# Numerical modeling of buckling failure in a mine slope

## *Modelagem numérica da ruptura por flambagem em um talude de mina*

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**Abstract**

*In this work the failure mechanism of flexural buckling that occurred in Pau Branco Mine, of Vallourec & Mannesman Group, in 2002, was studied through the finite element method. The software Phase2, from Rocscience Inc. was employed in the analyses. Despite being a method applicable to continuous rock masses, discontinuities may be included in the model using joint elements. Modeling is simpler, avoiding the difficulties of using distinct element methods, due to the relative complexity of the geological section examined, where it was necessary to represent the variability of the foliation attitude, due to the pattern of the observed folds. The consideration of this variability was essential to reproduce buckling failure. Back analyses of failure mechanism were done, leading to representative values of the in situ stress state and the normal and shear stiffness modulus of the foliation discontinuities. The parameters generated by the analyses are extremely useful for further stability analyses in the phyllite slopes of Pau Branco Mine.*

***Keywords:*** *failure mechanism, flexural buckling, mining slope stability, stress-strain analyses*

**Resumo**

Nesse trabalho, o mecanismo de ruptura por flambagem flexural ocorrido na Mina Pau Branco, do Grupo Vallourec & Mannesman, em 2002, foi estudado a partir da aplicação de modelagem numérica por elementos finitos. O programa Phase2, da Rocscience Inc., foi empregado nas análises. Apesar de ser um método aplicável a maciços contínuos, as descontinuidades podem ser incluídas no modelo, utilizando-se elementos de juntas. A modelagem é mais simples, evitando-se as dificuldades de utilização de um modelo de elementos distintos, devido à relativa complexidade geológica da seção analisada, onde foi necessário representar a variabilidade da atitude da foliação, devido ao padrão de dobramentos observado. A consideração dessa variabilidade de atitude foi essencial para reproduzir a ruptura por flambagem. Foram feitas retroanálises do mecanismo de ruptura, obtendo-se valores representativos do estado de tensões in situ e dos módulos de rigidez normal e cisalhante das descontinuidades de foliação. Os parâmetros gerados pelas análises são extremamente úteis para futuras análises de estabilidade nos taludes de filito da Mina Pau Branco. Além disso, o trabalho também serve de referência para estudos futuros de flambagem flexural, já que são muito raros os trabalhos envolvendo a modelagem numérica desse mecanismo.

**Palavras-chave:** Mecanismo de ruptura, flambagem flexural, estabilidade de taludes de mina, análises tensão-deformação.

## 1. Introduction

Rock masses of weak metamorphic rocks associated to the presence of intense tectonic activity are propitious to many failure modes in slopes. In some cases these rock masses behave as pseudo-continuum or equivalent continuum, especially if the alteration grade is high. However, even with high alteration grade, these rock masses present preserved geologic structures that can result in structural controlled failure mechanisms. Another possibility is the occurrence of hybrid failure mechanisms involving intact rock and discontinuities. In slope mines, especially in high ones, failure mechanisms are associated with considerable deformation, requiring a stress-strain analysis to provide the correct understanding and representation of the failure process.

Sjöberg (2000) discusses many possible failure mechanisms in large-scale rock slope mines. This author presents a comprehensive literature review on failure mechanisms in mine slopes, which focused on the author's understanding and analysis of physical process involved. Some of these mechanisms are studied by Sjöberg (2000) through numerical analysis. One of the mechanisms presented by Sjöberg (2000) that has received little attention in the literature is buckling. This author describes this mechanism and presents kinematic conditions for its occurrence.

Cavers (1981) was one of the few authors to study the buckling failure mechanism in slopes. In his work he discusses the flexural and the three-hinge buckling failure mechanisms (see Figure 1).

In Cavers' work (1981) simplified models for buckling and three-hinge buckling are proposed. In the case of flexural buckling, linear elastic behavior is assumed for the buckling column.

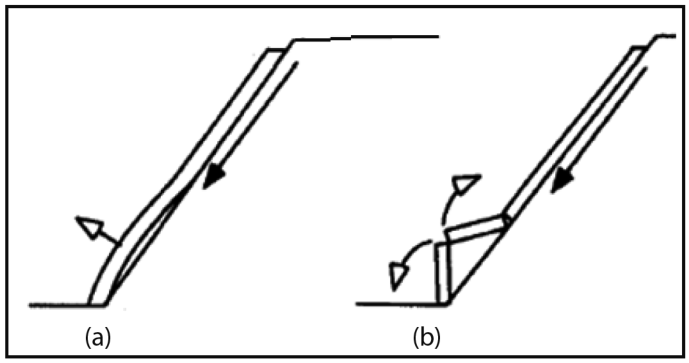


Figure 1
Buckling failure mechanism: (a) flexure buckling; (b) three-hinge buckling (after Cavers, 1981).

Cavers (1981) proposed a critical height for the occurrence of flexural buckling, based on Euler's theory.

In case of three-hinge buckling, rock blocks are considered rigid. Cavers' proposal is based on limit equilibrium methods.

Perhaps, due to arbitrary simplifications assumed by Cavers (1981), his models do not yield coherent results neither for flexural nor for three-hinge buckling failure in phyllite slope mines.

Adhikary et. al. (2001) discuss the occurrence of toppling and buckling flexural mechanisms in foliated rock masses, focusing their occurrence in slope mines (see Figure 2).

Based on numerical models, Adhikary et. al. (2001) also proposed a critical height to the occurrence of flexural buckling in large-scale rock slopes, subject to larger deformations. Their results contradicted Cavers' model (1981).

In Quadrilátero Ferrífero (MG, Brazil), a region of rich mineral deposits of iron and gold, the occurrence of buckling was observed in two slope mines, in Córrego do Sítio mine (Santa Bárbara) and in Pau Branco mine (Alphaville), as showed in Figures 3 and 4. In both cases, failure occurred in phyllite slopes.

In the Córrego do Sítio gold mine buckling occurred as a local failure mechanism in a bench slope (see Figure

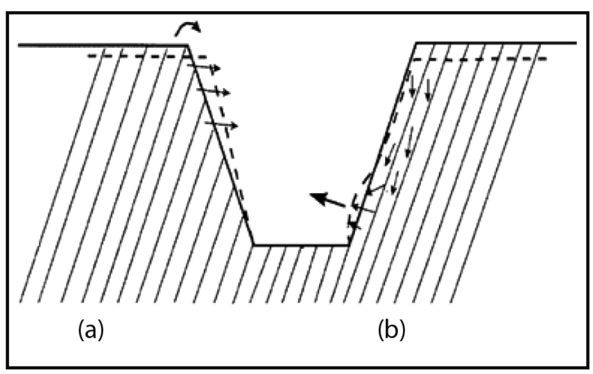


Figure 2
Failure mechanisms in foliated rock slopes: (a) flexural toppling; (b) flexural buckling (after Adhikary et al., 2001).

3). Lopes (2006) demonstrated that this failure mode has had no influence in global slope stability. This author studied a major failure occurrence in the slope of Figure 3 through numerical analysis; the results showed that the mechanism was a circular one combined with plane shear failure.

In Pau Branco iron mine buckling failure reached many benches of phyllite rock slope (see Figure 4). This failure is studied in this work through numerical models to permit the comprehension of the failure process. Also the carrying load conditions involved and the strength and deformability parameters of the rock mass and discontinuities were determined by back-analysis.

Figure 3
Buckling failure in a bench slope (Lopes, 2006).

Figure 4
Buckling failure observed at Pau Branco Mine in 2002

## 2. Materials and methods

### Area description – Pau Branco Mine

The Pau Branco Mine, belonging to the Vallourec & Mannesman Group, an open pit iron ore mine, lies approximately 23 km from Brumadinho city. Its access is done by the BR-040, 30 km from Belo Horizonte, the State capital of Minas Gerais.

The region is in the southwestern portion of the Quadrilátero Ferrífero. The ore exploited in the Pau Branco Mine is among the richest in the world, due to the privileged location of the extraction zone, in Moeda Sierra, in the western flank of Moeda Synclyne. The company extracts and processes three types of iron mines: hematite, goethite and itabirite.

The Pau Branco Mine rocks belongs to the Itabira and Caraça Groups, Minas Supergroup, and the mineralized zone is situated in the Cauê Formation, overlaid by the phyllite of Batatal Formation.

The general direction of this zone is NNW-SSE; the layers dipping to SE with an average dip around 45º, varying between 35º to 70º (Scarpelli, 1994).

These changes are due to secondary folds, associated with the main folding event, N-S. A second folding event, with axis nearly perpendicular to the major one, E-W, seems to be responsible for the winding pattern of the layers and for relatively abrupt changes in the general strike of foliation (Figure 5).

Figure 5
Folding with direction axis E-W, in the West Slope.

## Numerical model features

Buckling failure occurred as a global failure mechanism, affecting many benches. Large deformations were observed; see Figure 4. A stress-strain analysis is the best method for evaluating slopes affected by this mechanism because it considers the deformations of the rock mass.

The finite element method was chosen to study the failure mode occurred in the West Slope of Pau Branco Mine. The software Phase2, Rocscience (Canada), was used in the analyses.

Stress- strain analyses permitted the back-analysis of the failure mode. The main goals of the analyses were a better understanding of the phenomenon, as well as the calibration of rock mass geomechanical parameters.

Buckling failure occurred in 2002, affecting many benches. A geological preliminary model to understand the phenomenon, proposed by a consulting company (BVP Engenharia, 2007), was used in the analyses. This model is represented by a typical geological section, see Figure 6. The foliation trace of the rock mass in Figure 6 shows the dip variability of this structure, due to folding, as described earlier and already illustrated in Figure 5.

Folding of the foliation, with the consequent verticalization of this structure creates the favorable kinematic conditions for buckling occurrence. Due to impact of the failure, it has been mandatory to maintain a hematite portion below the dolomitic phyllite to continue safe mining.

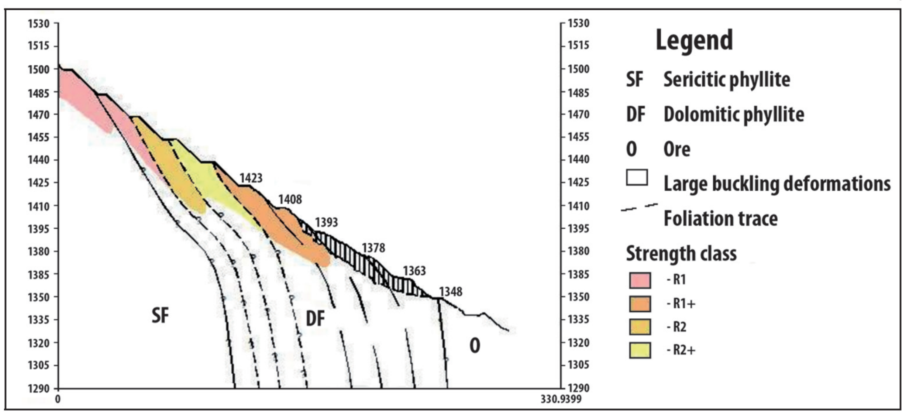


Figure 6
Proposed geologic model (BVP, 2007).

## 3. Results and discussion

The simplified geological model used in the analyses is presented in Figure 7, with the finite element mesh generated in Phase2. Foliation discontinuities were explicitly inserted in the model, using joint elements, only in buckling occurrence region to decrease computational effort. A discontinuity spacing of 1m was used in the analysis to represent the observed spacing of layers affected by buckling in 2007. The discontinuities in the superior portion of the model have a dip value of 60°, which gradually increases to 80° in the inferior part of the model, to represent the folding of the foliation (Figure 6).

The mesh definition was obtained through trial and error. The discretizations should be increased significantly along joint elements region to assure the results were not mesh-dependent.

Boundary conditions in terms of displacements were taken for the analyses, see Figure 7. Displacements are fixed in x direction along lateral boundaries of the model and fixed in y direction along the bottom boundary. Gravitational effects were introduced in the model, so stresses vary with depth.

The Mohr Coulomb constitutive plastic model was used in the analyses. Strength and deformability properties were obtained from internal reports of Pau Branco Mine. Mohr-Coulomb slip joint criterion was used for the discontinuities. Shear strength discontinuity properties were also obtained from internal mine reports.

Shear and normal stiffness of discontinuities were calibrated by back-analyses. Initial values of joint stiffness were calculated according to the following expressions from Barton & Choubey (1977) and Bandis et al. (1983):

$$ks=(100/L)\,\sigma_n \tan[JRC \log_{10}(JCS/\sigma_n)+\phi_r] \qquad (1)$$
$$\sigma_n \le 0{,}01\text{MPa},\; k_n=100k_s$$
$$\sigma_n \ge 0{,}01\text{MPa},\; k_n=10k_s$$

where
$k_s$ is the joint shear stiffness.
$k_n$ is the joint normal stiffness.
$L$ is the joint length,limited by the spacing of transverse joints."
$\sigma_n$ is the normal stress along the joint.
JRC is the joint roughness coefficient.
JCS is the joint wall compressive strength.
$\varnothing_r$ " is the basic friction angle of the joint.

The initial value of $k_s$ was 40MPa/m, and $k_n$ was 4MPa/m.

Further details about the model input can be found in Silva (2009).

The model was calibrated using displacement values described in BVP Engenharia report (2007), as well as region the occurrence of tension cracks in an extension of 400 to 500m beyond the slope crest, also according to the report of BVP. In situ stresses found through back-analyses yielded a value of k equal to 1, where k is the ratio between horizontal and vertical in situ stresses. Shear and normal discontinuity stiffness, also obtained through back-analyses were ks=5MPa/m and kn=50MPa/m.

Buckling occurrence can be seen in Figure 8, which shows the deformed boundaries of discontinuities. A scale factor to increase the size of deformed boundaries was used to allow the visualization of the model deformation mode. Buckling failure affected many benches, so it could be interpreted as a global model failure; it is clear from Figure 8.

Yielded elements in the model are shown in Figure 9. Tension crack occurrences are observed along the slope top, in the whole extension of the model, as described in BVP Engenharia report (2007). Yielded region is located mainly in the discontinuity region, showing their importance in slope failure mode.

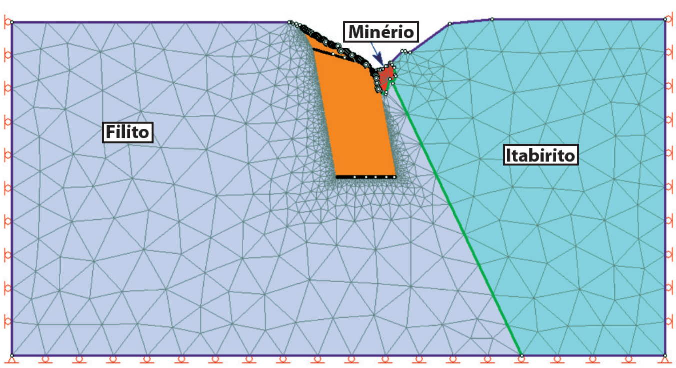


Figure 7
Geologic model and mesh used in Phase2

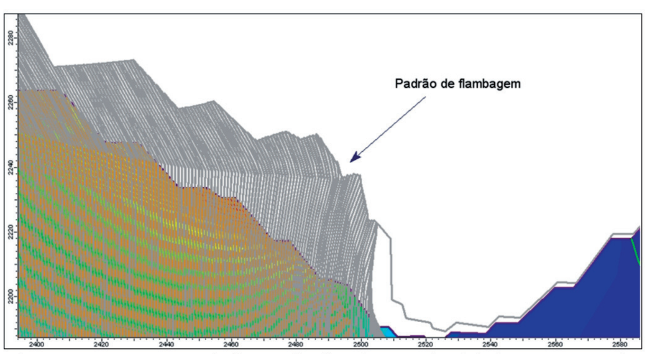


Figure 8
Discontinuity deformed boundaries, showing buckling failure.

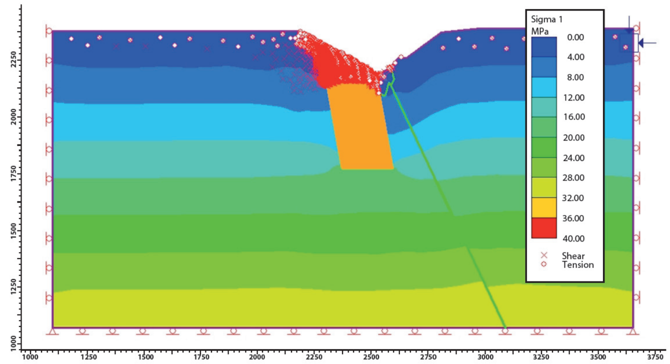


Figure 9
Yielded elements in the model..

The numerical modeling of buckling failure in Pau Branco Mine was very useful for the estimation of geomechanical parameters of the rock mass and the discontinuities.

Folding pattern of the foliation with consequent verticalization of this structure creates the kinematic favorable conditions of buckling failure. The representation of this pattern in the model was fundamental to obtain consistent results. On the other hand, the model achieves great complexity and convergence is reached after a large number of interactions. A small change in the input data can cause collapse of the model. If the discontinuities are removed from the model, displacements decrease considerably; the collapse risk is smaller and there in no formation of tension cracks in the slope top.

The use of a numerical model for discontinuous rock masses, as the distinct element method, would be of great interest to refine this study and to improve the understanding of the failure mode.

## 5. Referências bibliográficas

ADHIKARY, D. P., MÜHLHAUS, H. B., DYSKIN, A. V. A numerical study of flexural buckling of foliated rock slope. ***Int. J. for Numerical and Analytical Methods in Geomechanics,*** 25, p. 871-884 2001.

BANDIS, S. C., LUMSDEN, A. C., BARTON, N. R. Fundamentals of rock joint deformation. Int. ***J. Rock Mech. Min. Sci. & Geomech. Abstr.***, 20-6, p. 249-268, 1983.

BARTON, N., CHOUBEY, V. The shear strength of rock joints in theory and practice. ***Rock Mechanics***, 10, 1/2, p. 1-54, 1977.

BVP ENGENHARIA. ***Parecer Geotécnico da Inspeção dos Taludes da Cava, Mina Pau Branco Vallourec & Mannesman.*** (Relatório interno). 2007. 24f.

CAVERS, D. S. Simple methods to analyze buckling of rock slopes. ***Rock Mechanics***, 14, 191, 87-104, 1981.

LOPES, M. C. ***Comportamento geotécnico e mecanismo de ruptura em rochas brandas - Mineração Córrego do Sítio.*** Ouro Preto: Programa de Pós-Graduação em Engenharia Mineral - Universidade Federal de Ouro Preto, 2006. 94f. (Dissertação de Mestrado).ufop.br

ROCSCIENCE INC., ***Phase Version 7.0 - Finite element analysis for excavations and slopes.*** www.rocscience.com, Toronto, Ontario, Canada, 2008.

SCARPELLI, A.G. ***Classificação geomecânica aplicada à avaliação da estabilidade de taludes em minas de ferro do Quadrilátero Ferrífero.*** São Paulo: EESC-USP, 1994. 187f. (Dissertação de Mestrado).

SILVA, C. H.C. ***Comportamento geotécnico dos filitos do Talude Oeste da Mina Pau Branco.*** Ouro Preto: Programa de Pós-Graduação em Engenharia Mineral - Universidade Federal de Ouro Preto, 2010. 111f. (Dissertação de Mestrado).

SJÖBERG, J. ***Analysis of large scale rock slopes.*** Sweden: Department of Civil and Mining Engineering, Division of Rock Mechanics, Lulea University of Technology, 2000. 788f. (Doctoral Thesis).

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