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INFLUENCE OF INDUCED STRESSES BY SUBLEVEL STOPES IN STABILITY CONDITIONS OF DEVELOPMENT OPENINGS IN UNDERGROUND MINES

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Abstract

This work aims to investigate the influence of induced stresses by sublevel stopes in development excavations, which are excavated to access these stopes. Parametric studies changing the position of development openings in relation to stopes were performed in order to evaluate the stability conditions of these openings. Numerical modeling using finite element method was applied to the simulations. An elastic behavior of the rock mass was assumed to allow the simulation of a lot of different opening locations. The results have showed distinct scenarios. Some cases of global collapse were found as well as some situations where the integrity of the openings could be kept. Therefore, the most favorable situations were chosen to perform a plastic analysis in order to have a better knowledge of opening stability conditions. The geometry of the excavations from Caraiba Mining Company, which extracts copper from an underground mine in Brazil, was used in these analyses to illustrate a real situation where many failure problems in these development openings were observed.

Keywords: Mine stope induced stresses; Finite element analyses; Spalling failure; Parametric analyses.

INFLUÊNCIA DAS TENSÕES INDUZIDAS POR REALCES EM LAVRA POR SUBNÍVEIS NAS CONDIÇÕES DE ESTABILIDADE DE GALERIAS DE DESENVOLVIMENTO EM MINAS SUBTERRÂNEAS

Resumo

Este trabalho tem por objetivo analisar a influência das tensões induzidas por realces em lavra por subnível nas galerias de desenvolvimento, que são escavadas para acesso a esses realces. Foram feitos estudos paramétricos variando a posição das galerias em relação aos realces para avaliar as condições de estabilidade dessas galerias, utilizando modelagem numérica através do método dos elementos finitos. Um comportamento elástico para o maciço rochoso foi assumido para permitir a simulação de várias posições para as galerias de acesso. Os resultados mostraram cenários distintos. Alguns casos de colapso global das galerias, bem como situações onde a integridade dessas aberturas pode ser mantida. Como consequência, nas situações mais favoráveis foram feitas análises plásticas de modo a obter um melhor conhecimento acerca das condições de estabilidade dessas galerias. A geometria das escavações da Mina Caraíba, que extrai cobre em mina subterrânea no Brasil, foi utilizada para ilustrar uma situação real, onde muitos problemas de ruptura nas galerias de acesso aos realces foram observados.

Palavras-chave: Tensões induzidas por realces; Simulações por elementos finitos; Ruptura por clivagem axial; Análises paramétricas.

1 INTRODUCTION

The knowledge of the geomechanical behavior of rock masses in large excavations at high depths is a challenging issue that has been studied by engineers for decades. This is a typical situation in underground mines where the induced stresses by large stopes can affect other mine structures, like stope development access or even main service excavations.

The security of mine structures depends on the stress state of the rock mass and its strength. Discontinuities tend to

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control failure mechanisms at low depths but failure process in brittle rocks at high depths often occurs through intact rock. Stresses increase with depth because of gravitational load leading to many instability problems. In addition, the presence of large excavations, i.e., the stopes, creates stress redistributions that affect the stope development accesses, which are usually close to the stopes.

As the development openings are many times smaller than the stopes and because of their position in relation to the stopes, they are usually into the stope zone of influence. Brady and Brown [1] discuss the concept of zone of influence of a larger excavation in a small one closer to it. These authors explain that the zone of influence is a domain of significant disturbance of the pre-mining stress field caused by an excavation. When a large opening is close to a small one, the latter is usually inside the zone of influence of the former. Indeed a good estimation of the in situ stress field which influences the small opening can be yielded by the induced stresses of the large opening in the location of the small one.

In this paper the stability conditions of development openings in an underground mine is studied by parametric analyses of their location, considering the presence of stopes near them. The geometry of the excavations from Caraiba Mining Company, which extracts copper from an underground mine in Brazil is used in the analyses. The mining method employed in Caraiba is sublevel stoping, which leads to very large stopes. These stopes influence the boundary stresses around development openings, leading to failures which compromise the global stability of these openings. Support structures installed in development openings cannot assure their stability because the stress concentrations around these openings are very high. An alternative solution for this problem is the change of the position of the development openings in relation to the stopes as a way to minimize these stress concentrations. On the other hand it can increase significantly the extraction costs, so the focus of the study is trying to keep the development openings as close as possible to the stopes.

1.1 Spalling

A typical failure mode observed in brittle rock masses around underground excavations, subjected to high boundary compressive stresses, is slabbing or spalling from the roof or sidewalls. In this failure mode slabs of rocks can detach themselves from the excavation boundaries with an audible sound. In extreme cases this failure mode may be severe enough to be considered a rockburst. In other situations it is gradual and progressive.

Spalling initiates at right angles to the major principal stress direction, where stress concentration due to compression occurs. The propagation direction of spalling is then parallel to major principal stress. Fairhurst and Cook [2] were the first authors to describe this failure mechanism in a proper way.

Martin et al. [3] remarked that at medium depths spalling occurs close to the boundaries of the openings but as the depth increases the failure zone tends to progress to the interior of the rock mass and, in many situations, causing the global collapse of the opening.

In case of excavations near the production openings of a deep underground mine, stress concentrations are enormous, even when the stopes are backfilled after exploitation. Hoek et al. [4] showed a serious rockfall in an opening caused by spalling in a large metal mine. In another situation these authors showed spalling in a massive quartzite in an underground mine of uranium at a depth of about 1,500m. In this case the spalling did not pose a major threat to the opening stability, although it occurred over many years.

2 METHODOLOGY

As the size of stopes is very large compared to the size of development openings, the study of both excavations in the same numerical simulations is not adequate to predict the behavior of the rock mass around these development openings. The influence of the stress redistributions by stopes on development openings is better represented considering them as single excavations submitted to an in situ stress determined by the stope induced stresses. This issue has been adequately discussed by Brady and Brown [1]. Thus the first step of the methodology is the numerical modeling of the stopes in order to calculate the induced stresses around them.

After calculating the induced stresses around the stopes the in situ stress acting on development openings can be determined. For each different position of the development opening the in situ stress input in development opening simulations is equal to the induced stresses by the stopes on this point. This means that the in situ stress considered in development openings varied during parametric analyses according to the distance of the opening to the stopes and the development opening level.

In order to calculate the induced stresses by the stopes two dimensional numerical modeling of these excavations were performed using the software RS^2, of Rocscience. The geometry of these two dimensional models was obtained by evaluating many sections in the east-west direction. These sections were obtained using the software Examine 3D, of Rocscience [5], over a three-dimensional geometry of the stopes, yielded by the Caraiba Mining Company (Figure 1). After many tries, a representative section of the stopes was achieved, by the superposition of all sections considered. In this way the complexity of the geometry was represented by a conservative approach. The representative section and the finite element mesh used in numerical analyses are showed in Figure 2.

The representative section of the stopes was modeled using the software RS^2 [6] to establish the induced stresses around them. Elastic analyses were performed. Three

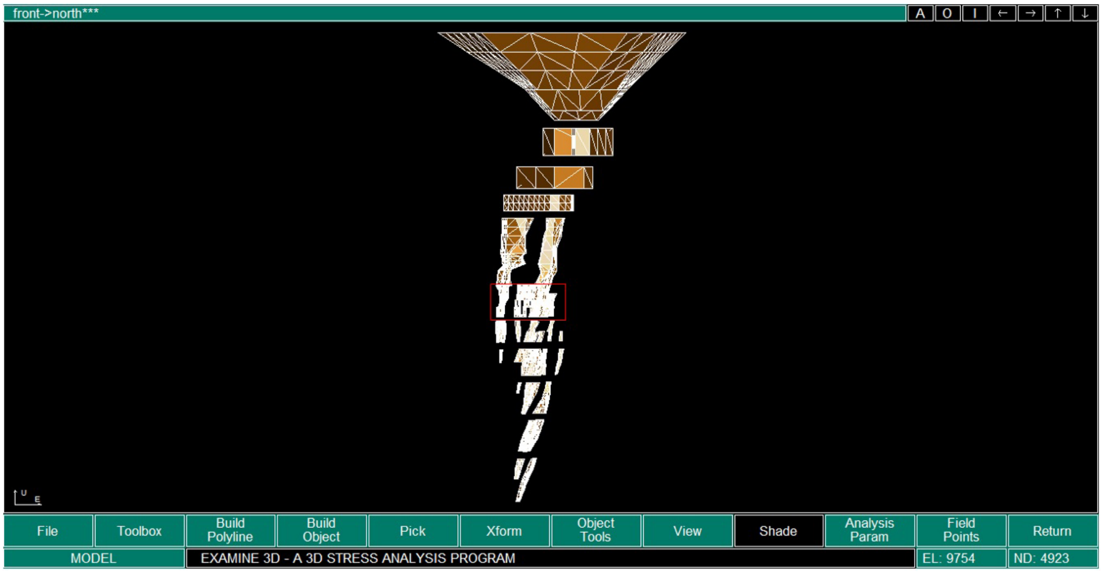

Figure 1. Model geometry showing the open pit and the stopes.

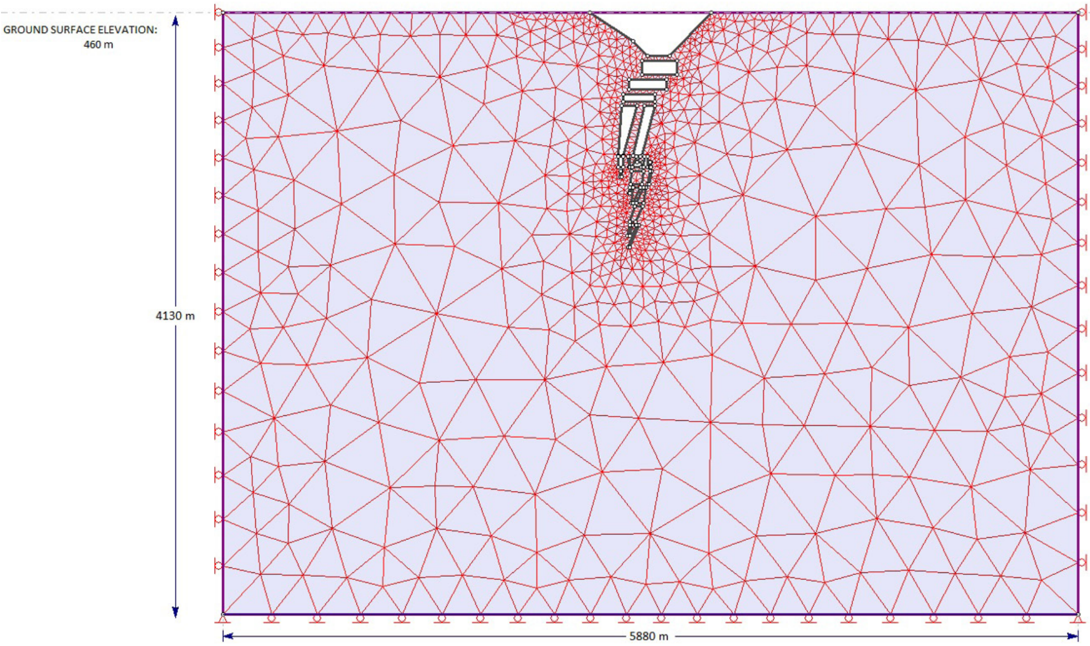

Figure 2. Two-dimensional model of mine geometry showing the finite element mesh.

distinct levels exploited by the company were considered. The position of these levels is showed in Figure 1 by a rectangle. According to information given by the mining company geotechnical staff, development openings in these levels have presented stability problems. Development openings were considered in the region between the stopes, at intervals of 5m. Additionally, development openings along 200m at the right and the left sides of the stopes were considered.

In Figure 3 the representative section of the stopes is showed zooming in the three levels analyzed. The more deepened levels of the model have not exploited yet. In Figure 3 the future excavations in these levels are represented with the finite element mesh inside them. It is also possible to observe in Figure 3 the refinement of the mesh close to the excavations, which has been extensively tested during the finite element analyses. It is necessary to avoid distortions in the results near the excavations.

After defining the stress conditions in the position of each development opening considered, two-dimensional numerical modeling was done. Induced stresses by the stopes calculated using the representative section showed in Figure 2 yielded an estimation of the in situ stresses for

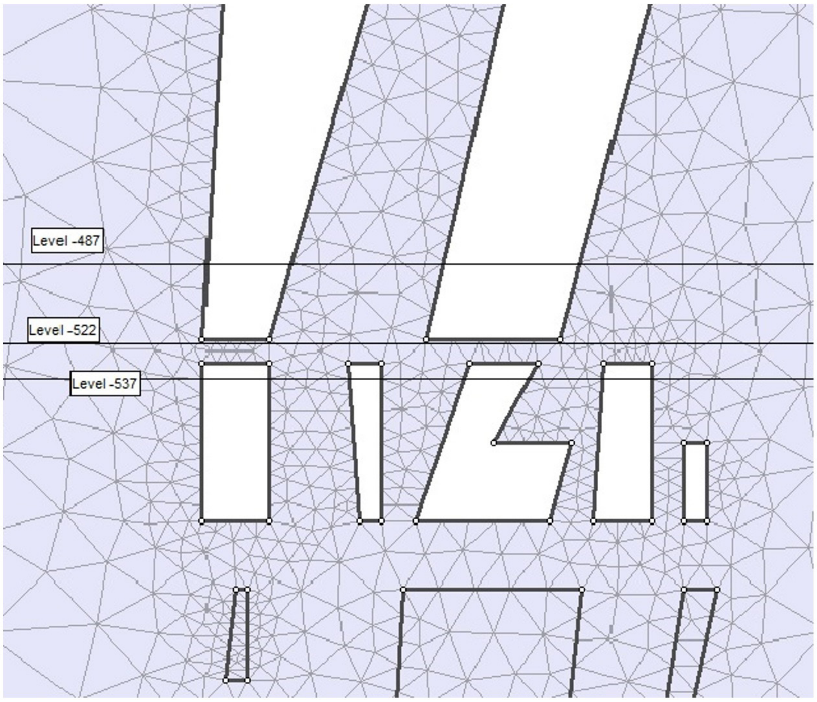

Figure 3. Detailed geometry of the stopes in the three levels analyzed.

these analyses. Values and directions of principal induced stresses at the points where the development openings are positioned were calculated using the results found in the numerical modeling of the section showed in Figure 2. Elastic analyses using the software RS^2 were performed. Factor of safety distributions in the rock mass around openings were generated for each situation.

Plastic analyses were performed using RS^2, only for those elastic simulations which have presented acceptable stability conditions. Yielded points and total displacement in each simulation were observed. These simulations have permitted more accurate analyses of the stability conditions of the openings.

3 RESULTS AND DISCUSSIONS

3.1 Geotechnical Data

Stope development openings in Caraiba Mining Company are excavated in gneiss. The observed failures have showed clear evidences of intact rock failure caused by the stress level. Occurrence of spalling has been largely observed in the development openings.

There have been many previous studies at Caraiba underground mine to determine the in situ stress state. These studies consisted of measurements and back analyses of failures which occurred at the mine in different situations. Vertical stresses are due to gravitational effect and can be calculated by the unit weight of rock mass versus the depth of the point considered. Confining stresses are equal to vertical stresses, yielding a ratio of the average horizontal stresses to the vertical stresses *k* equal to 1, for both lateral directions. The unit weight of the rock mass is equal to 0.027 MN/m^3 and the depths of the three levels modeled are 947 m (level -487), 982 m (level -522) and 997 m (level -537).

The trends and plunges of the principal component in situ stresses are:

- vertical stress: 0/90;
- horizontal stresses: 90/0 and 0/0.

Geotechnical properties of the rock mass have been determined through lab tests and back analyses of failure case studies. Nevertheless the post peak geotechnical properties are completely unknown.

The Hoek & Brown strength criterion [7] was used in the analyses.

In Table 1, the geotechnical properties of the rock are presented.

3.2 Determination of the Induced Stresses by the Stopes

Using the representative section of the stopes showed in Figure 2, induced stresses were calculated by elastic analyses. Stress contours of principal stress σ_1, σ_2 and σ_3 were generated. At the points for each position of stope development openings defined in the methodology, the principal stresses were collected. The inclination of σ_1 with the horizontal axis had to be calculated in order to define the in situ stress directions for numerical models of the stope openings.

The inclination of σ_1 with the horizontal axis was calculated using a tool in RS^2 named "*define user data*", which permits that the user defines an equation through results generated by the software.

3.3 Numerical Modeling of Stope Development Openings

Stope development openings in Caraiba mine have a rectangular section, with 6 m wide and 5 m high. In Figure 4 the model of the development openings and the finite element mesh used in numerical modeling are showed. Again it is possible to observe the refinement of the mesh close to excavation to avoid distortion of the results in this region.

A total of 180 elastic analyses were performed. Elastic analyses were performed due to the great number of simulations. They are very rapid and can yield a first idea of the stability conditions of the excavations.

Safety factor contours were generated to interpret these analyses. They were able to establish the difference between global collapse and potential stable situations, because safety factors show limiting conditions of stress and strength relations where they exist.

Table 1. Strength properties and elastic constants of the gneiss

Parameter	Value
Unconfined compressive strength	162 MPa
m (Hoek & Brown constant)	11.056
s (Hoek & Brown constant)	0.0622
Young modulus	53 GPa
Poisson ratio	0.25

For those situations where contours of safety factors have showed potential stable situations plastic analyses were performed. They were able to confirm if the stability of a development opening can be assured.

For all studied levels, stress conditions which are prone to spalling occurrence were observed. It can be seen in Figure 5, for one of the simulations in the level -487. The excavation showed in Figure 5 is located between stopes, at a distance of 45m from the right stope, at coordinates (964, -487). Values of σ_1 above 30MPa can be observed near the corners of the excavation, demonstrating the presence of compressive stress concentrations, perpendicular to the σ_1 direction.

Due to large differences between in situ stresses σ_1 and σ_3, occurrence of tension around development excavations was a frequent phenomenon.

The results obtained for each level are presented in the following sections.

3.3.1 Level - 487

According to an economical point of view, it is desirable to locate the development excavations between stopes. The results of the simulations showed that the majority of development excavations between the stopes or close to them have suffered global collapse due to the large region of tension around their boundaries, except for some few

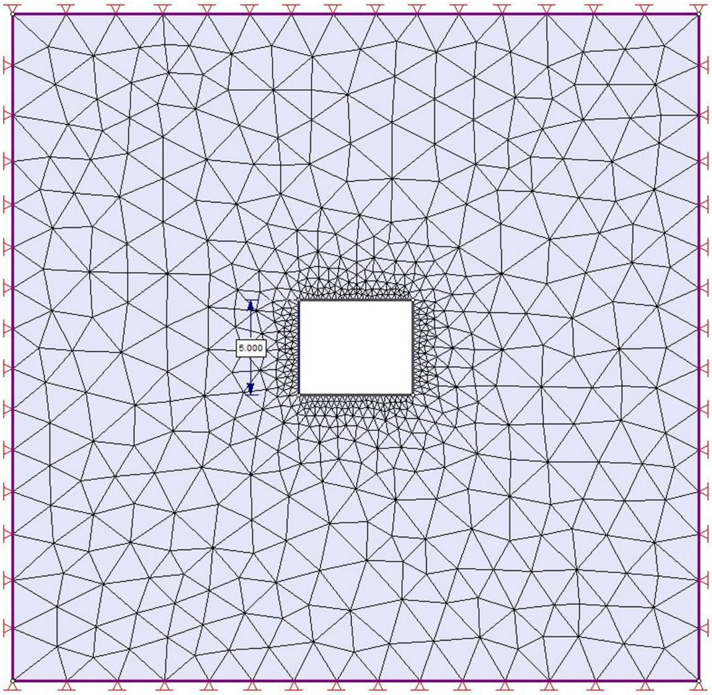

Figure 4. Model of stope development opening with finite element mesh.

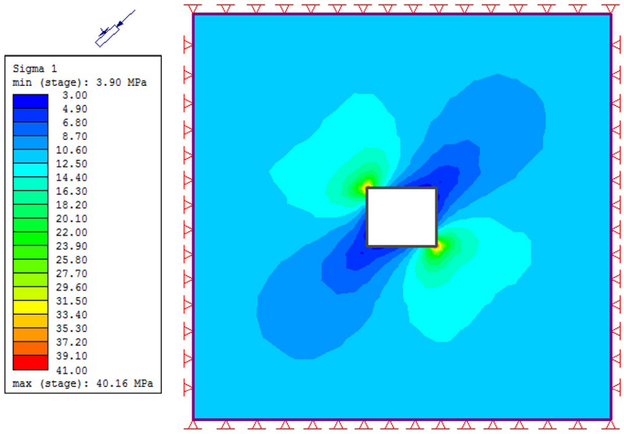

Figure 5. Distribution of maximum principal stresses around excavation, level -487, showing spalling.

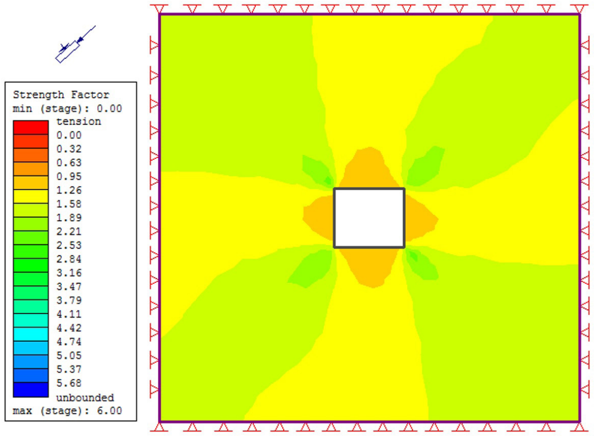

Figure 6. Strength factor contours for an excavation between stopes, at coordinates (964, -487).

situations. An excavation located at 25 m from the left stope, at coordinates (964, -487), has not showed the presence of tension at its boundary, see Figure 6. But strength factors close to 1 due to compressive stress concentrations can be seen around the boundary of the excavation.

Another option for the location of stope development excavations would be at some distance apart from the stopes, instead of a position between them. In some of these situations a noticeable improvement of stability conditions of the excavations could be observed. Nevertheless, in order to reach acceptable strength factor values the distance from the stopes needs to be 60 to 80m, which can lead to impracticable economic conditions, due to transportation costs.

3.3.2 Level - 522

Induced stresses by the stopes in this level cause high stress concentrations in the proximity to these stopes. In points below the stopes, stress levels have reached extreme values, at around 200MPa. For this reason, these regions were not considered for the location of development excavations.

Development excavations between the stopes and close to them have showed worse stability conditions than those in the level -487. One of the best situations is for a development excavation located at a distance of 10m from the right stope, at coordinates (990, -522), see Figure 7. It has showed a potential failure zone which extended about 1 m beyond the excavation boundary. In addition, the presence of tension at the boundary sides of excavation might indicate a potential failure condition.

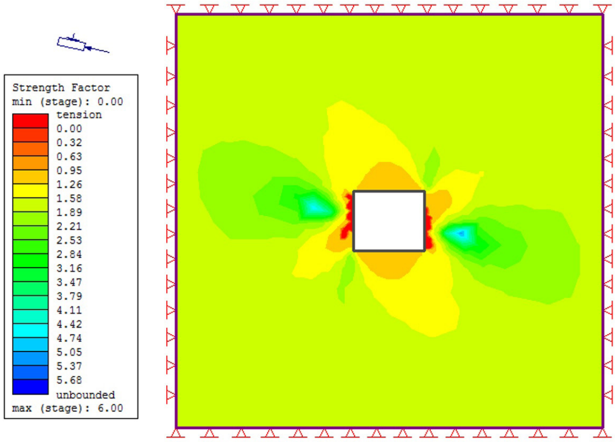

Figure 7. Strength factor contours for an excavation between stopes, at coordinates (990, -522).

Development excavations outside the region between the stopes, at a distance of 20 m from the left stope have not showed the presence of failure by tension. However the strength factor contour values showed a region of compressive stresses with values close to 1 in the entire excavation boundary. Again only those excavations located far from the stopes have presented acceptable strength factor values. The minimum distance from the right stope to assure good stability conditions for the development excavation was 60 m. This situation is the same of the level -487. In case of the left stope the minimum distance from it to assure good stability conditions is at around 30 m.

3.3.3 Level - 537

This level is particularly different from the others because it intersects many stopes of small dimensions. Development excavations located at the left or right side of the stopes, until a distance of 10 m beyond them have showed the presence of tension at their side walls. For distances more than 10 m beyond the stopes, right or left side, compressive stress concentrations can be observed and strength factor contours have showed values close to 1 around the entire boundary of the excavations.

3.3.4 Plastic analyses

Elastic analyses only yield the potential failure zones around an excavation. No information about the displacements can be taken from these analyses, because in elastic behavior they are not representative of real situations. Moreover yielded region and the failure mode (shear or tension) can only be obtained by plastic analyses.

The residual properties of the gneiss are not known. Considering that the rock mass is subjected to high levels of stress, conservative estimations of residual properties were assumed. The Hoek & Brown strength criterion [7] requires three residual parameters, *m*, *s* and *dilation*. Values assumed in the simulations were 1, 0 and 0, respectively.

Some simulations performed using elastic analyses were chosen to proceed with plastic simulations. Only levels -487 and -522 were considered. All the selected cases represent excavations between the stopes because they are more favorable according to an economic point of view.

In the level -487 the excavation showed in Figure 6 was chosen for plastic analysis. Plastic analysis of this excavation has showed excellent stability conditions, with only one yielded element at the side wall. Maximum displacement at the excavation boundary was approximately 1mm.

In the level -522 the excavation showed in Figure 7 was chosen for plastic analysis. The results have showed a large area of yielded elements around its entire boundary, most of them by tensile failure. Maximum displacement of approximately 6mm was detected at the side walls.

4 CONCLUSIONS

Excavations of small dimensions inside the zone of influence of larger excavations are affected by stress redistributions caused by these large excavations. It is the situation observed in underground mines where induced stresses by large stopes cause instability problems in stope development openings. As the development openings are commonly located near the stopes to diminish economic impacts, the effect of stress redistributions by stopes is significant.

This study showed that stress redistributions caused by large stopes have a significant influence in nearby small excavations. These stress redistributions were not homogeneous, leading to a complex in situ stress acting on stope development openings, where the maximum principal stress can be many times larger than the minimum one. These stress differences caused serious instability problems in development openings, as confirmed by the majority of models.

Only one situation modeled with development openings between the stopes have resulted in a stable condition. The other stable situations were for development openings which are located very far from the stopes, bringing major economic impacts on transportation costs.

Living with instabilities in stope development openings could be considered an option but, in this case, it is very important to monitor these excavations continuously. Internal displacements of the rock mass could be an important parameter to control.

According to information yielded by Caraiba mine geotechnical staff costs of support measures to keep the development openings in an acceptable stability condition are prohibitive, so these openings will be located from now on at considerable distances from the stopes.

Three-dimensional models of stopes would be desirable for calculating the stresses at the points where the development openings are located. Yet more efficient three-dimensional software should be used to perform these analyses. In a close future these simulations will be used routinely in engineering practice.

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