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ORIGINAL PAPER

Room and Pillar Design and Construction for Underground Coal Mining in Greece

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Abstract The underground mining is the only potential way for the utilization of the lignite reserves from an open pit exploitation which could remain unexploited due to high stripping ratios. This paper is dealing with the findings of a pilot scale underground exploitation that was developed in the Prosilio open pit coal mine in Northern Greece. The method used is the room and pillar mining method where the initial entry galleries are driven into the coal seam starting from the surface excavation face, as used in the highwall mining cases. The design of the mining scheme is presented in detail along with the building of the 3D numerical model which simulates the overall development of the pilot mine. The evaluation of the stability conditions is further discussed and analysed with the use of the results of the numerical model and through their validation with the findings and observations of the actual excavation's response. The mine scheme selected exhibited its flexibility in coping with the prevailing conditions and its performance, in terms of the stability conditions attained, further supporting the development of a large scale underground coal excavation.

Keywords Underground coal mining · Mine design · 3D FEA · Open pit to underground

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1 Introduction

Greece is still heavily depended on its lignite recourses for its electricity demands. According to Eurocoal (2017) lignite production accounts approximately for one-third of the electricity market (31% in 2016), with 37.0 Mt in 2017 making it Greece's most important indigenous energy resource. Lignite mining is mainly located at the north-western Greece through massive surface exploitations that are now taking place in the greater Plotemais area. Nevertheless, large quantities of coal reserves remain unexploited when the open pit mines become marginal due to the constant increase of the overburden volume that must be removed to proceed with the coal extraction.

Those unexploited reserves are now in the spotlight for their potential utilization through a subsequent underground mining scheme. This is the first time after almost 40 years where the underground exploitation of coal is pursued in Greece, after the closure of the underground Aliveri mine site in the early 1980's (PPC 2010). Former coal mines used to exist in the

Athens greater metropolitan area, in Peristeri and in Kalogreza, even under the current location of the Athens' Olympic complex.

Of course, the concept of establishing a direct underground excavation through the coal face is not a new one. It goes back to 1940 in the US where the first such efforts were made and gradually evolved to a new mining method; highwall mining that is capable of facilitating the enhanced recovery of the coal seam (Mo et al. 2016). This method is now used throughout the world, an indication of its importance in the coal mining business, mainly with the use of continuous miner equipment (Luo 2014; Shimada et al. 2013), that report capacities of more than 1 Mtpa. In Australia, the peak production of CHM reached around 3–4 Mtpa in the late 90's while in the US the total run of mine production from highwall mining (CHM and auger) was estimated to be 59 million tn in 2003 (Zipf and Bhatt 2004; Mo et al. 2016).

In the Prosilio mine case, near Kozani in Northern Greece, that the underground exploitation is analysed in this paper the mining is not made through the use of continuous miner but rather with the development of a room and pillar mining scheme though conventional mechanized excavation. Nevertheless, this method can also offer important potential economic advantages. Obviously, the feasibility of such underground exploitations is something that is heavily depended on the attained stability conditions of the underground workings as well as on the productivity characteristics as attained by the mining scheme selected. In this direction, the research presented in the paper is dealing with the findings of a pilot scale underground exploitation that was developed in the Prosilio coal mine. Due to higher stripping ratios, a large part of the coal reserve is remaining unmined in an open pit exploitation. In order to be utilized a much bigger part of the coal reserve, an underground mining scheme is designed to be developed underneath the slopes of the existing open pit mine. The method utilises the room and pillar mining method where the initial entry galleries are driven into the coal seam starting from the excavation face of the open pit, as used in the highwall mining cases. This endeavor is undertaken with main aims to analyze the rockmass response to the underground excavations and to test the general cost-efficiency of the followed mining method.

In the following sections the mine design is analysed and the stability conditions are evaluated and discussed by using both the findings of the 3D numerical analysis on the pillars' performance and ability to provide the required stability of the excavation and the actual on-site response of the mine workings as recorded throughout the mining period.

2 Going Underground in the Prosilio Mine Site

The Prosilio mine site of METE S.A. is located in the Nortwestern Greece at the Kozani prefecture, exploiting the brown coal deposit found there (Fig. 1). The coal strata is found as a single, almost horizontal, layer having a thickness of about 5.5 m. The coal is of good calorific value (2000–2400 kcal/kg), superior to the other lignite deposits of the area and is currently being used as booster to the PPC power plants. The mine started with the exploitation of the deposit using typical open pit excavation, nevertheless in order to maximize the recovery in the boundaries of the current excavation the underground mining of the coal seam is being investigated (Fig. 2). In those parts, the overburden is gradually increased up to around 150 m. This renders that particular coal body section as non-mineable by surface excavation. Thus, the exploitation of the coal deposit directly from the pit bottom seems as a promising practice following the principles given by the highwall mining system (Porathuir et al. 2017). In this manner, the coal is accessed from galleries starting at the base of the highwall and driving their way through the deposit. Nevertheless, in the case examined the exploitation is not being made by auger systems but by using the room and pillar mining scheme without any recovery of the pillars. The thickness of the deposit enables such a scheme and under this method a number of horizontal and transverse galleries are excavated (rooms or entries), each of which serves the multiple roles of ore source, access opening, transport drift and airway. Pillars are generated as coal remnants between entries, to control both the local performance of immediate roof rock and the global response of the host rock medium.

Combining those two mining methods, the efficient recovery of the 5.5 m-thick deposit is achieved and the flexibility in the mining excavations in terms of pillar dimensioning and support requirements is attained to cater for the different conditions encountered. At the same time, limited capital expenditure is required for

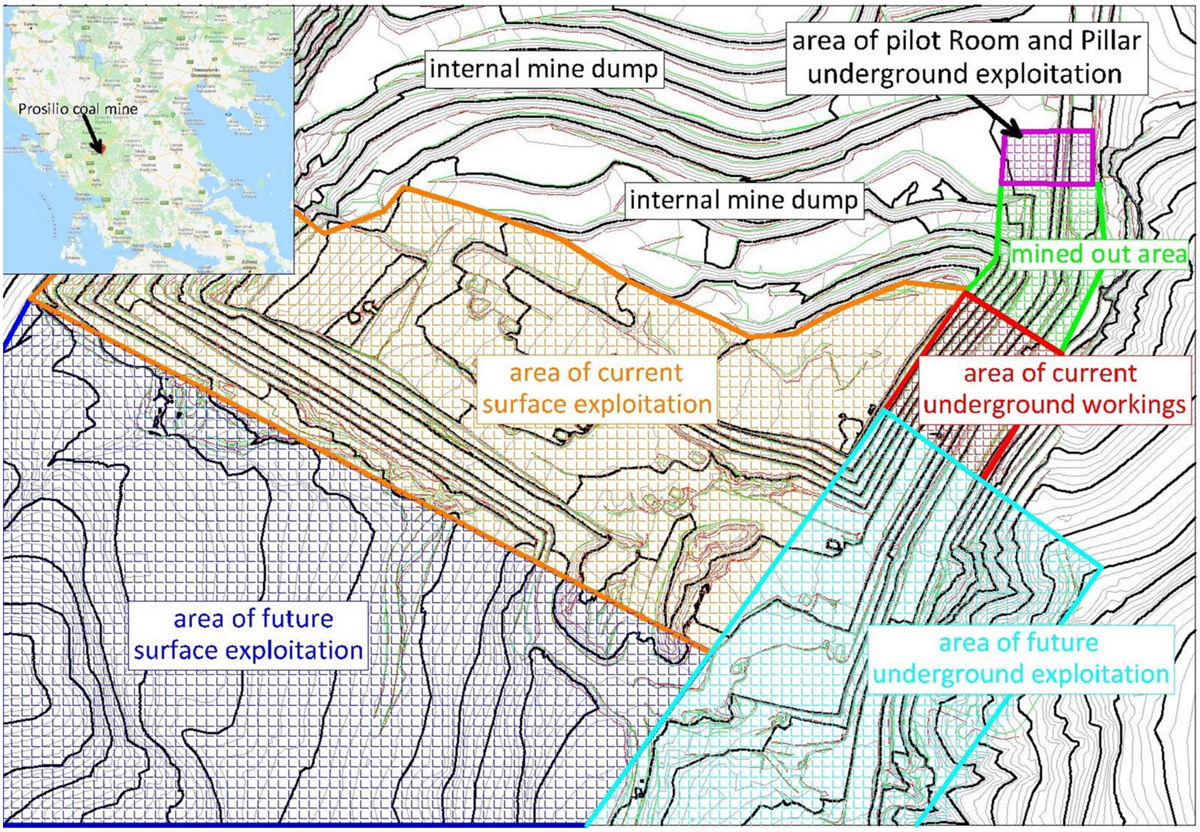


Fig. 1 Location and general plan of the Prosilio mine

Fig. 2 General view of the Prosilio coal open pit mine

the excavation development, a key issue for the successful development of the project.

METE S.A. mining company, commenced the pilot scale exploitation to showcase the validity of the mine design and to gather valuable information on actual pillar performance and support requirements. Beyond that, the data collected would assist in benchmarking the cost-efficiency of the followed mining method when applied under the real conditions of the Prosilio mine site.

3 Design of the Pilot Scale Exploitation

Ensuring the stability of the excavations and the safety of the personnel is of paramount importance to the development of the mining plan. The key to this is the dimensioning of the coal pillars that govern the overall mine stability performance (Hustrulid 1976). For almost a century now coal pillar design has attracted the interest of many researchers (Du et al. 2008) trying to capture the mechanics of pillar strength as Greenwald et al. (1941), Holland (1964), Salamon and Munro (1967), Obert and Duvall (1967), Bieniawski (1992), Madden (1996) or Mark (1999) just to name some of the classics.

This has come a long way from the initial formulae (Mark 2006) to modern approaches taking into account probabilistic design (van der Merwe and Mathey 2013). Of course now, apart from the empirical design the estimation of pillar strength is possible using numerical modeling and it may provide a viable and perhaps better alternative to earlier conventional pillar strength approaches (Mohan et al. 2001), either in the form of 3D numerical FEA or using 2D approximations (Deliveris and Benardos 2017). In this manner, numerical models can further assist in the understanding of pillar performance, especially if validated by the actual feedback gained from the actual excavation's response.

For the development and the numerical analysis of the following 3D-model, the Rocscience's RS3 software was used. The first step was to gather the geotechnical properties of both the coal orebody and the surrounding strata. Such data are based on geotechnical studies made for this underground exploitation, on field observations and on international experience. The rock mass comprises of a flat-lying and relative shallow brown coal orebody with an average thickness of 5.7 m and of marl formation found both in the hanging wall and in the footwall. The height of the overburden is taken at 65 m, the average actual value of the overburden at the pilot mine area.

The general setting can be seen in Fig. 3 where the cross-section of the lithological types is identified along with the values of the main geotechnical properties. The geotechnical properties of the formations that were selected and used for this analysis (Table 1) are based on the in situ campaign, field observations and the lab testing of the Prosilio mine site marl and lignite deposits (Vardakastanis and Pantekis 2014), as well as on international experience in similar formations. This encompasses the intact rock properties σ_{ci}, E_i, and geotechnical classification values with the GSI system (Marinos and Hoek 2000), while m_i parameters for the marl and lignite formation were obtained from the literature (Hoek et al. 2002; Shen and Karakus 2014). Especially for the assignment of the GSI values, field observation from the stopes' crown and sidewalls and bored sampling of the formations were taken into account. It is witnessed that the density of the discontinuities become gradually higher when moving from the upper marl to the middle and lower strata, as shown in the core samples of Fig. 4a, b and c (Vardakastanis and Pantekis 2014). In this manner, a value of 70 selected for the GSI of the upper marl while 60 was the GSI value selected for the middle and lower marl, as it is also shown in Fig. 5.

The geological environment was modeled assuming elasto-plastic deformation using the Mohr–Coulomb failure criterion, as according to the ISRM classification, both the lignite and marl can be described as weak rocks; therefore, the Mohr–Coulomb failure criterion was considered as the most appropriate for the analysis.

It was decided to develop two main access tunnels (X1, X2) from which the main part of the pilot mining was developed (Fig. 6). This consisted of two additional galleries (Z1, Z2) parallel to the main access tunnels and of four perpendicular cross-cuts (Z1, Z2, Z3 and Z4) that eventually developed a total of nine coal pillars, as it is shown in Fig. 7.

The width of the main entries was decided to be 7 m, while the span of all other openings was set to 6.4 m. The total height of the all galleries matched the coal thickness at 5.7 m, with 4.5 m high vertical walls followed by a curved roof design at their 1.2 m crown area. The pillars have rectangular shape with

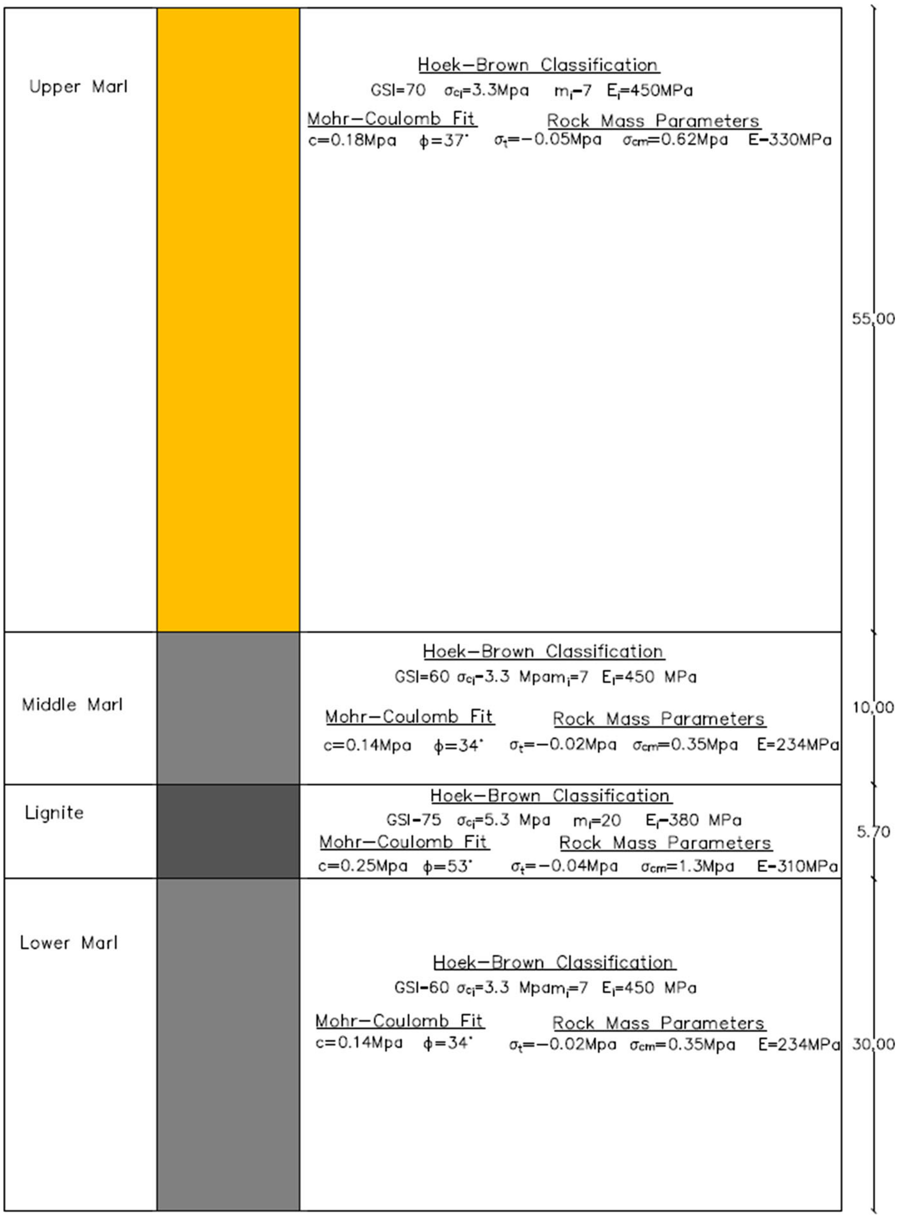


Fig. 3 Cross section of rock mass geotechnical parameters

Table 1 Rock mass geotechnical parameters

	σ_{ci} (MPa)	m_i	E_i (MPa)	GSI	c (MPa)	ϕ (°)
Upper marl	3.3	7	450	70	0.18	37
Middle marl	3.3	7	450	60	0.14	34
Lignite	5.3	20	380	75	0.25	53
Lower marl	3.3	7	450	60	0.14	34

dimensions 5.4 m by 7.4 m. The recovery rate reaches 74% at the main mine area of the pillars, while the total attained recovery for the whole underground mine, including the non-mined panel at the entrance section, is 54%. For the FEA model the shape of the galleries was taken as rectangular instead of the curved design

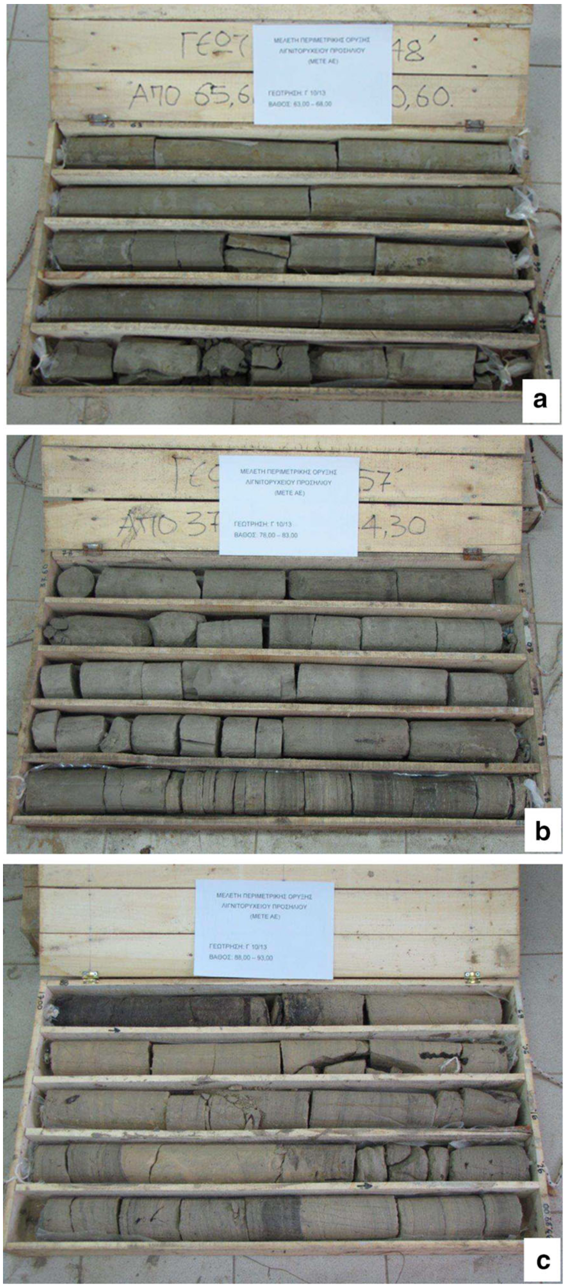


Fig. 4 Core samples from the **a** upper, **b** middle and **c** lower marl formation

due to some aberrations of the software used that didn't make it possible to perform the computing (Fig. 8).

The excavation uses a 2-m step length, and is made with the use of mechanical excavator. The support of the galleries is consisted by the application of Swellex rock bolts (2.4 m length, 120 KN typical bearing capacity) at a grid of 2.0 m by 1.5 m at the stopes' roof (Fig. 9), followed by the application of steel mesh. Furthermore, at the intersection areas the bolting was decided to follow a more aggressive pattern to minimize potential failures and thus the grid was further reduced to 1.0 m by 1.5 m.

The finite element model tries to simulate the pilot-scale room and pillar coal exploitation by taking into consideration not only the above layout, dimensions and roof reinforcement but also, as far as it was possible, the excavation's progression. In this manner, in the model developed, the main entries X1 and X2 were first excavated simultaneously, followed by the stopes Y1–Y4 and finally by the stopes Z1, Z2, making up a total of 84 excavation stages (Fig. 10).

4 Results from the FEA Analysis and the On-Site Observations

The results of the FEA analysis and the actual measurements made in the mining period were in good agreement. Starting from the pillar loading in Fig. 11 the redistribution of the sigma 1 effective stress through the different phases of the excavations, as they are shown in Fig. 10, are presented. This is modelled at the roof section of the mine at the intersection between coal and marl at the section Y–Y′. Stage 0 refers to the premining conditions (virgin stress field), stage 66 refers to the stress values corresponding to the development of the three main pillars (29.0 m × 7.4 m) whereas stage 84 refers to the stress value at the end of mining activity when the final 7.4 m × 5.4 m pillars are formed (see Fig. 9). As it shown, the value of sigma 1 effective stress at the pillars at stage 66 is around 2.0–2.2 MPa while at stage 84 the stress value reaches around 3.0–3.2 MPa having an increase in the order of 45–50%.

The FE analysis shows that the modelled displacements appear to have their maximum values at the middle of the excavated galleries (rooms), especially at the center of the pilot mine area, around the central pillar at the intersection of the Y2 and Y3 galleries with the Z1 and Z2 ones. Those appear to be the most critical sections with the convergence values ranging from 50 mm to 70 mm (Fig. 12). At the main access galleries (X1 and X2) as well as at the back end of the mine (gallery Y4) the roof displacements seem to have lower values of around 40 mm.

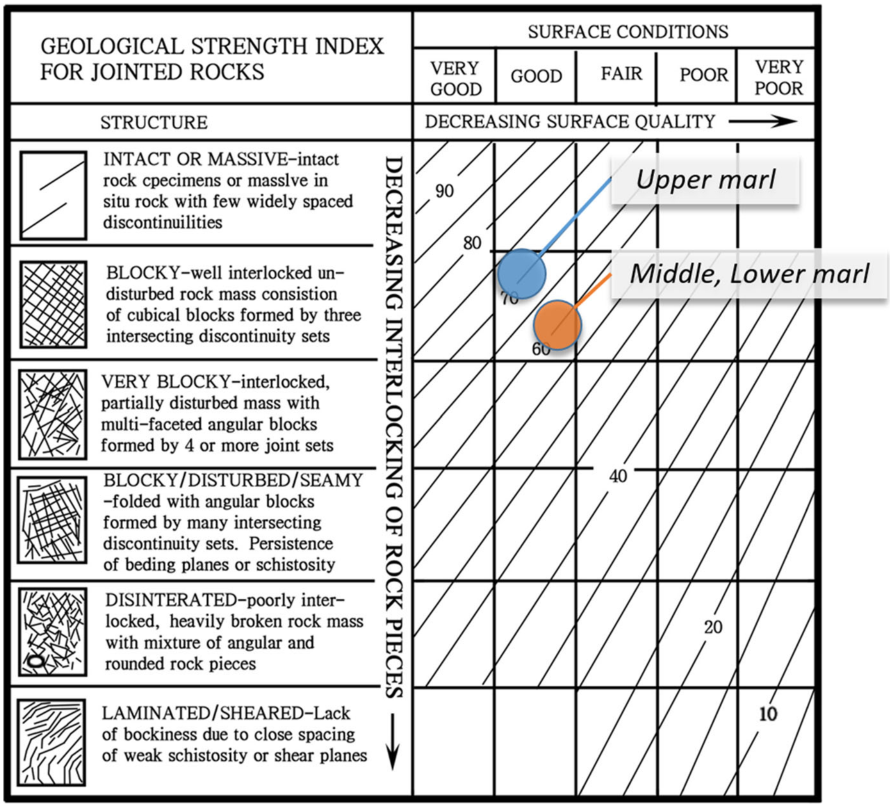


Fig. 5 GSI values of different marl layers

Fig. 6 View of the main mine entries

Apart from Fig. 12, in Fig. 13 the total displacements along the X–X′ cross section (see Fig. 7) are presented. The maximum roof displacement is around 50 mm at the central rooms. As a result of the stress redistribution and the increase in pillars' loading due to the mining activity, the pillars deform in all three

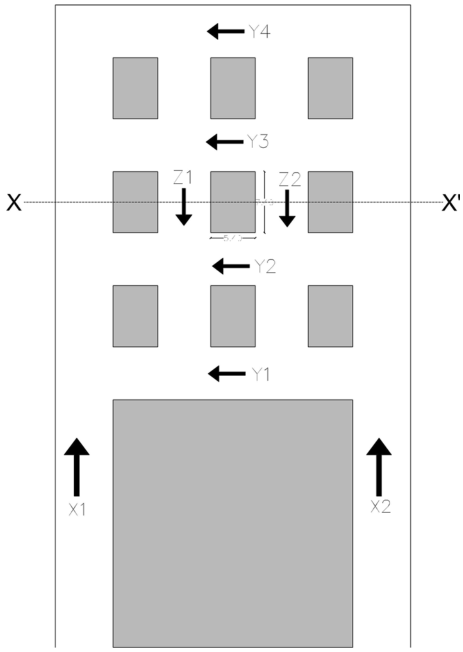


Fig. 7 Layout of the pilot application of the room and pillar mining at the Prosilio mine

main axes, as it is shown from the FEA where displacements of approximately 15 mm are calculated at the pillars' sidewalls (Fig. 14) and validated by field observations.

The actual convergence measurements were executed by topographical equipment with the assistance of targets located at the central part of the roof and at the middle section of the pillars. The closest point to the face, where the targets were installed and displacements were measured was at approximately 6 m. This monitoring campaign provided detailed data about the actual performance of the mine in terms of displacements. The measured displacements show good agreement with the actual performance of the mine. The deformations in the pillars' sidewall were between 10 mm and 20 mm. For the case of the roof's displacements the data from the main access galleries that were measured throughout the pilot mining application showed an average value of 30 mm, with the maximum values reaching around 40 mm.

The following chart (Fig. 15) is refering to the development of the convergence as measured at the roof of the X2 entry stope. As it is shown, the tunnel face progresses up to 25 m, from the control point, and then stops, with the measured convergence to reach 18 mm at that point. The face of the X2 gallery doesn't progress any more but the convergence continue to rise, until the end of the underground excavations, for more than 100%, reaching the final value of 40 mm. This is due to the excavation of the neighboring Y1, Y2 and Z1, Z2 stopes which affect the overall stability conditions of the mine and hence lead to the deformation of the X2 gallery's roof.

The distribution of the Strength Factor and the yielded elements as calculated by the numerical analysis at the cross section X-X' are shown in Fig. 17. The analysis calculates a minimum Strength

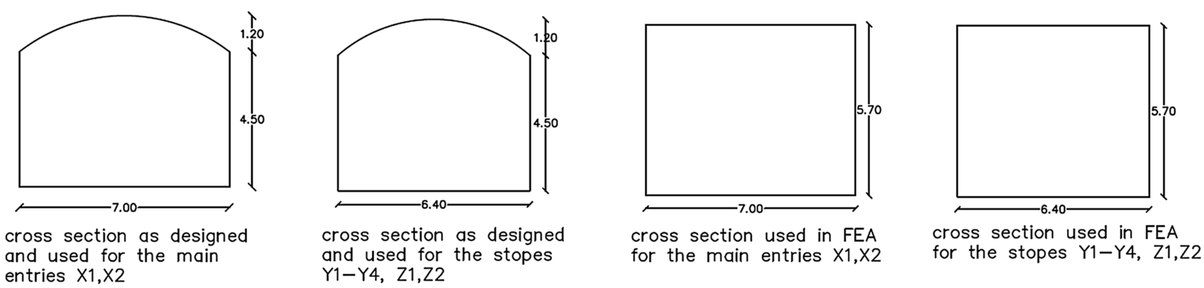


Fig. 8 Cross sections of the stopes used in the pilot mining scheme and in the numerical analysis model, respectively

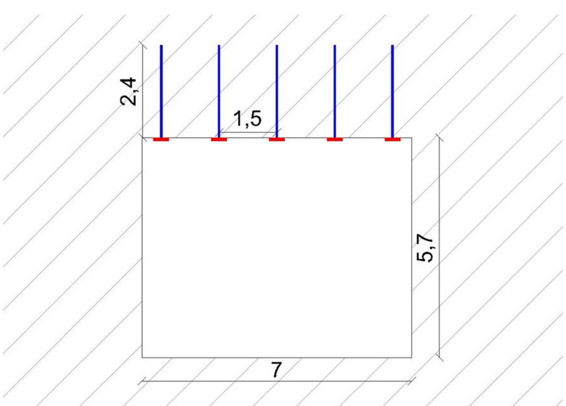


Fig. 9 Main characteristics and layout of the roof bolting applied at the Prosilio coal mine

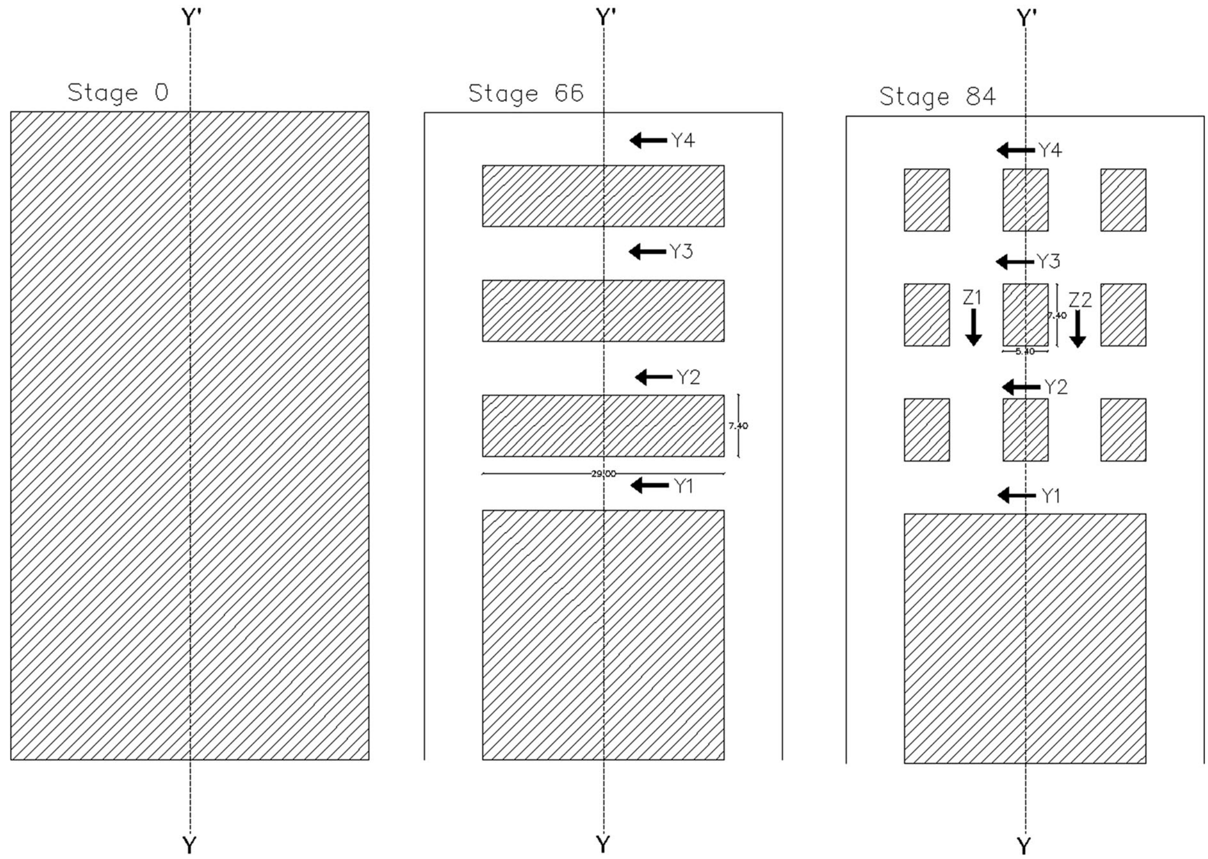


Fig. 10 Different phases of the stoping activity as it was modeled in the FEA

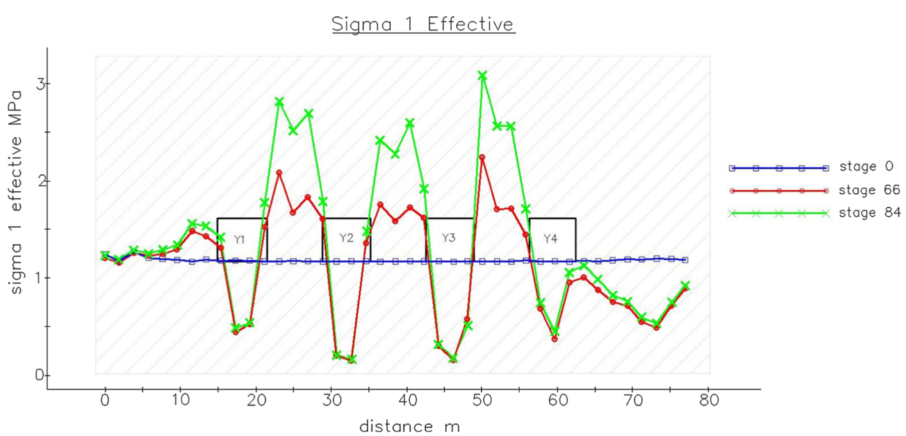
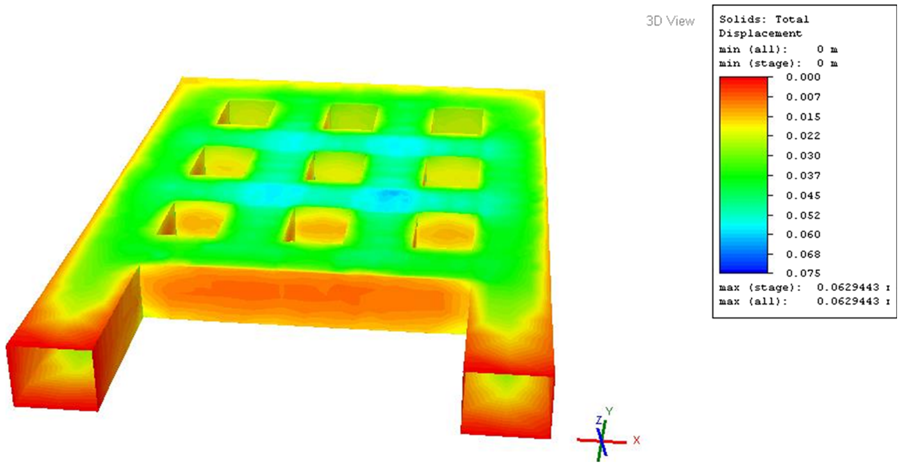


Fig. 11 Sigma 1 effective stress through the different phases of the stoping activity as it was modeled in the FEA

Factor of 1.16 at the core of the pillar, with the total unyielded width to be about 2.70 m or 50% of the pillar's body.

Following this observation of the FEA analysis, it is witnessed that the core of the pillar remains intact in spite of the yielded area that is localized at the pillar's skin. This suggests that the pillar's response to the load imposed is adequate and consequently the pillar's overall stability in terms of performance is sufficient, given the temporal character of the mining excavation.

Fig. 12 Total displacements contours at the spatial model



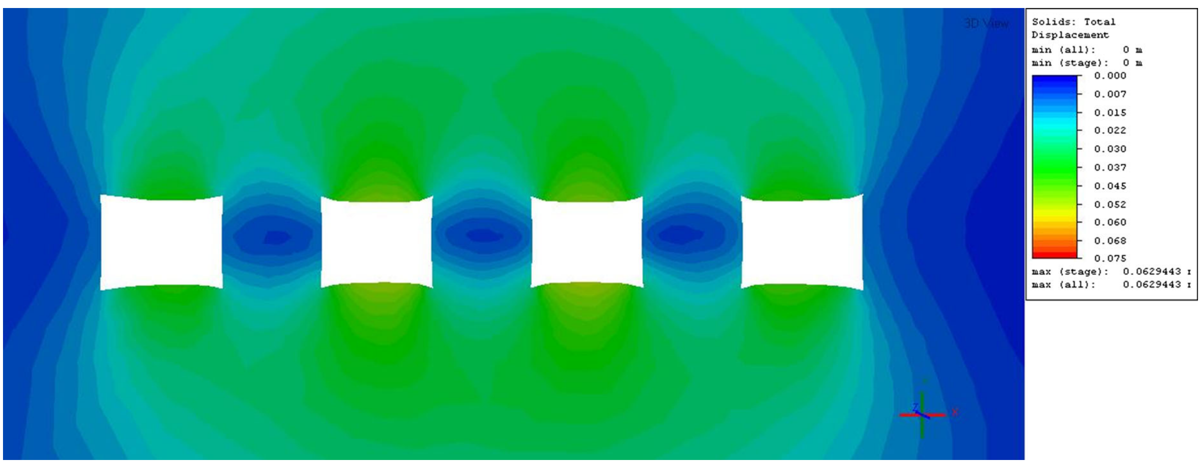


Fig. 13 Displacement contours at the deformed X–X′ cross section

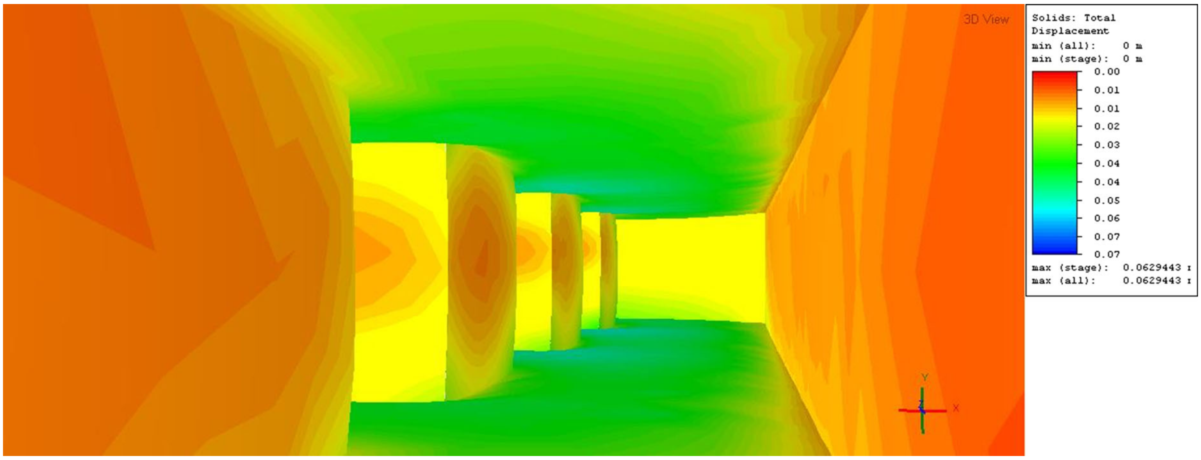


Fig. 14 Total displacements in the coal pillars as derived from the FEA model

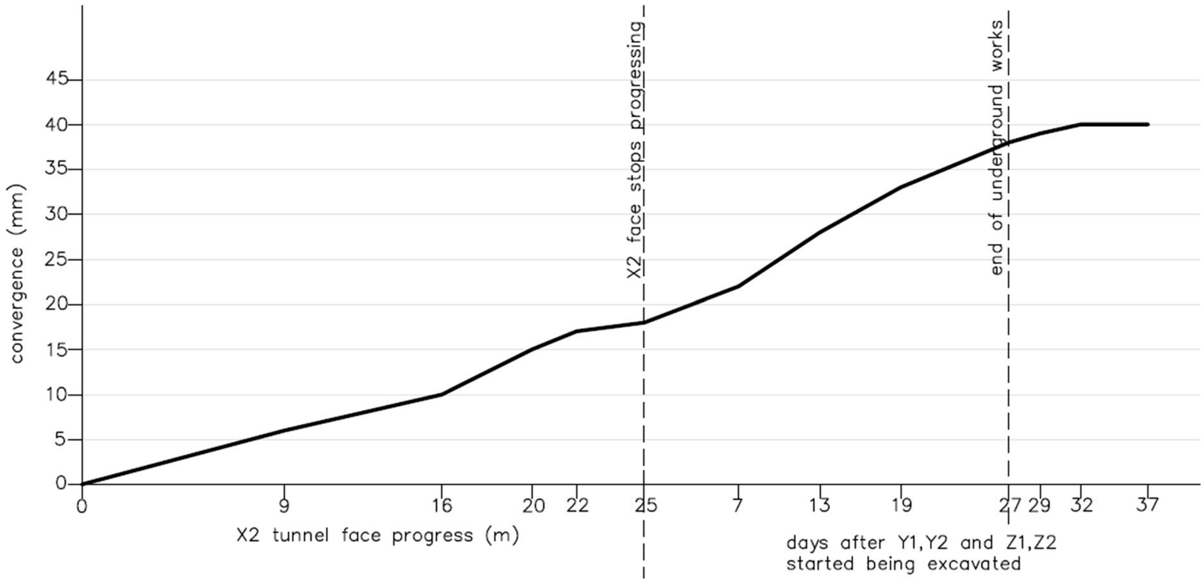


Fig. 15 Measured convergences related to the progress of underground works

This was verified by the actual performance of the pillars not only during the mining period but also after the end of the excavations. In the worst case scenario, where the yielding area would progress though the core of the pillar, the application of immediate support measures (e.g. bolting, shotcreting or clamping of the pillar's sides) could be used to remediate the pillar's stability conditions.

The pillars' deformation behaviour is also related to the structure of its geology, as the foliation of the lignite is perpendicular to the principal axis of loading and this affects positively the pillars' geomechanical response against failure. During the underground mining period, limited cracking was observed at the excavation's corners as a result of local shear failures (Fig. 16). Furthermore, at the main body of two pillars a limited surficial spalling was observed, as it was seen in the 3D analysis at the yielded areas of the pillars (see Fig. 17). Both of these two failure conditions were described by Lunder and Pakalnis (1997) (Fig. 18a, b, c, d). Nevertheless, such issues didn't result to any further degradation of the pillars' performance, indicating that their core remained intact and can withstand the loading imposed to them. This is seen in the numerical model, as well.

The performance of the support measures in both the numerical model and the actual mining can be considered as satisfactory. The data from the numerical analysis shows that a small number of rock-bolts has failed, mainly as the support load exceeds its bearing capacity. Nevertheless, such failures are only localized without affecting the overall

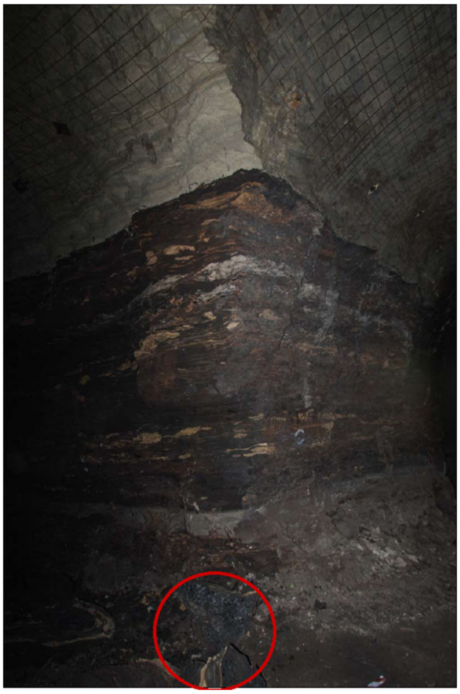


Fig. 16 View of lignite pillar edge. Detached lignite rocks from the lower corner due to local cracking

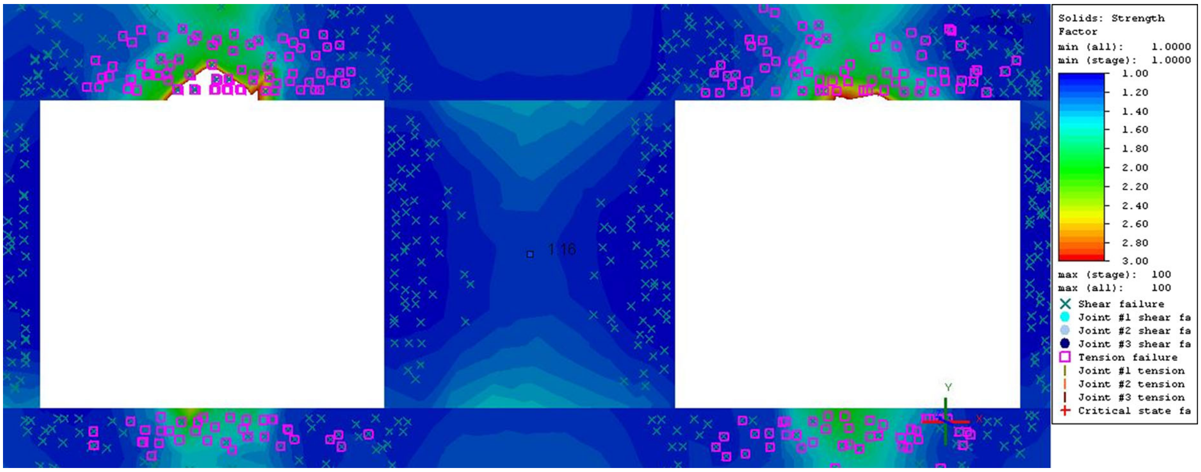


Fig. 17 Strength Factor contours at the central pillar and yielded elements (A–A′ cross section)

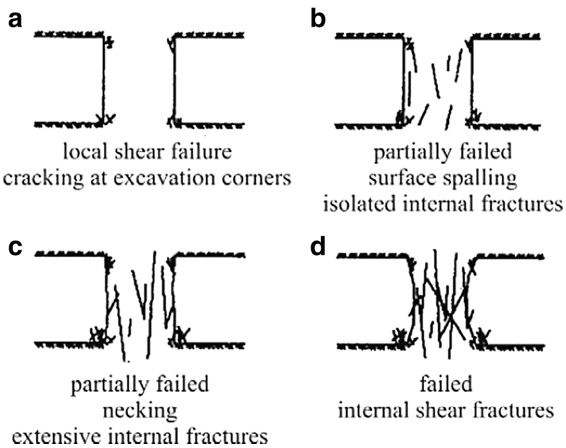


Fig. 18 Schematic illustration of the evolution of fracture and failure in a pillar in massive rock (after Lunder and Pakalnis 1997)

stability of the immediate roof. The sound rock mass properties of the marl in the immediate roof and the limited extend of the yielded zone of the roof (yielded elements are highly concentrated in a zone up to 2 m over the roof) are factors that make the applied supporting system suitable for this pilot-scale underground lignite exploitation.

This is validated from the experience gained in the pilot mining scheme. Apparently, no bolt failure was witnessed (e.g. large deformations, possible bending or rupture or plate failure) until the end of the mining campaign. The observation of the stopes' crown during the excavations and the very good response of the immediate roof to the stoping activity are indications that the actual yielded zone of the roof was much more limited than modelled. This is also partially due to the actual geometry of the tunnel crown where the arching effect also develops more stable conditions as the stress redistribution prevents the development of a tension stress field.

The support system selected works not only in suspension mode but also develops a support beam throughout the bolt's length capable of addressing major failure threats. This system can be further enhanced with the application of an additional shotcrete layer in the latter stage when the underground mining will be fully deployed.

In addition to the generally good structural response of the lignite pillars, factors such as the use of mechanical excavation which reduced significantly the disturbance of the surrounding rock mass in conjunction with the temporal nature of this underground mine affected favorably the global stability and allowed the completion of this pilot exploitation without any significant difficulties (Fig. 19).

However, it should be noted that for the case of higher overburden, a new pillar design would be required. The main aim would be to provide design guidelines that are compatible with the prevailing geotechnical and stress conditions. In doing that, the room-and-pillar method provides the required flexibility. The major change would be focused in the dimension of the pillars. The room width could follow the general guidelines of the pilot application (approx. 6.5 m); however, the width of the pillar would most probably be increased to new design values that would

Fig. 19 View of the underground exploitation after the completion of the stoping activity

ensure the stability of the excavation and the required FoS of pillar.

5 Conclusions

The development of underground exploitations can provide viable solutions for the mining of reserves that cannot be economically mined through classic surface exploitation schemes. The stability conditions of the pillar structures however are a key aspect that could determine the feasibility of the endeavor. In the Prosilio mine site the pilot mining was implemented to test the implementation of the room and pillar mining scheme in order to be further investigated the potential of further utilization of the lignite reserve through an underground exploitation.

Based on the results of the numerical analysis and the field observations it can be deduced that:

- The pillar design and dimensioning appear to be capable of withstanding the loading from the overburden at this level. Although minor failures appeared in the pillars' skin, the core remained intact. Thus, in the case where a less aggressive design is selected the problems can be further minimized.
- The most critical parts of the mine are located at the central rooms. In there the maximum displacements are found to be around 60 mm. Displacements of lower magnitudes are experienced in the pillars sidewalls.
- The support system selected shows a very competent performance minimizing any failures of the roof strata. Although at these conditions the selected support is sufficient, in cases where areas of lower geotechnical properties are to be encountered more support options should be further considered (e.g. shotcrete, lattice girders, etc.).

Finally, the good agreement between the 3D numerical model and the actual conditions is to be noted. This is a big advantage to the exploitation engineers as they can explore further options in the overall mine design as the model develop seems to have the ability to accurately capture and model the excavation's response.

The pilot mining application revealed interesting features and provided useful experience. In the next mining phase, which is now under planning a larger area will be exploited by underground excavation that will closely follow and sync with the open-pit mining activities.

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