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Discrete element modelling of the buckling phenomenon in deep hard rock mines

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ABSTRACT

In deep and high stress hard rock mines, large deformations are often associated with the presence of foliation. Traditionally, the study of the non-linear anisotropic response of foliated rock masses to high stresses and excavations has focussed on the use of continuum numerical modelling methods. This approach, however, has several limitations and fails to reproduce the buckling mechanism observed in underground hard rock mines. This paper presents a methodology for capturing these conditions using the distinct element method. The proposed technique considers the role of fractures within the rock mass and results in the reproduction of the buckling mechanism. This has been achieved by progressive reduction of the forces acting at the boundaries of the excavation by a reduction factor through a series of modelling steps. This approach overcomes the computational and time constraints on modelling the development of a mining drift. The numerical modelling results are in agreement with the observed squeezing mechanism and deformation levels recorded in Canadian and Australian hard rock mines.

1. Introduction

A large number of underground openings is developed under squeezing ground conditions. The associated deformation has often a significant effect on the safety and the cost of underground excavations. In civil engineering applications, Barla[1] provided an outline of the methods used for the identification and quantification of squeezing as well as the numerical methods for the simulation of these conditions.

In deep and high stress mines, large deformations are associated with the presence of a prominent structural feature such as a dominant fracture set, intense foliation or a shear zone and high stress.[2] A higher magnitude of deformations is tolerated in mining as opposed to tunnelling applications for operational purposes.[3] This paper focuses on the behaviour of foliated rock masses in underground hard rock mining that often results in a buckling type of failure.[2]

It has been demonstrated that the magnitude of deformations in mining drifts developed in foliated ground can be reduced by choosing a more favourable angle between the foliation and the drift.[3] Furthermore, a discussion on the parameters controlling the deformation under these conditions has been provided by Mercier-Langevin and Hadjigeorgiou.[4]

The failure modes of openings in steeply foliated rock masses have been examined by Lin et al.[5] using physical modelling while Kazakidis[6] proposed an analytical approach to quantify the influence of eccentric loading applied in a slab under buckling loading around underground openings. The study of the nonlinear anisotropic response of foliated rock masses around an underground opening, under the influence of high stress, requires the use of numerical modelling methods. Although continuum methods are used to simulate the rock mass behaviour around underground excavations, they are quite limited and do not fully capture the buckling mechanism observed in the field. Discontinuum numerical methods, even though more appropriate, have not been widely used due to long solution times and other computational restrictions.

This paper reports on the application of the distinct element method to capture the buckling mechanism in foliated ground under high stress conditions. The constructed numerical models focused on reproducing the mechanics of the failure mechanism in hard rock mining. They explicitly consider the influence of structure thus overcoming limitations of continuum models. Furthermore, they have addressed some of the time and computational constraints in running large discontinuum models. The numerical investigations are based on case studies from two underground Canadian mines owned by Agnico Eagle Mines Ltd, LaRonde and Lapa.

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2. LaRonde and Lapa mines

The LaRonde and Lapa mines are situated in the Abitibi region of Northwest Quebec within 11 km from each other and are operated by Agnico Eagle Mines Ltd. The mines have an extensive network of drifts in foliated ground. This has resulted in a wide spectrum of squeezing ground conditions. Wall to wall convergence in excess of 2 m or 40% strain (defined as the total wall deformation over the drift width) has been reported including high convergence in the back and high floor heave.[7]

LaRonde is a world-class Au–Ag–Cu–Zn massive sulphide lenses complex. The mine operates between 860 m and 2930 m using two mining methods: transverse open stoping with cemented and unconsolidated backfill and longitudinal retreat with cemented backfill. Permanent infrastructures are located in competent basalt. However, most of the footwall ore access developments are driven in felsic tuff with uniaxial compressive strength of 100 MPa and tightly spaced foliation resulting in excavations prone to squeezing and buckling. The foliation strikes parallel to the orebody and has a dip angle between 70° and 85°.[8] Squeezing ground conditions have been observed at several levels and as far as below 1790 m depth.

Lapa is a high grade gold mine operating through a 1369 m deep shaft using two mining methods: longitudinal retreat with cemented backfill, and locally transverse open stoping with cemented backfill. Squeezing conditions appear in shallower developments than in LaRonde starting from 510 m depth. The rock mass behaviour is mainly controlled by three distinct geological units: a weak schist zone and more competent sediment and volcanic zones.[9] Extreme squeezing conditions typically appear at the schist zones due to the tight foliation spacing and the presence of talc-chlorite alteration.

3. Phenomenological failure mechanisms

In civil engineering tunnels, squeezing ground conditions can be caused due to shear failure of the medium, shearing and sliding, or buckling failure.[10] Buckling is specifically observed in metamorphic rocks (i.e. phylite, mica-schists) or thinly bedded ductile sedimentary rocks (i.e. mudstone, shale, siltstone, sandstone and evaporitic rocks). The relative similarities of the squeezing issues in civil engineering tunnels and mining have been addressed by Potvin and Hadjigeorgiou.[2]

In underground hard rock mines, large deformations are often controlled by the presence of foliation and the orientation of foliation with respect to the direction of the drift. A phenomenological interpretation of the failure mechanism has been proposed for several Western Australian high stress mines.[11] For drifts driven parallel to the foliation, shearing of foliation in the sidewalls results in "guillotining" of the support elements. Stress induced fractures, sub-parallel to the drive back and floor, shear and dilate resulting in significant bulking of the rock mass. This results in closure between the floor and backs of the drifts and possibly drives the shearing in the walls. Bulking above the back is usually indicated by an open crack where the backs meets the hanging wall. The support elements installed at the top of the hanging wall are often the first to be sheared.[12] Buckling may appear at the walls if shearing is prevented (Fig 1). The buckling tends to develop in the lower part of the footwall as a result of the confinement provided by the drive floor and the beneficial effect of the support at the upper part of the walls. The shearing in the walls is promoted by the local rotation of the major principal stress.

A similar failure mechanism has been observed in Canadian hard rock mines. Potvin and Hadjigeorgiou[2] noted that squeezing in LaRonde promotes shearing in the top of the hanging wall and the bottom of the footwall and clamping in the top of the footwall and bottom of the hanging wall. Failure of the support in the top of the hanging wall at the early stages of the deformation process along with the schematic representation of the squeezing process observed underground are shown in Fig. 2.

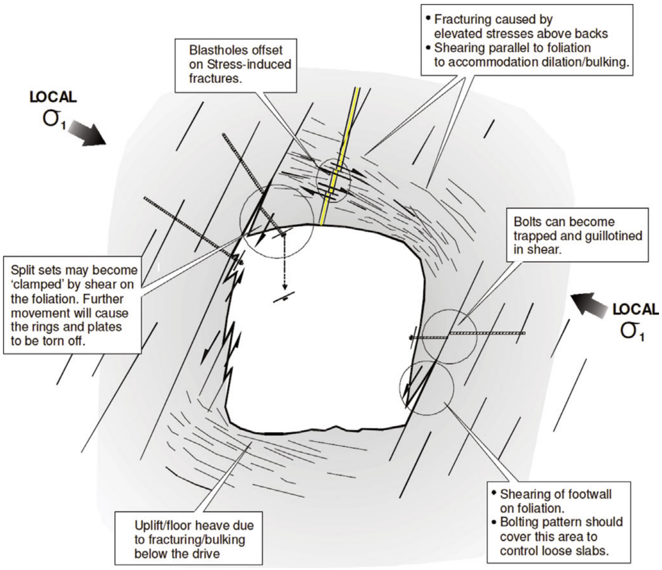

Fig. 1. Modes of large deformation ground behaviour.[10]

An interpretation of the failure mechanism at LaRonde and Lapa has been provided by Mercier-Langevin and Wilson.[9] They identified that the stress redistribution around an opening results in loading of the intact rock in a direction parallel to the foliation planes. This leads in contraction along the foliation and dilation towards the opening. This dilation increases the deflection of the rock layers and decreases the critical buckling load. Bulking is orthogonal to the foliation as the foliation planes open up. As buckling occurs in the sidewalls, this process is transferred deeper into the rock mass. The buckling process in the sidewalls results in a much larger effective span, and reduces the confinement provided to the back and the floor as well as the friction between the foliation planes. At the early squeezing stages, there is a higher convergence rate in sidewalls whereas later in the process the closure rate reduces in the sidewalls and increases in the back. A review of empirical approaches for quantifying the observed squeezing at LaRonde and Lapa and the potential of numerical tools to capture the buckling phenomena has been presented in Ref. 13.

4. Numerical methods for modelling large deformations in hard rock

4.1. Continuum modelling approach

Material deformation in underground excavations in hard rock is often modelled using finite element and finite difference methods. These methods can provide a rapid design assessment in relatively fast solution times. The analysis can incorporate the effect of the support installation and the influence of the 3D development of an underground opening using 2D models[14] or 3D models.[15] The main limitation is their ability to capture the buckling failure mechanism observed underground.

4.1.1. Implicit representation of fractures

There is a plethora of documented modelling case studies in squeezing ground conditions referring to civil engineering