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Back-analysis and chart creation as a graphical tool for the characterisation of cave interaction at División El Teniente, Codelco, Chile

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Abstract

Codelco Chile's División El Teniente mine has experienced over a hundred years of ore exploitation by underground mining methods such as block caving and panel caving. The challenges of the increasing depth have resulted in a series of problems which, from a geomechanical approach, can be turned into solutions that offer stability and security during operations which are progressing from mining a secondary rock type to a primary rock type.

One of the main challenges for the productive sectors and projects in the short, medium and long terms is to establish mining activities adjacent to and below older sectors previously exploited. This has been a historical problem for the División mine as it causes changes in the stress field between the cavities in formation, and an increase in both the quantity and magnitude of seismic events in the pillars of rock between the sectors, creating a phenomenon denominated cave interaction. To overcome this and take preventative action to avoid a seismic event, a graphical tool called a 'cave interaction chart' was developed. Its objective was to determine the current and/or future state between cavities through the geometrical disposition amongst them using the recompilation of historical data at the mine alongside an analysis with 2D numerical modelling of the convergent and divergent cases (at the same and/or different heights).

The following document shows the back-analysis undertaken and the criteria used to understand and order the historical data. It explains the specific numerical modelling associated with different conditions in which an interaction can be generated to explain the whys and wherefores of this graphical tool, which will be used to standardise and complement future studies regarding new sectors in the División mine.

Keywords: *cave interaction, geomechanics, stress field, chart, seismicity, underground mining, back-analysis, numerical modelling*

1 Introduction

With the progress of mining in the productive sectors and the División El Teniente Projects (Andesita, Andes Norte and Diamante) at lower levels than sectors currently being exploited or that have already been exploited, different types of problems have occurred that were recorded along with the history of the División mine. These are related to the geometry of the cavities generated by mining (size and advancement), the stress field redistribution and an increase in seismic activity.

One of the problems that has occurred over time corresponds to the phenomenon called cave interaction, which is a response to the advancement of mining between sectors located at the same and/or different levels. Such a manifestation in the rock mass has been documented as part of the analysis in rockburst reports (as in the cases of Pilar Norte and Bloques of Esmeralda Sur), as well as specific analysis of the seismic response in a sector (such as the case of RENO-Dacita) and of changes in the stress state (Bloque 1 of Esmeralda Sur and Fase II of Diablo Regimiento). However, to date there was no statistical or graphic tool

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that would allow the occurrence to be identified from the initial engineering stages (profile stage) of this phenomenon.

It is necessary to mention that in the initial stages of an engineering project, the preliminary geomechanical parameters are considered through a theorical background. Thus having simple and easy-to-understand tools and the extractive history of División El Teniente are relevant to decision-making.

Because of this, the need arose to establish a standardised database founded on information from historical events to identify the different conditions in which the interaction phenomenon can be caused and to explain its occurrence.

Additionally, to achieve continuous mining and avoid production stoppages as a response to the process of interaction, work is being done on the proposal of a chart: a graphic tool that seeks to correlate the phenomenon in an analytical way using data from historical interactions registered in the División mine.

2 Conceptual framework

In the División El Teniente, the emplacement of new projects or the growth of current productive sectors causes operational and geomechanical challenges due to the uncertainty related to the behaviour of the rock mass and the location of older mining.

One of the main geomechanical challenges is understanding the phenomenon of cave interaction. In particular, definitions of the panel cave mining method and cave growth should be considered. In this section these topics will be addressed, starting from subsidence and going through to the interaction itself.

2.1 Subsidence

The literature provides a wide range of definitions that begin with the conceptualisation of a cave, which is expressed as a volume limited by the floor of the undercut level and the surrounding rock mass, where blocks of rock have fallen as a consequence of ore extraction (Brady & Brown 2004). This phenomenon is due to a process that has been defined in previous publications (Karzulovic 1999) for the División El Teniente, where the subsidence results from mining activities related to the extraction of ore. This in turn is associated with fracturing and displacement of the rock mass adjacent to and above a sector in exploitation, and its last manifestation is observed in the surface (crater), as shown schematically in Figure 1.

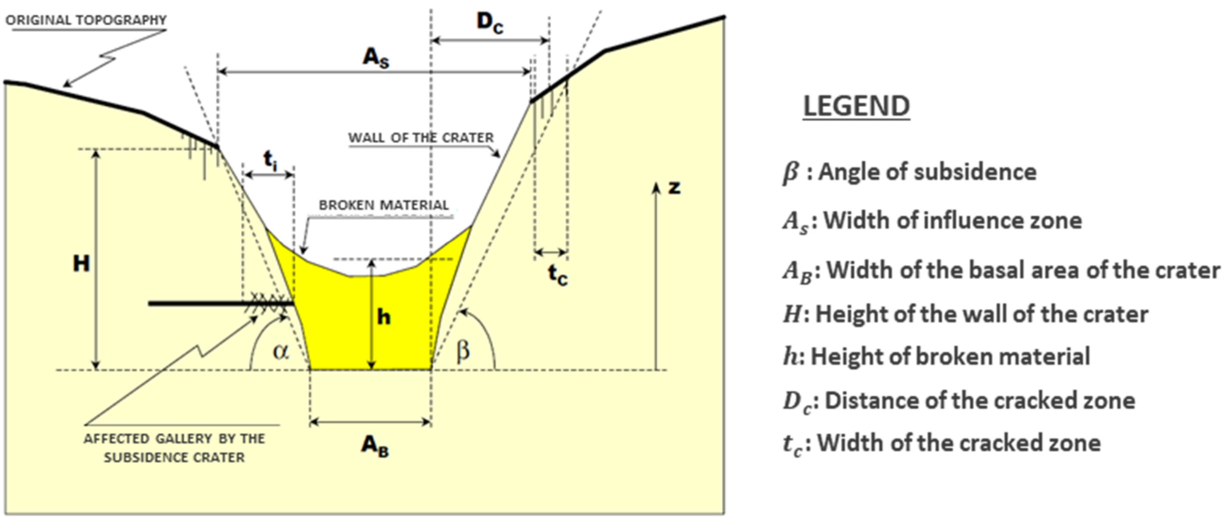

Figure 1 Diagram of parameters related to the morphology of a crater produced by subsidence (Karzulovic 1999)

Regarding the evolution of the cave, eight stages are highlighted to describe the mechanisms of crater formation, and four of them mark the main milestones (Karzulovic 1999). Figure 2 shows the stages of initial formation, crown pillar generation, connection and final wall generation.

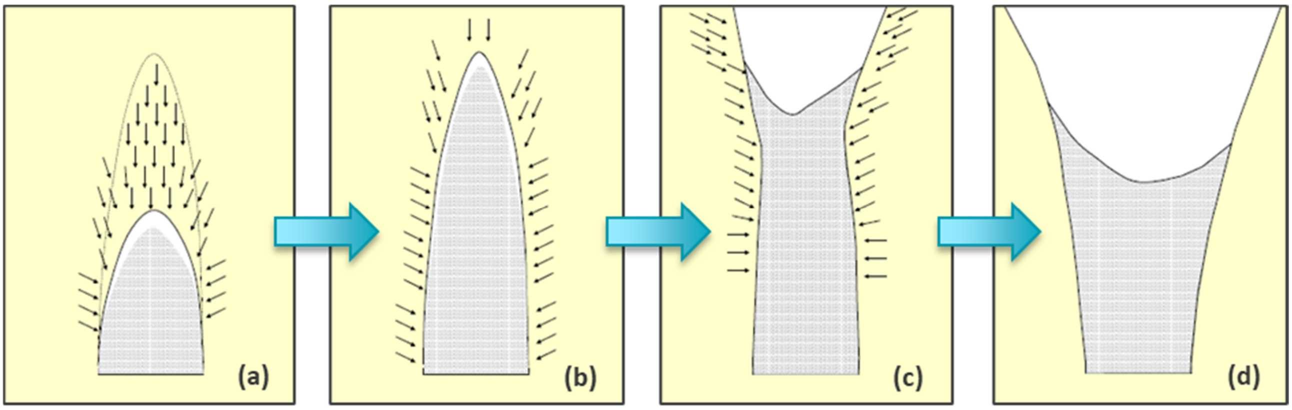

Figure 2 Diagram of cave formation (Karzulovic 1999): (a) Initial formation; (b) Crown pillar generation; (c) Connection; (d) Final wall generation

2.2 Cave wall classification by extraction condition

Every cave, being a volume with broken material inside, is defined by the walls that limit it. It is possible to classify these walls as active or passive according to their extraction and growth conditions, as seen in Figure 3.

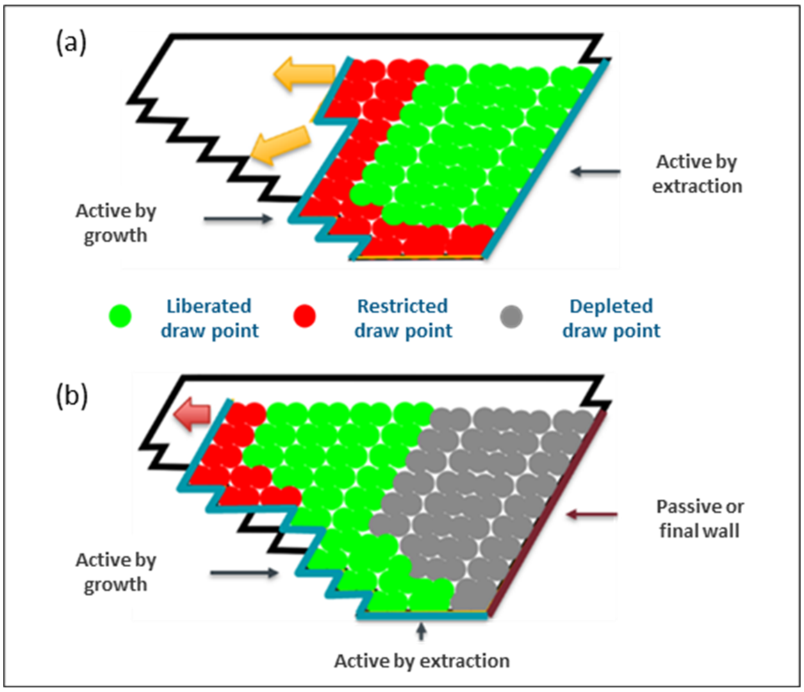

Figure 3 Type of walls according to their condition of extraction and growth: (a) Case for an active wall by extraction; (b) Case for a passive or final wall

An active wall one affected by the process of extraction of reserves (ore or mud-water) and/or the growth of the cave. It can be active by growth, i.e. directly associated with the advance of the cave front, or active by extraction, i.e. undergoing changes in the geometry due to the extraction process itself. See Figure 3a.

A passive wall is one not affected by the extraction process (ore or mud-water) or growth of the cave, and which therefore does not undergo a change in its geometry. See Figure 3b.

2.3 Previous definition of cave interaction

Based on the advancement of mining and also its deepening, the sectors currently in production and the projects are located under existing caves (depleted) and even coexist spatially in their vicinity. See Figure 4.

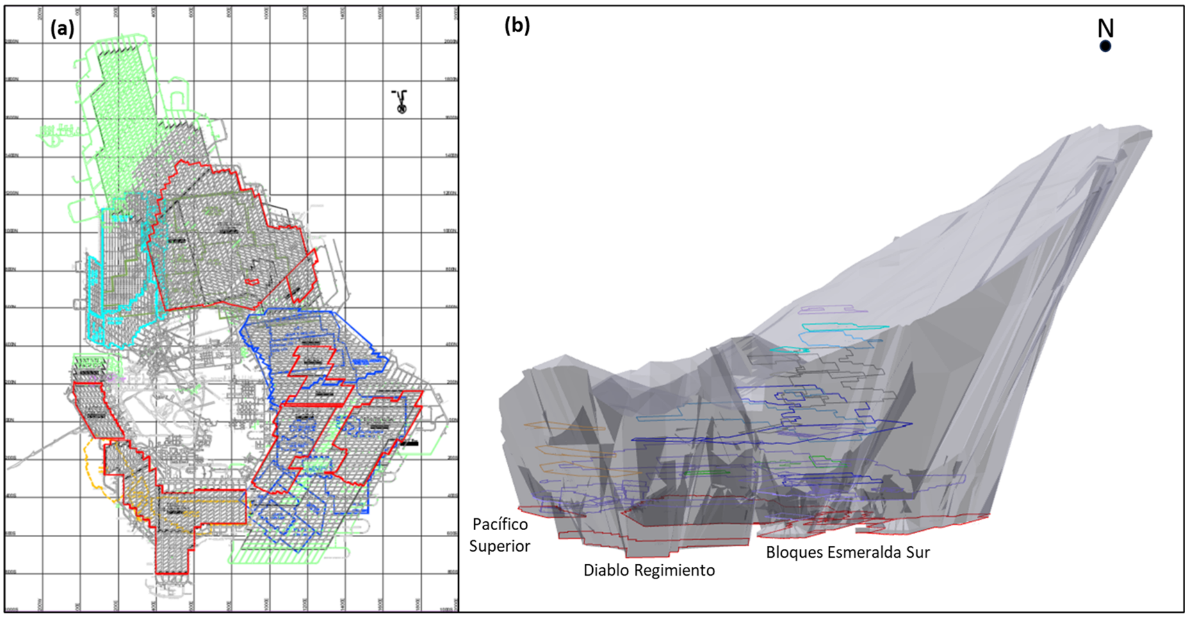

Figure 4 Spatial distribution of the upper caves in the División El Teniente: (a) Plan with upper caves up to 150 m from productive sectors; (b) 3D view of the upper caves to the surface

As described, the cave formation initiates gradually; ascending from the beginning of the undercut until the formation of the crater on the surface (subsidence crater), or the coupling with a sector that is already depleted. During this process, or along with the advancement of the cave fronts, the cave interaction can cause a phenomenon that has been studied since 2004; the understanding of which has since been enriched. Parraguez & Vásquez (2004) define the interaction as an 'effect that can cause subsidence (a seismically active wall of collapse and fracturing) and induced stresses by the excavation of a sector on an adjacent one and vice versa', while Olguin (2021) defines it in a much broader way:

> *'Reciprocal effect generated by the proximity between two or more cavities in primary rock, resulting in the redistribution of the stress field and the reduction in size of pillars of solid rock that separate the cavities as a result of the progress of the mining of one or more productive sectors, causing with it an increase in seismic activity and potential damage in extractive galleries of the sectors involved in the cave convergence process.'*

Over a period of 17 years, different events have occurred at the División, including:

- damage in construction (developments and infrastructure)
- greater seismic understanding
- advancement of the mining and deepening
- new productive sectors
- rockbursts.

2.4 Interaction types

Considering the different cave configurations, the variety of walls that comprise them and the wide range of interaction types (depending on the advancement of the fronts previously exposed), it is useful to divide them into two large groups: convergent interactions and divergent interactions.

2.4.1 Convergent interaction

This type of interaction is associated with the advance of cave fronts where the rock pillar decreases in size, either unidirectionally or bidirectionally, depending on the state of mining extraction of the cavities involved. It is possible to identify four types of convergent interactions, as show in Figure 5.

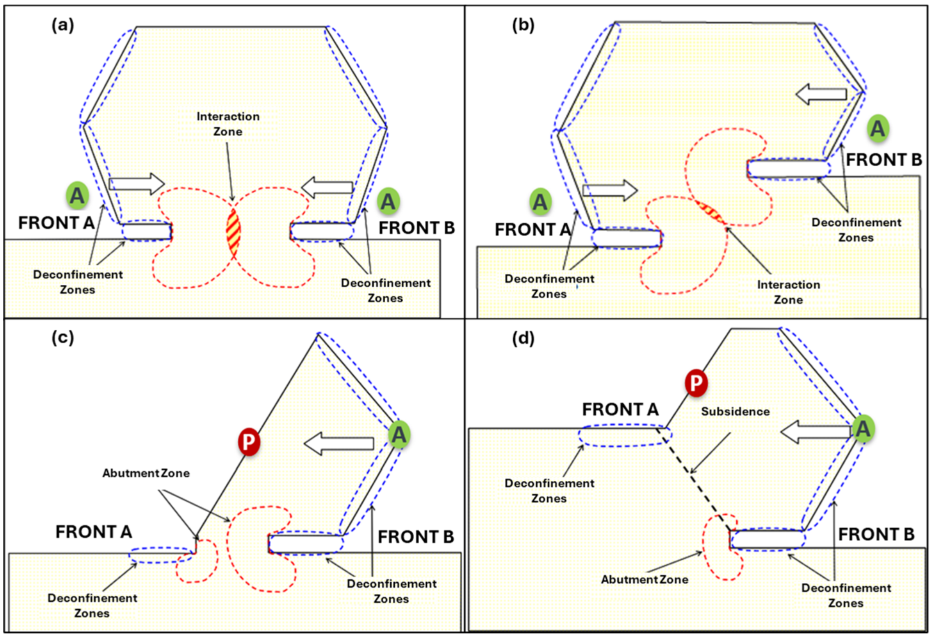

Figure 5 Type of convergent interactions: (a) Active walls at the same level; (b) Active walls at a different level; (c) Active-passive walls at the same level; (d) Active-passive walls at a different level

2.4.2 Divergent interaction

This type of interaction is related to the distancing of two cavities from each other. Depending on the subsidence configuration and growth stage in which a cave could be found, one of the fronts can directly affect the other due to changes in the stress field and the seismicity in its forming wall. It is possible to differentiate four types of divergent interactions, as shown in Figure 6.

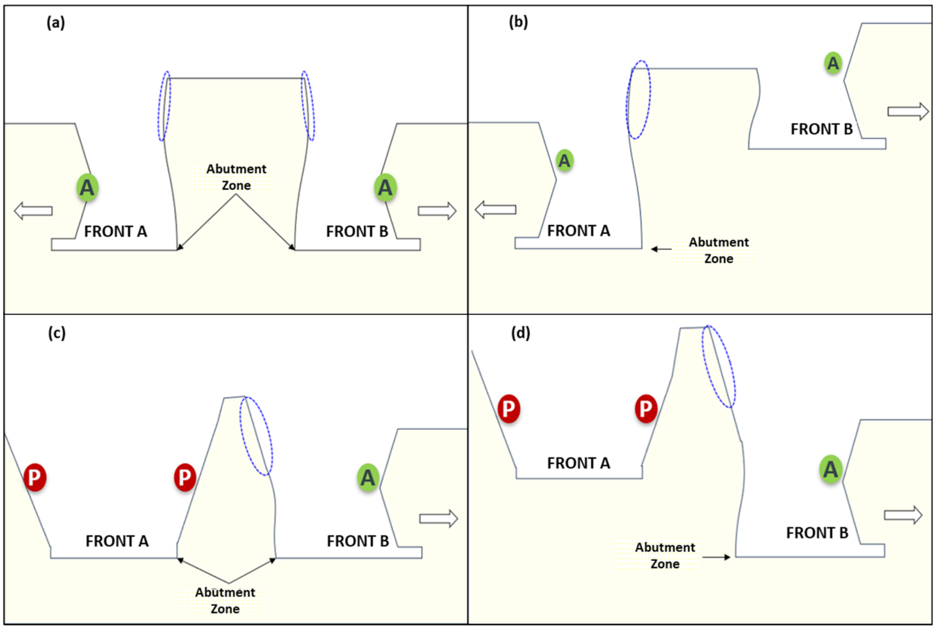

Figure 6 Types of divergent interactions: (a) Active walls at the same level; (b) Active walls at a different level; (c) Active-passive walls at the same level; (d) Active-passive walls at a different level

2.5 Geometrical disposition of interaction between cavities

Although the geometric and growth concepts of the cave fronts are necessary to differentiate the type of interaction that can form, the spatial distribution in which the cavities are found plays an essential role in interpreting the potential of an interaction.

Each case of interaction registered in División El Teniente has a different spatial distribution. Therefore it is necessary to identify the metric parameters that allow this phenomenon to be parameterised. Those considered are:

- horizontal distance of the interaction (ΔHz)
- vertical distance of the interaction (ΔV).

Both distances are measured with respect to the undercut level of each sector, and always responding to the shortest distance that may occur (Figure 7).

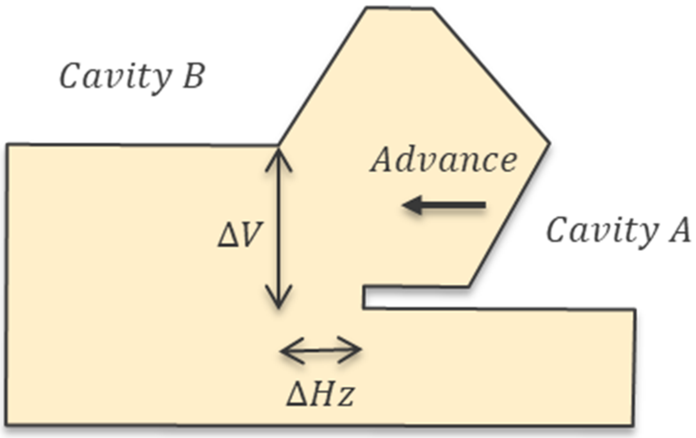

Figure 7 Diagram of distances between cavities for an interaction

3 Cave interaction back-analysis in the División El Teniente

Throughout the history of División El Teniente, different phenomena of cave interactions have occurred. The vast majority, dating from 2003 to 2020, have been documented. Figure 8 details a total of eight interactions between depleted and active sectors, and Table 1 shows the characterisation of each of them.

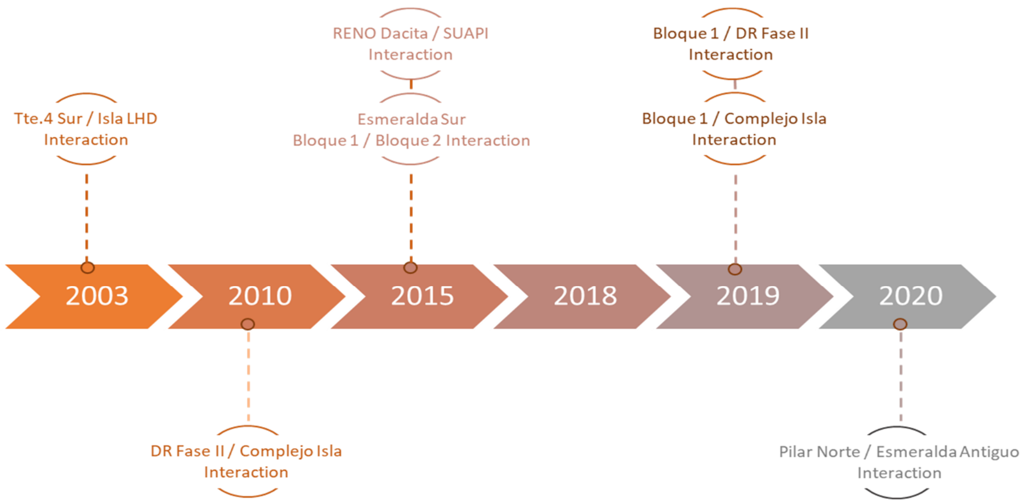

Figure 8 Timeline of interactions registered at División El Teniente

The parameters used to declare each interaction are:

- redistribution of the stress field (values greater than 80 MPa for the major principal stress or less than 5 MPa for the minor principal stress) in the rock pillar
- seismic rise of events equal to or greater than MW1 (mine magnitude) in the rock pillar.

Table 1 Summary of historical cave interactions documented in División El Teniente

Historical cave interaction	Interaction type	Wall type	Vertical distance of interaction	Horizontal distance of interaction
Tte. 4 Sur/Isla LHD (Constanzo & López 2008)	Convergent	Active/Passive	54 m	130 m
DR Fase II/Complejo Isla (Hidalgo 2017)	Convergent	Active/Passive	107 m	137 m
RENO Dacita/SUAPI (Balboa et al. 2015)	Convergent	Active/Passive	87 m	105 m
Esmeralda Bloque 1/Bloque 2	Convergent	Active/Passive	0 m	128 m
Esmeralda Bloque 1/DR Fase II (Balboa et al. 2018)	Convergent	Active/Passive	0 m	120 m
Esmeralda Bloque 1/Complejo Isla	Convergent	Active/Passive	106 m	115 m
Pilar Norte/Esmeralda Antiguo	Convergent	Active/Passive	91 m	90 m

4 Numerical modelling

Each of the antecedents presented experienced seismic events equal to or greater than MW1 (mine magnitude) in the rock pillar.

Table 1 shows a particular stress condition in which the cave interaction happened. Given the above, and with the intention of assimilating the redistribution of the stresses that occurred in the pillar, 2D numerical models are generated via RS2 software that uses lithological and stress field parameters along with the topography (as shown in Figure 9).

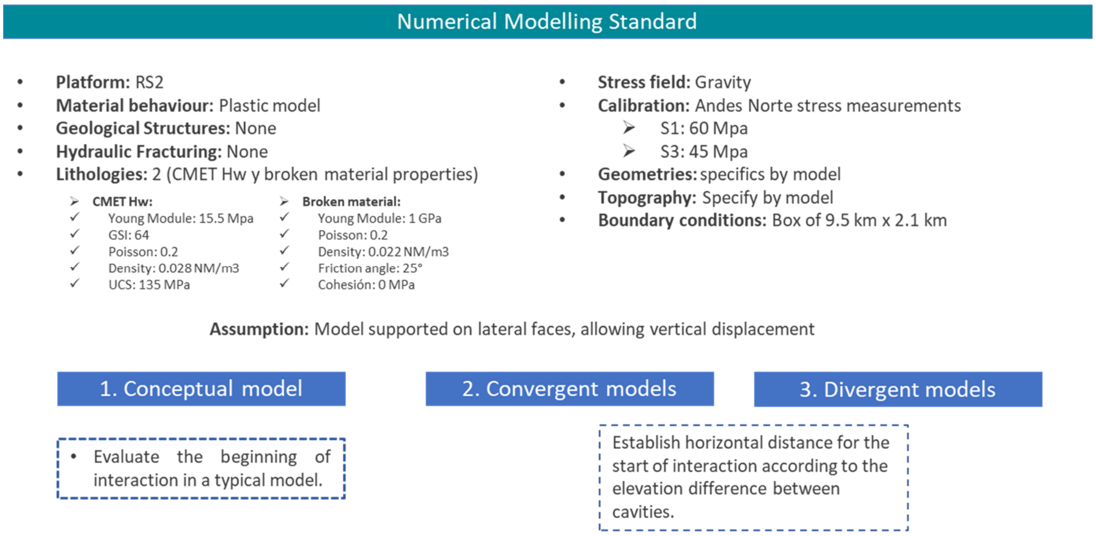

Figure 9 Limitations of the 2D numerical model using RS2 software

Using the data presented, a total of 12 models using plastic material were made for the convergent type where the distance between undercut levels (of interacting caves) and the horizontal distance between cave fronts are varied, as shown schematically in Figure 10.

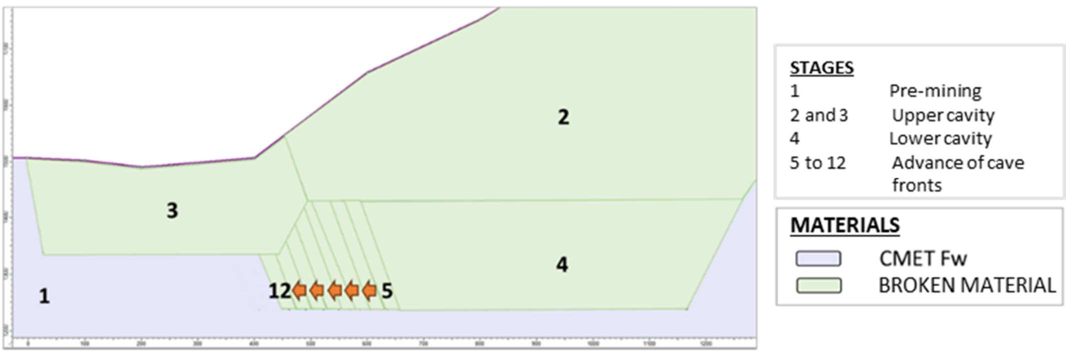

Figure 10 Sequenced growth for models of the convergent type

The divergent type models are constructed similarly to the convergent type, considering an opposite advance direction between cave fronts, as seen in Figure 11

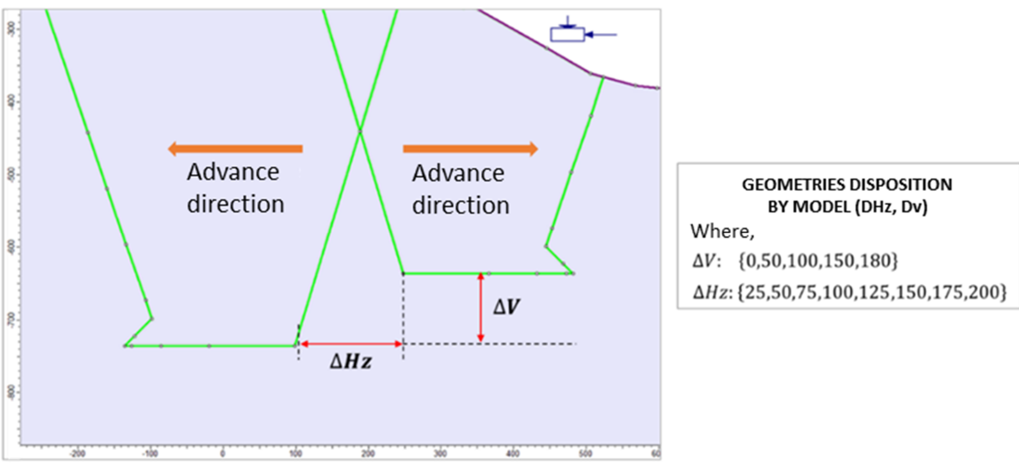

Figure 11 Sequenced growth for models of the divergent type

For each of the convergent and divergent cases a change is sought in the distribution of stresses exerted by the advancement of the lower cave on the upper cave, which is monitored using three points of control distributed in the upper cave: the first is on the UCL, the second at the productive levels and the third below the UCL to review the effect of abutment stress.

Preliminarily, and seeking the best representation of the interaction, simple models are made using the major principal stress (S1), the minor principal stress (S3) and the deviatoric stress (S1–S3); looking for graphic patterns that indicate obvious increases or decreases in stresses. It is of great importance to find which of the three parameters will be used to characterise the types of interaction, which is why the data is extracted from all the information of the principal stresses in the base models.

Figure 12 shows the results of using the deviatoric stress of the base model, the representation of the control points and the redistribution in the stresses at the lower zone of the upper cave.

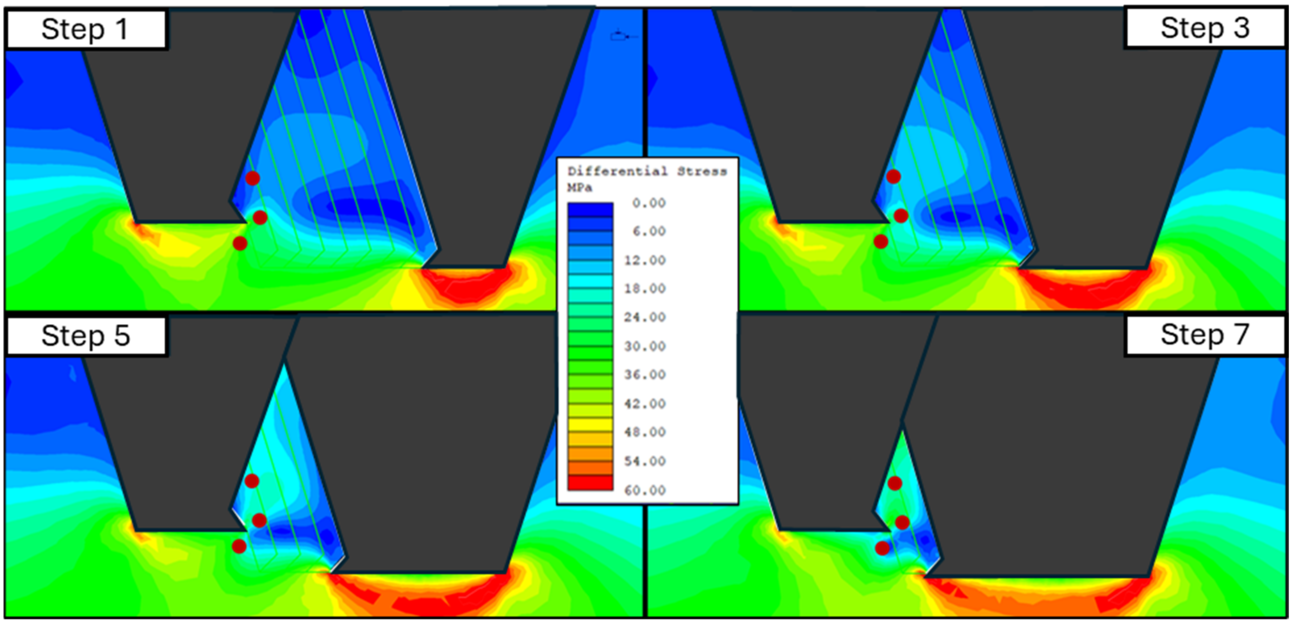

Figure 12 Example of the increase in deviatoric stress as a result of the active cave growth

From results provided by the three control points for the principal and deviatoric stresses in the different modelling stages, three graphs (S1, S3 and deviatoric stress) were made, with the results shown in Figure 13.

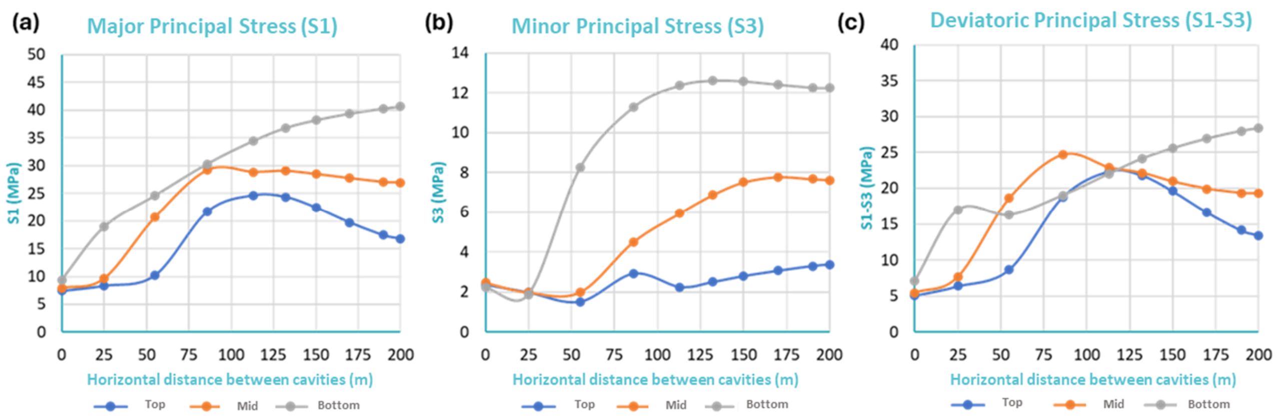

Figure 13 Example of the stress path in a conceptual model according to the growth from an active wall to another active but static wall: (a) S1 results; (b) S3 results; (c) S1–S3 results

In de Lucia (2022) a graphical and visual analysis was carried out using failure shear points and S1–S3, visualising the plastic failure of a simplified model. In this model there is a moment in which, given the arrangement of the cavities, a plasticisation occurs that addresses the total distance between them and a redistribution of S1–S3 that reaches a peak in the pillar between both geometries. This is why, to represent this situation in the present models graphically in Figure 13, an interval of occurrence of horizontal distances was selected that marks the change in slope due to the increase and subsequent decrease in the stress (around the peak). Those points were named the upper limit and lower limit, respectively.

Given that the model also incorporates the vertical distance variation between the geometries of the cavities, it was determined when analysing the data and graphs obtained that the main stress which most represents the situation described in its different control points corresponds to S1. This also makes sense regarding the historical analyses undertaken for División El Teniente that were presented in Table 1.

As a second filter for the three control points, the one that best shows the situation described (with the increase and subsequent decrease in stress) is chosen. For example, the upper point in Figure 13a, and selection of the two previously mentioned limits by the change in the slope of the curve, as represented in Figure 14.

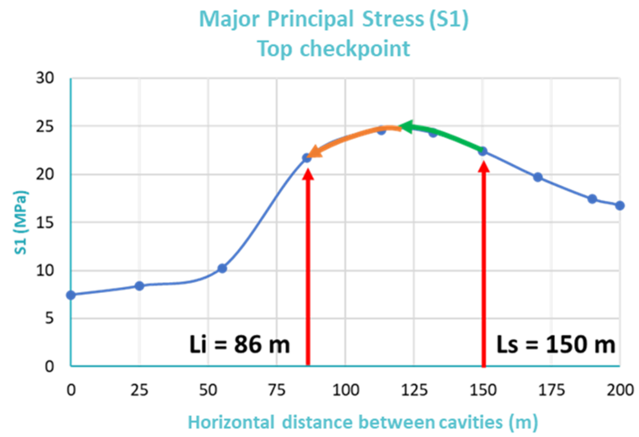

Figure 14 Selection example for a horizontal distance range between cavities to define the beginning of interaction

For each vertical distance covered between cavities, the upper and lower limits of horizontal distance between cave fronts are selected. The results are presented in Figure 15a for convergent cases and in Figure 15b for divergent cases.

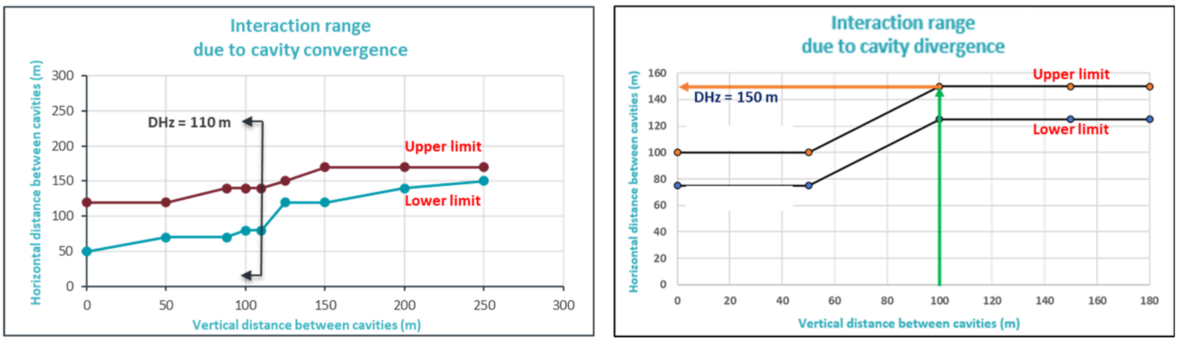

Figure 15 Graphic results of 2D numerical models: (a) Convergent cases; (b) Divergent cases

5 Cave interaction chart

Once the back-analysis of the historical interactions registered in División El Teniente and the results of the 2D numerical modelling of the convergent and divergent cases have been completed, a graphical tool that can characterise the phenomenon studied and simplify the spatial conditions in which convergent or divergent interactions will occur is created, using the procedure in Figure 16.

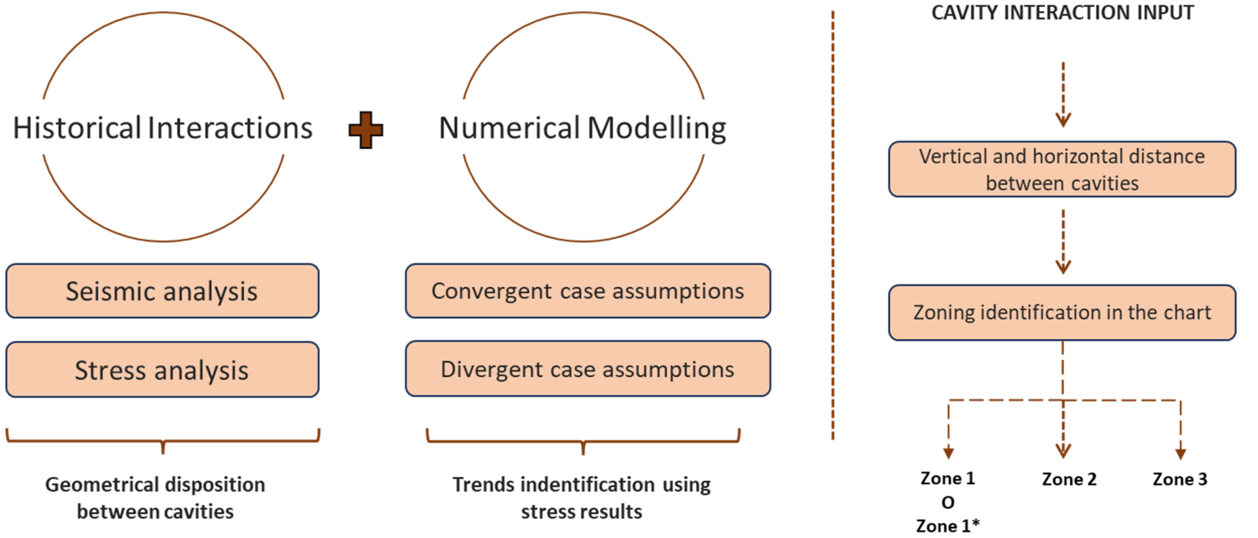

Figure 16 Necessary topics for the construction of the graphic tool

As a first step, the different vertical and horizontal distances between cavities from historical interactions are plotted, in which, according to the seismic and stress analysis, the interaction phenomenon is declared. The result can be seen in Figure 17.

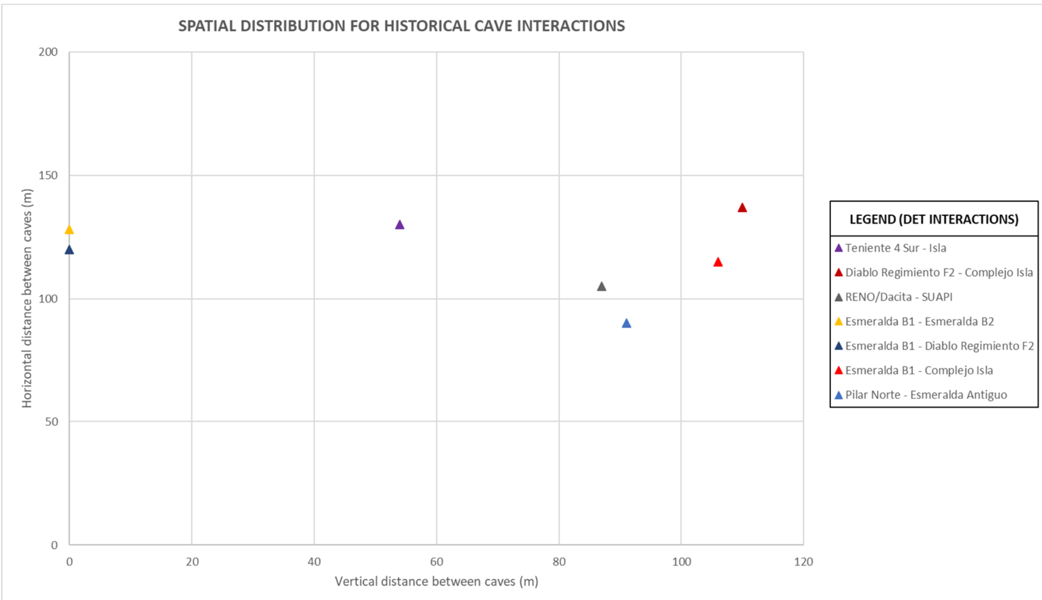

Figure 17 Spatial distribution graph for registered cave interactions

When extrapolating both graphs in Figure 15 it was highlighted that the trends are similar; maintaining a convergence towards 150 m of horizontal distance when the 110 m of vertical distance between cavities are exceeded. Given the above and to create common limits for the results of the numerical models, the upper and lower limits are rectified (considering greater distances greater and lower distances for both limits), as is shown in Figure 18.

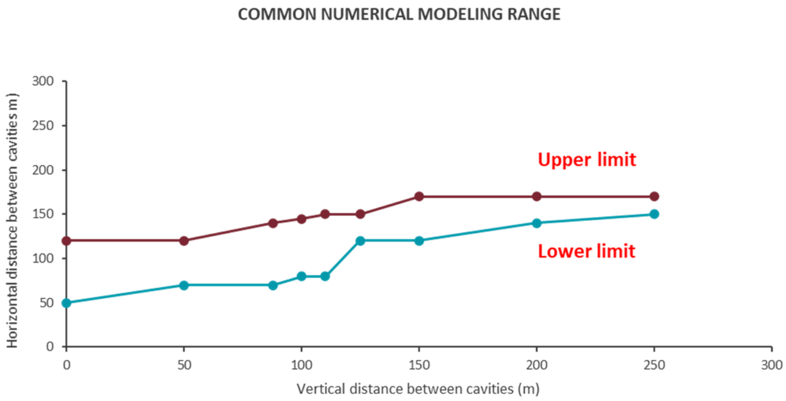

Figure 18 Common result of cave interaction limits for convergent and divergent cases

By combining the results in Figures 17 and 18, a smoothing of the upper and lower limits of the model curves was carried out using a statistical criterion using the mean plus and minus the half of the mode. On the other hand, there is no experience in División El Teniente beyond 110 m of vertical distance between cavities, so this value was established as the boundary length for the beginning of the cave interaction phenomenon. See Figure 19.

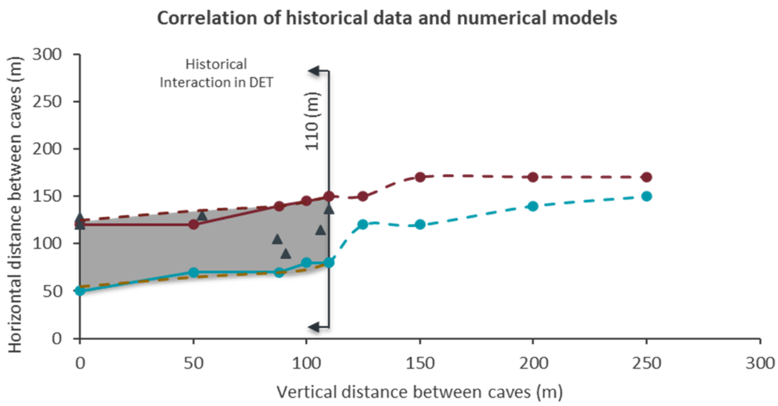

Figure 19 Smoothed graph of historical data and numerical modelling results

The graph highlights that:

- The smoothing of the data with the statistical criteria used allows 100% of the historical data to be captured within the lower and upper limits (in the grey area).
- In general, it can be observed that there tends to be an increase in the horizontal distance with an increase in the vertical gap between sectors.
- Beyond the 110 m of vertical distance between cavities in División El Teniente there is no experience of the interaction phenomenon. However, it is possible to observe that at 200 m of vertical distance both limits begin to stabilise, delivering a convergence at 150 m of horizontal distance (as an average of both curves).

These results were used to create the cave interaction chart, which is zoned depending on the vertical and horizontal distances between cavities, in Figure 20.

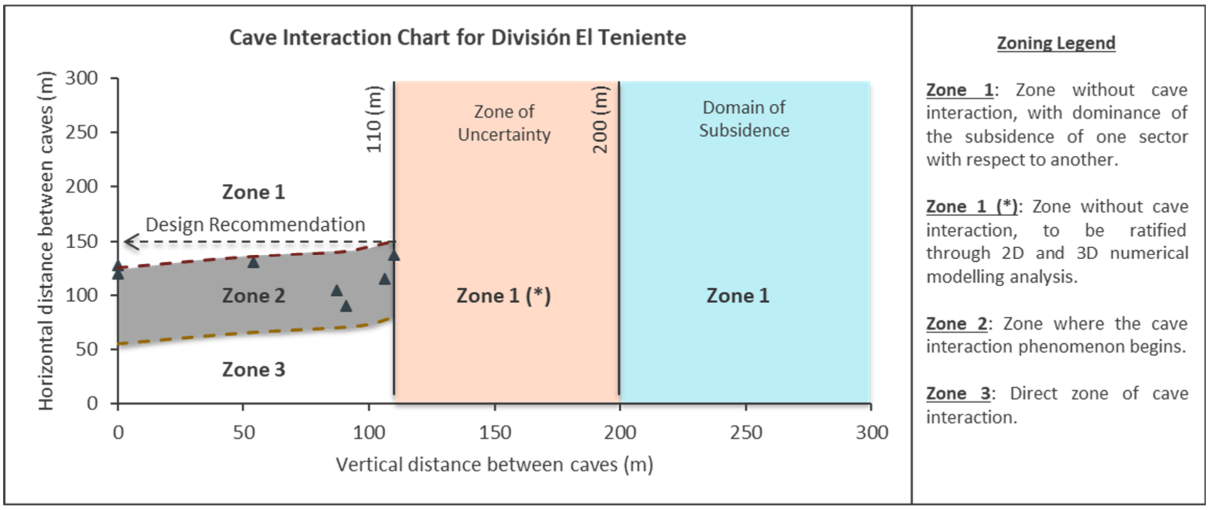

Figure 20 Cave interaction chart for División El Teniente

Both analyses, that is the history of División El Teniente and the results of 2D numerical modelling, complement the other. On the one hand, the back-analysis contains the different distance metrics in which the phenomenon under study occurred in División El Teniente, which were obtained with geometric, seismic and stress analyses. On the other hand, the 2D analysis corresponds to a conservative case which, through geometric profiles and the use of reliable information of the rock mass (stresses and geological properties), delivers two curves with distance metrics capturing 90% of the historical data.

The zones characterising the chart have the following aspects:

- Zone 1 – without cave interaction, with dominance of the subsidence of one sector with respect to another
- Zona 1 (*) – without cave interaction, to be ratified through further analysis. It is recommended that 2D and 3D numerical modelling be carried out, given that there are no interactions registered in this zone and a trend in numerical modelling results is beginning to be perceived
- Zone 2 – where the cave interaction phenomenon begins, located between the smoother upper and lower limits, and which contains all the cave interaction data registered for División El Teniente
- Zone 3 – direct zone of cave interaction, located under the smoothed lower limit.

This chart provides the geometric arrangement of the cave fronts belonging to the sectors under study and thus knowledge, based on their advancing direction, of whether they will have cave interaction for a given period.

6 Conclusion

The phenomenon of cavity interaction is triggered by the convergence or divergence between two or more caves where the main identification factors include a change in the distribution of stresses, an increase in seismicity in the crown pillar between the caves and the potential for damage to the work of the productive sectors involved.

Other variables that can accelerate or enhance these three factors include the presence of geological structures, resistance changes in the environment and geometric variations of the cave. However, the objective of this study was to identify the phenomenon before the placement of new projects in División El Teniente, during exploratory or profile stages where not all relevant information was available.

According to back-analysis of the cave interactions at División El Teniente, this condition, which was recorded from 2003 to 2020, occurs to a greater extent through the deepening of mining coexisting with multiple productive sectors or a productive sector being emplaced below a depleted one.

Although divergent cave interactions have not been recorded in División El Teniente, it is an analysis that should be considered as the new projects will be located under and adjacent to productive sectors.

The 2D numerical modelling shows that, when analysing the interaction through the results of S1, both the convergent and divergent cases tend to a maximum value of 150 m of horizontal distance between cavities. This can be noted to a greater extent from the 110 m of vertical distance between cave fronts (which matches the data used during the back-analysis).

The cave interaction chart corresponds to a graphic tool created to analyse cave interactions for new projects, considering only the spatial disposition of neighbouring sectors. It can also be used to observe the current conditions for the emplacement of a productive sector with respect to depleted sectors, establishing clear guidelines for operation and growth in such a way as to deal with changes in the stress field and a seismic rise of relevant events with a magnitude greater than MW1.

The creation of an abacus to be used in División El Teniente corresponds to the first step for understanding the cave interaction phenomenon. It is a simple and easy-to-use tool which encompasses experience with 2D numerical modelling but which must subsequently be strengthened by the use of 3D tools that cover a greater amount of information.

Acknowledgement

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