Optimisation of Underground Mining Method through Numerical Modelling and Monitoring for Deep Limestone Mine in Central Chile

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ABSTRACT: Navio Mine, a Lafarge Cement (previously Blue Circle Cement) limestone mining operation located in Central Chile, has recently completed a series of geomechanics studies in support of its mine planning strategy to achieve two closely related objectives: technical optimisation of its underground (sub-level stoping) mining method, and maximisation of economic ore recovery for the remainder of its operating life. It is anticipated that deteriorating geomechanical conditions are to be encountered during this period, particularly in terms of rock mass strength and field stresses. Based on extensive geomechanics characterisation from all previous work, a cost-efficient numerical modelling methodology was adopted for all further mining method design, combining two dimensional (Finite Element) and three-dimensional (Boundary Element) formulations. Early validation of some modelling results was provided by a limited displacement monitoring program. Key components in such studies include down-dip and along-strike dimensioning of stopes for the two main limestone seams or "mantos", as well as the design of both main and rib pillars. These assessments have been conducted within broad sensitivity analyses, in order to also address the crucial issue of formulating a mining sequence capable of yielding the complex, precise ore-blending requirements of the nearby cement-manufacturing plant. Potential vulnerabilities of some particular mining configurations have been detected, and resolved through further analysis. While mine design optimization, with modestly increased ore recovery, is now feasible and already underway, the central conclusion from these studies is that a more substantial increase in the overall extraction ratio for the mine would bring a number of key pillars and hanging walls close to a "limit equilibrium" condition, thus jeopardising both global stability and closure plans already being considered. Hence, the extraction ratio for Navio Mine is now said to be close to a geomechanical optimum.

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8.1 INTRODUCTION

As prime limestone supplier for its La Calera cement manufacturing plant in Central Chile, **LAFARGE CEMENT** (previously Blue Circle Cement) operates its nearby underground Navio Mine, at approximately 140 km north of the capital city of Santiago.

As more massive operations became feasible, and in order to remain competitive with surface operations in the same region, the mining method at Navio has evolved from various forms of Room & Pillar some decades ago, to the latest version of a more massive Sublevel Open Stoping,operation. This need for continuous optimisation and refinement of the mining method has become more acute as mining progresses into deeper geological horizons, where problems arising from high *in situ* and induced stresses are further compounded by the significant dislocation of the two main sub-parallel seams being mined. Such dislocation is in turn related to the severe tectonics inherent to this particular geological environment, with intense fracturing by geological structure.

Mine management has thus called for the development of a series of geomechanics studies in support of its mine planning strategy to achieve two closely related objectives: technical optimisation of its mining method, and maximisation of economic ore recovery for the remainder of its operating life. In this context, this paper deals with the main findings from a recently completed stage of such studies, devoted to the geomechanics design of the latest modification to the mining method, i.e. Sublevel Stoping with a 40m vertical distance between drill drifts.

With due recognition for the three-dimensional complexity of this geomechanics environment, and assisted by the results from monitoring of a trial stope, the main objective of the study has been to adapt this evolving mining method design to the particular conditions prevailing in an area of significant future production.

8.2 GEOLOGICAL SETTING

The Navio orebody is located within a marine sedimentary sequence, known as the La Calera formation, of Jurasic age. Over a global horizon of about 430m, this sequence comprises alternating sandstones, lutites, limestones, and fine conglomerates, flanked at floor and roof by lavas, tuffs, and volcanic breccias. The limestones of economic interest are disposed in two sub-parallel limestone seams, designated as Upper and Lower *Mantos,* both with an average thickness of about 12 to 15m, and a dip increasing to about 45º in the deeper areas to be mined in the future. A 65m thick inter-seam stratum separates both mantos, and plays a key role in the geomechanics interaction between stopes being mined in various sequences. This general arrangement is illustrated in Figure 1.

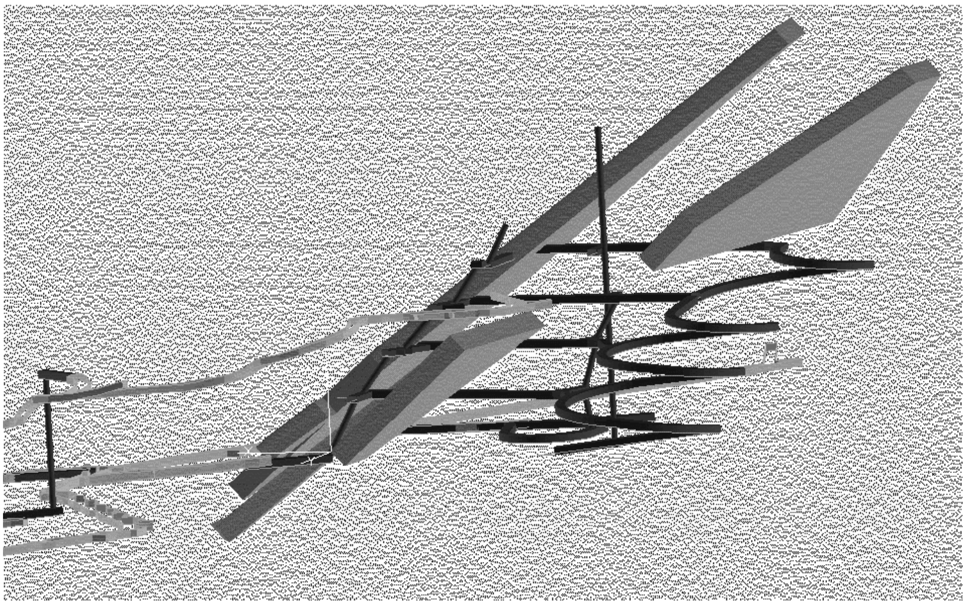


Figure 1: Overall View of Upper & Lower Seams

8.3 MODEL VALIDATION VIA MONITORIG OF TRIAL STOPES

Since the beginning of a series of geomechanics studies instigated by mine management, a large data base has been assembled, mainly pertaining to strength and deformational parameters for the various rock types present in the Navio environment. On this basis, a limited number of design verifications and modifications have been undertaken in the recent past, by means of locally developed two-dimensional finite element codes.

In preparation for the adoption of geomechanics software of widespread use internationally (such as Phase^2 and Examine^{3D}, developed by Rocscience, Toronto), various validation or "calibration" exercises were performed for such data base in conjunction with the code adopted (Phase^2 initially), by conducting a comparison between: actual displacements monitored in two trial stopes of representative dimensions, as they were progressively excavated; and the respective displacements "predicted" for such stopes during the same progression.

Parameters adopted for modelling are summarised in Table 1 below, as extracted from the data base for the particular mine sector where such stopes are located.

Table 1: Strength and Deformation Parameters

Strength and Deformation Parameters	Between Seams	Lower Seam	Seam Floor
Material	Field Stress Only	Field Stress Only	Field Stress Only
Initial Element Loading			
Elastic Properties	Isotropic	Isotropic	Isotropic
Material Type	19000	8600	19000
Young´s Modulus [MPa]	0.2	0.2	0.2
Poisson´s Ratio			
Strength Parameters	Elastic	Elastic	Elastic
Material Type	Hoek-Brown	Hoek-Brown	Hoek-Brown
Failure Criterion	151	97	87.5
Comp. Strength [MPa]	4.298	3.482	4.298
M parameter (peak)	0.0205	0.104	0.0205
S parameter (peak)			

A representative example of the comparison between displacements monitored by extensometers, and modelled data, is shown in Figure 2, also depicting the excavation stage diagrammatically. This corresponds to a "fourth monitoring instant", when full-section excavation of a stope has progressed to a total down-dip length of 96m, i.e. near completion of excavation. Extensometer points are located at depths of 1, 2, 3, 4, and 5m into the hangingwall, and this figure shows good agreement over the total displacement range of about 7mm.

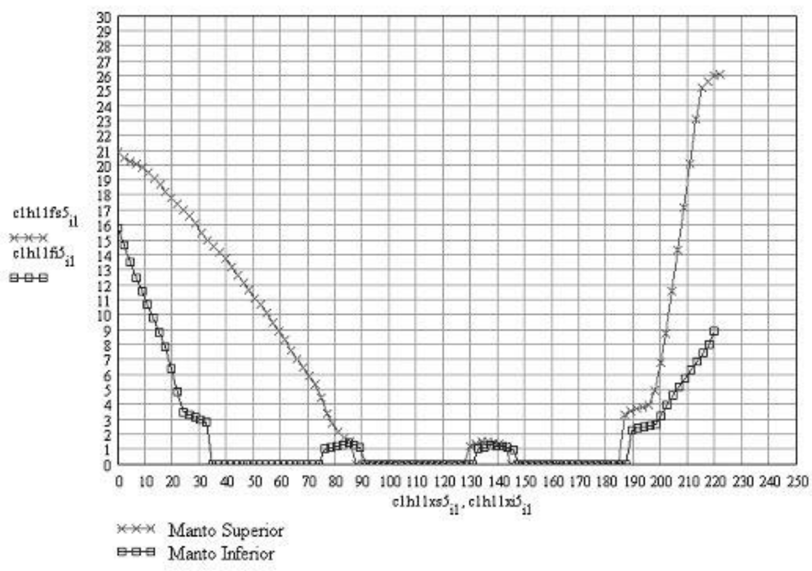


Figure 2: Displacement Monitoring in Trial Stope

A pattern similar to the above is exhibited by most such comparisons, except for some monitoring "jumps" requiring re-zeroing, which appeared to coincide with some of the larger nearby blasts.

8.4 "GENERIC" MINE DESIGN BY TWO-DIMENSIONAL MODELLING

Design optimisation of the current Sublevel Open Stoping mining method has proceeded in two stages, hereby outlined for a single mine sector or district. Firstly, a broad series of "generic" designs has been developed, via two-dimensional modelling, in an attempt to explore the geomechanical impact of simultaneously mining stopes from both *mantos*, for a large number of scenarios or configurations compatible with ore blending requirements. The essential result from this stage, dealt with in the present section, is a limited number of "promising" mining sequences warranting further consideration.

The second stage, covered in the next section, undertakes the optimisation or refinement of the above-selected configurations. Through a limited number of more detailed, three-dimensional modelling applicatons, it seeks the satisfactory balance of two central requirements: assurance of local and global stability, and maximisation of ore extraction ratio via minimisation of pillar dimensions.

8.4.1 Modelling Program and Parameters

The modelling work for this first stage was performed with Phase^2 (v. 5.0), a widely used two-dimensional plastic finite element program for calculating stresses and displacements around underground openings. A broad range of associated excavation and support problems may be analysed, with an integrated graphical environment for data entry, visualisation, and interpretation.

Most of this initial work was carried out in Zone 5 of the mine, where the applicable strength and deformation parameters for various rock types are those already presented in Table 1.

Estimating the in-situ state of stress has constituted by far the greatest difficulty in these studies. Primarily due to time and economic constraints, the best possible estimate finally adopted has been arrived at through an interactive process involving: a limited number of "old" measurements, and a series of sensitivity analyses based on modelling results and observed behaviour. In the latter, the output of various numerical modelling exercises for different excavations was critically examined, and the assumed in-situ stress "generation law" was varied so as to more closely reproduce the observed (sometimes qualitatively) behaviour of the same modelled openings (and pillars).

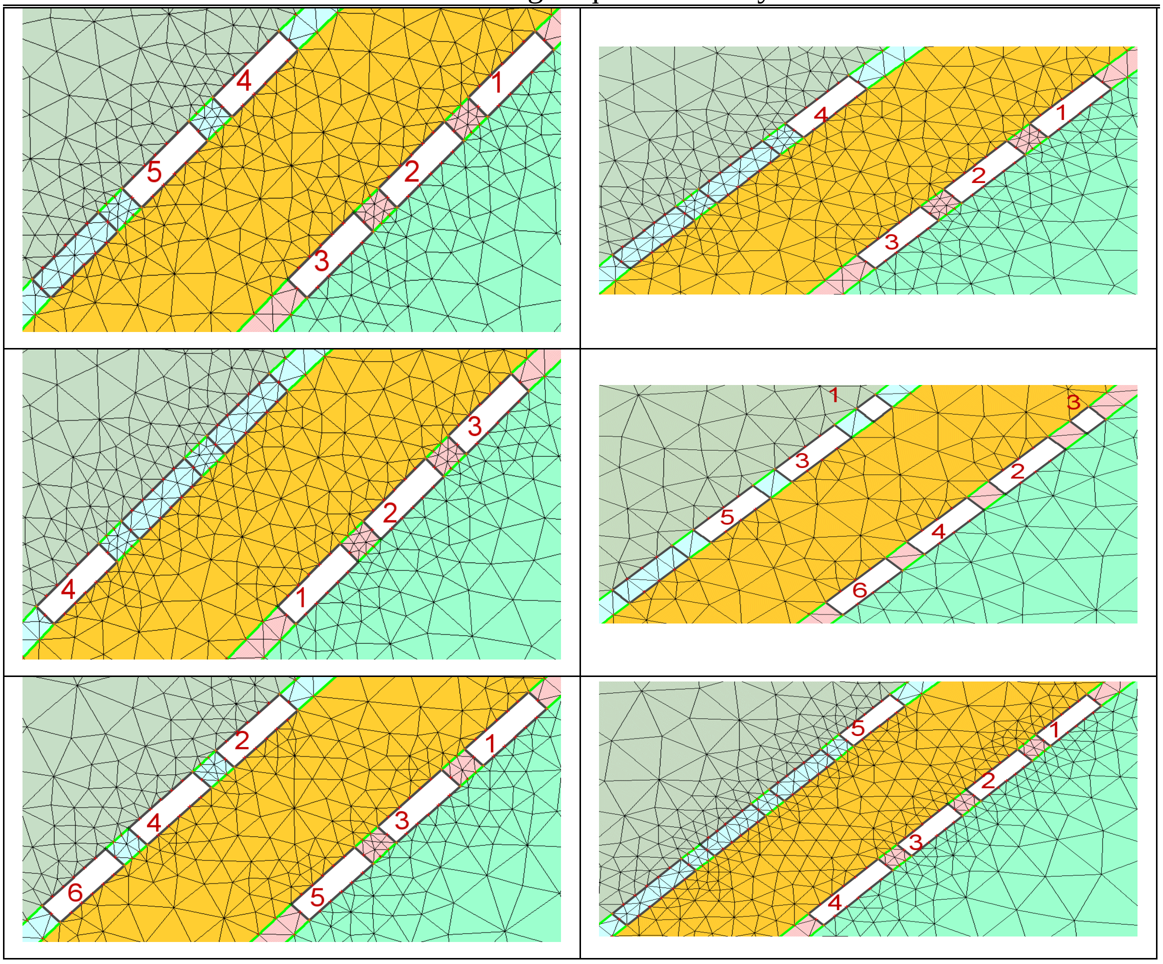
Such process finally resulted in the adoption of the following working assumptions:

- The major principal stress is vertical, and closely related to depth stress.
- The ratio of average horizontal stresses to the vertical stress approaches k = 0.9

8.4.2 Mining Sequence Configurations Analysed

Through close interaction with Mine Planning, an extensive search of promising mining sequences was conducted, so as to select a limited number of configurations, satisfying economic and ore-blending requirements, for initial geomechanics feasibility assessment. Table 2 summarises the 20 configurations finally analysed by numerical modelling, where the correlation numbers indicates the actual mining sequence adopted in each case. A representative range of depth below surface is also indicated.

Table 2 Mining Sequences Analysed



Subsequently, any particular sequence from the above Table is to be further analysed for deeper sectors designated for future mining, as early geomechanics support to mine planning.

Finally, the very first sequence defined in this same Table has been selected for design refinement through three-dimensional modelling, to be dealt with in Section 5.

8.4.3 Typical results

A set of typical results from a given configuration in the above process is presented graphically below, Figures 3 and 4, in terms of Safety Factor distribution (iso-contours) around stopes and pillars. Results may be additionally sampled in the “radial” (Figure 3a) and “longitudinal” (Figure 3b) directions.

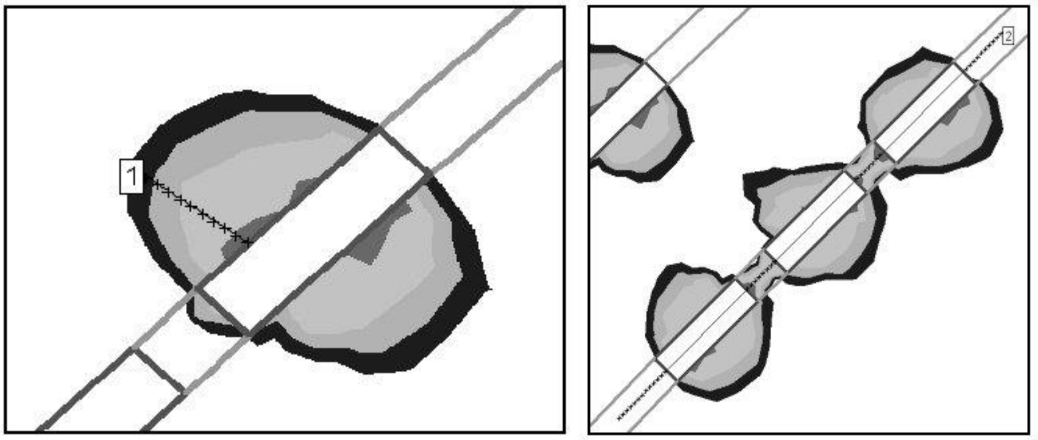


Figure 3: Safety factor sampling directions

a) Radial b) Longitudinal

Above sampled results are displayed in Figures 4a and 4b for the radial and longitudinal directions, respectively. Figure 4a shows that, as a convention, the radial sampling of results is only displayed for the hangingwall of the latest stope in a given excavation sequence. Additionally, such representation obviously shows the expected decrease in the safety factor as extraction ratio increases. The minimum value of FS = 1.0 is reached in the last stage, and remains below an acceptable design criterion of say, FS = 1.25, for about 5m into the hangingwall. However, irregularities in the actual excavation may modify this trend.

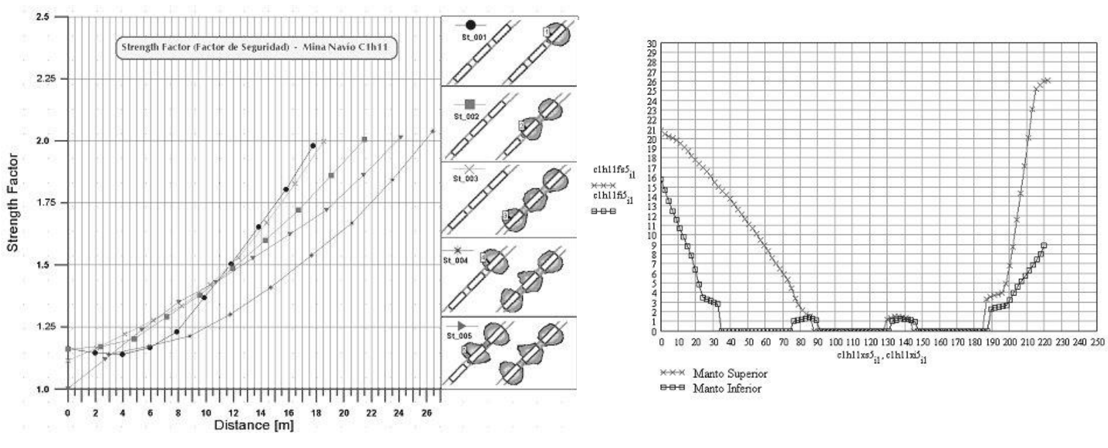


Figure 4: Safety factor sampled results

a) Radial b) Longitudinal

8.4.4 Acceptable Sequence Configurations

With particular reference to the broad range of mining sequences shown previously in Table 2, global results from this stage indicate that most sequences are "manageable" with varying degrees of support, and that support requirements increase more rapidly in two typical situations:

- when both seams are subjected to similar extraction ratios; and
- in configurations where mining of the lower seam is in a more advanced stage.

8.5 MINE DESIGN REFINEMENT BY THREE-DIMENSIONAL MODELLING

8.5.1 Geomechanics Software Adopted

Examine^{3D}, v.4.0 (Rocscience, Toronto) was adopted for this design refinement stage. This is an engineering analysis program to essentially perform stress and displacement analysis for underground excavations in rock, by means of the direct boundary element method. However, its powerful data visualisation tools make it amenable for application to a wide range of mining and civil engineering problems, such as the visualisation of various microseismic datasets.

8.5.2 Problem Geometry

Because of its broad representativeness in this particular application of the Sublevel Open Stoping mining method, and its more complex geomechanics interaction, the first mining sequence configuration included in Table 2 has been selected to illustrate this design refinement process. To generate this three-dimensional model, the original (two-dimensional) model has been expanded along the seams' strike to incorporate up to three stopes and two "rib pillars" in that direction. As illustrated in Figure 5, this results in a total of 15 stopes and 10 rib pillars distributed in both seams or *mantos.* Additional modelling dimensions are stope spans of 45m down-dip and 60m along-strike, and pillar thicknesses of 10m for rib pillars and 15m for main pillars.

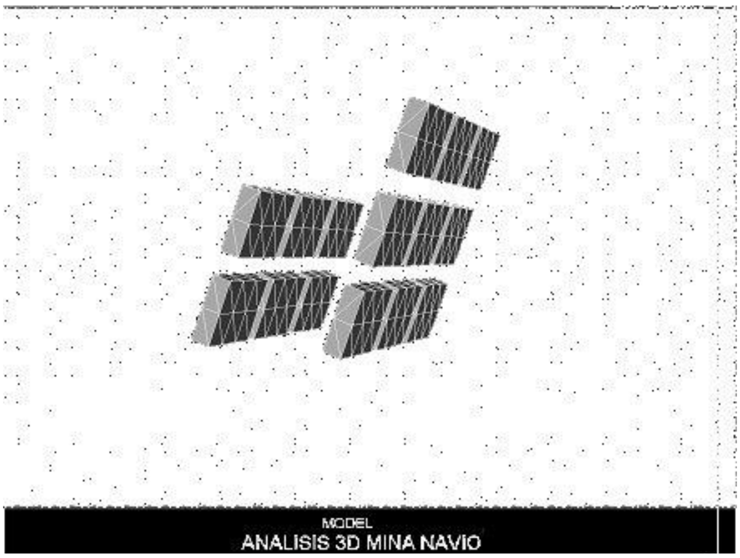


Figure 5: Three-Dimensional Sublevel Stoping Model

8.5.3 Visualisation of Results

Making use of the “on plane” and “within volumetric grid” visualisation tools, modelling results are presented below according to three sampling modes, which may termed: “Central Block”, “Rib Pillar”, and “Pillar & Adjacent Stopes”. These are briefly outlined below.

8.5.3.1 Central Block Visualisation

This first mode presents Factor of Safety (“strength factor”) results as sampled within a central block or plate that intersects the global 15-stope, 10-pillar model, as shown in Figure 6.

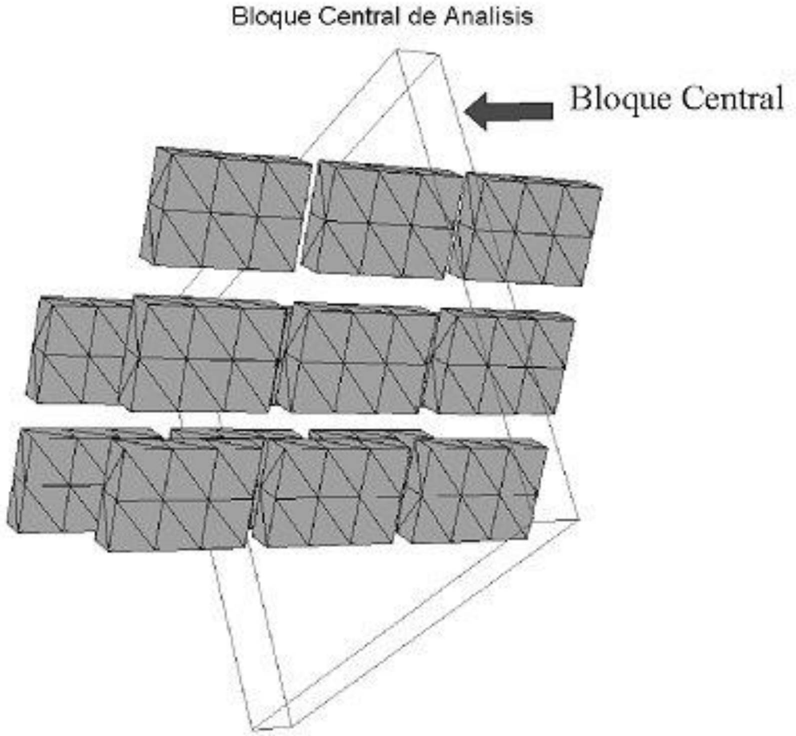


Figure 6: Central Block Visualisation

This particular representation allows the analysis of the geomechanichal behaviour of stope walls down-dip and along-strike. Specific results captured within this volume are displayed in Figure 7, in terms of Safety Factor iso-surfaces inside this volume, but having “put out” all stopes in front of the central block, and such block itself, for ease of observation. Total and “zoom” views are included in this figure.

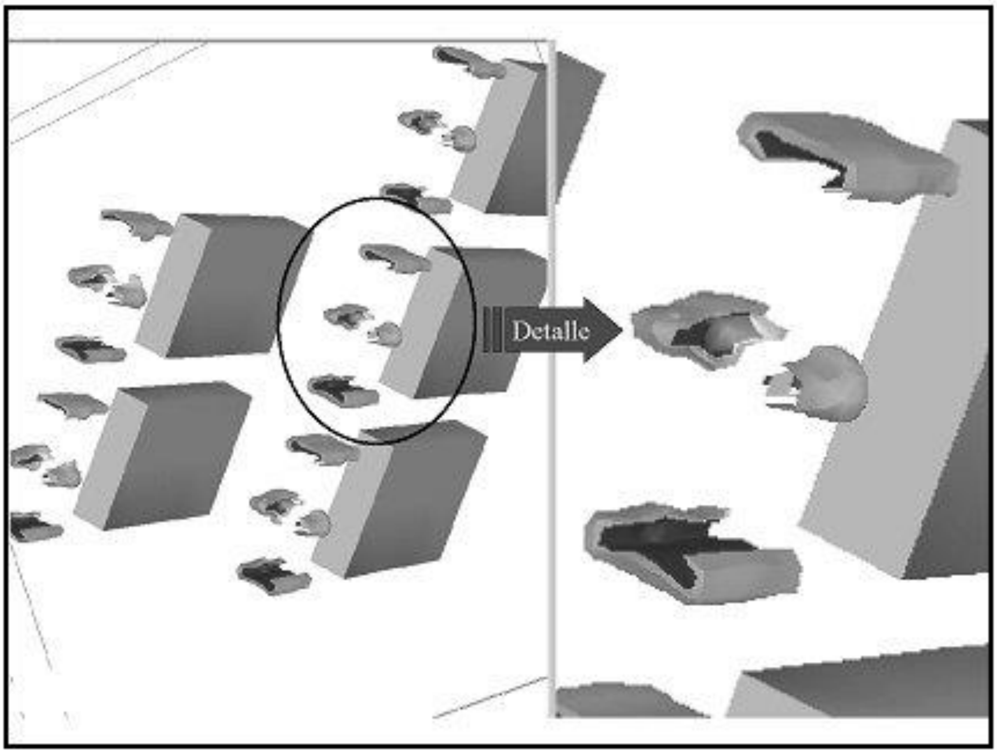


Figure 7: Safety Factor Distribution at Central Stope Walls.

The depth of safety factors below limit equilibrium extends to a maximum of 1.4m into the walls, and laterally for some 4m down-dip and 6.5m along-strike. The most unfavourable safety factor distribution regarding our design criterion (minimum Safety Factor of 1.25) corresponds to an iso-surface which extends some 2.7m into the walls, and laterally for 4.5m down-dip and 13m along-strike. If these design dimensions are to be adopted, appropriate support would be designed and installed to stabilise these volumes.

8.5.3.2 Rib Pillar Visualisation

This makes use of the "on plane" result display, which captures all results on a cutting plane passing through the middle of a given rib pillar, thus permitting an assessment of conditions in the pillar core, to either confirm or modify its dimensions. The total distribution of Safety Factor iso-contours for this case is shown in Figure 8a, whereas Figure 8b affords better visualisation of the same distribution, where the portion (half) of the model in front of the cutting plane has been removed.

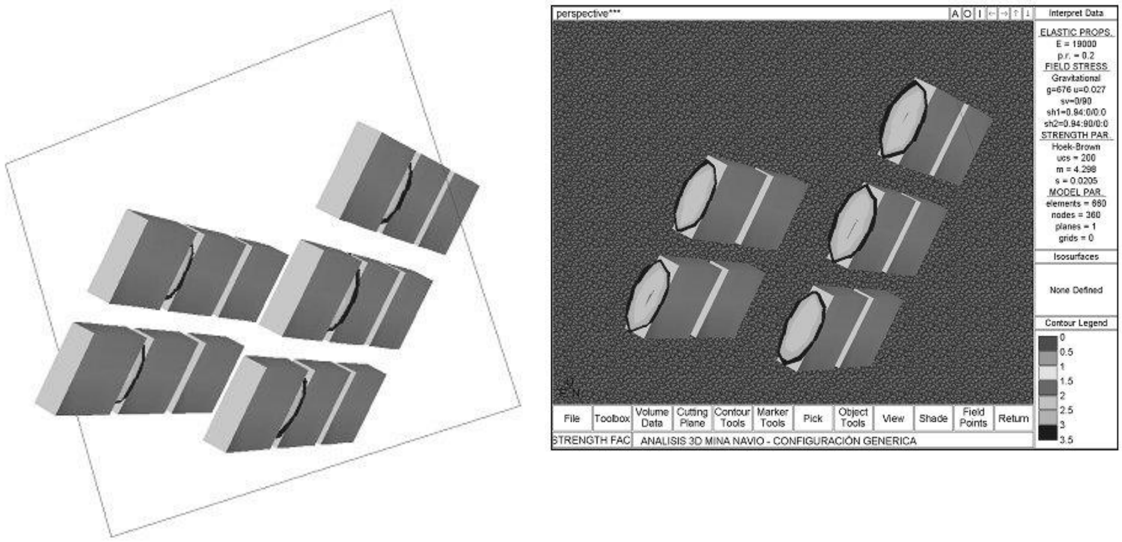


Figure 8: Safety Factor iso-contours through Rib Pillars

a) Full View b) Half View

Detailed analysis of above results yields a more than adequate range of Safety Factors from 1.8 to 2.0, with the marginally lower values distributed in the central pillar.

8.5.3.3 Rib Pillar and Adjacent Stopes

This visualisation mode captures all results within a vertical plate volume incorporating the sampled rib pillars and about one third of the volume of stopes adjacent to either side (Figure 9). Sensitivity analyses of pillar dimensioning, based on pillar/stope interaction, are better conducted in this mode.

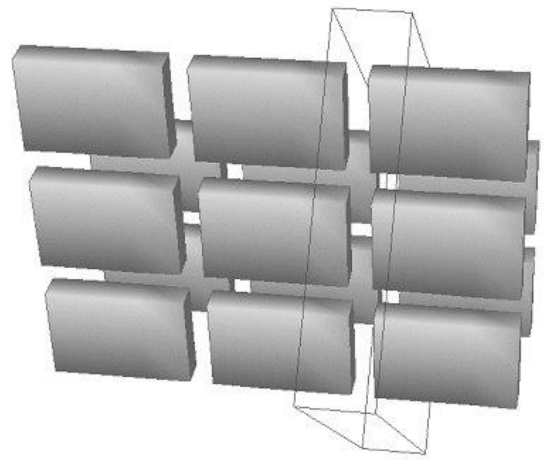


Figure 9: Sampling Volume for Pillar/ Stope Interaction

The full potential of this visualisation capability is displayed in Figure 10, with a three-dimensional view of all Safety Factor iso-surfaces contained within this sampling volume, but having removed that portion of the model located immediately in front of such volume.

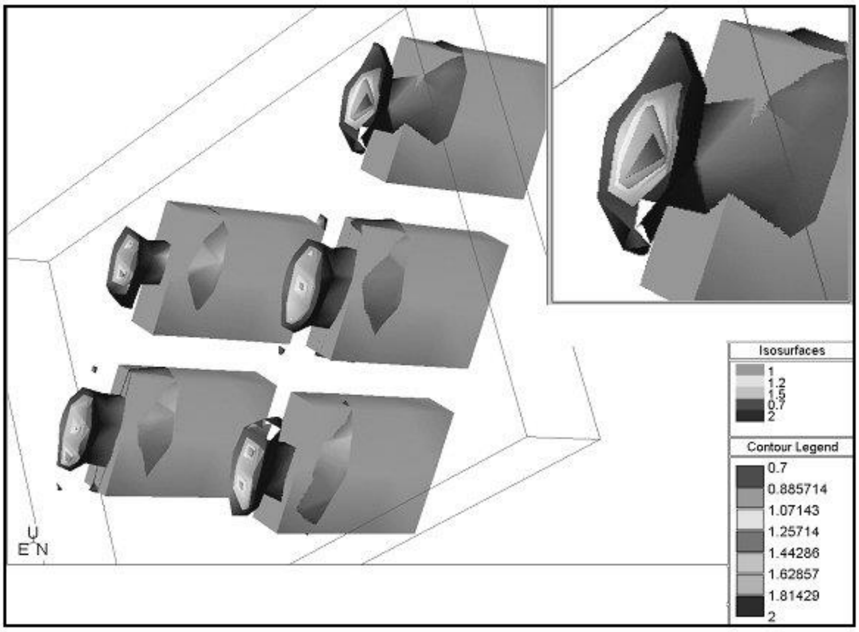


Figure 10: Safety Factor Iso-Surfaces inside Pillar/Stope Sampling Volume

8.5.4 Essential Result of Typical Design

The final, summary result of the above typical example of design refinement is that only small scale instability, relative to stope and pillar dimensions, has been detected by various visualisation modes. Typically, rib pillars exhibit iso-surfaces of Safety Factor values in excess of 1.4 at very shallow depths into them, which clearly depicts a geomechanically benign situation. On the other hand, the main pillars (orthogonal to rib) do show a trend to limited instability in some sectors. These findings, combined, raise the interesting potential for an optimised dimensioning of pillars, whereby the thickness of rib pillars may be moderately reduced, and that of main pillars modestly increased, while at the same time materialising a discernible increase in the extraction ratio or overall recovery for this orebody. The first results from further modelling work, currently underway, are already providing preliminary confirmation of the above potential.

8.6 CONCLUSIONS

The impact of these studies, a typical application of which is exemplified above, may be summarised as follows:

1. Extraction ratio may be marginally increased by a generalised reduction of rib pillar thickness from 10m to 7m, which only in some sectors requires the compensation of increasing main pillar thickness from 15m to 17m to avoid the onset of *limit equilibrium* conditions in some of the latter. Alternatively, rib pillar thickness may be left unchanged, with this "surplus" invested in a moderate increase of the along-strike dimension of the stope.
2. Sensitivity analyses involving a broad range of mining sequences show a clear trend towards marginal stability with a further increase in extraction ratio, which suggests that the current mining method is economically efficient. Thus, extraction ratio is said to be close to a "geomechanical optimum".
3. Two optimised mining sequences emerge from this study. In sectors where the presence and effects of geological structures are more pronounced, the optimum sequence calls for more advanced mining of the lower seam or *manto*, where the scatter of safety factor distribution is reduced (lower dilution is an added benefit). In sectors without such marked structural influence, the optimum sequence is one of similar advance in both *mantos,* in which mining of the next stope alternates between them.
4. The results from these studies have important implications for the global stability conditions at Navio mine, and pose additional constraints on closure plans currently being developed.

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