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Use of predictive numerical models in exploring new reinforcement options for mining drives

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1. Introduction

The selection of ground support systems at the greenfield stage in underground mines is based on empirical guidelines for similar conditions. These decisions are often based on limited geomechanical field data. As the mines develop, there are further opportunities to collect more geomechanical data and observe the performance of the ground support systems. This allows the opportunity to fine-tune the design of ground support. The revised standards are documented in the ground control management plans. In extreme ground conditions such as rockbursts and squeezing ground it is necessary to develop new strategies to ensure the integrity of excavations and the safety of mine personnel. This invariably involves the introduction of new reinforcement and surface support elements.

In a mining environment, the introduction of new ground support systems can be a long process. Due diligence requires that any new reinforcement or surface element complies with health safety specifications and performance requirements. This is usually provided by the suppliers but verified by the technical services at a mine site. Provided these requirements are met it is then necessary to undertake field trials. For example these involve an on-site demonstration that a specific rock bolt can be installed in specific ground conditions. Subsequently, pull tests are employed to evaluate the performance of these bolts. If the results of these investigations are successful these are followed by large scale field trials, and the new element can eventually become part of the mine standard.

Numerical modelling is a useful approach for the design of ground support. However, the challenge remains in constructing numerical models that capture the behaviour of different reinforcement and support elements. This requires that the reinforcement elements are explicitly introduced in the stress analysis software. The ultimate objective of numerical modelling is not to reproduce the behaviour but to capture salient elements in a calibrated model. In this respect, once confidence is gained in a calibrated model it can be employed as part of forward modelling to provide indications of anticipated behaviour. In this way, numerical modelling becomes a powerful tool to investigate the potential benefits of introducing or replacing any specific rock bolt in the ground support system.

An important objective in the use of numerical models is the selection of appropriate techniques and constitutive models for the rock mass behaviour (Barla et al., 2010; Gao et al., 2015). Once this is established there are several stress analysis packages that have the option for the explicit representation of rock reinforcement and support elements. It is recognised that the introduction of these elements increases the degree of model complexity and consequently the length of the calibration process. A further important consideration is how to best simulate the ground support sequence in the development of the excavation, Vlachopoulos and Diederichs (2014). Several 3D models have simulated the role of reinforcement and support in both mining and tunnelling applications (Beck et al., 2010; Vakili et al., 2013; Vlachopoulos et al., 2013; Zhao et al., 2014). Most of the numerical applications of ground support, however, have focused in back analysing past performance. The real potential of numerical modelling, in terms of ground support design, however, it is to explore anticipated behaviour under different ground support scenarios.

This paper provides a case study where forward modelling was employed to investigate the performance of different rock bolts and sequence of excavation under difficult ground conditions. It extends previous work that captured successfully the influence of different reinforcement options and time of installation at the LaRonde Mine. The investigated ground conditions are characterized by structurally defined deformations driven by high stress and resulting in a buckling failure mechanism. The reported deformations were, in certain cases, in excess of 40% wall-to-wall strain. Under these conditions, the loads are greater than the capacity of conventional support systems resulting in significant failure of ground support and extensive rehabilitation work. This requires continued efforts to optimize the ground support strategy and minimize rehabilitation costs.

2. Ground support design

2.1. Design methods

The first step in choosing an appropriate analysis method for ground support design is to identify the governing mode of rock mass failure. This requires an understanding on the stress regime, excavation

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geometry, geology, structure, and rock mass characteristics. There are several empirical, analytical and numerical tools available with specific data requirements that necessitate a series of simplified assumptions. Lorig and Varona (2013) listed a series of methods appropriate for different modes of tunnel instability distinguishing between weak rock shear failure, brittle rock shear failure and structurally controlled instability.

Stress induced brittle spalling can be found parallel to the boundary of the excavation in blocky and massive rock masses under high stress conditions. Based on empirical evidence, Martin et al. (1999) suggested that brittle failure occurs when the ratio of the maximum tangential boundary stress to the unconfined compressive strength of the rock mass, exceeds 0.4 ± 1 MPa. For ground support design purposes this can be used to estimate the required bolt length and the anticipated gravity loading on the support. In weak and soft rocks masses, a shear failure mechanism can be observed. In this case, the rock mass displacement is often assumed to be a plastic flow of rock under the influence of high stress. Hoek and Marinos (2000) proposed a squeezing chart for the prediction of the anticipated strain in tunnels. Analytical closed form solutions can also indicate elasto-plastic response of circular underground excavations in rock masses (Carranza-Torres and Fairhurst, 1999).

In structurally controlled instability, limit equilibrium analysis (Hudson and Harrison, 2000) can be used to assess the stability of distinct blocks formed by structures under low stress conditions. Under high stress conditions, structurally controlled deformations can occur in thinly bedded rock masses. In this case the orientation of the structures is critical for the stability of the excavation. The hard rock squeezing index proposed by Mercier-Langevin and Hadjigeorgiou (2011) has been used to assess the anticipated level of squeezing. Large deformations are mitigated in underground mines using yielding reinforcement and surface support elements (Potvin and Hadjigeorgiou, 2008).

Analytical methods can assist in understanding the parameters that affect tunnel instability. They are, however, mostly limited to simplified representations of rock mass behaviour, geometry, boundary and loading conditions. Empirical methods, are used in the early stages of design. As they are based on past experience they cannot be used to assess the anticipated performance of new reinforcement tools that are not available in their original database. Numerical modelling methods can be used to investigate different ground support strategies provided that they can be adequately calibrated on field data. Once this is accomplished, forward modelling can potentially simulate the impact of new support scenarios and assist towards the optimization of ground support systems.

Continuum modelling methods can be used to capture shear failure of the medium in weak rock masses. These methods cannot explicitly reproduce the non-linear anisotropic behaviour of thinly layered rock masses to high stresses and excavations. In cases of structurally controlled instabilities, a discontinuum numerical method should be used to capture the mechanics of the phenomenon.

2.2. Problem definition

This paper focuses on the role of ground support in mining drives at the LaRonde underground mine reporting very large deformations. The presence of foliation under high stress results in a buckling squeezing mechanism including detachment and rotation of rock slabs. The mechanics of the problem have been described by Karampinos et al. (2015a) based on field measurements and observations. The stress redistribution around the opening results in loading of the intact rock in a direction parallel to the foliation planes leading in contraction along the foliation and dilation orthogonal to the foliation planes. The dilation decreases the critical buckling load. Shearing in the top of the hanging wall and the bottom of the foot wall appears from the early squeezing stages. As buckling occurs in the sidewalls, this process is transferred deeper into the rock mass.

Analytical methods as the Euler's formula (Gere and Timoshenko, 1991) for buckling cannot predict the level of deformation in a tunnel. The hard rock squeezing index can indicate the anticipated level of squeezing. The index prediction is based on the orientation of the foliation with respect to the orientation of the drift, the foliation spacing and the stress to strength ratio. It does not, however, provide guideline on the selection of appropriate support. Well calibrated numerical methods can represent the rock mass conditions and investigate different design strategies and support scenarios.

3. Capturing the buckling mechanism in numerical modelling

The buckling mechanism at the LaRonde Mine has been reproduced using the 3D DEM, Karampinos et al. (2015a). The use of DEM models was justified in order to explicitly reproduce the rotation of rock blocks, the dilation of the fractures and the detachment of rock blocks from their initial positions. The developed 3DEM models were successfully calibrated to underground observations.

In this analysis it was necessary to make certain simplifications, due to computational and time constraints, in the way a 3D advancing face was represented in a 3D model. The progressive stress redistribution and displacement was simulated using a pseudo-3D approach. This was achieved by the progressive reduction of the forces acting at the boundaries of the excavation by a reduction factor (r) through a series of modelling steps (Karampinos et al., 2015a). For $r = 1$ the mining face is considered to be ahead of the modelled section. As r reduces, the face approaches and overpasses the modelled section. At the last modelling step ($r = 0$) the face has no influence on the modelled section. This is illustrated in Fig. 1. The model captured the progressive extent of joint slip and plastic zones around the opening as observed in several squeezing case studies and indicated a direction of squeezing normal to the foliation planes. These calibrated models were subsequently extended for the explicit introduction of reinforcement elements at different deformation stages. This has resulted in an improved understanding of the impact of different support strategies mitigating ground deformations at the LaRonde Mine.

4. Explicit representation of reinforcement

Once a series of numerical models capturing the buckling phenomena were constructed and calibrated it was possible to explore the role of reinforcement. The mechanical behaviour of reinforcement can be modelled explicitly using structural elements. Following a series of numerical experiments, the global reinforcement elements (Itasca Consulting Group Inc, 2013) were successful in capturing the performance of the reinforcement in structurally driven squeezing conditions at LaRonde, Karampinos et al. (2016).

Global reinforcement elements take into account the plastic deformation in the rock mass in which the bonding between the rock bolts and the rock may fail in shear. The elements allow the modelling of shearing resistance as provided by the bond between the reinforcement element and either the grout or the rock as presented in Fig. 2. Each element is divided into a number of segments with nodal points located at the end of each segment. A finite difference zone is associated with each node for the calculation of the shear forces between the element and the zones. The rock bolt shear behaviour of the interface between the bolt and the grout or the rock is simulated as a spring-slider system between the nodes. An elastic perfectly plastic material model is assigned to this system. The axial stiffness of the steel is controlled by the cross sectional area and the Young's modulus of the bolt. A tensile strength and a strain limit can be assigned to the element. It is consequently possible to simulate the rupture of the bolts under loading.