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Assisted geotechnical design for sublevel open stoping using MineRoc® software

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Abstract

The prediction of rock mass stability in sublevel open stope (SLOS) mining is performed in the design of open stopes to estimate the stope size required to reduce operational hazards and achieve continuous production. For almost four decades, the Stability Graph method has been used for this purpose. Several improvements of the Stability Graph method have taken place through the years. However, there is still work to be done. Accordingly, new case studies need to be continuously collected in order to update the Stability Graph, improving its reliability in predicting the stability state of open stopes to a specific site condition.

Two main stages are considered for the collection of new case studies. First, the required geotechnical data of a specific site condition is collected. Then, in the back-analysis of open stopes, performance parameters related with the geometry are calculated, and a stability state is assigned to each case study. When these stages are systematically performed, the Stability Graph can be calibrated, delineating more reliable new stability boundaries.

However, some problems in the collection of new case studies in SLOS operations such as disorder in geotechnical data or miscalculation of performance parameters impede the correct improvement of the stability boundaries. To deal with these problems, several computational tools have been developed and integrated into the software MineRoc®.

This paper shows a geotechnical analysis of a proposed open stope design through an updated version of MineRoc®, using Stability Graph boundaries previously defined. New features of the software and an application to a specific sublevel open stoping mine are presented, illustrating how MineRoc® positively impacts on the mine design and planning processes.

Keywords: *sublevel stoping, Stability Graph method, geotechnical analysis, mine design, MineRoc, software*

1 Introduction

The potential for instability in the rock mass surrounding underground mine openings is an ever-present hazard to the safety of both people and equipment in sublevel open stoping operations. Several tools for the design of open stopes have been developed over the years with the purpose of reducing these threats.

Based on a study of 26 case histories in sublevel open stoping, Mathews et al. (1981) proposed the Stability Graph method in which a qualitative stability state for each open stope surface is given based on visual evaluations and/or reconciled data. The graph introduced by Mathews et al. (1981) became popular following the expansion of the original database and/or the re-calibration of the stability number factors. According to Madenova & Suorineni (2020), to date, five major Stability Graph variations exist: the Modified Mathews Stability Graph by Potvin (1988), the Extended Mathews Stability Graph by Mawdesley & Trueman (2003), the Equivalent Linear Overbreak Slough (ELOS) Stability Graph proposed by Clark & Pakalnis (1997), the

Stability Graph for cable bolt support design proposed by Diederichs et al. (1999), and the Dilution-based Stability Graph introduced by Papaioanou & Suorineni (2016). Authors such as Nickson (1992), Suorineni (1998), Bewick & Kaiser (2009), Vallejos et al. (2016a, 2018a), and Vallejos & Díaz (2020), among others, have also contributed adding new case histories to the original method, adapting some stability factors and proposing new qualitative stability boundaries.

However, in practice, qualitative description of stability is not useful in the estimation of quantified dilution or overbreak levels. Clark & Pakalnis (1997) introduced the concept of ELOS in the Stability Graph that makes it possible to describe how much unplanned dilution (overbreak) a stope surface plotted on the Stability Graph is likely to generate (Suorineni 2010).

Perhaps the most comprehensive qualitative Stability Graph available in literature is the extended Stability Graph developed by Mawdesley et al. (2001), based on more than 400 sublevel open stoping case histories from over 38 mines in North America, Australia, and England. Whereas the ELOS Stability Graph developed by Clark & Pakalnis (1997) is based on 47 case histories (open stopes) from six Canadian mines, and introduces the cavity monitoring system (CMS) in the study.

Chilean sublevel open stoping case histories were not considered by Mawdesley et al. (2001) and Clark & Pakalnis (1997). The recent evidence (Azorin et al. 2018; Castro 2015; Vallejos et al. 2018b, 2016b) shows that particular geotechnical conditions and operational standards in Chilean sublevel open stoping mines are not being truly represented in both qualitative and quantitative Stability Graphs. A similar behaviour is observed globally when the Stability Graph has been implemented without adaptation to site conditions.

Issues with the definition of the stability zones and the delineation of the boundaries of the qualitative Stability Graph have been identified. The interpretation of the stability definitions can vary from mine to mine, and depend on operational standards, mining methods, acceptability of dilution (overbreak) and type of mineral. Thus, every mine must develop its own database of case histories to calibrate the stability curve for the unique characteristic (local conditions) of the mine. However, the lack of systematic collection and storage of geotechnical data, incorrect calculation of performance parameters (such as ELOS and overbreak), and variation in the database due to human management can lead to several difficulties in the process.

To deal with these problems, several computational modules aimed at improving the Stability Graph method in specific sublevel open stope mines have been developed. These tools have been integrated into a single technological platform: MineRoc® introduced by Vallejos et al. (2015) and updated through recent years (Vallejos et al. 2017, 2016b). The software provides an interactive environment where Stability Graph analysis adapted to specific site conditions can be performed. The latest version of MineRoc® (version 2.0) is comprised of five principal modules, including:

- Acquisition module: This allows geotechnical data to be stored in a single platform. This information is available to be used in the performance and design modules.
- Performance module: In this module, the back-analysis of sublevel open stoping case histories is performed. New data can be included in the database module.
- Database module: This module helps to delineate new stability boundaries based on the back-analysis of case histories previously obtained.
- Design module: The design and analysis of new sublevel open stoping case studies can be performed based on new stability boundaries previously delineated or Stability Graphs in the literature.
- Mine exploration module: Integration of visual and graphical tools developed for the analysis of sublevel open stoping case histories and new case studies. This module provides a comprehensive interpretation of the studied site.

In this paper, the Stability Graph method is reviewed, modules and new key features of an updated version of MineRoc® are illustrated, and the application of MineRoc® software to a specific sublevel open stoping mine is presented, illustrating how MineRoc® positively impacts on the mine design and planning processes.

2 Stability Graph method

The Stability Graph method introduced by Mathews et al. (1981) requires the calculation of two different factors: the shape factor S, and the stability number N. The shape factor (Equation 1) is related to the geometry of the analysed wall, whereas the stability number N (Equation 2) represents the characteristics of the rock mass modified by adjustment factors for induced stress, orientation impact of critical defects and gravity effects.

$$S = \frac{Wall\ area\ [m^2]}{Wall\ perimeter\ [m]} \tag{1}$$

$$N = Q' \cdot A \cdot B \cdot C \tag{2}$$

where:

Q' = adapted rock tunnelling quality index developed by Barton et al. (1974).

A = rock stress factor obtained from the graph presented in Figure 1a. σ_c is the uniaxial compressive strength of intact rock and σ_1 is the induced compressive stress at the centre of the analysed stope wall.

B = joint orientation adjustment factor. It measures the relative difference in dip between the analysed stope wall and the critical joint set. It can be determined from Figure 1b.

C = gravity adjustment factor. It reflects the effect of the analysed stope wall orientation on its own stability under the influence of gravity. It can be determined from Figure 1c.

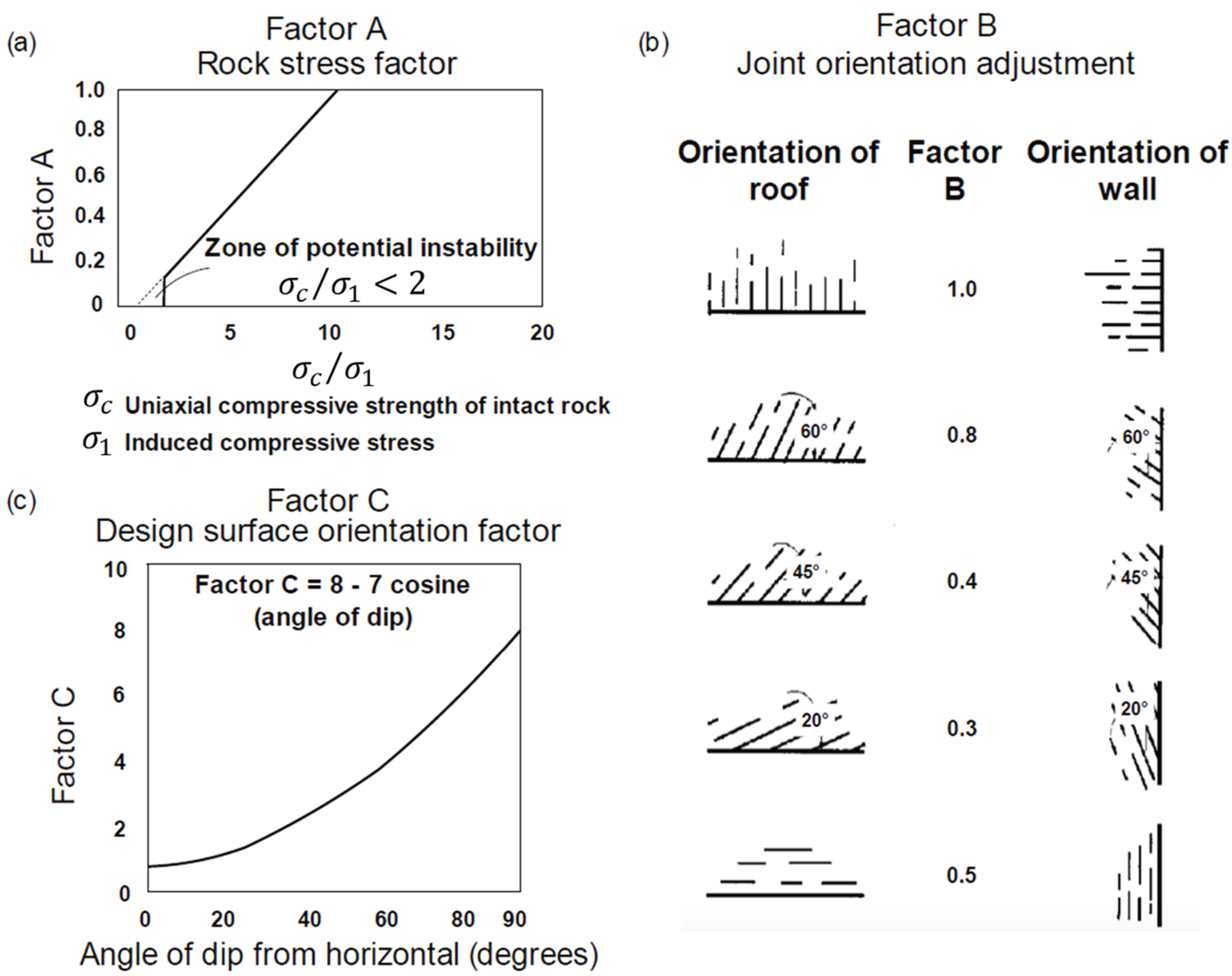

Figure 1 Adjustment factors for determination of the stability number (after Mathews et al. 1981)

2.1 Qualitative Stability Graph

The qualitative Stability Graph is the plot originally introduced by Mathews et al. (1981) where the stability number N is compared against the shape factor S. In this graph, the stability of each open stope wall is evaluated independently. Possibly the most comprehensive qualitative Stability Graph available in literature is the extended Stability Graph developed by Mawdesley et al. (2001), where three stability states were defined:

- Stable: The open stope is essentially self-supporting with minimal dilution (<10%).
- Failure: A localised failure occurs in the open stope, but it forms a stable arch. Failures cover the range between stable and major failure.
- Major failure: The open stope requires an extensive support or has an excessive failure and dilution (>30%).

The dilution is defined as low grade material (waste) introduced to the ore stream, reducing its value (Equation 3) expressed as a percentage of total tonnes extracted. It should be noted that the dilution concept is defined mainly for mine planning purposes. In terms of geotechnical stability, it is preferable to express this concept as overbreak rather than dilution, because overbreak considers unplanned ore material and low grade (waste) material.

$$Dilution[\%] = \frac{Waste\ tonnes}{Ore + waste} \cdot 100 \quad (3)$$

The extended Mathews Stability Graph proposed by Mawdesley et al. (2001) is presented in Figure 2. The extended database contains more than 400 sublevel open stoping case histories. Logistic regression was applied to delineate the stability boundaries. These boundaries (stable-failure and failure-major failure) are represented by Equation 4 (Mawdesley 2002).

$$N = aS^b \quad (4)$$

where:

N = Mathews stability number.

S = Shape factor.

a, b = parameters obtained by logistic regressions.

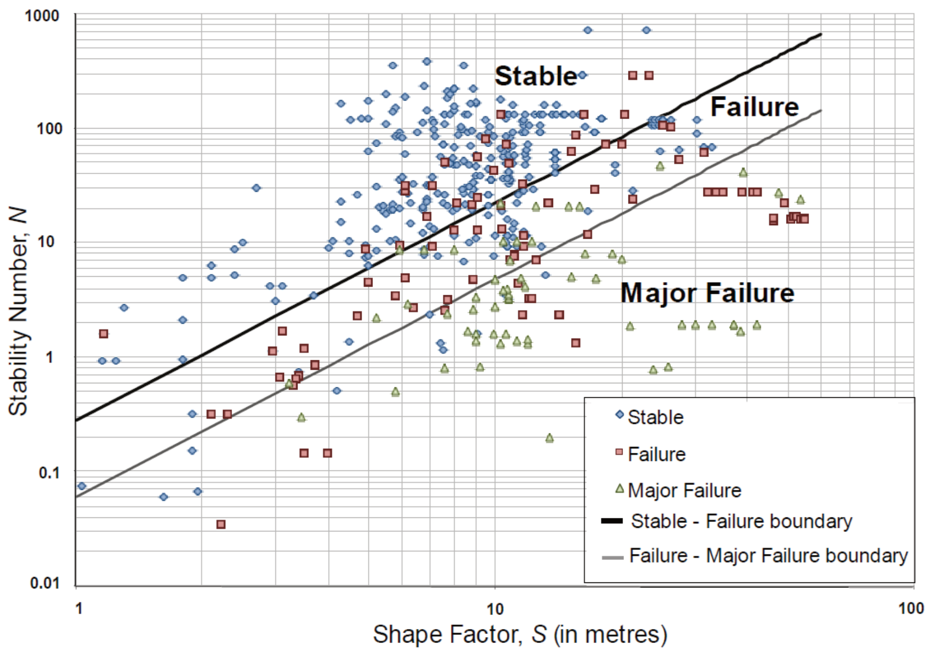

Figure 2 Extended Mathews stability log-log graph based on logistic regression (Mawdesley 2002)

2.2 Quantitative Stability Graph

The ELOS Stability Graph introduced by Clark & Pakalnis (1997) was developed for narrow vein ore bodies, since the qualitative Stability Graph takes into account case histories from massive ore bodies. This quantitative Stability Graph is based on the ELOS defined by Equation 5.

$$ELOS = \frac{Volume\ of\ overbreak\ from\ analysed\ stope\ wall\ (V_{OB}^{wall})\ [m^3]}{Wall\ area\ from\ analysed\ stope\ wall\ [m^2]} \tag{5}$$

The calculation of the volume of overbreak from an analysed stope wall (V_{OB}^{wall}) is possible since the introduction of the CMS (Miller et al. 1992) that allows three-dimensional cavity models to be obtained. Then, V_{OB}^{wall} corresponds to the volume between the designed wall of the open stope and the cavity model.

As an example, the volume of overbreak on an open stope back and the ELOS stability index is presented in the Figure 3a. MineRoc® also includes the percentage overbreak (%OB, extending the dilution concept) stability index and the depth of failure (DF) stability index as illustrated in Figures 3b and c, respectively.

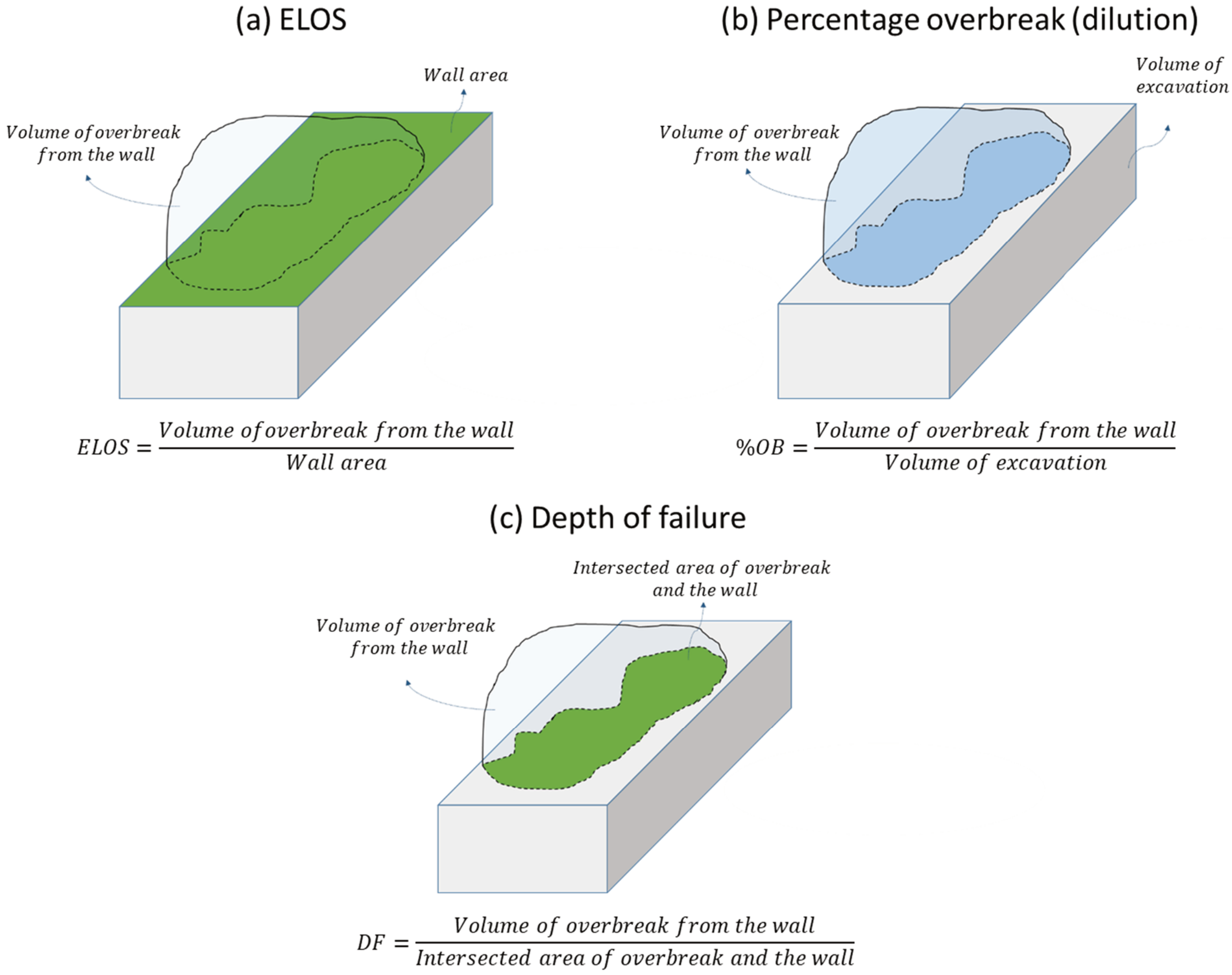

Figure 3 Schematic showing definition of overbreak volume of a back (modified from Cepuritis 2010)

3 MineRoc® software

MineRoc® is an underground mining application that assists geotechnical engineers and mine planers to define the optimal open stope size. The software adapts the Stability Graph method to a mine planning context or specific site conditions, based on local case histories and site specific definitions of stability. This is possible due to the interaction between different modules in the software. The latest version of MineRoc® (version 2.0) includes five modules: the acquisition module, the performance module, the database manager module, the design module, and the mine exploration module. Figure 4 presents the main features of each module and its interaction in the MineRoc® software application.

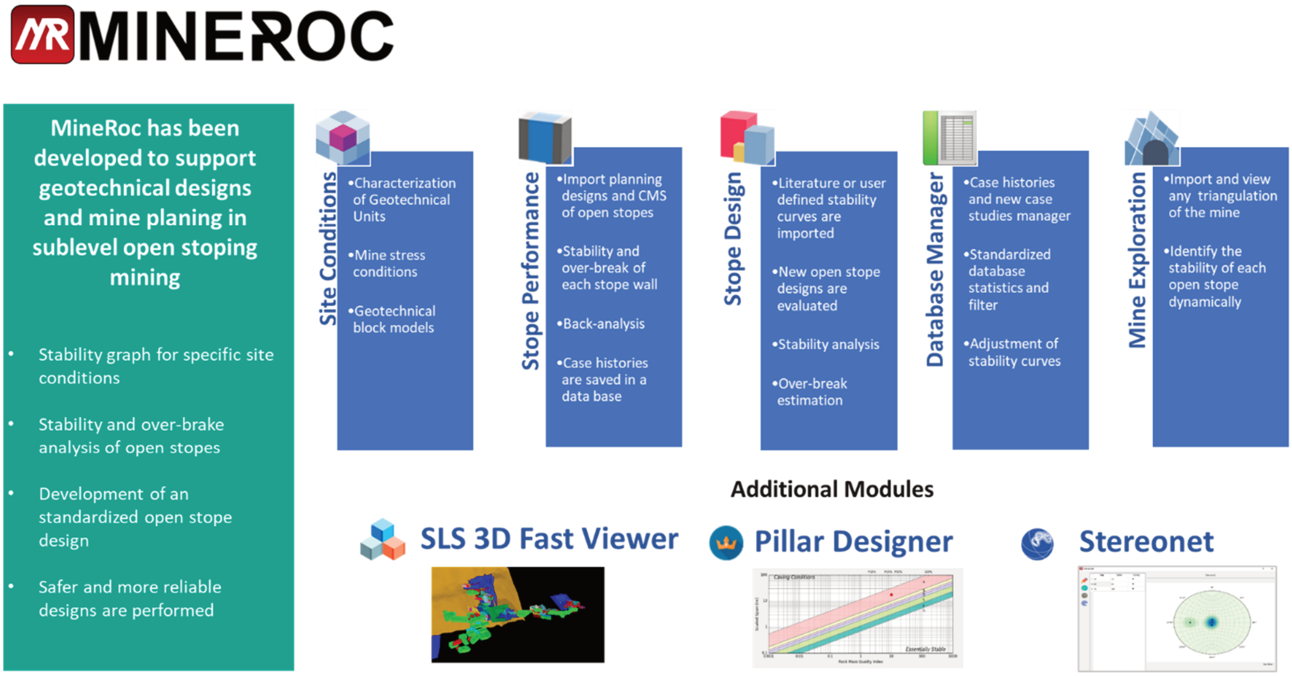

Figure 4 **Interaction and features of each module in MineRoc®**

The following sections briefly describe each module, specifying the information required and generated by each of them.

3.1 Acquisition module

The module stores the required geotechnical data for the stability analysis. The data is then analysed, divided, and saved as geotechnical units (GU), geotechnical block models (BM) and in situ stress model (ISM). Subsequently, they can be used in either the performance module or the design module. The GU and/or BM can be assigned to each open stope wall, whereas one estimation of the ISM is required for an open stope.

- GU contains the parameters for intact rock properties and rock mass classification (RMR_{89}, Bieniawski 1989) and Q-system (Barton et al. 1974).
- BM saves the geotechnical and mine planning variables in the mine spatial domain.
- ISM can be defined by direct in situ measurements or overburden models. Then, the induced stresses for each wall are calculated by the methodology presented by Stewart & Forsyth (1995).

This information allows the calculation of the Mathews adjustment factors for each open stope wall analysed in the performance module (back-analysis) and the design module, respectively. It is important to be aware that the quality of the information provided in this module will directly impact on the accuracy of the analyses performed in other modules.

3.2 Performance module

This module allows the back-analysis of open stopes, adding case histories to a user-defined database. One of the key features of this module is the automatic calculation of performance parameters and the Mathews adjustment factors per open stope wall. This considerably reduces the processing times when the back-analysis of a large number of open stopes is carried out.

The module requires:

- The three-dimensional model of the open stope design from mine planning.
- The CMS.
- Geological structure model for structures that intersect the open stope.
- The geotechnical information (GU, BM) per wall (from acquisition module).
- The ISM (from acquisition module).

To calculate the parameters and the Mathews adjustment factors of an analysed open stope, the following steps are carried out:

1. The user provides the three-dimensional models of the open stope design: the CMS and the geological structures that intersect the open stope, which are displayed in a 3D viewer allowing the user to check the accuracy of the case history to be analysed.
2. The wall recognition algorithm is performed to identify the different open stope design walls.
3. Geotechnical information (GU and BM) for each open stope wall and ISM are imported from the acquisition module.
4. Using built-in algorithms, geometrical parameters per wall (shape factor, orientation, and open stope dimensions), stability index per wall (%OB, ELOS and DF), and the Mathews adjustment factors are automatically assessed.
5. The input and calculated data for the case history analysed are summarised in a report.

When the back-analysis of open stopes is systematically performed, a large amount of case histories can be obtained and stored in the database manager module. The information generated in this module is subsequently incorporated into the delineation of new stability boundaries in the database manager module to calibrate the design failure envelope.

3.3 Database module

New local and user-defined databases for open stopes can be generated in this module. New case histories obtained in the performance module can be combined with databases from literature (included as consulting material for mines without mine-specific case histories) allowing new stability boundaries to be delineated. When a large amount of local mine case histories are considered, the modified Stability Graph accounts for local geotechnical and operational conditions. This improves its reliability in calibrating the stability curves for predicting the stability of planned open stopes.

Two options can be assessed for the generation of new stability boundaries:

- For new mines, new case histories can be combined with built-in databases, generating a first approximation to the local stability criteria. MineRoc® includes three built-in databases:
  - The Canadian and Australian qualitative database (Mawdesley et al. 2001).
  - The Canadian quantitative database collected by Clark & Pakalnis (1997), recalibrated by Castro (2015).
  - The Chilean quantitative database developed by the authors of this paper.
- For mines with enough local case histories, local stability criteria, based on the performance parameters (%OB, ELOS and DF), can be developed.

When a new database is generated, new user-defined stability boundaries can be delineated. In MineRoc®, new stability boundaries can be defined by varying the parameters a and b shown in Equation 4. The statistical classifier Peirce Skill Score (PSS) is used (Vallejos et al. 2016a) to evaluate the performance of new user-defined stability curves to divide the database and to represent the local stability conditions.

3.4 Design module

This module allows the evaluation and design of new open stopes. The evaluation of proposed designs from mine planning (budget or life-of-mine designs) are performed based on literature or previous user-defined Stability Graphs. The information used for the analysis includes:

- The same information used in the performance module, without the CMS model.
- New stability boundaries from the database manager module. When new case histories are not available to calibrate the design curves, stability boundaries from literature can be used (Castro 2015; Mawdesley et al. 2001).

The stability state and stability index (%0B, ELOS and DF) of each open stope wall can be interpolated using the selected Stability Graph from the database manager module. The required open stope size can be calculated using a specific literature stability curve or through a previous user-defined stability boundary.

In this module, the three-dimensional model of the open stope design and the geotechnical information (GU, BM and ISM) can be manually changed, observing their impact on the Mathews stability factors and the stability state of the walls. Finally, a report of the new case study analysed is produced and the result stored in a user-defined database (database manager module).

3.5 Mine exploration module

The mine exploration module is dedicated to the visual representation of the complete mine offering to the user a comprehensive interpretation of the studied site. The faster 3D viewer integrated into MineRoc® allows to visualise up to 10,000 triangulations, including open stope designs from mine planning and blasting, CMS, geological structures, lithological models, topography, BMs, drifts, and exploration drillings.

Graphical tools developed for the analysis of sublevel open stoping case histories and new case studies can be evaluated, integrating the 3D viewer with the stability analysis performed previously for each open stope. This gives the user a tool to enhance the complete analysis cycle performed through the previous modules.

Figure 5 summarises the workflow and the interaction between modules in MineRoc®.

Figure 5 Workflow and summary of the modules in MineRoc®

4 Assisted geotechnical design of a case study in MineRoc®

4.1 Back-analysis performed to a specific sublevel open stoping mine

To characterise the in situ behaviour and the stability of a specific sublevel open stoping mine, a large amount of case histories from the mine were analysed using MineRoc®.

A geotechnical characterisation of each open stope was performed in the acquisition module, taking into account the GU in which each open stope was located, the geotechnical BM, and the depth from surface (topography) to obtain the induced stresses in each open stope wall from the in situ stress model (ISM).

Once the geotechnical characterisation was done, the geological structures that cross each open stope were entered into the performance module of the platform. The users set the hanging wall, footwall and back to analyse for each open stope, and the built-in algorithm of MineRoc® recognised the surface, calculating the Mathews adjustment factors and the performance parameters (%OB, ELOS and DF) for each wall. The process was repeated several times resulting in 54 analysed walls of open stopes that were stored in a user-defined database.

The stored database was statistically analysed by the database manager module. Based on the performance parameters (stability indexes), user-defined quantitative curves were set by the adjustment parameters of Equation 4. The PSS was used to evaluate the performance of the curves in MineRoc®.

The site-specific quantitative Stability Graph with the 54 open stope walls analysed using MineRoc® is illustrated in Figure 6. This is the visible and more effective result of a complete back-analysis process involving case histories of a mine performed in MineRoc®, demonstrating how the platform generates a powerful tool to be used by geotechnical and mine planning engineers. Note that the Stability Graph in Figure 6 is based on the ELOS performance parameter (stability index), being $\alpha < \beta < \gamma < \delta < \varepsilon$.

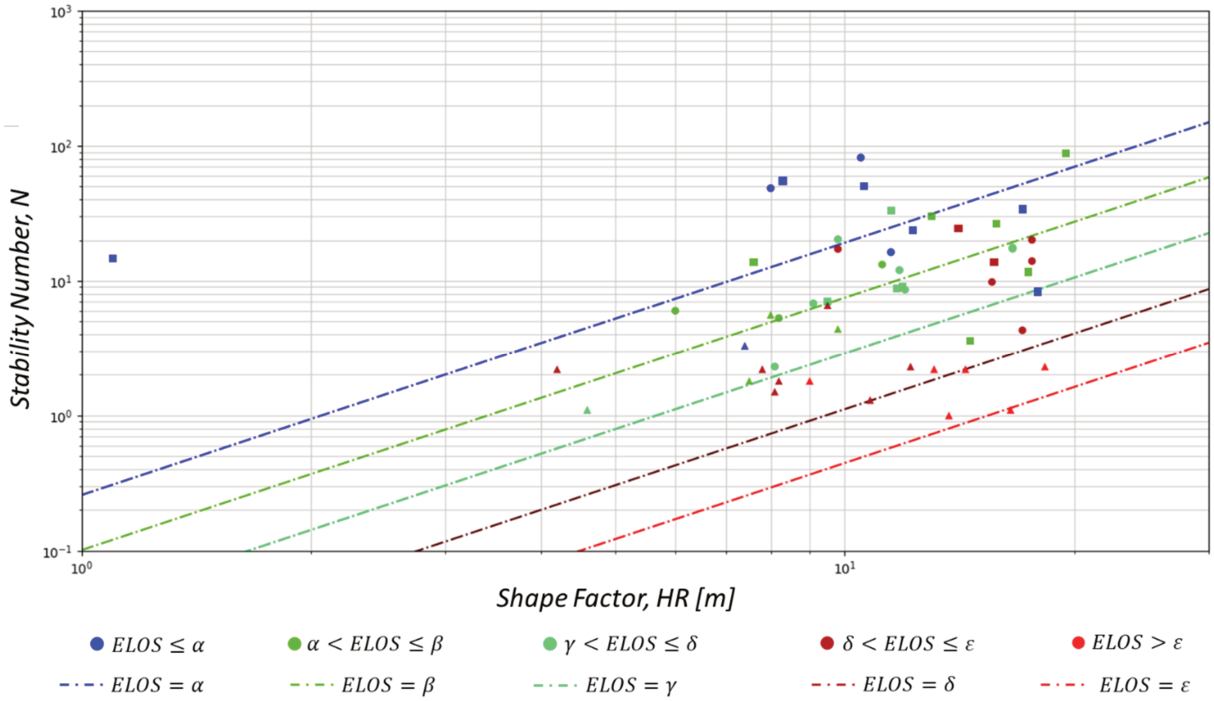

Figure 6 Site-specific quantitative Stability Graph for a sublevel open stoping mine in MineRoc®

A more detailed and visual description of the performance, design, and database manager modules will be presented in the next section.

4.2 Design module applied to a case study in sublevel open stope mining

Once the back-analysis is carried out by the performance and database manager modules, the next step is the evaluation of proposed designs from mine planning. In this context, the design module becomes a valuable tool to perform an assessment of new open stope designs.

To demonstrate how MineRoc® performs the empirical stability analysis of proposed design stopes, a mine planning open stope design from the budget of the same mine is presented. The proposed open stope design to be analysed has two possible extraction sequences (Figure 7). The first extraction sequence (sequence A) is composed of 13 steps, while the second extraction sequence (sequence B) is composed of 15 steps. The empirical stability analysis was performed identifying which of those extraction sequences were better to be performed in situ in terms of the stability results (ELOS, %OB, DF), enhancing the short-term mine planning and geotechnical decision.

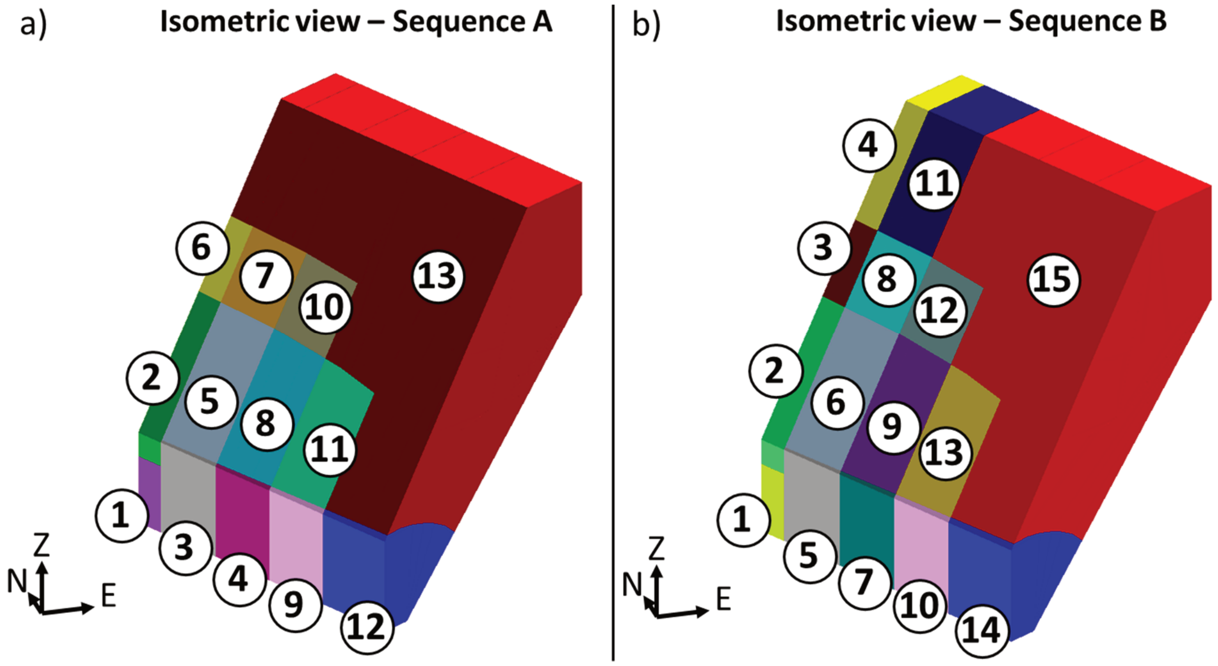

Figure 7 Possible extraction sequences for the new open stope design

The geotechnical characterisation of each extraction step for each sequence was carried out. The identification of the GU, BM and the induced stresses (calculated based on ISM) were performed through the acquisition module. Subsequently, the geological structures that influence each extraction step (step designs of the open stope) were added to the design module and were processed through the built-in algorithm in MineRoc®. Each result was stored in the database manager module and compared with the specific site quantitative Stability Graph shown in Figure 6, estimating its ELOS stability index in the process. As an example, the characterisation for the final extraction step (proposed open stope design) using BMs is illustrated in Figures 8a and b, respectively. Whereas Figure 8c, d and e show the proposed mine planning design of the final extraction step, the proposed design with the geological structures, and the result of the processing obtained from the design module in MineRoc®, respectively.

To illustrate the process of BM characterisation during the evolution of the proposed open stope design, Figures 9a and b show the rock quality designation (RQD) characterisation of some extraction steps, showing the evolution in sequence A and sequence B, respectively.

Finally, Figures 10a and b summarise the entire empirical stability analysis results of each sequence, showing how the analysis evolves through the extraction steps. Even though both extraction sequences have the same empirical final step, according to the results, sequence A shows better performance in terms of ELOS through the extraction steps (Figure 10b). Thus, the choice of sequence A appears to be correct during the extraction of the open stope, having a better performance especially on the back of the case study.

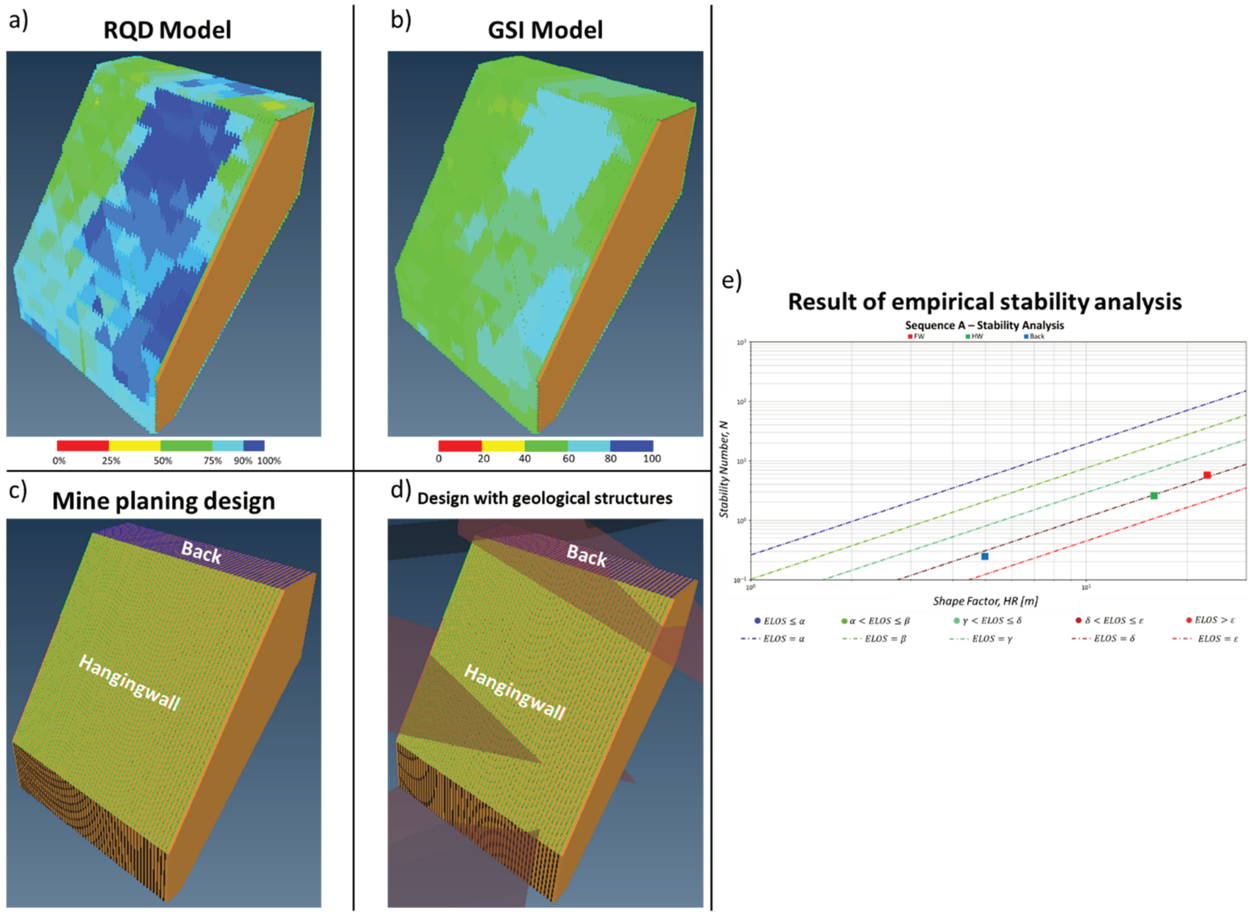

Figure 8 Mine planning proposed design analysis in MineRoc® showing the final step of extraction: (a) BM characterisation using RQD variable; (b) BM characterisation using geological strength index (GSI) variable; (c) Wall definition of the design; (d) Geological structures added to the design; (e) Result of empirical stability analysis

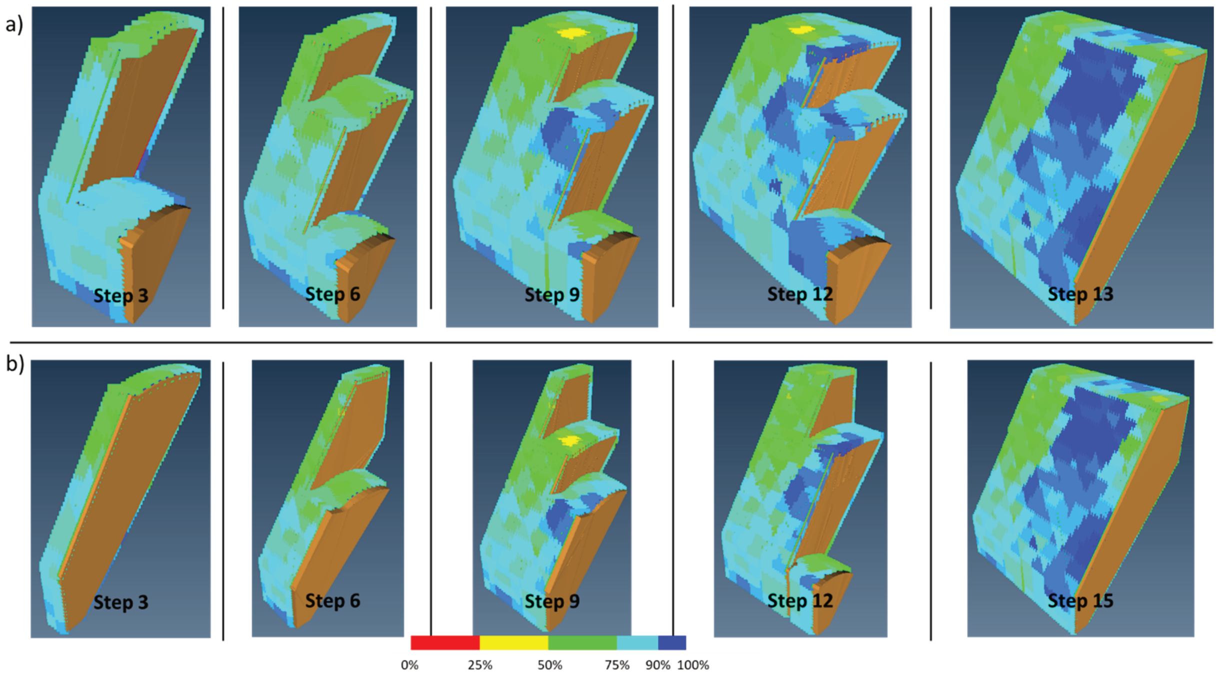

Figure 9 Extraction steps showing RQD characterisation in MineRoc®: (a) Sequence A; (b) Sequence B

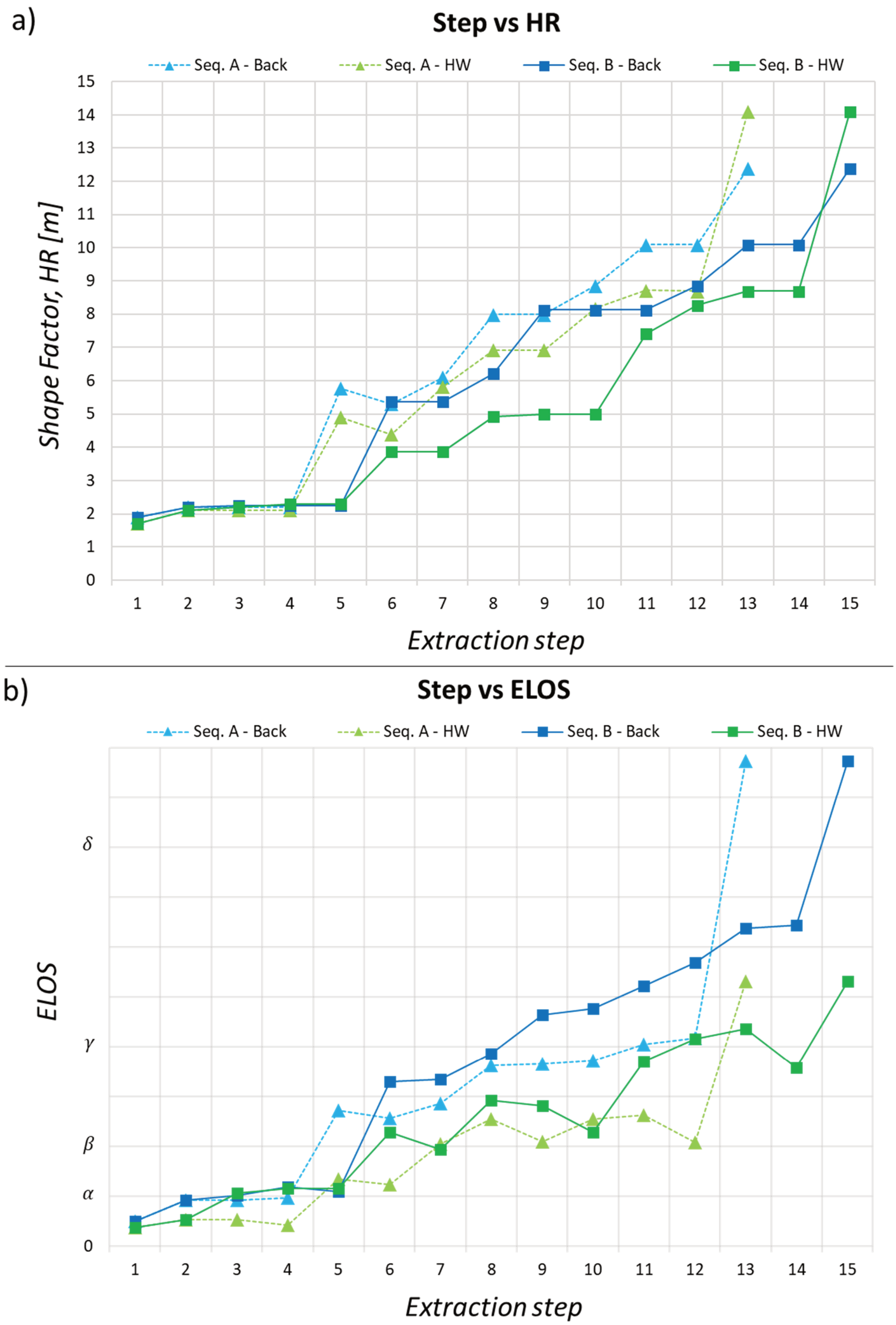

Figure 10 **Comparison of empirical stability results of each extraction sequence in MineRoc®: (a) Extraction step versus shape factor; (b) Extraction step versus ELOS**

5 Conclusion

In this paper, the key features and an example of assisted geotechnical design for a sublevel open stope in MineRoc® software have been presented. The software has been developed, tested and updated for the design of sublevel open stopes in underground mines reflecting site-specific geotechnical conditions. Currently, open stopes in mines are designed mainly based on empirical Stability Graphs developed by Mathews et al. (1981), Clark & Pakalnis (1997) and/or Mawdesley et al. (2001). These Stability Graphs are mainly based on Canadian and Australian operational experiences which do not reflect other operational standards and geotechnical conditions.

MineRoc® allows the rapid storage of the geotechnical data, case histories and new case studies in a single platform, obtaining new stability boundaries for specific site conditions. These key features continuously improve the stability prediction of the Stability Graphs from literature, increasing the safety and the productivity of the mine.

By using MineRoc®, a new specific site sublevel open stoping database has been obtained. The results have demonstrated that when new case histories are considered, different stability boundaries can be delineated. Thus, using these new stability boundaries, the assisted geotechnical design for a new case study could be performed, demonstrating how MineRoc® enhances the extraction sequence decision. This positively impacts on the geotechnical design and planning processes, since more accurate predictions of sublevel open stopes stability and incorporation of overbreak can be performed.

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