

Geomechanical evaluation of caving macro-block options at *Chuquicamata Underground Project* in Chile using three-dimensional numerical modelling

E. Hormazabal

Principal Engineer, SRK Consulting, Engineers and Scientists
Apoquindo 4001, 7th Floor
Las Condes, Santiago, Chile
ehormazabal@srk.cl

F. Villegas

VCP-CODELCO, National Copper Corporation of Chile
El Teniente Division
Millán 440, Rancagua, Chile
fvillegas@codelco.cl

F. Rovira

Project Engineer, SRK Consulting, Engineers and Scientists
Apoquindo 4001, 7th Floor
Las Condes, Santiago, Chile
frovira@srk.cl

C. Carranza-Torres

Associate Professor of Geotechnical Engineering
University of Minnesota, Duluth Campus
1303 Ordean Court, Duluth, MN 55812, USA
carranza@d.umn.edu

Abstract

The Chuquicamata Underground Project in the Atacama Desert in northern Chile is one of the largest planned mining projects in the world to use the method of block caving with macro-blocks option, to mine out copper ore. VCP-CODELCO (Vice-President Office of the National Copper Corporation of Chile) is currently completing a pre-feasibility engineering evaluation of this project, which considers the construction and operation of at least two macro-block mining units to be managed independently from each other. A geo-mechanical study has been carried out to evaluate various options related to pillar sizes and mining sequences for the macro-blocks caving configurations considered for the project. As part of this study, complex three-dimensional continuum models have been developed and applied to evaluate the influence of the above mentioned variables (and existing geological features such as the presence of a major fault and different lithological units) on the mechanical response of the underground openings —particularly, in regard to stress concentration developing in critical areas of the excavations such as macro-blocks pillars and rib-pillars. This paper describes general aspects of the Chuquicamata Underground Project, focalizing mainly on the three-dimensional geo-mechanical analysis carried out to evaluate the feasibility of the project.

Introduction

The *Chuquicamata Underground Project* in the Atacama Desert in northern Chile is one of the largest planned underground caving mining operations in the world —see Figure 1. The mining project contemplates using the method of block caving with macro-blocks caving option to mine out copper ore [1,2,3,4]. VCP-CODELCO (Vice-President Office of the National Copper Corporation of Chile) is finishing a pre-feasibility engineering evaluation of the project, which considers the construction and operation of at least two macro-block mining units to be operated independently from each other. A critical aspect of designing a caving operation such as the one at Chuquicamata Underground is controlling the stress concentrations developed in key areas of the excavations, such as abutments in pillars and rib-pillars. This paper describes general characteristics of the three-dimensional elastoplastic models developed for Chuquicamata Underground Project with the purpose of validating various macro-block design alternatives considered for the project.

Geological and geotechnical units for Chuquicamata Underground Project

The Chuquicamata porphyry copper ore is a prismatic body that dips vertically towards the west (see Figure 2). The mineralization at the site is controlled by the West Fault which forms the hangingwall of the copper deposit —the West Fault is a major regional fault with an almost North-South trend, 4 to 6 m in thickness and leading to a 150 to 200 m wide shear (or breccia) zone on its western side. The predominant rock types at Chuquicamata Underground are granodiorites and porphyries in contact with the West Fault. This shear zone has poor to very poor geo-mechanical quality. On the eastern side of the West fault a massive quartz-sericitic rock body occurs; beyond this body, porphyries with different types of alteration are present. The main rock mass types at Chuquicamata Underground project are shown in Figure 2. A simplified set of geotechnical units considered in this study is shown in Figure 3.

The geotechnical characterization of the Chuquicamata Underground site has been carried out based on geological-geotechnical borehole logging and surface mapping information [5]. The quality of the rock mass has been rated using the Rock Mass Rating (RMRL) system by Laubscher [6] and GSI by Hoek et al. [7]. The rock mass geo-mechanical properties for the geotechnical units have been evaluated using the Hoek-Brown rock mass failure system [8] as implemented in the software ROCLAB (available from www.roscience.com) and also using results of laboratory testing (unconfined and triaxial compression tests of intact rock provided by VCP-CODELCO). Calibrations of rock mass properties have been also conducted in exploration drifts [5]. Table 1 summarizes mean geotechnical properties parameters for the various rock mass units considered in the three-dimensional models.

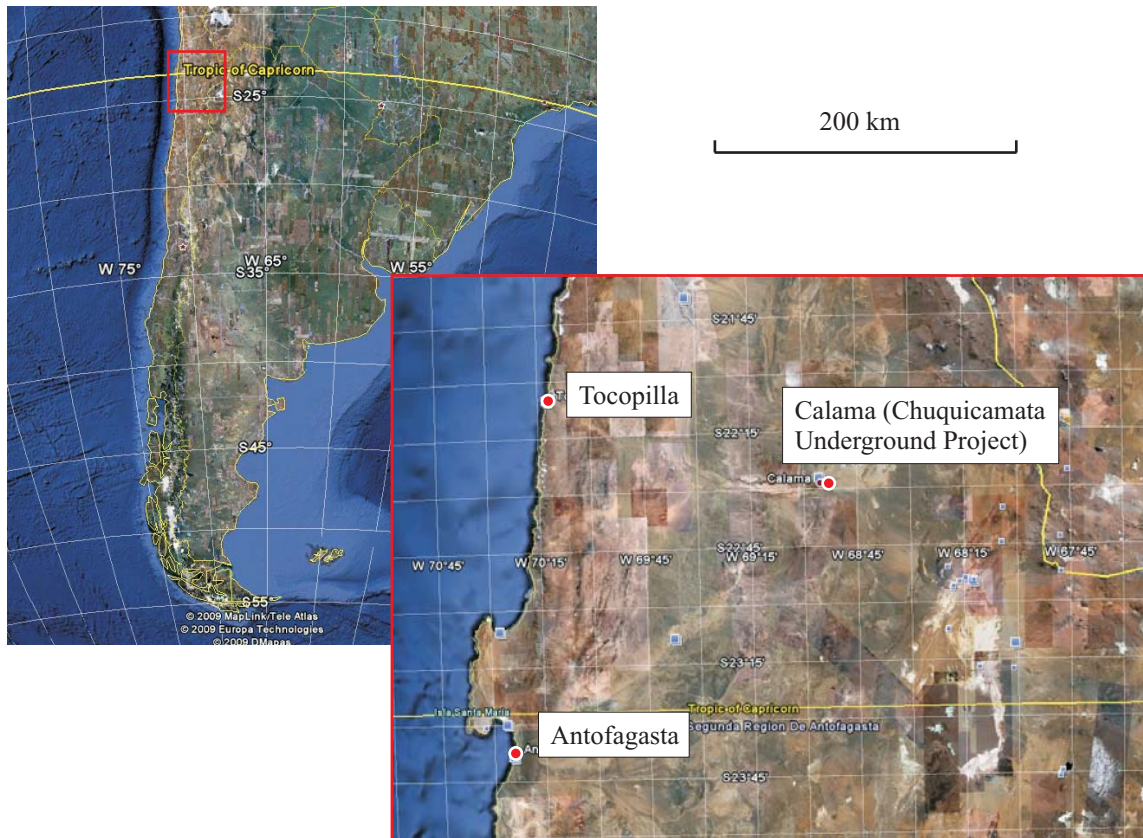


Figure 1. *Chuquicamata Underground Project* location in relation to Antofagasta and Calama cities in northern Chile.

The pre-mining in situ stress field was provided by VCP-CODELCO [2] and is given by the following principal stress components:

$$\sigma_v = 0.026 \times h \quad [\text{MPa}] \quad (1)$$

$$\sigma_{EW} = 0.033 \times \sigma_v + 9.7 \quad [\text{MPa}] \quad (2)$$

$$\sigma_{NS} = 0.033 \times \sigma_v + 10.0 \quad [\text{MPa}] \quad (3)$$

Table 1. Summary of geotechnical properties for the various geotechnical units considered in the three-dimensional elasto-plastic models —mean values of properties are indicated.

Geotechnical unit	γ [kN/m ³]	σ_{ci} [MPa]	m_i [–]	GSI [–]	σ_t [MPa]	E [GPa]	ν [–]	c [kPa]	ϕ [deg]
RQS (Q<S)	25.9	15	25.0	70	0.06	9.38	0.20	2665	35
RQS (Q>S)	26.7	89	10.5	70	0.88	22.57	0.20	4700	41
RQS (Q=S)	26.6	52	11.9	70	0.46	13.48	0.20	3670	38
BEF (West fault zone)	25.1	37	17.0	35	0.02	1.06	0.28	1910	29
ZCI (Intense shear zone)	23.0	20	17.0	35	0.01	0.82	0.28	1435	25
Broken material	20.0	–	–	–	–	1.03	0.29	200	38

Notation: γ is the bulk unit weight of the rock mass; σ_{ci} is the unconfined compression strength of intact rock; m_i is the Hoek-Brown parameter; GSI is the Geological Strength Index; σ_t is the uniaxial tensile strength of the intact rock; E the rock mass Young's Modulus; ν is the Poisson's ratio; c is the equivalent rock mass cohesion; ϕ is the equivalent rock mass internal friction angle —parameters E , ν , c and ϕ have been computed with software ROCLAB.

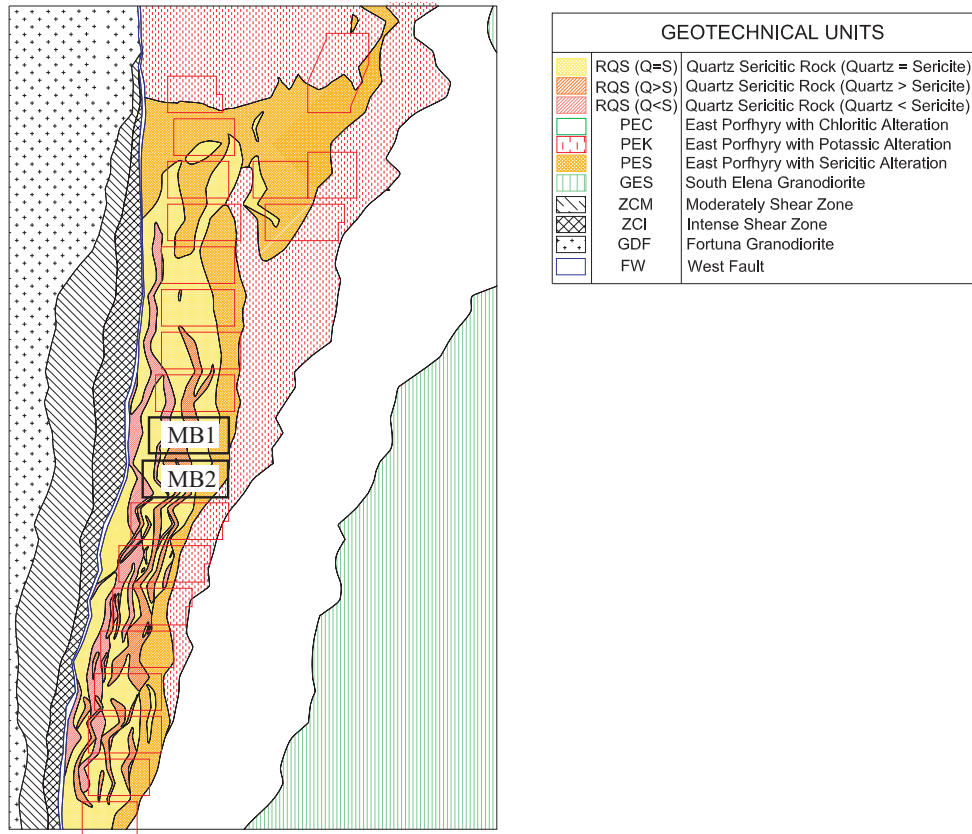


Figure 2. Geotechnical units considered for the *Chuquicamata Underground Project*. Red lines indicate the various macro-blocks units considered in the project (outline of excavations are for production level 1,841 m). Black lines indicate the two macro-blocks units analyzed as part of the study (macro-block unit MB1 and macro-block unit MB2).

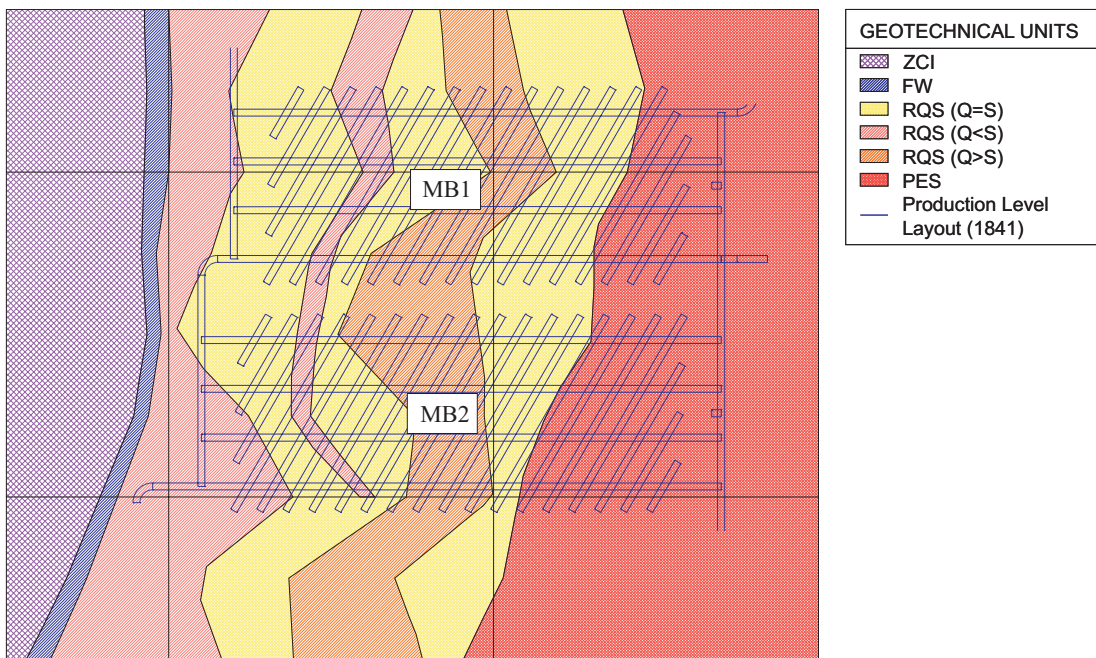


Figure 3. Layout of geotechnical units (at production level) and layout of underground caving infrastructure for the two macro-blocks units considered in this study (production level 1,841 m).

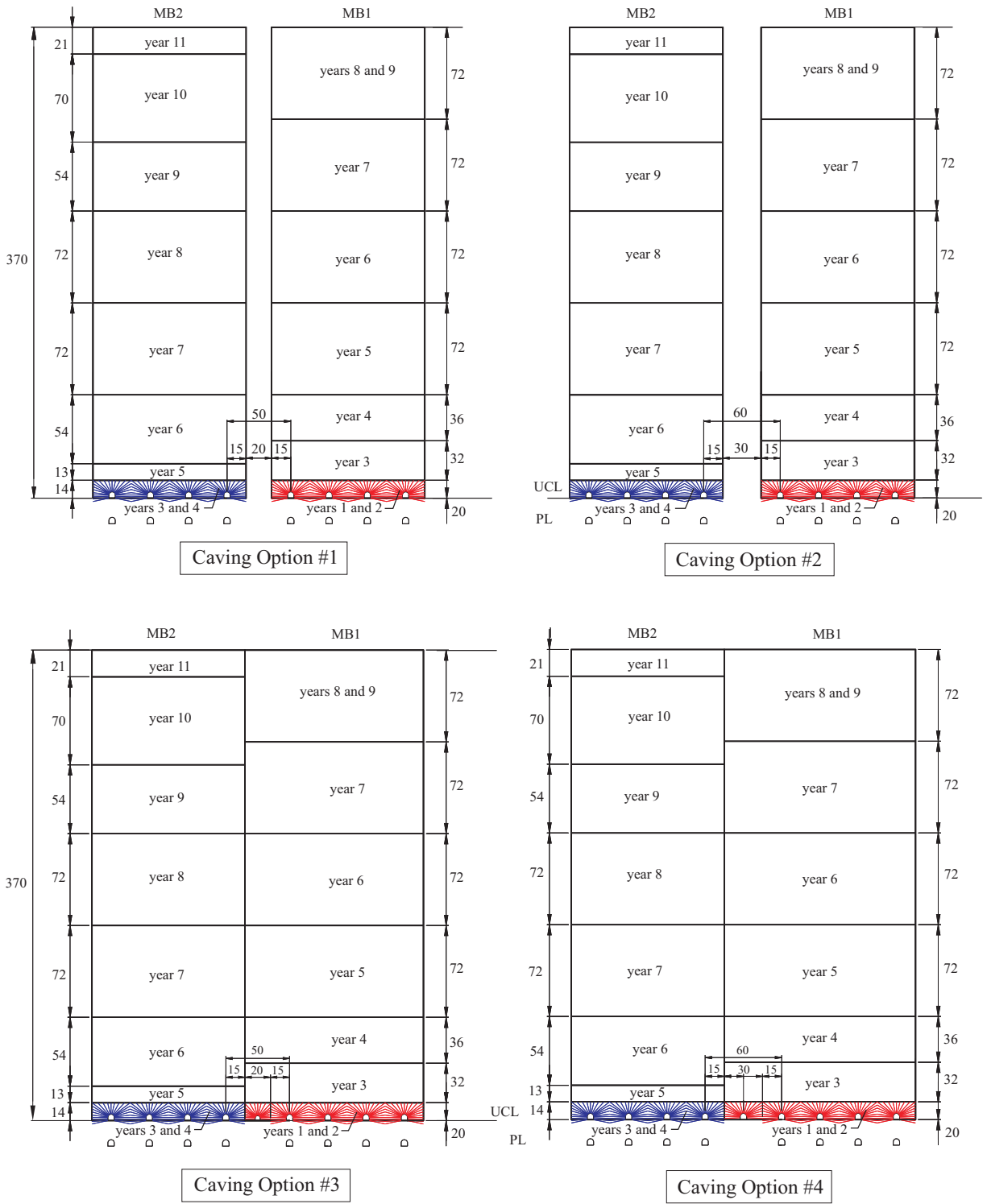


Figure 4. Caving options #1 through #4 analyzed with three-dimensional elasto-plastic models.

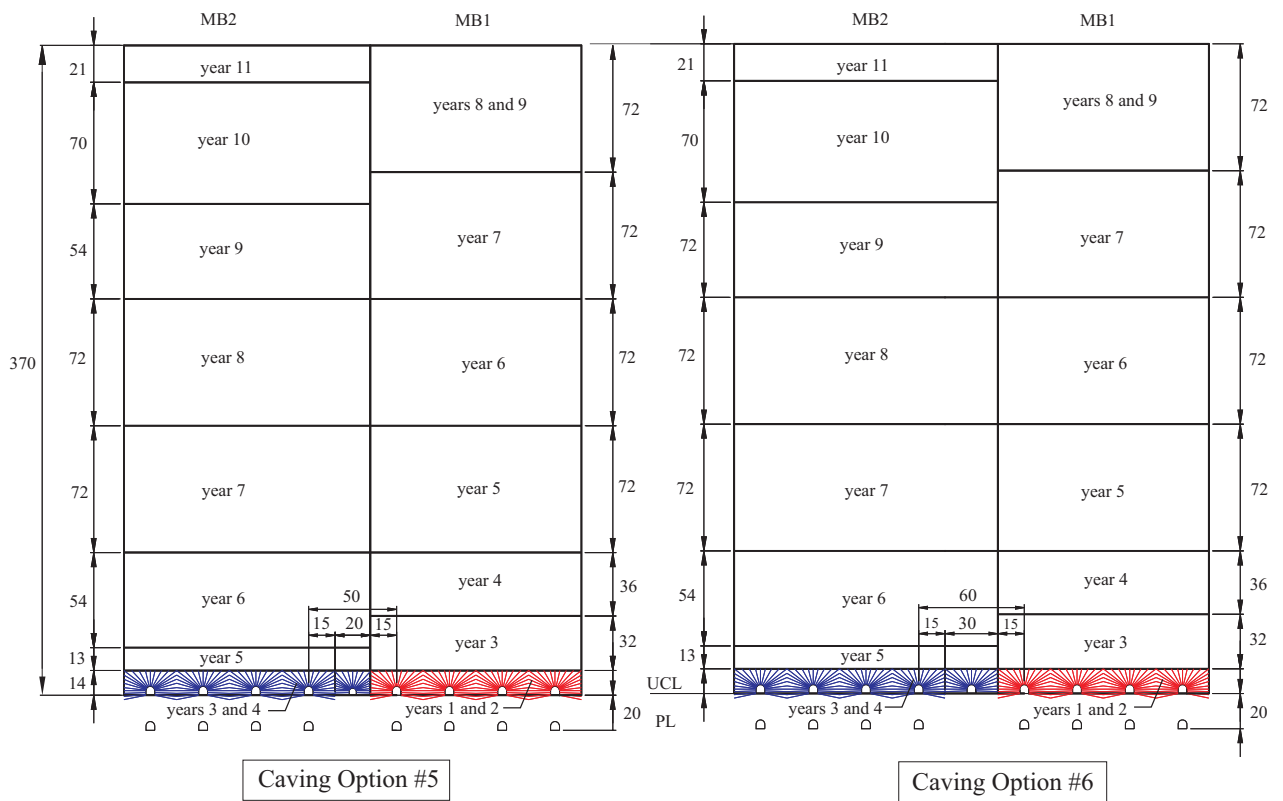


Figure 5. Caving options #5 and #6 analyzed with the three-dimensional elasto-plastic models.

Numerical Modelling

The main objective of the numerical modelling work done for this project has been to quantify the stress concentration at various critical areas of the planned caving infrastructure (galleries, drifts, pillars, rib-pillars, etc.). The following are the most relevant assumptions made in the models:

Drifts and galleries for extraction and undercutting levels have been considered with a square cross-section of 4 m by 4 m; undercutting height of 14 m and undercutting advance of 25 m have been assumed; the crown pillar has 16 meters in height; the caving scheme follows the scheme used at 'El Teniente' mine with a production grid of 15 × 16 meters; block caving method with macro-block variant and conventional caving sequencing has been considered; the West fault has been incorporated with a uniform thickness of 10 meters.

Six different caving options have been considered in the study. These options, referred to as caving options #1 through caving options #6, do have the following characteristics:

- Caving option #1: a pillar of width 20 m is left at the undercutting level between macro-blocks MB1 and MB2.
- Caving option #2: a pillar of width 30 m is left at the undercutting level between macro-blocks MB1 and MB2.
- Caving option #3: this caving option is similar to the caving option 1, except that the pillar at the undercutting level next to macro-block MB1 is removed before preparation of macro-block MB2 takes place.
- Caving option #4: the option is similar to the caving option 2, except that the pillar at the undercutting level next to macro-block MB1 is removed before preparation of macro-block MB2 takes place.
- Caving option #5: the option is similar to the caving option 1, except that the pillar at the undercutting level next to macro-block MB2 is removed during extraction of the macro-block MB1.
- Caving option #6: the option is similar to the caving option 2, except that the pillar at the undercutting level next to macro-block MB2 is removed during extraction of the macro-block MB1.

Figures 4 and 5 show the different caving options considered in the study. The figures also indicate the mining sequence (i.e., evolution of caving regions in time) provided by VCP-Codelco [7].

The numerical models for this project have been generated using the code FLAC3D (available from www.itasca.com). The models incorporate detailed geometrical features of the caving infrastructure, as well as different lithological units at the site —see, for example, Figures 6 through 9. Numerical algorithms developed to incorporate the various geo-mechanical features in the numerical models (such as initialization of ground stresses, caving sequencing, etc.) follow current geo-mechanical modelling practice —see for example [9].

Although the material constitute models in the numerical model do not present a rheological behavior, the models account for a 'time' component associated with the excavation sequencing. For example, each of the caving options described earlier on (see Figures 4 and 5) is comprised of 21 phases of

excavation and each of these phases of excavation is assumed to occur during a period of 11 years —i.e., the ‘year’ time unit indicated in Figures 4 and 5 relate to each excavation unit indicated in the same figure.

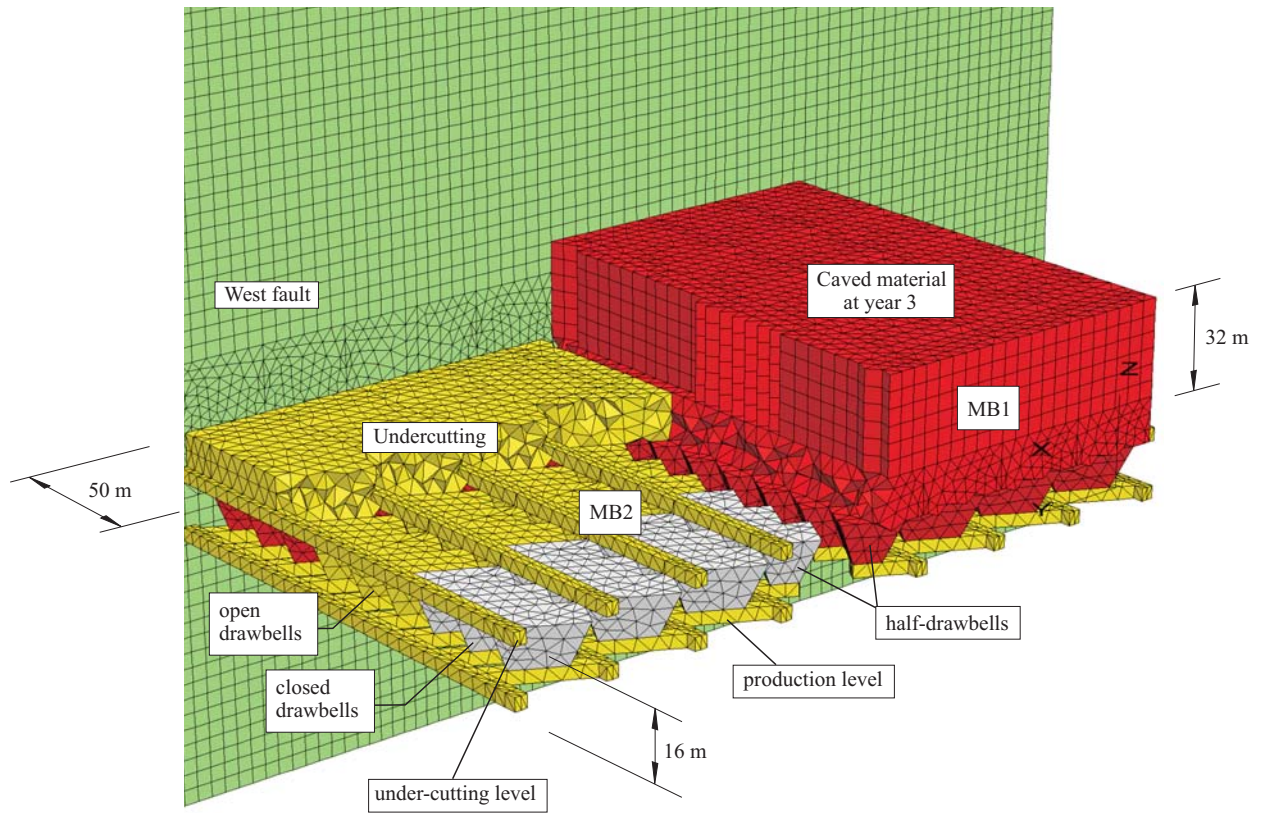


Figure 6. View of the three-dimensional numerical model for caving option #5, for year 3. The stage shown considers extraction of approximately 32 m of ore column for macro-block unit MB1; undercutting of 50 m, and opening of 9 drawbells for macro-block unit MB2. Represented in red is the broken material; represented in yellow are the excavations; represented in white are the galleries and drifts (before excavation); represented in green is the West Fault (rock mass has been hidden on purpose for clarity in the presentation).

Interpretation of results

The following is a summary of results obtained from the numerical study carried out for Chuquicamata Underground Project, as reported in detail in [4]:

1. In general, the abutment stress reaches 75 to 85 MPa for caving option #1 and #2, while the abutment stress for others options are lower than 50 MPa —see Figure 7.
2. The abutment stresses are localized in the geotechnical unit RQS ($Q > S$) while accumulated deformations are localized in the geotechnical units RQS ($Q < S$) and RQS ($Q = S$), for options #1 and #2, respectively —see Figure 8.
3. Low-level stresses (corresponding to unloading or deconfinement) are observed 10 m below the extraction level for options #3, #4, #5 and #6. For options #1 and #2, the zone of low-level stresses gets reduced significantly —see Figure 9.
4. Figure 10 shows the stress path for a point located 10 m above the extraction level floor in the macro-block pillar. For caving options #1 and #2, the peak strength of the rock mass is exceeded at year 3 (undercutting of MB2), while for options #3 and #4, the peak strength of the rock mass is exceeded at year 2 (undercutting of MB1). For options #5 and #6, stress deconfinement and tensile stress development can be observed at year 3 —see Figure 9.
5. Figure 11 shows the stress path for a point located 2 m above the extraction level floor in the macro-block pillar. For options #1, #2, #3 and #4, the peak strength of the rock mass is not exceeded at any year. For options #5 and #6, stress deconfinement and tensile stress development can be observed at year 3 —see Figure 9.

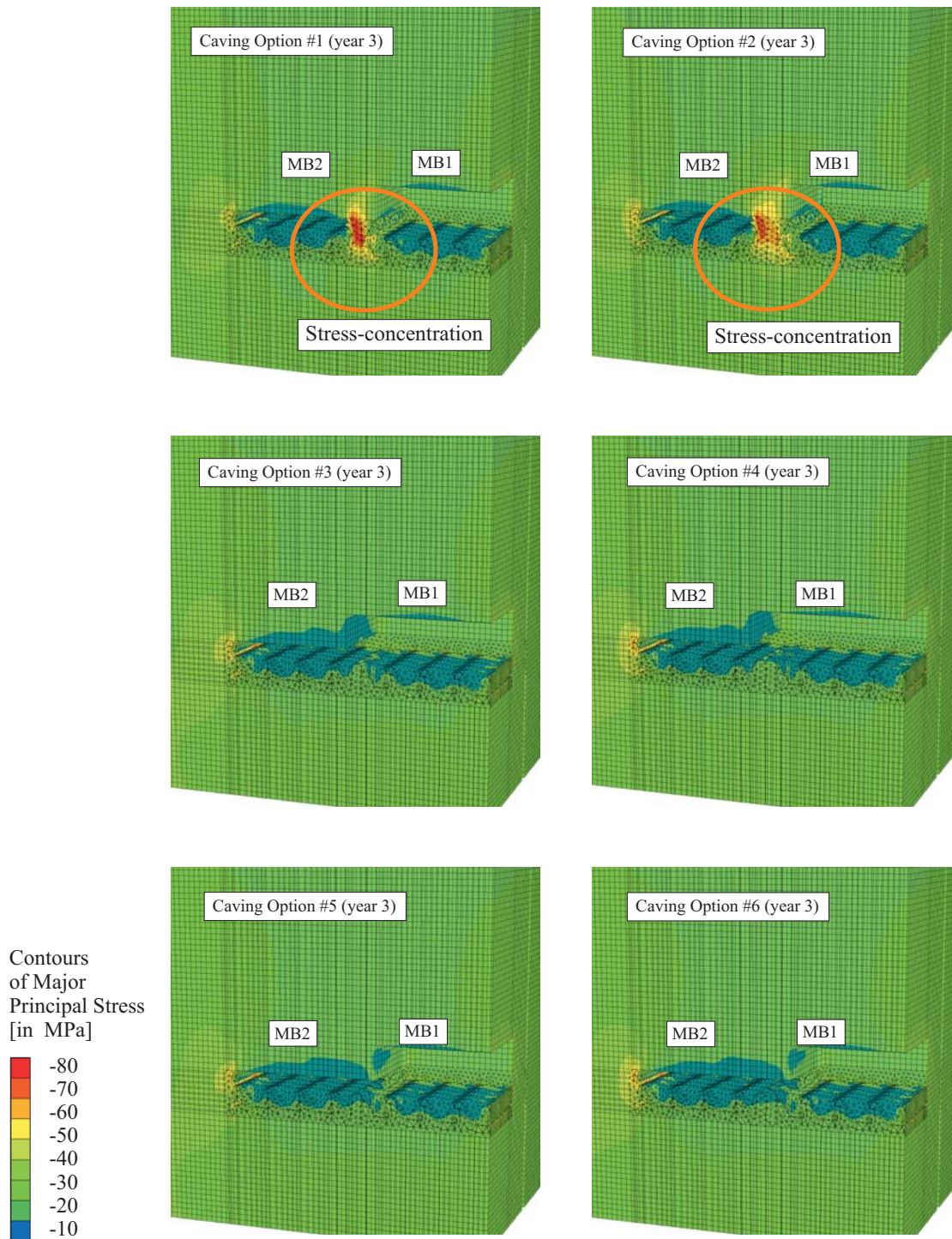


Figure 7. Comparison of different caving options in terms of major (i.e., most 'compressive') principal stresses. Note abutment stress concentrations developing in macro-block pillar for caving options #1 and #2.

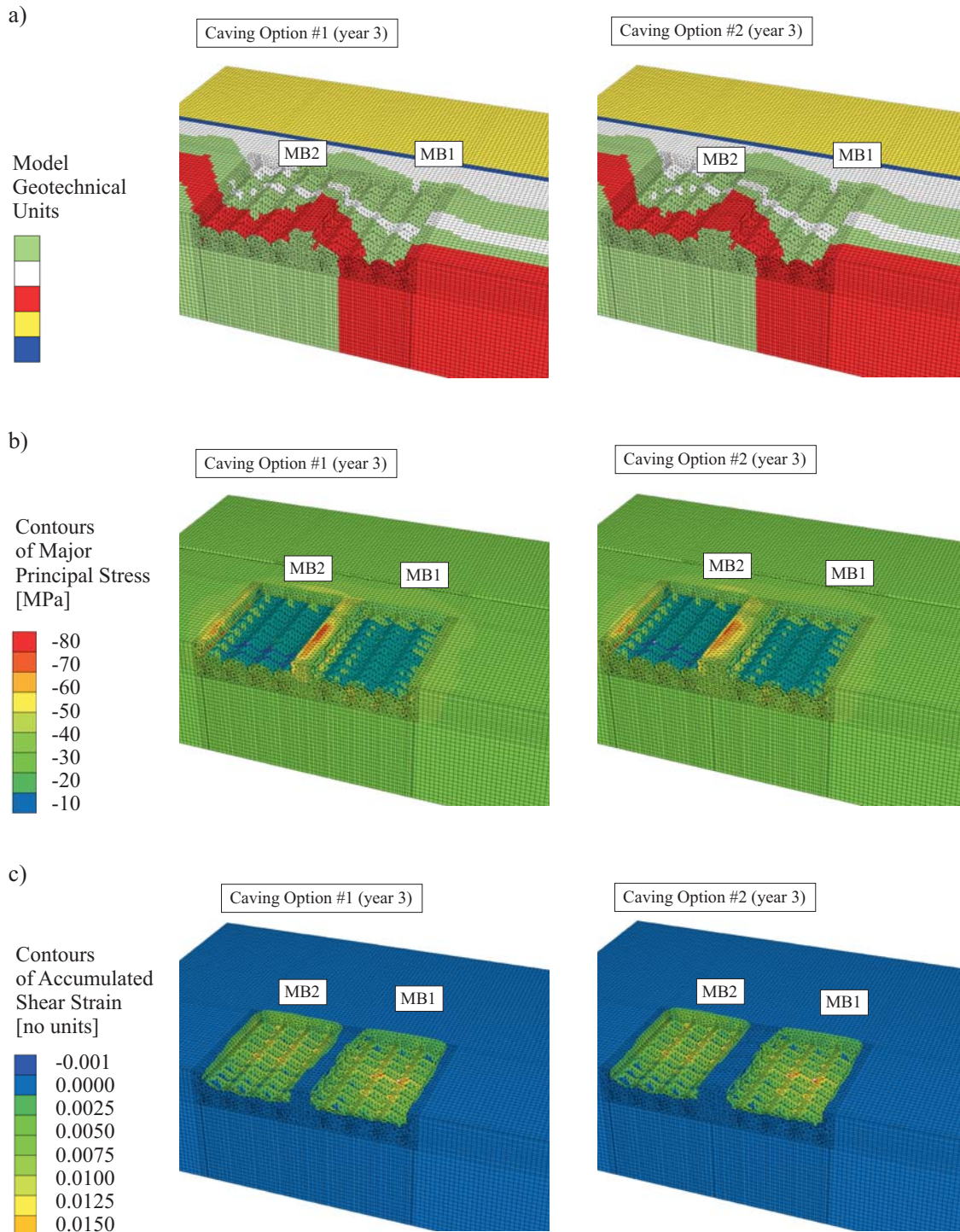


Figure 8. Representation of results in the model sliced by a horizontal plane located at the roof of the under-cutting level for caving options #1 and #2. Represented are: a) geotechnical units; b) abutment stresses for geotechnical unit RQS ($Q>S$) of good quality; c) shear strain increment for geotechnical unit RQS ($Q<S$) of poor quality.

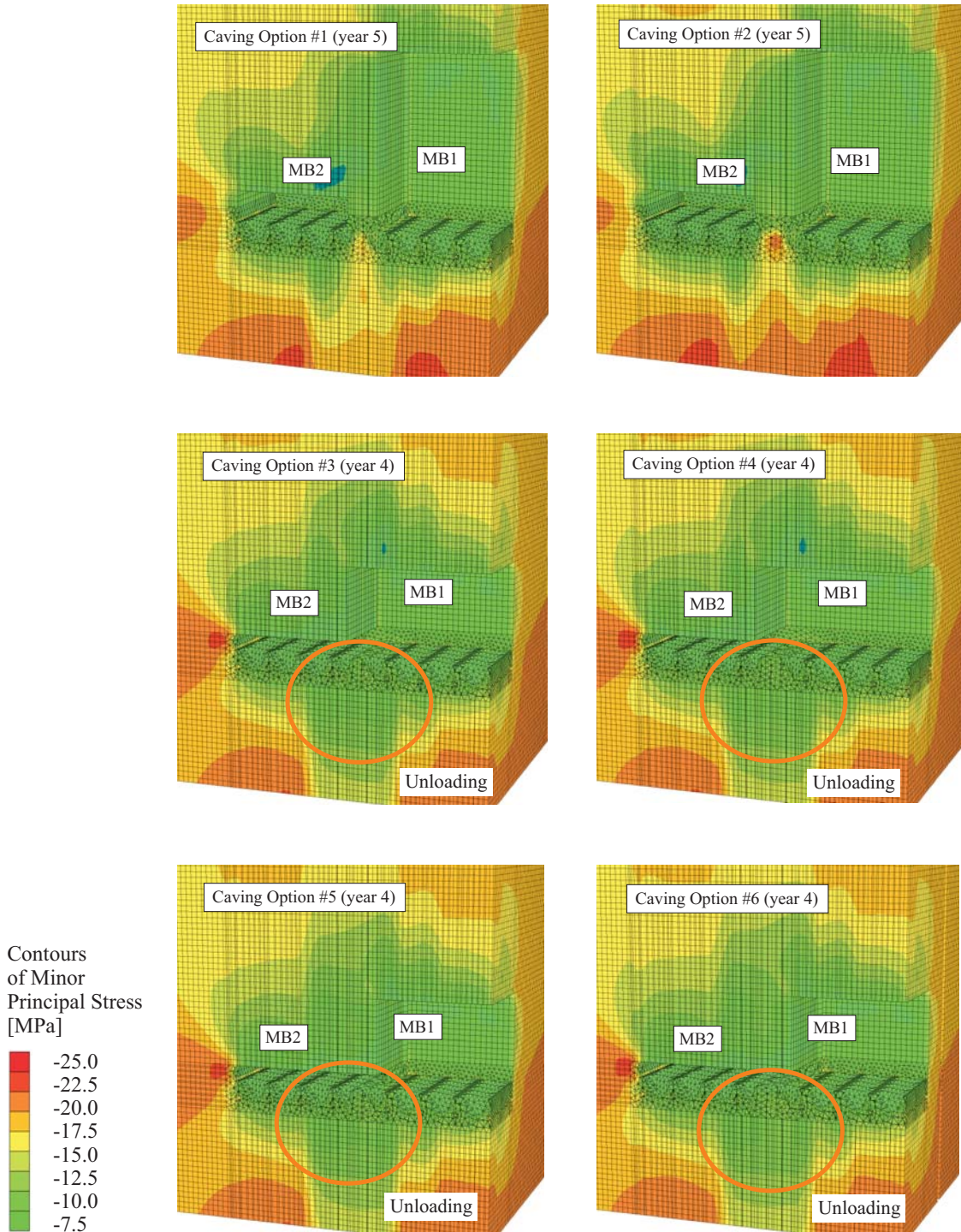
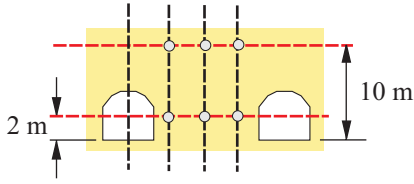


Figure 9. Comparison of different caving options in terms of minor (i.e., most ‘tensile’) principal stresses. Note the concentration of low stresses (i.e., unloading) developing below the extraction level in caving options #3, #4, #5 and #6.



PHASE	YEAR	DESCRIPTION
01	01	Construction of Undercutting drifts for MB1.
05	02	Drawbells opening for MB1 and first undercutting for MB1.
07	02	Third undercutting for MB1.
09	03	Extraction of 32m column of MB1. Layout MB2 construction .
13	03	Third undercutting of MB2.
17	07	Extraction of 284m column of MB1 and 126 m column of MB2.
21	11	Extraction of 100% of MB1 and MB2.

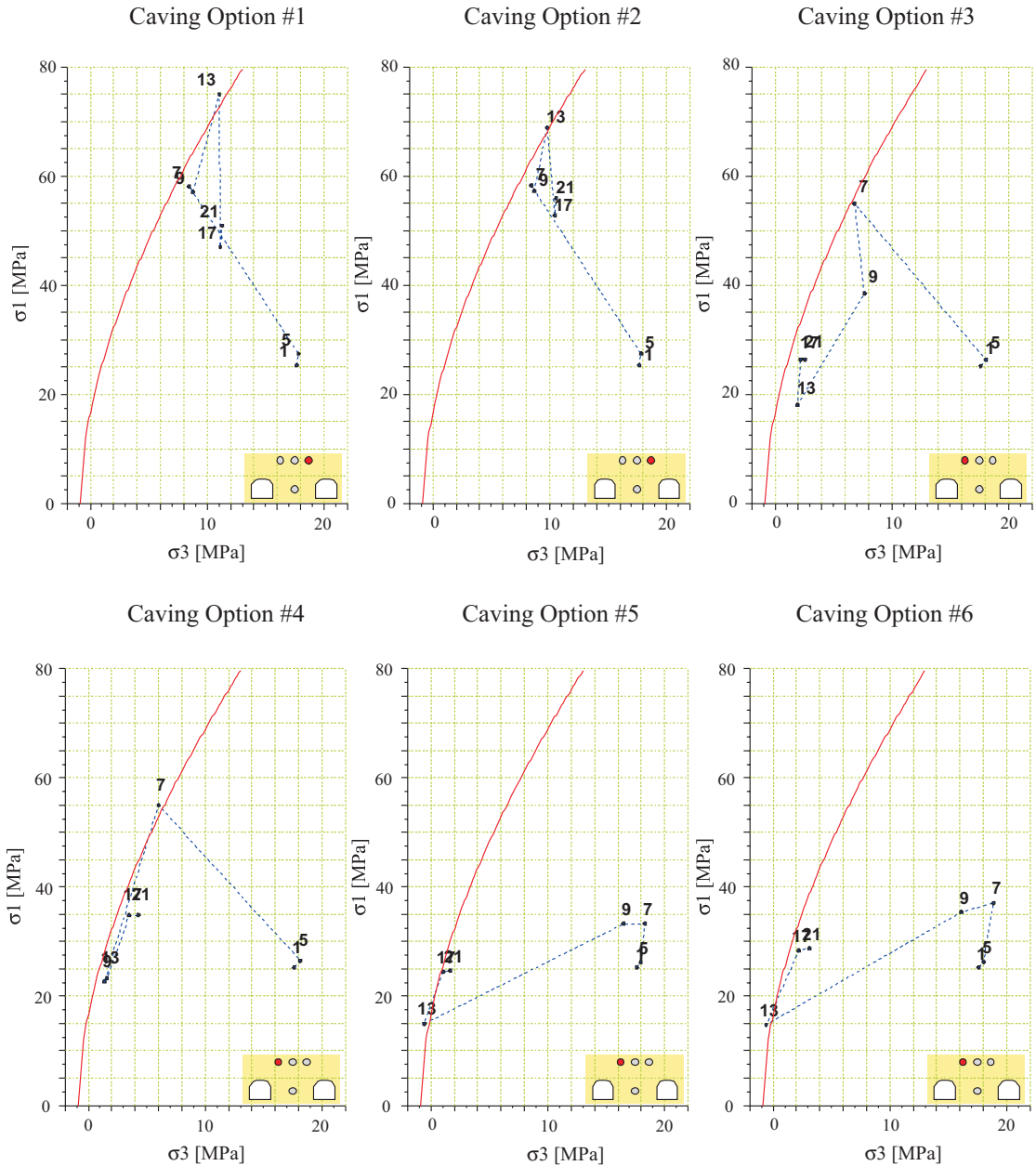
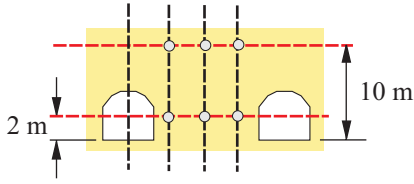


Figure 10. Stress paths for various points at 10 m above the extraction-level-floor in the macro-block pillar (the Hoek-Brown shear failure envelope is indicated in red). For caving options #1 and #2, the peak strength of the rock mass is exceeded at year 3 (undercutting of MB2); for caving options #3 and #4, the peak strength of the rock mass is exceeded at year 2 (undercutting of MB1); for caving option #5 and #6, concentration of low stresses (i.e., relaxation stresses) can be observed at year 3 (undercutting of MB2).



PHASE	YEAR	DESCRIPTION
01	01	Construction of Undercutting drifts for MB1.
05	02	Drawbells opening for MB1 and first undercutting for MB1.
07	02	Third undercutting for MB1.
09	03	Extraction of 32m column of MB1. Layout MB2 construction.
13	03	Third undercutting of MB2.
17	07	Extraction of 284m column of MB1 and 126 m column of MB2.
21	11	Extraction of 100% of MB1 and MB2.

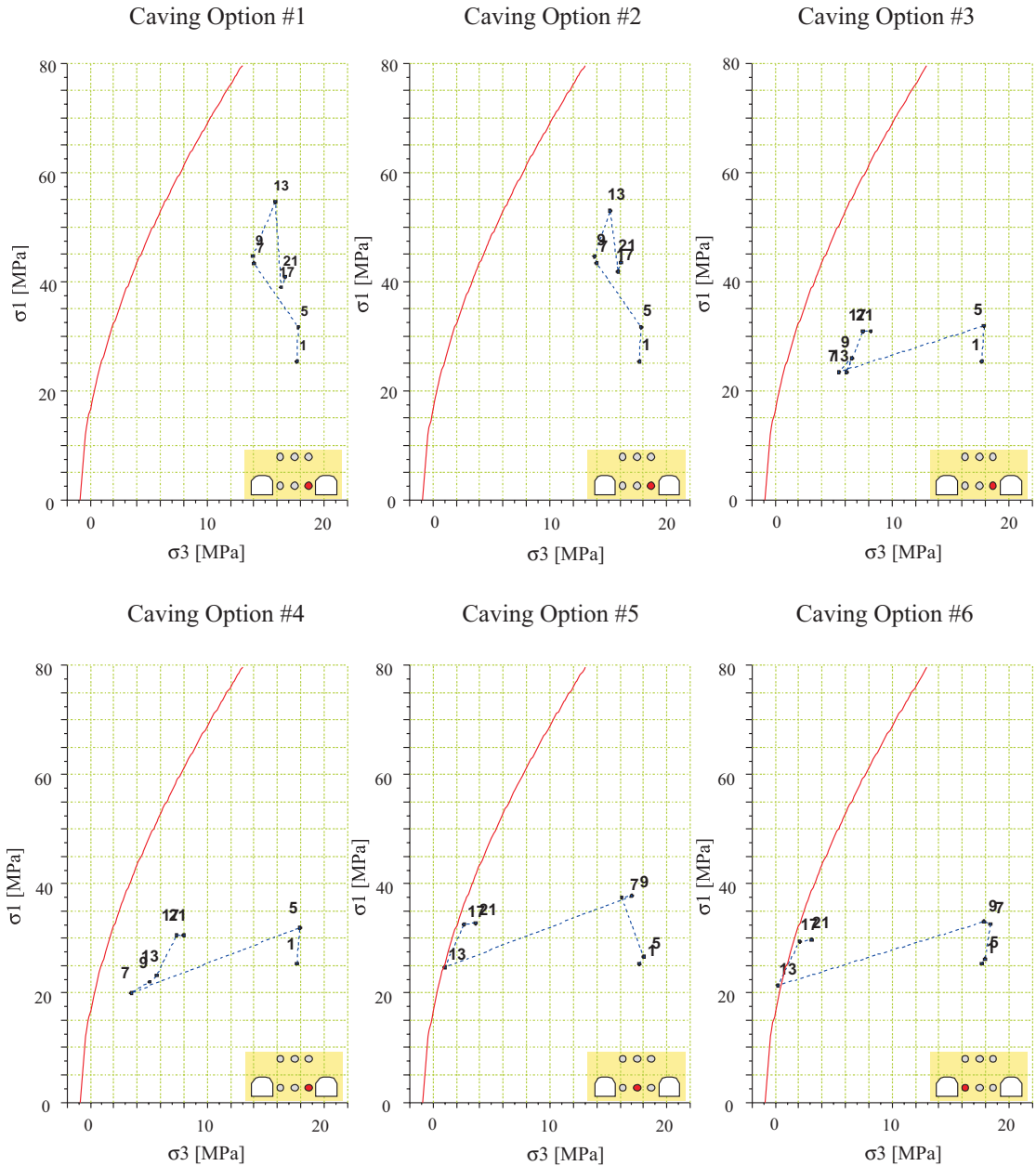


Figure 11. Stress paths for various points at 2 m above the extraction-level-floor in the macro-block pillar (the Hoek-Brown shear failure envelope is indicated in red). For caving options #1, #2, #3 and #4, the peak strength of the rock mass is not exceeded in any year; for caving options #5 and #6, tensile and relaxation can be observed at year 3 (undercutting of macro-block MB2).

Final comments

This paper has presented a general description of a geo-mechanical stress analysis carried for the Chuquicamata Underground project in Chile. Based on geological and geotechnical characterization of the site, and by application of three-dimensional elasto-plastic numerical models the stability of the macro-block pillars in the proposed caving operations has been assessed.

The results obtained from the analyses suggest that caving option # 6 (one of the six options considered in this study) leads to smaller stress concentration for abutment stresses; the results also suggest that for this option stress deconfinement and tensile stress development could potentially trigger rock mass instabilities. [It should be mentioned, nevertheless, that in this engineering design stage, no support has been considered for the underground caving infrastructure; thus stability of galleries and drifts could potentially and easily achieved by incorporation of support in areas of the infrastructure that would require so.]

The numerical models developed for this project do not simulate the actual propagation of caving (rather they account for a front of 'broken' material that advances in time, as dictated by the given sequencing of excavation). In a next feasibility stage, it is recommended that caving propagation is better taken into account, e.g., by simulating evolution of the front using or softening/strength reduction schemes.

Acknowledgements

The authors would like to thank CODELCO (National Copper Corporation of Chile), and in particular, Mr. Sergio Fuentes Project Manager and Sergio Olavarria, Project Director of Chuquicamata Underground Project, for granting permission to publish this paper.

References

1. CODELCO, "Geología y Recursos Minerales para la Ingeniería Conceptual del Proyecto Chuquicamata Subterráneo", Subgerencia de Geología. Dirección de Geología de Desarrollo. División Codelco Norte. CODELCO, Chile, 2007.
2. CODELCO-VCP, "Estudio de Prefactibilidad Proyecto Chuquicamata Subterráneo API N07DM43", VCP, CODELCO, Chile, 2009.
3. SRK Consulting Ltda., "Trabajos Geomecánicos Complementarios del Proyecto Chuquicamata Subterráneo", Technical report MSC-ICO-SRK-2000-GTE-INF-002-Rev P. SRK Consulting Ltda. Santiago, Chile, 2009.
4. SRK Consulting Ltda., "Evaluación Geomecánica de la Malla de Extracción Proyecto Mina Chuquicamata Subterráneo", Technical report MSC-ICO-SRK- 2000-GTE-INF-001-Rev P. Santiago, Chile, 2008.
5. A. Karzulovic, "Revisión Caracterización Geológico Geotécnico Proyecto Mina Chuquicamata Subterránea", PMCHS MSC-ICO-AKL-2000-GEM-INF-001-REV P. A. karzulovic & Asoc. Ltda., Chile, 2007.
6. D. H. Laubscher, "A Geomechanics Classification System for the Rating of Rock Mass in Mine Design", J. S. Afr. Inst. Metall., vol 90(10), 1990.
7. E. Hoek, "Strength of rock and rock masses", ISRM News Journal, 2(2), pp. 4-16 1, 1994.

8. E. Hoek, C. Carranza-Torres and B. Corkum, "Hoek-Brown Failure Criterion 2002 Edition", 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada. Editors: R. Hammah, W. Bawden, J. Curran and M. Telesnicki, University of Toronto Press: Toronto, Vol 1, 2002, 267-273, 2002.
9. HClasca-SRK, "Complementary Geotechnical Studies for Conceptual Design of an Underground Mine at Chuquicamata", HClasca-SRK, Vancouver, Canada, 2006.