Induced stress management in underground mining excavations.

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ABSTRACT: The task of mining the rock body of a naturally distributed ore system is highly complex. This implies fill the mined voids and chambers with fill material of minor strength moduli. This condition may lead to structural unbalance, where the fill performs only as a strain buffer agent. This unbalance progressively subjects the adjacent pillars to overstress beyond the design values. The pillars, in turn, are further mined to reduced their sections, thus originating high stresses that dynamically worsen the overall mining system. It is therefore very important to manage with precision a series of parameters that lead to rational mining practices. This work shows practical examples of induced stress management, and makes contributions to this difficult underground mining issue.

1 INTRODUCTION

Through its various decision-making stages, the exploitation of an underground mining field is greatly conditioned by rock system stability and its various development stages. A large number of mines have been left unexploited and their reserves have been definitively lost because their induced stress problems became unsolvable. Therefore, a series of sensible decisions have to be made at each mining stage of the deposit. The main objective of these decisions should consider a thorough exploitation planning based on stabilizing criteria, to account for the particular features that these deposits may present.

One problem that may arise lies on the complex arrangement of orebodies, compounded with unfavorable geology that does not contribute to mine development stability. This panorama is worsened when considering the mining history of such deposits. It is most likely that significant stresses were induced by the mining process itself, e.g. caved spaces filled with waste rock of heterogeneous strength and qualities and, quite often, a significant increase in caved depth, all of which calls for a sensible planning that takes into account these factors under a new solving criteria.

The initial, natural stress pattern developed at depth in the deposit is transmitted throughout the heterogeneous rockbody. Nonetheless, when performing underground mining operations, regardless their nature, a discontinuity is imposed on such rockbody that results in the release of one or more degrees-of-freedom as a response to such solicitations. No stress can then be transmitted over such discontinuity, thus causing changes on the initial stress distribution in the surrounding rock. Further excavation will increase this effect, even exposing weaker structures and faults, which implies releasing a greater number of degrees-of-freedom within the rockmass. Therefore, a multi-faced problem of stress-strain tradeoff state will be developed through time for each geometrical stage of the system.

From now on, "stress transmission ways" will be the denomination for rock blocks that structurally link and support the masses adjacent to the excavated spaces. They transmit the loads affecting the whole solid. Therefore, any yield from solicitations will arise or progress towards the void surfaces between these structures. Said supporting blocks are the so-called pillars in mining operations, which can be arranged in various configurations, depending on their performance under stress from weight and lateral pressure.

There are numerous reports of underground mining projects which had to resign their reserves due to rockburst problems. A limit situation may arise when rockburst cannot be controlled, either instantly or progressively, without being possible to manage the induced overstress, therefore bringing along the following possible phenomena:

- Triggering the motion of existing faults, which in turn release residual stresses of uncontrollable negative effects.
- New faulting, new discontinuity or yielding planes as a response to the solicitations induced by the mining activities.
- Breakage of the supporting pillars, the indispensable structure for mine life.
- Significant seismic events due to any of the above stress-release phenomenon.
- Other adverse effects.

In addition to reporting on specific stress induction cases that the authors were able to witness, this paper shows an approach to diagnosing the associated problems and the way they were solved in order to continue towards the objectives of rational mining, i.e., the set of procedures that must obligatorily be applied in every excavation made with universally accepted standards for safe and efficient mining.

2 INDUCTION OF ROCK STRESS. BASIC CONCEPTS

At any given depth, the initial stress state of a rockbody can be explicited on a three-axis spatial coordinate system. The vertical component acting on a given point can be determined by the density of the overlying rock mass and its depth, according to expression 1 and Figure1.

$$\sigma v = \gamma z \qquad (1)$$

Where σv is the vertical stress component, γ is the density of the overlying rock mass and z is the rock mass depth.

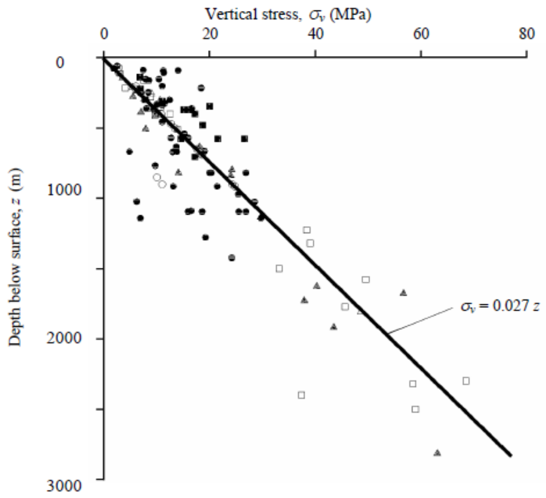

Figure1. Vertical stress measurements from mining and civil engineering projects around the world. (Hoek *et al.* 1993)

The mean horizontal component can be stated as the expression 2:

$$\sigma h = k\ \sigma v = k\ (\gamma\ z) \qquad (2)$$

Where σh is the mean horizontal stress component and k is a relational factor.

The value for k is preliminarily defined by the following expression 3 (Sheorey, 1994) and Figure 2:

$$k = 0.25 + 7\ Eh\ (0.001 + 1/z) \qquad (3)$$

Where *Eh [GPa]* is the mean strain module due to the overlaying rock, measured along the horizontal axis.

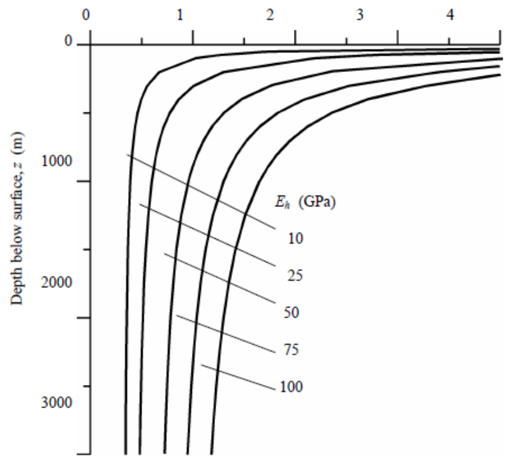

Figure 2. Ratio of horizontal to vertical stress for different moduli based upon Sheorey's equation.(Hoek *et al.*1993)

Based on a thorough statistical analysis performed for the entire planet, the following map in Figure 3 was composed by (Zoback, 1992), showing the direction of the maximum horizontal component of rock stress.

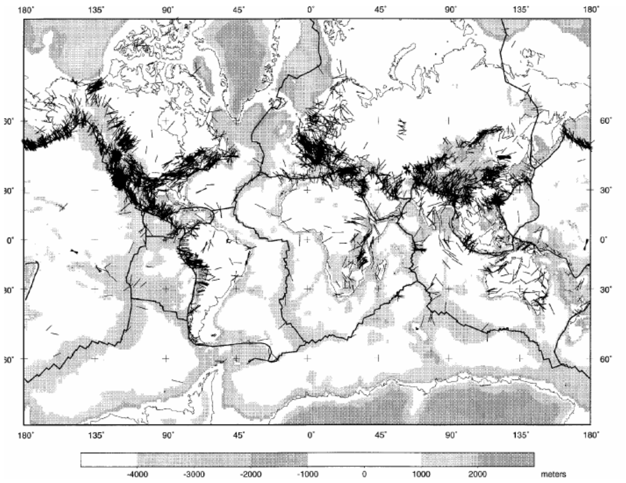

Figure 3. World stress map giving maximum horizontal stress orientations on a base of average topography. Zoback (1992).

The next map (Figure 4) shows the general horizontal stress trends derived from the previous map, as computed by Zoback.

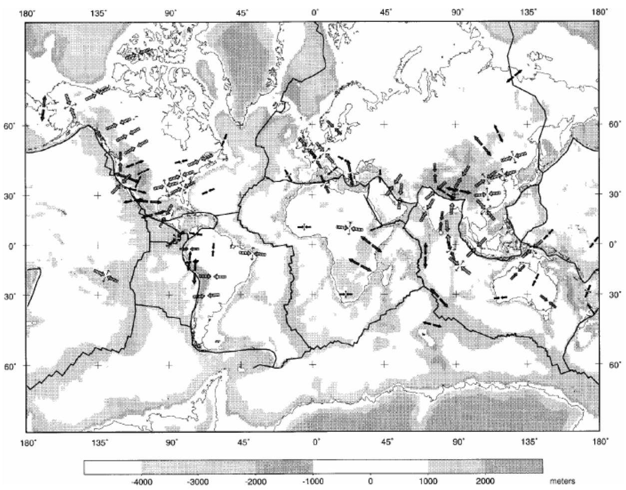

Figure 4. Generalized stress map showing mean directions based on average clusters of data shown in Figure 3. Map provided by Dr M.L. Zoback (1992).

It can be inferred that the likelihood for maximum, mean and minimum ($\sigma 1 > \sigma 2 > \sigma 3$) preliminary stress patterns can be:

- σh-max > σh-min > σv
- σhv > σh-max > σh-min
- σh-max > σv > σh-min

It is recommended to perform, at least, this prioritary analysis in every mining project, in order to know the initial field stress state of the deposit. Nevertheless, it is also critically important to consider all parameters and variables that characterize the deposit's zone and region. In fact, the topocenter's genesis history had most likely to be affected by some altering source, e.g. by the local phenomena that occurred in the forming stage of the deposit, by later tectonical seismicity (main faulting, folding and related phenomena), by the evolution of the deposit confinement in terms of geological and temporal terms, and similar occurrences.

Once the preliminary stress values had been obtained, they are used to design the project excavations that, for the case of mining reserves of orebodies, will be dynamically intensified. That is, continuous changes may be expected for the stress pattern as the overall mining process progresses through time. The mining activities include ore extraction, replacement of chambers and voids with rockfill, reduction of pillars, steady advance towards other level developments, and similar modifying tasks.

3 ROOM AND PILLAR MINING

This system of ore mining does not initially take into account the room (chamber) filling tasks, thus leaving to the pillars the role of being the only bearing structures of the deposit. Stated otherwise, all the loads initially attributed to the depth of the current mining stage, plus the induced stresses, will have to be supported by the pillars.

Firstly, the pillar´s strength shall be such as to withstand the developed stress pattern and, secondly, the excavations adjacent to the pillar must remain stable. This stability, associated to the hydraulic radii generated in the ceiling, can be computed through the Method of Stability Number N'.

In order to understand and measure the above phenomenon, the calculations will consider the strictly vertical load of the overlying rock mass that subjects the pillar throughout the area of support. This area is defined as the half-distance sector separating two consecutive pillars of adjacent chambers. As for the load, it corresponds to the rockmass volume of the overlying pillar sector supported by the proportionally designed pillar´s cross section and rock strength module (see Figure 5).

If the pillar cross-section needs to be reduced for further mining recovery, such action will undoubtedly increase the pillar stress state, being this mining practice a classic example of induced stress on the bearing structure.

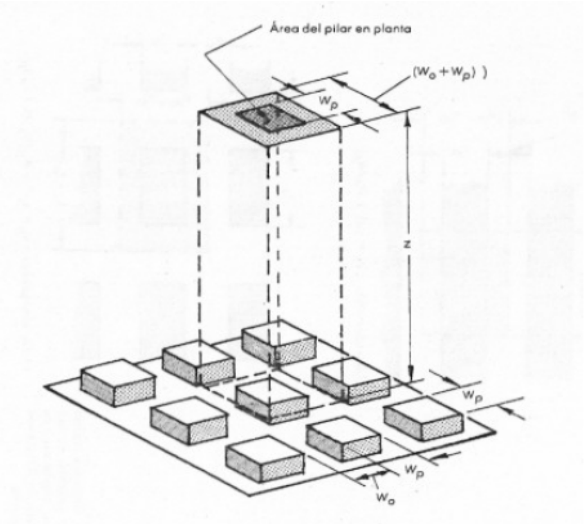

Figure 5. Diagram of distribution of stress by each pillar. Hoek & Brown (1980)

The stability limit for a generic pillar is stated as expression 4:

Pillar strength x pillar area = γz x bearing sector area (4)

Then, the stability condition will be established likewise in expression 5:

Pillar strength x pillar area > γz x bearing sector area (5)

The pillar strength is also conditioned by its slimness. Since the pillar is not confined (i.e. not embodied in a rock mass), its strength will then be related to its non-confined compression strength. The Figure 6 by Hoek & Brown (1980) is used to compute its value.

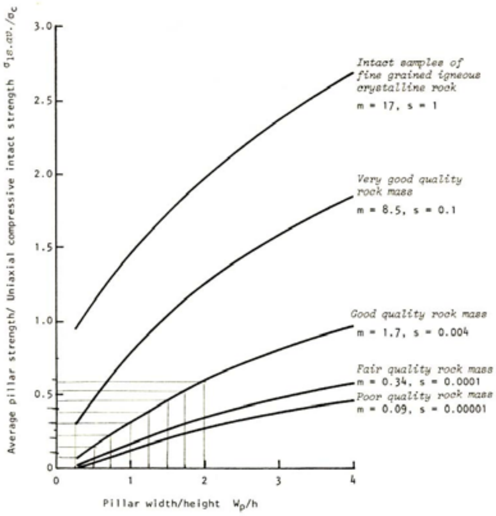

Figure 6. Influence of pillar width to height ratio on average pillar strength.

In sum, for attaining a stabilized system the following factors will be considered:

- Pillar strength (defined by its geometry and strength module as a rock body)
- The stability of roofs and walls of void spaces and chambers adjacent to the pillars.
- Checking for probable punching effects of pillars on roof and floor.

An example of pillar reinforcement is shown below in the Figure 7, aimed at improving its strength and bearing behavior under non-confined conditions. Single and double bolt cables are installed through the rock mass, in addition to metal mesh and shotcrete as aiding elements.

Figure 7. Example of pillar reinforcement

Chamber roofs must be stabilized with anchoring bolts, while choosing them from various options, along with electrowelded steel mesh, or other alternative reinforcing methods.

If void dimensions are large, bolt cables can be incorporated as the main stabilization means.

In summary, the stages to keep this excavation system stable are as follows:

- Adecuate design for room (chamber) and pillar configuration
- Early diagnosis of overstress conditions in pillars (beyond what was expected) as the system mining progresses.
- Application of solving alternatives for the arising problems.

4 MINING OF STEEP DIP OREBODIES

This section shows conceptually the typical problems arising in mining steep dip (strike) orebodies.

In this case, the main stress pattern is related to the horizontal stress that is perpendicular to the orebody. The rock mass is mined at various levels employing the long-hole method, resulting in large chambers without roof control. The equipment is remotely controlled in order to avoid exposing the workers to potential danger.

As the number of sill pillars is progressively reduced, it can be observed how the stress level increases in the remaining ones. Correspondingly, this also augments the pillars' confinement that firstly brings along higher stability indexes that those of a previous state, and this, in turn, evolves into a state closely resembling that of rockburst, or sudden instability, some totally undesirable conditions. To solve this issue, the sill pillar must be mined with longhole-drilling techniques, though always trying to avoid reducing the pillar down to dangerous dimensions, especially when the personnel and equipment are working nearby. The following Figure 8 shows an example.

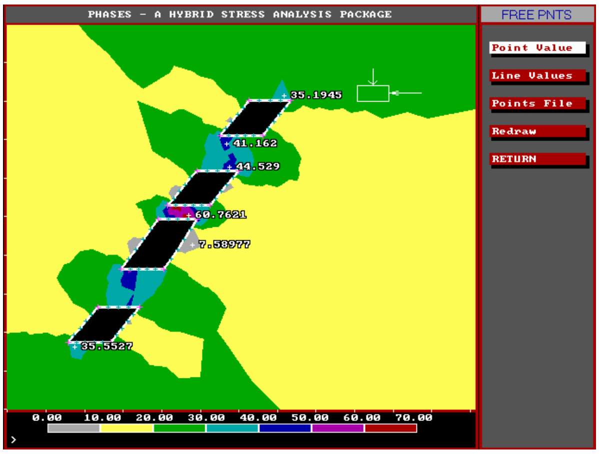

Figure 8. Stage 1.

In addition to this condition, if there are other excavation works adjacent to the pillars, e.g. access ramps, shafts, stopes, horizontal drifts and galleries, and similar excavations where various structural rockbody features may arise such as faulting, jointing,said features will be "tightened" (compressed) by the stress transmitted by the sill pillars in a first instance (sill pillar overstressing). But these stress features will be totally released when the adjacent chambers become united upon withdrawing the pillar, and they may become subject to gravity fall, collapse or other faulting effects.

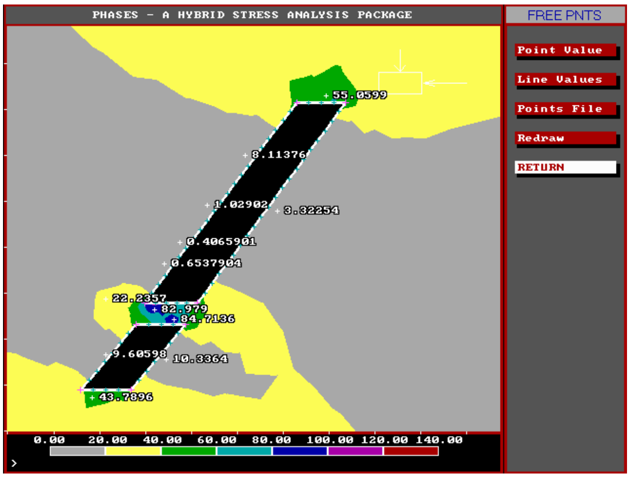

Figure 9. Stage 2.

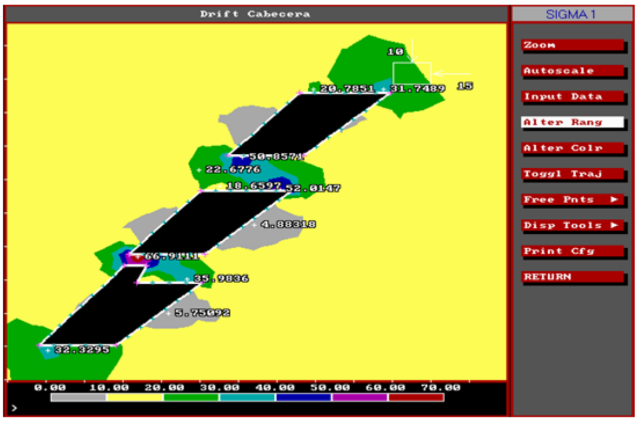

Figure 10. Stage 3.

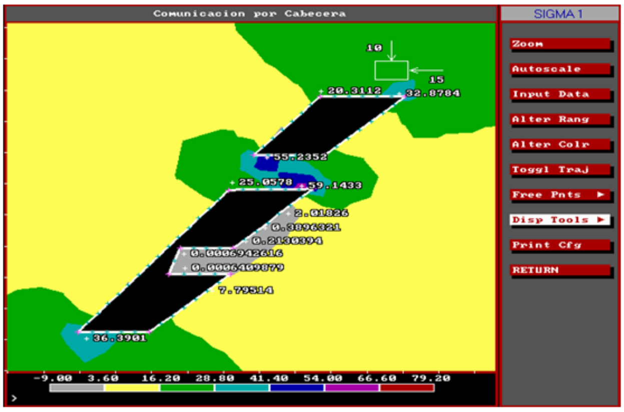

Figure 11. Stage 4.

The above images (Figure 9, Figure 10 and Figure 11) show some examples of stress release that normally cause the fall or collapse of blocks and wedges. In order to prevent such accidents, a careful planning has to be made that includes a stabilization strategy aimed at impeding the fall of rockmass prone to become dettached by using proper supporting means, e.g. bolt cables, anchoring, etc.

In order to take into account in the diagnosis the rockblast phenomena, for these cases and in general as well, the ocurrence of a series of indicative aspects should be observed in the operative stages, like the following situations:

- A significant decrease in penetration rate of drill holes, for example, slowing from a nominal drill rate of 1.5 m/min down to 0.5 m/min o even slower rates.
- Changes in the behaviour of the excavation wall when hit with a rockhammer; for example, a significant increase of bouncing upon hitting the wallrock.
- The occurrence of typical pre-bursting sounds (low or high-pitch noises, weak or strong noises, screech or sounds like teeth-grinding, etc) that can be heard previously to the burst of rock chips (light rockburst), or larger rockfall, or a localized seismic event (high-degree rockburst)

The necessary measures to be taken forth start from considering a well-planning of the initial mine design by regarding the potentials for these events, by applying preventive supporting means to contain these instability hazard. For example: staged anchoring or combined (active/passive) anchoring, where one such anchors may break upon occurring the rockburst but the second and following stages may take over and perform accordingly as a second front; a well-planned engineering that considers the mining operations at the proper, most convenient stages, preferably in retreat sequence, whenever this is possible so as not to cause overstress or excavation subsidence when there is circulation of persons and wheeled equipment.

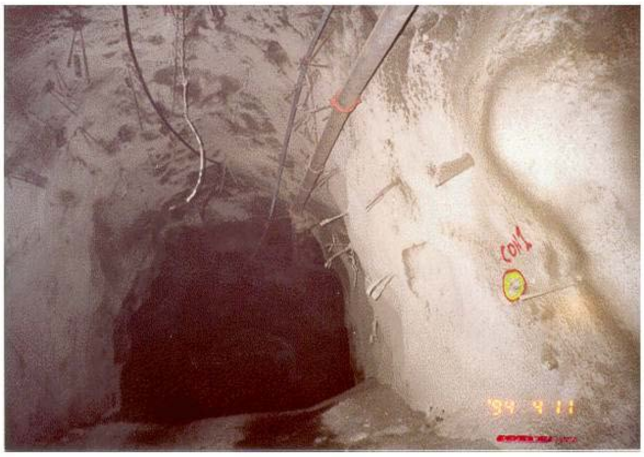

Figure 12. Excavation adjacent to mind chambers, stabilized by double-cable bolting and shotcrete.

Figure 13. Example of induction fracturing follow-up marked with red paint.

The Figure 12 shows excavations adjacent to mind chambers, stabilized by double-cable bolting and shotcrete (shown in color are the measuring points for convergence), and the Figure 13 shows an example of induction fracturing follow-up marked with red paint.

5 CASE OF MASSIVE OREBODY MINING SYSTEM

This case is s chamber mining of massive orebodies in two main phases. The first phase entails excavating and filling with "paste fill" (a newly introduced special cemented fill) of the so-called primary chambers (P), leaving massive pillars between chambers. The second phase is the subsequent recovery of the pillars, or secondary chambers (S), which will be separated by the previous cemented fill. In such an instance, the dominant maximum stress is the vertical one.

The primary chambers, generally mined simultaneously, are mined by caving an upper pilot centered on the planned cut, and then widening towards the projected lateral borders and finally mining down to the design limit. In order to enable for this mining operations while still complying with universal mining safety standards, supporting means has to be applied at each excavation phase. For example, stabilization in moving the pilot forward, along with swellex bolting and electrowelded mesh; the widenings are stabilized by considering the final hydraulic ratio of ceiling exposure with bolt cables. Once this reinforcement has been applied, the system proceeds to bench mining, with a safe ceiling for helping recover the ore reserves. Finally, upon finishing the ore extraction, the chambers and voids are filled with paste fill.

The second phase (recovery of secondary pillars are mined likewise the primary phase, i.e., upper pilot placement, widening and bench mining; but, since the pillar is centered, this step left temporary pillars that turned out to be extremely thin as to withstand the strong induction stresses generated by such an action (it should be noted that the filling material is not any supporting structure), as it can be seen in the sequences depicted in the Figure 14.

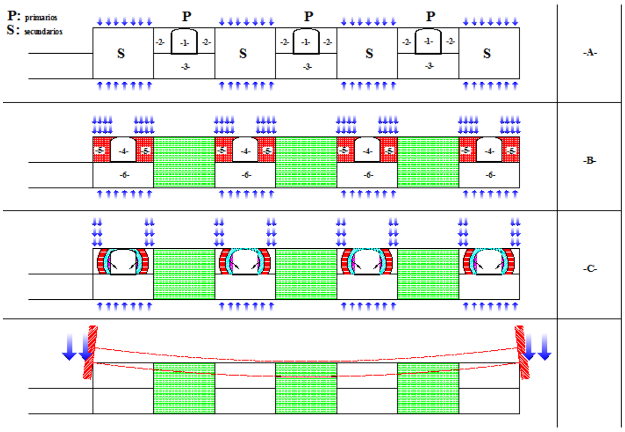

Figure 14. Standard sequences with stability problems.

As it happened in this case, pillar thinning resulted in pronounced rockburst in all excavations made so far, which led to applying the general evacuation protocol for said deposit. In its most intense feature, the instability ocurred with a strong noise, like that of an explosion, heard even at the shelter posts, with a 5-minute frequency for each bursting event, with rock blocks falling down. The following Figure 15 shows some fallen blocks and debris caused by the above described rockburst phenomenon.

Figure 15. Examples of rock mass lost and debris caused by rockburst phenomenon.

The short-term solution entailed taking immediate actions such as the above general evacuation, as soon as the first signals appeared, i.e. dilling rate decrease and 'teeth-grinding' noise, a typical feature of this mine. Later on, at the evaluation station (a place in a safe mine sector), timing was recorded for each rockburst event, until they ceased down. The total duration timed from the first event to the last one was 45 hours. Finally, it was decided to do an inspection, followed by re-stabilization tasks as the crew moved forward, and to rehabilitate the affected sectors in order to bring continuance with safe mining procedures. It is further stressed that all these steps were performed by following the regulating protocols.

Important as it is to describe how this problem was solved, it is regarded furthermore important to define future mining policies and procedures in order to prevent these events from occurring, by selecting and applying the most convenient strategy. In this case, it was opted for mining down the upper pilot in contact with the primary rockfill mixed with paste fill, while stabilizing the advance stoping so as to double the supporting critical pillar. This is depicted in the Figure 16.

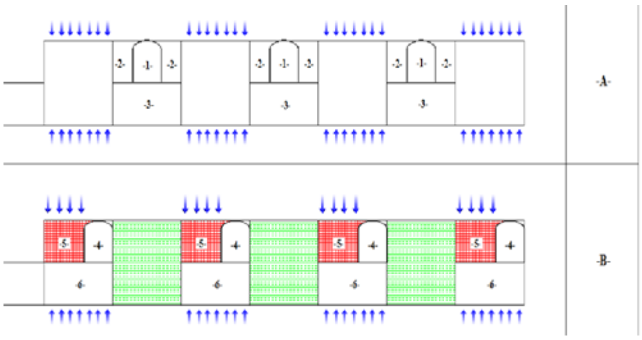

Figure 16. Sequence convenient of mining.

This way the problems were systematically overcome, and this configuration of excavation sequence was included in the protocols.

It is important to note that a ‘critical vision’ (keen awareness) to be able to do an early diagnosis of overstress signs is a fundamental asset in underground mining. Just to illustrate this furthermore, it is worth mentioning that, in another mine, it was possible to detect high overstress induction by watching the behavior of the excavation walls in response to the ground vibrations irradiated by blasting operations nearby; it was notable how the wave transmission performs differently. The following Figure 17 helps describe it.

Figure 17. Picture of floor of an excavated area under over stress.

The picture shows the floor of an excavated area, namely, an auxiliary ventilation drift. The excavation was supported on ceiling and walls with shotcreted bolting and electrowelded mesh. This labor area, at the time of observation, was restricted for access due to safety reasons, and because it is close to an open pit being mined. Such open pit mining was causing the lateral reduction of the pillar structure between the underground and open pit systems. The development of significant overstress was evident because the dust that the elecrowelded mesh had collected through time fell down to the floor after a surface operations blast. A perfect mark was left as a white contrast with the black ash deposited on the tunnel floor.

6 GROUND CONTROL

When performing underground excavations, either civil or mining ones, it is critically important to do a periodical, systematical and formal follow-up of rock structure stability.

In many instances, the tasks of follow-up, control and auditing of mining works are based on subjective observations, mainly relying on the experience of senior engineers and personnel, but without having any technical foundation for the results and measures taken, nor had they been homologated in an attempt to unify the stabilization criteria with a coherent and definite manner.

The objective of the ground control audit is to render effective tools for solving the problems arising in underground mining operations, mainly those stemming from geological uncertainties or non-definitions, so as to avoid ambiguities in the criteria for decision making for a timely and precise structural stabilization.

From the technical viewpoint, the formal indexes stated by the authors in references can be supported as well. However, it is necessary to define with precision the following fundamental points:

- Delimitation of Responsibilities for the Stability of the Rock Mass, for each and all sectors involved in excavation practices. A "Protocol of Responsibilities for System Stability must be defined and issued, and it shall be accepted and enforced by each participant party.
- The availability or creation of a Geomechanics Department within the mine premises in charge of performing field inspection, recommending solutions, scheduling normalized periodical meetings, discussing on decision-making matters, controlling the execution of the approved measures and procedures, writing of engineering reports and drawings, elaborating the supports standards and a general report, issued under a preset standardized schedule.
- To set forth the decisions made, in accordance to schedule and preset procedures.
- To hold meetings between the involved areas, to do periodically scheduled reviews.
- To comply with external audits

In the next diagram (Figure 18), presented as an example, ground control implies an interdisciplinary task which sums up in a set of formal tasks related to the interaction between operation, planning and auditing labors.

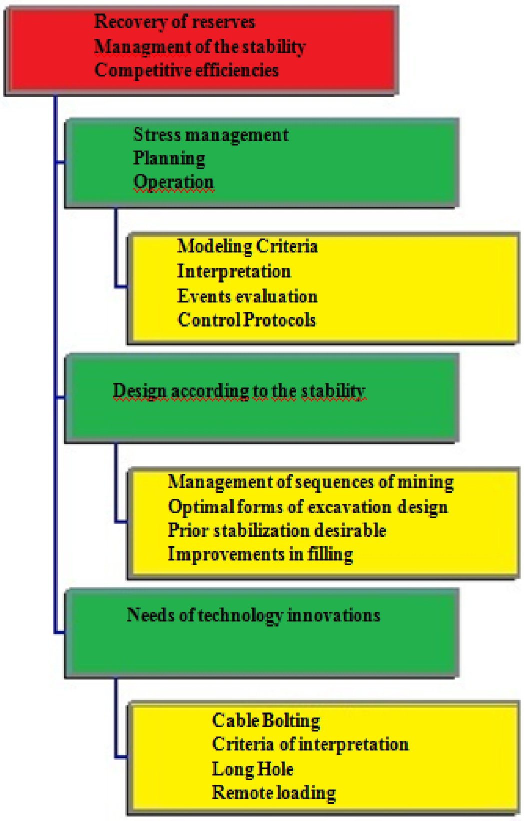

Figure 18. Example of decision diagram.

7 CONCLUSION

This work has been focused in describing the rock stress induction phenomena, but mainly in creating awareness on the importance of induced stress management that must be practiced at all rational mining operation and, quite fittingly, in all general underground excavation task, including civil underground excavations. Emphasis should be put on the critical importance that this management means, fundamentally on the responsibility that each operations member must adopt and meet. This approach embodies an overall methodology and work system that unavoidably must work aiming at reaching efficiency, productivity goals and similar aspects, though, most importantly, these objectives must be met safely, so as to ensure the continuity of the productive source. At every rational mining project, each professional should be clearly aware of all the above statements, so as to elaborate a team-work methodology, with each member complying responsibly the induced stress management plan according to the role that the protocol establishes.

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