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Numerical modeling of failure mechanisms in phyllite mine slopes in Brazil

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ABSTRACT

This paper presents three case studies comprising failure mechanisms in phyllite mine slopes at Quadrilátero Ferrífero, State of Minas Gerais, Brazil. Numerical modeling techniques were used in this study. Failure mechanisms involving discontinuities sub parallel to the main foliation are very common in these mines. Besides, failure through the rock material has also been observed due to the low strength of phyllites in this site. Results of this work permitted to establish unknown geotechnical parameters which have significant influence in failure processes, like the in situ stress field and the discontinuity stiffness.

1. Introduction

Soft rocks affected by complex tectonic processes tend to present a very peculiar behavior. When slopes are excavated in these rocks, a variety of failure mechanisms can take place. These mechanisms have usually been affected by many different factors, like the geological structures and the weathering grade of the rock. A typical case of this behavior is associated with metamorphic rocks. Intense tectonic activity and the effects of chemical degradation of these rocks in tropical climate are of concern.

There is an important province of gold and iron ore occurrences in Brazil called Quadrilátero Ferrífero (QF), whose structural geology is connected to several past deformation tectonic events. This region is located in the central-southern portion of the State of Minas Gerais, at the southern side of São Francisco Craton (Fig. 1). It ranges an entire area of 7200 km^2. Metamorphic rocks in this region were extremely susceptible to past deformation events. Besides, the weathering grade of these rocks is normally high, which is another effect to be considered in their behavior.

Iron and gold open pit mines at QF usually present failure problems in phyllite slopes. This study is focused on case studies involving failure along these slopes. Large scale mine slopes were also considered in this study. Therefore, stress–strain analyses have been applied to consider deformation of the discontinuities and rock masses.

This paper has been based on researches developed by Lopes, Silva and Pinheiro [1,2]. Two types of failure mechanisms due to discontinuities are discussed: flexural toppling and buckling. These mechanisms are related to discontinuities sub parallel to the main foliation in phyllites. A combined failure mechanism along the rock mass and the main foliation discontinuity is also presented.

The studies show the importance of geological structures and the low strength of phyllites in failure mechanisms of mine slopes at QF.

2. Numerical modeling of failures in large scale phyllite mine slopes at QF

2.1. Flexural toppling failure in an iron mine

A flexural toppling failure in an iron mine located in Itabirito, Minas Gerais, QF, is presented. The software UDEC, from Itasca Consulting Group Ltd. was used. As the discrete element method is able to represent failure along discontinuous materials, a comprehensive insight in the failure process was expected with this study.

The failure occurred in 2004 involving foliation discontinuities of a sericitic phyllite. It happened after a rapid pushback in the sericitic phyllite slope face. Vertical displacements measured in the toppling region at the slope face reached a maximum value of 0.8 m, with average value equal to 0.3 m.

The studied region is constituted of a slope with benches 10 m high, catch benches 6 m wide and projected face angles of 480. The

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pit had reached a profundity of 220 m. Fig. 2 displays a partial view of the slope with the position of sericitic phyllite.

Although the failure mechanism had not affected the global stability of the slope, the displacement values evoked some questions about the final pit stability and the safety of mining operations at the toppling area.

Figueiredo and Aquino had presented a previous study of this failure [4]. They used the software Phase 2, Rocscience Inc., in the analyses; their model is displayed in Fig. 3. Many materials were included in that model representing the various lithologies. The lithology directly involved in toppling failure is the Fs (sericitic phyllite). The Fd (dolomitic phyllite) presented large values of displacements during the flexural toppling failure process in the Fs. This lithology is below the Fs (see Figs. 2 and 3).

Initial values of mechanical properties of these materials were obtained by internal mine reports and by literature review. During the analyses they were settled, according to the field evidences of displacements in toppling region.

The in situ stress field was supposed to vary with k values equal to 0.5, 1.0 and 1.5. This range has been considered typical of the problem depth, according to international experience of in situ stress measures and the behavior of rock masses with similar deformability parameters [5,6].

Shear and normal stiffness of joints are dependent on the applied normal stresses. Expressions for calculating them can be found in the literature [7,8]. For small depths, where applied normal stresses are less than 0.01 MPa, normal stiffness and shear stiffness were 40 and 0.4 MPa/m, respectively. For greater depths, more than 40 m, applied normal stresses are in the range 0.1–3 MPa and values were 40 MPa for the normal stiffness and 4 MPa/m for the shear stiffness. Figueiredo and Aquino used these values during the analyses with Phase 2 (Rocscience Inc.) [4].

According to the back-analyses of flexural toppling done by Figueiredo & Aquino an in situ stress field with a k value of 1.5 was a situation that yielded displacements close to those observed in the field [4]. The maximum displacement occurred near the contact between sericitic and dolomitic phyllites. The large deformation of the dolomitic phyllite when excavated was found to be the inducing factor of the failure mechanism in the sericitic phyllite.

Some simplifications of the model presented in Figueiredo & Aquino were necessary to facilitate execution of the software UDEC [4]. One of them was to consider an elastic behavior for the rock material to reduce the computational effort and to simplify the input data. It avoided the specification of mechanical material properties, peak and residual, for all the rock mass and focused the study only on toppling mechanism, as failure of the rock mass is not possible in elastic behavior.

Discontinuities were introduced in the model only in sericitic phyllite; this simplification was done in the model studied by Figueiredo & Aquino [4].

Fig. 1. Quadrilátero Ferrífero location [3].

Fig. 2. Partial view of east portion of the slope, in February, 2005 [4].

Mesh automatic generation in UDEC was used. It fills each block with triangular-shaped finite difference zones. Mesh refinement in toppling region was necessary due to the large displacements expected. Fig. 4 shows the mesh aspect in the phyllite region and its neighborhood.

Values of normal and shear stiffness of discontinuities used by Figueiredo & Aquino were also used in this study [4]. They were considered representative of the foliation discontinuities in the site because they had already been obtained after back-analyses of the failure.

In situ stress field was also varied with k values equal to 0.5, 1.0 and 1.5 as it had been done in Figueiredo & Aquino [4].

2.1.1. Model results and discussion

Magnitude of displacements and deformations and displacement pattern vectors were monitored in this study for three values of in situ stress field, $k = 0.5$, 1.0 and 1.5.

Horizontal displacements for $k = 1.5$ are presented in Fig. 5. Maximum values of horizontal displacements in all models occur in the top of discontinuity columns and are associated with their separation, which is a typical characteristic of flexural toppling.

Vertical and horizontal displacements became larger with the increase of k value. Higher values of displacements are observed near the contact between sericitic and dolomitic phyllite, demonstrating the importance of dolomitic phyllite deformation in the beginning of the failure process.

Toppling column separation is a common feature of all models with different k values. Fig. 6 shows the displacement pattern vectors for $k = 1.0$. Vector displacement directions show clearly the top column separation and the flexure of columns.

The results showed the effect of in situ confining stresses and the excavation in sericitic phyllite. Lateral stress relief due to this excavation is directly related to tension stresses in top flexural columns and their consequent separation. As the value of k increases this effect is more pronounced, as expected.

2.2. Buckling failure case study

Buckling failure has been observed in mine slopes of the QF as a local failure mechanism in a slope bench or affecting many benches in a mine slope. Although these buckling failure