar for two rock mass cases. Hence, as the results were more distinct and clear for the developed shear bands, the maximum shear strain was chosen as an indicator for predicting compressive stress-induced fallouts.

Based on comparison between field observations and predictions of an access drift in the Kristineberg mine (Edelbro and Sandström, 2009), it was concluded that potential compressive