ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Practical span and support design strategies for underground rooms in stratified rock masses

I. Pérez-Rey
CINTECX, GESSMin Group, Dept. of Natural Resources and Environmental Engineering, University of Vigo, Vigo, Spain
Division of Soil and Rock Mechanics, Dept. of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, Sweden
iperez@uvigo.gal

F. Johansson
Division of Soil and Rock Mechanics, Dept. of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

L. R. Alejano
CINTECX, GESSMin Group, Dept. of Natural Resources and Environmental Engineering, University of Vigo, Vigo, Spain

Abstract

Stratified rock masses present bedding and cross-joints normal to it that makes them natural heterogeneous and non-isotropic materials difficult to characterize. A successful engineering design of mining rooms with flat roofs in this type of rock masses would benefit from a heuristic perspective and various approaches including analytical (voussoir-beam analogue for roof stability assessment in laminated rock masses), empirical methods, numerical models, and observational approaches, which should be applied in the context of the project constraints. This study addresses how to best proceed in the design of rooms and associated support, in new areas of the mine with different geotechnical features of a room and pillar mining operation in a bedded carbonate rock mass in NW Spain. To do that, the authors present a multi-technique back-analysis-based design approach for roof support. Starting with a first estimate based on empirical approaches, the authors combine the *voussoir-beam* analogue concept with rock mass characterization and on-site observations in the mine allowing to back-calculate a representative rock-mass deformation modulus as a key design parameter, considering the main instability mechanisms to be associated with buckling phenomena acting on the roof beam. With these results, room span, and associated support were designed considering two scenarios for different roof-beam dip and rock mass properties as observed in two new development areas of the room-and-pillar mine. This room width and support design approach has successfully been applied so far. The interest of the presented study relies on how rather simple analytical approaches, fed with appropriately computed key parameters derived from various sources (empirical methods and observations) can be a sufficiently reliable and reasonably rigorous practical tool for the design of the mine, besides satisfying design guidelines based on empirical stability assessment techniques like the stability graph method.

Keywords: stability graph method, voussoir-beam, support design, room-and-pillar, deformation modulus.

ISRM

NBG

1 Introduction: the mine and its history

A 14-m thick, 20° dipping seam of magnesite ($MgCO_3$) was identified somewhere in Galicia (NW Spain) during the 1970s, when mining in the area started as an open-pit quarry. After 10 years, the quarry achieved its economic limit, so the possibility of an underground exploitation was evaluated, and it was concluded it was feasible and economic. After some trials in situ, the selected mining method was room and pillar with diamond-shaped panels to limit the slope of the drifts and rooms to 10 % (allowing the correct operation of the machinery), with 11-m wide rooms and 7-m wide pillars (Fig. 1).

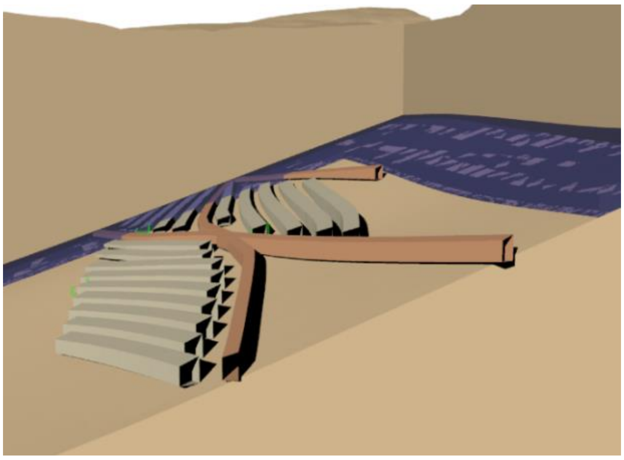

Fig. 1 Illustrative 3D perspective of the mine.

Over the magnesite seam, the occurrence of a 2–3-m thick layer of fissured marly slate usually complicates the support operations. So, the original room design strategy implied leaving a 1-m thick bed of magnesite at the room hanging wall and support it with three 24-t cemented cables every 2 m of advance. The mine started its operations in 1986 without noticeable problems until 2005, when a roof collapse occurred in a room in the deeper part of the mine. An initial visit to the mine was conducted to understand the failure event. The roof collapse took place when a small direct fault was crossed, resulting in a thinning of the magnesite 'protective' beam from approximately 1 to around 0.5 m. Consequently, the magnesite beam bent and cracked, leading to a bell-shaped failure extending roughly 20 m to the end of the open room (Fig. 2).

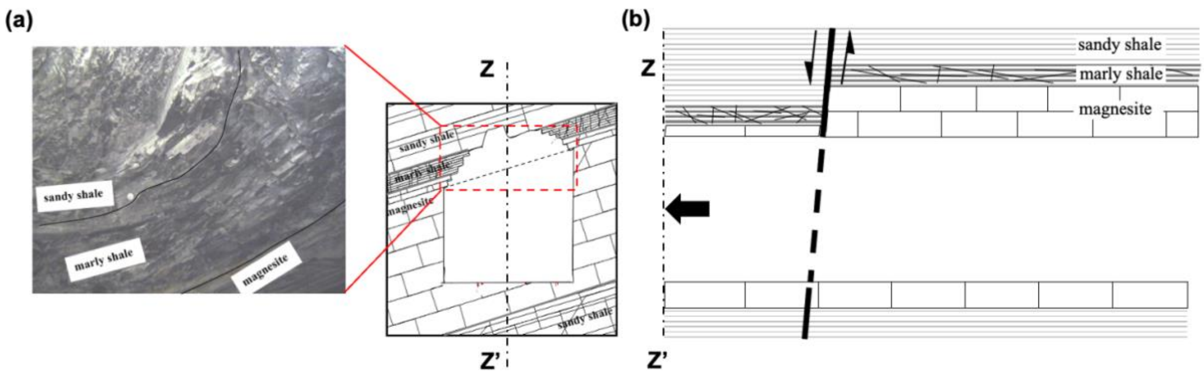

Fig. 2 (a) Photo and schematics of the vault-shaped collapsed area; (b) longitudinal section view of the room, illustrating the geological conditions for the occurrence of the roof collapse.

A study was subsequently started to characterize the rock mass from joint surveys. This characterization included laboratory rock testing, classification systems, voussoir–analogue analytical approaches, and numerical models (Alejano et al. 2008). From these studies and based on in-situ observations and tailored calculation methodologies, a support procedure was suggested after some instability mechanisms were identified. In 2006, two types of support systems were recommended, as per specific rock mass features and discontinuities, with good performance. In 2014, following the occurrence of new instability issues in a specific area of the mine, a more advanced support scheme was introduced, accounting for different room widths, magnesite roof thickness, influence of marly slate layers on top of the magnesite roofs, and the presence of sub-horizontal fractures within the magnesite seam. This new scheme was useful in guiding safe and effective design activities to date.

Currently, as part of the natural evolution of the mining operation, two new mineralised areas with potential mining interest have recently been accessed, requiring updates in the geotechnical design criteria to align with the specific characteristics of these new zones.

Specifically, on the western area of the mine, a faulted and karstified material that significantly influence the increase of water flow into the mine have been crossed. This operation has allowed the access to a new area with substantial mineral reserves, previously estimated from field surveys and drilling campaigns. The dip of the magnesite layer remains relatively constant in this area (18 to 20°), with a reduction in the original thickness (about 14 m) to 6-8 m. In the eastern side, a new area has also been reached after crossing a diabase dike that roughly divides the deposit into two parts, along with another fault and a prominent karstification band. Here, the seam thickness remains similar to the original one (14 m), but the dip increased from 18° to 28-30°. Additionally, localized sections of the area are affected by karstified fractures. These new mining areas are illustrated in a local map of the mine in Fig. 3.

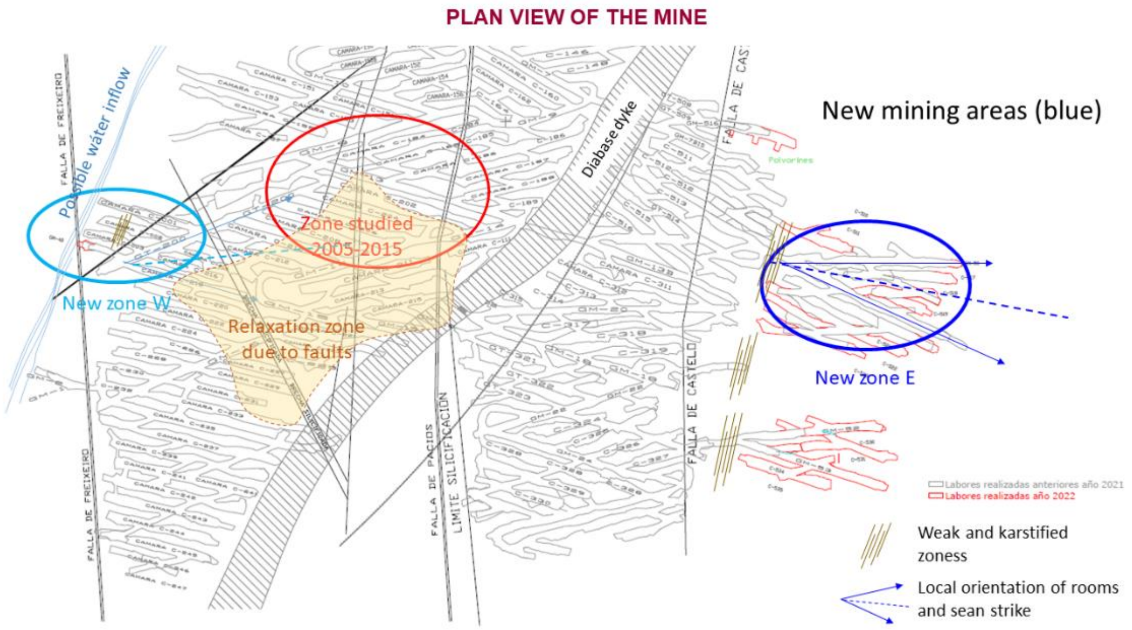

Fig. 3 Plan view of the mine showing the relaxation areas associated with faults and the new mining zones at the East (new zone E) and West (new zone W) of the mine.

The already referred conditions will cause further adaptations to the original former mining approach and, therefore, an update in the support guidelines. Based on a combination of empirical methods, the *voussoir-beam* analogue concept with rock mass characterization and on-site observations in the mine, a representative rock-mass deformation modulus can be calculated for a considered "worst possible" scenario, in terms of stability, and is suggested as a key parameter controlling the buckling instability mechanisms acting on the magnesite roof. It is the main objective of this paper to present a simple but effective approach based on the back-calculation of the rock-bass modulus, considered a key parameter controlling the mechanical behaviour of the magnesite roof beam, based on a collapsed room and a summary of some support-design guidelines resorting to this methodology.

2 Roof stability approaches in stratified rock masses

Mining in stratified rock masses is considerably common and some features are associated with this type of environments: a somewhat high persistence and planarity of rock joints, besides the advance of the mining operation towards a cross-sectional geometry that leaves an immediate roof and floor of the excavation coincident with the rock bedding planes (Brady and Brown 2006). These features have therefore motivated different excavation stability approaches, specifically concerning the stability of this immediate roof. As aforementioned, in the context of the new areas of the magnesite mine under study, a combination of different techniques was used, and a summary of each specific method and its application is hereinafter provided.

2.1 The stability graph method

The stability graph method was introduced by Matthews et al. (1981) and later improved by Potvin (1988) and Nickson (1992). This method offers an empirical basis for underground open-stope support design, but also a useful and simple tool for assessing the suitability of the stope geometry and the maximum allowed roof span in stratified rock masses – an aspect in which other more conventional geomechanical classifications (RMR, Q) may not work such well. The implementation of this method is summarised in Table 1, based on Potvin's (1988) modified stability number *N*'. The calculations were made for general standard (non-faulted) and faulted areas in the mine by Equation 1, where parameters A, B and C were retrieved from specific graphs as presented by Potvin (1988). For the magnesite mine scenario under assessment, this method suggests the stability of the rooms without any support in general, even though near faults, the stability condition cannot be ensured, being the use of cables recommended.

$$N' = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times A \times B \times C = Q' \times A \times B \times C \tag{1}$$

Where *RQD* Degree of jointing (*Rock Quality Designation*)
J_n Joint set number
J_r Joint roughness number
J_a Joint alteration number
A Rock Stress Factor
B Joint Orientation Factor
C Gravity Adjustment Factor

Table 1 Summary of parameters for estimating Potvin's (1988) modified stability number *N*'.

	Q'	A	B	C	N'
Standard (non-faulted) mine zones	21	1	0.3	2.25	14.17
Faulted mine zones	3	1	0.3	2.25	2.02

2.2 Immediate roof stability: analytical and 2D numerical approaches

The design of room roofs in stratified rock masses often relies on theories that model the roof as a *voussoir* beam. This approach presents an indeterminate problem, requiring specific initial assumptions to resolve. These assumptions, typically related to the geometry of the resulting compression arch, have led to the development of various calculation methods. In this study, the method proposed by Diederichs and Kaiser (1999) was applied (further details are available in the original source). Using this framework, the maximum beam deflection (δ) and the maximum compressive/tensile stresses at the abutments and mid-span of the beam (f_m) were determined for combinations of different scenarios, namely, room widths varying from 8 to 14 m, three values of the dip of the magnesite roof seam (0°, 18° and 28°) and two loading assumptions (self-weight of the roof beam, and overload caused by an overlying marly slate layer). Remark that the load of the support can also be accounted for in this approach.

Some numerical models were implemented in a 2D distinct element method coded in UDEC (Itasca, 2022). A key aspect in this modelling stage relates to the calibration of the mechanical behaviour of the so-called "cross joints" defining the voussoirs in the beam models. The friction angle influencing these cross-joints (ϕ = 33°) was derived from field measurements. The joint normal stiffness, k_n, can be estimated indirectly based on the computation of the elastic modulus of the rock mass, for instance based on an approach developed by Barton (2002) and that of the rock as estimated in the lab. This estimation is based on the rock mass deformation modulus in the area, determined as E_{rm} = 7.2 GPa through rock-mass geomechanical classifications. Additional parameters include the elastic modulus of the intact rock, E_r = 70 GPa, obtained through laboratory tests, and the in-situ measured average joint spacing, s_j = 2 m. Using these inputs, the normal stiffness k_n was calculated through Equation 2.

$$\frac{1}{E_{rm}} = \frac{1}{E_r} + \frac{1}{k_n \cdot s_j} \tag{2}$$

From Equation 2, k_n = 4 GPa/m was obtained. The shear stiffness, k_s, was assumed as $k_s = 1/5 \cdot k_n = 1$ GPa/m (Itasca, 2023).

Specific δ and f_m values resulting from the application of both the analytical (*voussoir-beam* analogue) technique and the numerical models can be found in Pérez-Rey et al. (2024) and summarised in Fig. 4. The combination and comparison of results from these two approaches allowed to confirm that the analytical approach effectively captures the maximum beam deflection and stress distribution (mid part of the beam, and abutments), assessed through comparisons with numerical models. This validation also provided insights into the types of instability mechanisms and validates the voussoir-beam analogue approach for different scenarios in the mine under scrutiny.

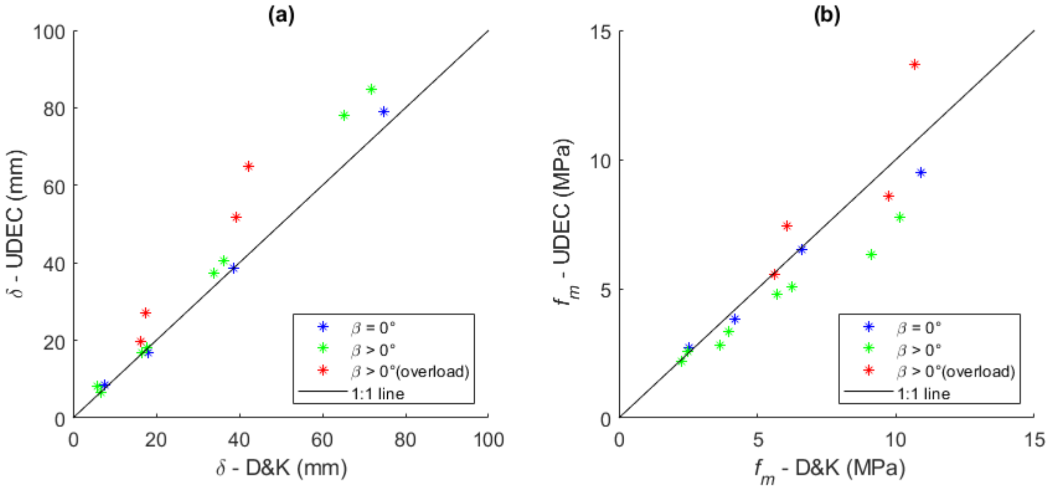

Fig. 4 Graphical comparison for the analytical (Diederichs and Kaiser 1999) and numerical (UDEC) (Itasca 2022) results: (a) comparison of the maximum beam deflection (δ) in mm; (b) comparison of the maximum compressive stresses within the beam (f_m) in MPa. Reproduced from Pérez-Rey et al. (2024).

3 Reality vs. models: back analysis of a collapsed room

Although the referred approaches allow to explain the original room collapse illustrated by Fig. 2, alternative designs of an increased reinforcement (including, i.e., 2 Swellex® bolts between every two rows of cable bolts) were required for other areas in the mine. It was observed that the occurrence of collapses still persisted in some other locations and, a particularly large collapse extending about 50 m along the roof took place at some point in a room contiguous to the one where the initially described failure (Fig. 2) occurred. This collapse was attributed to a particularly deconfined area located between faults (Arzúa et al. 2015), where the assumptions of the Voussoir approach are not met.

Fig. 5 Photo of a collapsed room after being stable for some time and contiguous to the originally collapsed room illustrated by Fig. 2. Note that the magnesite beam and the overlying marly slate were detached, and the failure ended at the overlying (harder) slate, not progressing upwards. It is also relevant to remark how the cable bolts were pulled by the magnesite beam because the contact strength in the magnesite and plate were stronger than its strength in the upper slate, whereas the Swellex® bolts (indicated by white arrows) broke their plate and remained attached to the hanging wall.

The instability mechanism observed in Fig. 5 can be associated with distressed areas of the mine with presence of faults and with stress relaxation at the abutments, caused by the opening of contiguous rooms as well. A summary of the geology, failure mechanism and data for calculation is presented in Fig. 6. This mechanism can be considered as one of the worst possible scenarios, so by combining the analytical *voussoir-beam* analogue approach suggested by Diederichs and Kaiser (1999) and the consideration of the stress relaxation effect at the beam abutments through the introduction of an 'equivalent' rock-mass deformation modulus (E_{rm}), a back-analysis of this scenario was then carried out. This equivalent rock-mass deformation modulus is intended to represent the worst possible conditions in the mine and helps in designing the support with some degree of conservativeness. The geometry and features of the room under analysis were a roof span, S = 12 m, a beam thickness, t = 1 m, a dip angle of the magnesite seam, β = 18° and a resulting overload on the magnesite beam caused by a fissured slate layer lying on top up to 1.5-m thick. The corresponding support load was also included, considering 3 super-Swellex® bolts installed every 3 m of face advance. Through the Diederichs and Kaiser's (1999) calculation scheme, the 'equivalent' rock-mass deformation modulus (causing a *bluckling limit* (B.L.) similar to the threshold value considered for instability, that is, B.L. = 35%) was back-calculated as E_{eq} = 1 GPa. This value was taken for forward support design.

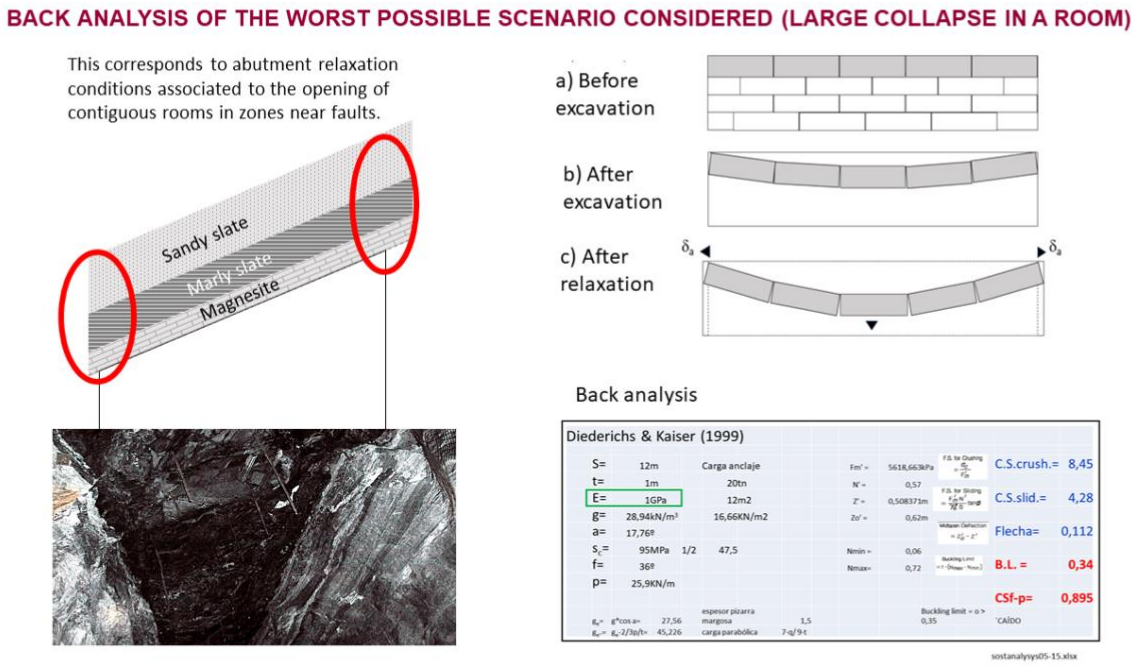

Fig. 6 Schematics and data for the analytical back-analysis of a collapsed room by means of the Diederichs and Kaiser (1999) approach.

4 Application of a design methodology

Support designs in the new parts of the mine (West and East, as already presented) have been based on the application of the *voussoir-analogue* approach (Diederichs and Kaiser 1999) with reasonably conservative assumptions. The magnesite beam thickness (t) is, in this case, considered equal to 0.5 m for design purposes, even a common mining practise is to leave up to a 1-m thick magnesite roof beam, something that is not always achieved due to faulting and difficulties in its control. The 'equivalent' deformation modulus (E_{eq}) for the stability analysis of the new roof beams was retrieved from the back-analysis procedure for a worst-possible scenario as described in Section 3, being E_{eq} = 1 GPa. With these assumptions, new room widths spanning S = 8 m in the West part of the mine (due to a narrowing in the magnesite seam), and S = 10 m in the East part (original 14-m-thick magnesite seam) were suggested.

The room support was re-dimensioned considering Swellex® bolts, installed right after blasting and excavation, and cable bolts installed in groups of three rows, once the face has advanced three blasts (or rows). The pre-defined criteria to validate the designs implies the safety levels presented in Table 2 against the failure mechanisms for roof beams suggested by Diederichs and Kaiser (1999), following their analytical methodology.

Table 2 Safety levels adopted for support and reinforcement design.

Safety criterion	**Name**	**Safety criterion value**
FS against crushing	$FS_{crushing}$	> 2
FS against shear failure at the abutments	FS_{slide}	> 2
Buckling Limit	B.L.	< 10%
FS reflecting bending of the beam (deflection)	$FS_{deflection}$	> 2

Complemented with discussions with the technical management team of the mine, it has been decided to propose support systems for the upcoming years of operation that allow prioritizing conservative approaches to minimize instability risks (even though karstic zones or the presence of sub-horizontal discontinuities are unavoidable), ensuring reasonable flexibility and potential scalability, adapting to the specific conditions of both exploitation areas (West and East) and maintaining economically feasible costs. Based on these premises, and after analysing the behaviour of magnesite hanging walls both theoretically and practically within the mine, it became clear that the room span is the most critical parameter affecting stability. Consequently, this parameter has been reduced in the East zone from 11 m to 10 m to enhance safety. In the West zone, where the magnesite seam thickness varies between 7–8 m and the zone is near a fault with potential relaxation or decompression risks, the span has been further reduced to 8 m for added safety. In both areas, a reinforced basic support scheme has been adopted, with adjustments tailored to the reduced chamber dimensions and tighter bolt meshes, resulting in a higher support density.

In both cases, the support system will include fully grouted steel cables and 4-m-long super-Swellex® bolts. Additionally, a degree of flexibility has been incorporated into the support design, with specific adjustments. If from an on-site face inspection, the need for additional support is revealed, it will be defined and implemented based on the following considerations:

- Reduction in roof beam thickness or detachment planes: when the roof layer narrows or detachment planes are observed, the bolt spacing will be decreased, either by adding an extra cable per row or by placing the rows closer together (2-m spacing),
- Fractures forming blocks in the roof: if fractures delineate unsupported roof blocks, bolts will be installed to anchor those blocks safely.
- Distance from the face for support installation: support will typically be installed 10 m from the face; however, in cases of highly stable and minimally fractured roofs, this distance may be extended until 25 m.
- Aiming at optimising the support installation procedure, super-Swellex® bolts will be installed first due to its straightforward operation.

This adaptive approach is intended to ensure the necessary stability adjustments for varying geological conditions within the mine and has ultimately been assessed based on applications for support based on empirical methods (stability graph method), as proposed by Hutchinson and Diederichs (1996).

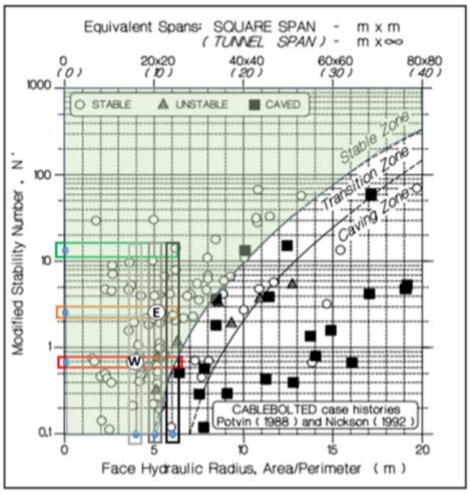

Fig. 7 Graphed locations of rooms in the West (W) and East (E) of the mine based on the chart of the stability graph method for cable bolted mine stope paraments (green area = stable excavations), according to Hutchinson and Diederichs (1996).

These designs would be ranked as stable, even for faulted areas according to the stability graph method version for cabled stopes, as presented in Fig. 7. Considering the nature of this mine (room-and-pillar), it should be noted that the pillar design was also carried out based on classic approaches and without producing any relevant issue, even though this aspect is out of the scope of this paper and is not presented herein for the sake of brevity.

5 Concluding remarks

As a natural evolving process of any mining operation, new mineral zones were identified and characterized and, therefore, accessed for further exploitation as part of a room-and-pillar magnesite mine project in NW Spain. These newly accessed areas are located in the West and East parts of the mine, where some geological features occur, namely, a narrowing of the magnesite seam width (from 14 m to 6-8 m) keeping the main dip of the layer (about 18°) for the western area, with some karstified fractures and the occurrence of a fault, or an increase of the dip in the 14-m thick layer up to 28° for the eastern area, which is also affected by karstification. These features led to a revision of the former support design used in the mine, adapting it to these new scenarios. In this paper, the authors propose some guidelines in the form of a simple yet useful design methodology for rooms in a carbonate stratified rock mass. A "worst-possible" scenario corresponding to an already collapsed room was selected for back-calculating, by means of the voussoir-beam analogue approach (Diederichs and Kaiser, 1999) of an equivalent rock-mass deformation modulus, representative of some structural phenomena causing roof buckling instabilities, like distressing associated with the presence of a fault, but also relaxation at the abutments caused by the opening of contiguous rooms. Following this concept, an approximate deformation modulus of the rock-mass could be back-calculated being $E_{eq} = 1$ GPa and ultimately used as a key input for designing the support in the new areas of the mine. To ensure a conservative design approach, tailored solutions were developed, even for specific scenarios involving reduced roof beam thickness. The effectiveness of these suggested support designs was assessed and validated using an empirical method (the stability graph method), based on several analyses of real mining stopes.

References

Alejano LR, Taboada J, García-Bastante F, Rodriguez P (2008) Multi-approach back-analysis of a roof bed collapse in a mining room excavated in stratified rock. International Journal of Rock Mechanics and Mining Sciences 45: 899-913.

Arzúa J, Alejano LR, Rodriguez P (2015) Back-analyses of failures and support redesign of a magnesite room-and-pillar mine excavated in stratified rock. ISRM Congress 2015 Proceedings - Int'l Symposium on Rock Mechanics. Montreal (Canada), May 10-13.

Barton, N (2002). Some new Q-value correlations to assist in site characterisation and tunnel design. Int. J. Rock Mech. & Min. Sci. Vol. 39, pp. 185-216.

Brady BHG, Brown ET (2006) Rock Mechanics for underground mining. 3rd edition. Springer, The Netherlands

Diederichs MS, Kaiser PK (1999) Stability of large excavations in laminated hard rock masses: The voussoir analogue revisited. International Journal of Rock Mechanics and Mining Sciences 36: 97-117.

Hutchinson DJ, Diederich MS (1996) Cablebolting in Underground Mines, BiTech Publisher Ltd, Canada

Itasca (2022) Universal Distinct Element Code (UDEC), v. 7.0.

Itasca (2023) Software Documentation. Joint Properties. https://docs.itascacg.com/

Mathews KE, Hoek E, Wyllie DC, Steward SBV (1981) Prediction of stable excavations for mining at depths below 1000 metres in hard rock. CANMET report DSS Serial no. OSQ80-00081, DSS File no. 17SQ.23440-0-9020. Ottawa: Dept Energy, Mines & Resources.

Pérez-Rey I, Alejano LR, Estévez-Ventosa X, González-Fernández MA, Marchelli M (2024) Comparison of voussoir-beam stability assessments in underground rooms based on analytical and numerical methods. Eurock 2024 – New Challenges in Rock Mechanics and Rock Engineering - an ISRM Regional Symposium. Alicante (Spain), July 15-19.

Potvin Y (1988) Empirical open stope design in Canada. PhD thesis. Dept. of Mining and Mineral Processing. University of British Columbia (Vancouver, Canada)

Nickson SD (1992) Cable support guidelines for underground hard rock mine operations. MSc thesis. University of British Columbia (Vancouver, Canada)