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OPTIMAL SUPPORT DESIGN FOR GALLERIES LOCATED IN POOR QUALITY ROCK MASS AND UNDER THE INFLUENCE OF MINING WORKS

In this work, the support of two general galleries located in poor quality rock mass and subjected to the influence of high thickness coal layer exploitations is designed and optimized. The process is carried out in four phases:

A first preliminary support is defined employing different geomechanical classifications and applying the New Austrian Tunnelling Method (NATM) using bolts and shotcrete.

An instrumentation campaign is carried out with the goal of analysing the behaviour of the support. The study noticed the failure of the support due to the time of placement of the different elements.

A back-analysis using the Flac and Phases software has allowed the evaluation of the properties of the rock mass and the support, the study of the influence of the time of placement on the component elements (bolts and shotcrete), and the redefinition of that support.

Subsequently, a new support is designed and optimized through numerical modeling after the start of mining without experience in these sizes of sublevel caving that caused the failure of the previously designed support. The new support is formed by yieldable steel arches that are more suitable to withstand the stresses generated by nearby mining work.

Keywords: support design, back analysis, numerical implementation, bolt, shotcrete, yieldable steel arch

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1. Introduction

An underground cavity has to fulfil two basic requirements: guarantee the stability of the support and ensure that the deformations associated with the excavation do not affect the functionality of the structure.

These two requirements have to be met both during its construction, and its operation. In the case of mines, as is the case study, the stress over the support are enormous and variable in space and time, because the influence of the operation phase is more complex.

Currently, the empirical design of the support of underground excavations is based on the Geomechanical Classifications of the rock masses. This support is designed according to the quality of the rock mass and based on previous experiences. However, it should not be assumed that the geomechanical classifications replace analytical or numerical studies, since the geomechanical classifications omit certain considerations that are taken into account, such as: the natural state of stress, the effect of the shape of the excavation, the effect of the excavation phases, the mass movements, and the changes in stress.

In addition to the aforementioned considerations, the ground-support interaction and the influence that nearby underground works exert on the support are two key factors when addressing the design of the support. These have been demonstrated in various recent works, in 2009, (Fahimifar & Ranjbarnia, 2009) propose an analytical model of the behaviour of active bolts in circular tunnels, and conclude that decreasing rock bolts spacing increases the support system stiffness rather than preloading them. The next year (Prusek, 2010) analyses the different support systems applied in gateroads in different countries, concluding that outside of Europe the principal support type is rock bolting while in Poland or Germany the principal gateroad support is steel arch yielding support. Later in 2011, (Shing et al., 2011) analyse the ground-support interaction considering the flow of water in the ground and present an analytical formulation that is contrasted with a numerical hydraulic mechanical model. After several years (Niedbalski et al., 2013; Majcherczyk et al., 2014) publish works confirming the effectiveness of combining yielding steel arch with rock bolt support systems under different mining conditions. In 2016, Vrakas publishes his doctoral thesis about the analysis of ground response and ground-support interaction in tunnelling considering large deformations and provides practical tools for the analysis and design of tunnels crossing heavily squeezing ground.

In supports where bolts and shotcrete are combined it is important to know, according to the curing process, the change in their properties, specifically strength and rigidity. (Oreste & Pella, 1997) propose a model about the progressive hardening behaviour. They validate the model in a tunnel by means of back-analysis and numerical simulations.

On the other hand, (Carranza-Torres et al., 2013) propose a solution for the excavation of a circular tunnel in an infinite and elastic medium under a non-uniform stress state and taking into account the delay in the installation of the support. Later, (Wang et al., 2014) publish one study about the ground-support interaction when the ground has a viscoelastic behaviour and the support is formed by several layers of shotcrete progressively installed, with a certain time delay. They take into account the excavation in phases of the tunnel, assuming that its radius grows progressively over time.

In this work, the support of two general galleries called G-865 and G-740, located in the levels of one coal exploitation 865 and 740 respectively is designed, analysed and optimized. Both galleries are located in poor quality rock mass and they are under the influence of large-scale coal-bed exploitations.

2. Case of study

In this work, the support of two galleries are analysed. These two galleries (G-865 and G-740) are opened in rock with the New Austrian Tunnelling Method capable of integrating the surrounding ground into an overall ring-like support system. In it, the tunnel is excavated gradually and a composite lining (e.g., a flexible combination of rock bolts and shotcrete) is installed immediately after the tunnel face advances in order to stabilize the surrounding ground. Finally, the invert is installed to create a closed ring system for load bearing (Rabcewicz, 1965; Rabcewicz & Golser, 1973; Golser & Mussger, 1978; Müller, 1978; Golser, 1979; Müller, 1990).

The two galleries correspond, respectively, to the levels 740 and 865 of the "Mary Mine" coal exploitation located in the province of León in the north of Spain.

The exploitation has layers more than 15 m thick made by the system of horizontal descending strips with sublevel caving. The deposit is vertically divided into main levels with 100 m between them. In the direction of the coal layer, the deposit is divided by imaginary perpendicular planes and separated 400-500 m. The shaft is located between 30 and 40 m from the coal layer. The shaft is connected to the coal layer by cut-outs every 8-10 m of height that represent the levels of the exploitation. In each cut-out a main gallery is tunnelled and from this main gallery crosscuts are tunnelled that are retreat mining. The main galleries in "Mary Mine" have a useful section of 17 m^2 and the crosscuts and cut-outs have a useful section of 9-12 m^2. Figure 1 shows the employed exploitation scheme.

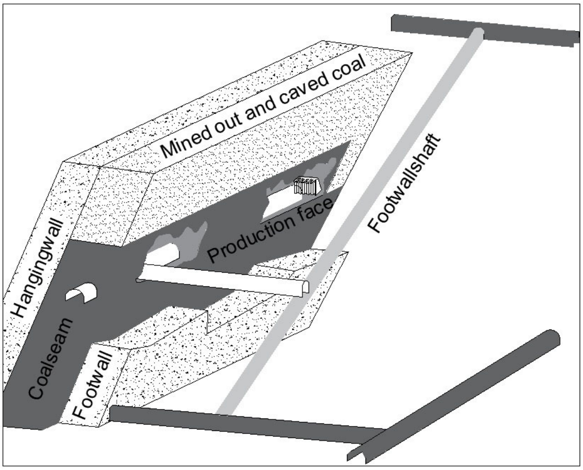


Fig. 1. Scheme of the exploitation

3. Initial support from geomechanical classifications

For the design of the initial support of the galleries, Bieniawski index (Bieniawski, 1989), HVL-94 index and TEPROTEC index (Tectonized deep-ground) were employed. These last two indices have been specially defined for the conditions of the mine (Vázquez-Silva, 2014). From this first classification two types of rock mass were defined (Table 1).

TABLE 1

Rock mass classification from the employed indices

Cohesion (MPa)	Friction	RMR (mean value)	Rock mass classification
0.10-0.15	30º-35º	34	Poor
0.15-0.20	30º-40º	44	Average

Based on this classification, an initial support formed by bolts and shotcrete was defined. In the zones considered of average quality the bolts have diameters of 32 mm, lengths of 4 m, and they are separated from each other by 2 m, while the shotcrete goes from 5 to 10 cm in the crown and 3 cm on the sides. In the zones considered of poor quality, the bolt length is increased to 5 m and the spacing is reduced to 1.2 m. The shotcrete has a thicknesses of 10-15 cm in the crown and 10 cm in the two sides. Where required, yieldable steel arches, type THN-21, with a spacing of 1.5 m are placed (Fig. 2).

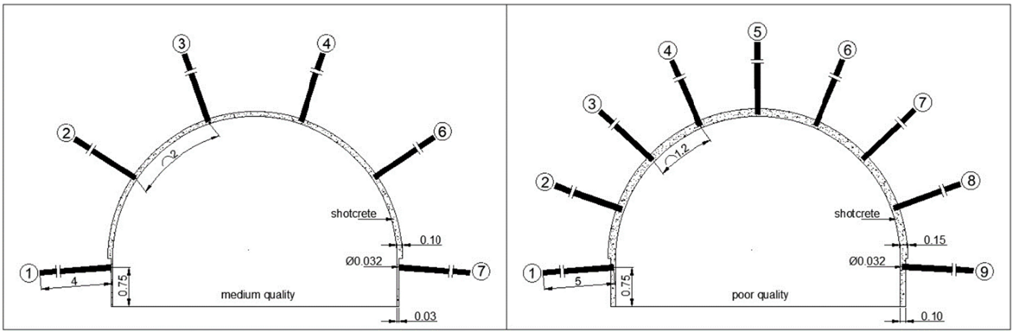


Fig. 2. Scheme of the initial support

4. Analysis of bolts and shotcrete support. Instrumentation campaign

The previous support is analysed by means of a campaign of instrumentation. Four control stations are installed in the points that are shown in Table 2.

TABLE 2

Instrumentation placed in G-740 and G-865 galleries

Gallery	PK	Instruments placed			
		Convergence	Pressure cells (shotcrete)	Load cells (bolts)	Strain gauge
G-740	213	1		2	2
G-740	347	1			2
G-865	201	1	4 Radial; 4 Tangential	5	3
G-865	335	1		2	2

From the data collected, it is noticed that.

4.1. G-865 Gallery

1. The convergence of sides at 60 days has values close to 150 mm causing a deterioration in the shotcrete and requiring the reinforcement of the support by an increasing the number of bolts.
2. The deformations of the strain gauge, over 105 days, oscillate in the crown between –7 mm/m and 3 mm/m; in the left-side, between –11 mm/m and 5 mm/m; in the right-side, between –30 mm/m and 25 mm/m. The result is a compression breakage of the bolts on the sides. For its part, the bolts of the crown reach the limit of their strength in the vicinity of the gallery. This behaviour has its origin in a bad coupling between the bolts and the shotcrete. Due to the rigidity of the shotcrete, a compression zone appears around the gallery affecting the bolts and producing their breakage by compression.
3. The pressure cells located in the shotcrete of the crown show a continuous increase in pressure, although without breaking. However, in the lower part of the sides the breakage of the shotcrete does occur.
4. The load cells register values with an increasing tendency until reaching 86.4 t. These values are inadmissible and confirm the observations made with the rest of the measuring equipment, as well as the breakage of the bolts.

4.2. G-740 Gallery

1. After 60 days, the convergence of the sides reaches 60 mm, but, there is no sign of a trend towards stabilization.
2. The 128-day deformations in the strain gauge oscillate between –11 mm/m and 2 mm/m in the left side and –24 mm/m and 17 mm/m in the right side. From the beginning, the bolts reach the breaking load, exceed the maximum deformation, and failure occurs. In the section closest to the gallery, the breakage is due to compression.
3. The values obtained in the load cells are similar to those obtained in G-865 Gallery and do not correspond to the values obtained in the measurements from the strain gages. Therefore, the breaking of the bolts is corroborated.

In conclusion, from this analysis it seems that the shotcrete holds up all the load. To ensure the integrity of the bolts, they should have been designed with greater length, higher load breaking capacity or larger diameter. The setting period of shotcrete must be modified so that it can deform, absorb ground loads and work together with the bolts.

5. Back analysis for the rock mass characterisation

From the observations made and from the data provided by the instrumentation, it can be deduced that none of the traditional geomechanical classifications manages to characterise the rock mass in a reliable manner and, consequently, it is difficult to design the support based on them. However, there are studies to improve the results obtained with the traditional geomechanical classifications. In 2016, (Małkowski et al., 2016) developed new indices which take into account the mining and technical factors and whose results are promising.

In this paper, the geotechnical characterisation is addressed using the concept of back-analysis. This analysis consists of simulating (analytical or numerical) real observed situations in order to evaluate the behaviour and get the average properties of the different materials involved in the geotechnical problem (Kovari, 1994; Miro et al., 2015; Janin et al., 2015).

The behaviour is simulated in two ways:

1. A first characterisation of the rock mass and the shotcrete using the Phase 2 software package (Rocscience Inc., 2014), using the measurements made at the stations over a mesh of points that define the different areas to be analysed.
2. A sensitivity analysis using the FLAC software package over a quadrilateral mesh where each internal node is joined to 4 neighbouring quadrilaterals, forming a regular array of elements (Itasca Consulting Group, 2008). The objective is to understand the influence of the support so as to propose improvements in its design and ensure its stability over time.

For this study, and taking into account that the classical theory is developed for circular section galleries and isotropic tensional states, a gallery with a radius of 2.347 m that is equivalent to the galleries in G-865 and G-740 has been evaluated. For the axis, a depth of 500 m equivalent to an "in-situ" tensional state of 11 MPa has been taken into account.

5.1. Characterisation of rock mass and shotcrete with Phase2

Phase2 is a displacements and stress analysis software in two dimensions, which combines the techniques of finite element analysis and analysis by contour elements. It allows the geotechnical characterisation of the ground under study by simulating different models in which the values of the geomechanical parameters of the rock mass and the support of shotcrete are modified. Table 3 shows the properties assigned to the different analysed combinations of ground-support, as well as the value of the resulting convergence, or in this case, the instability of the model.

TABLE 3

Characteristics of the analysed combinations of ground-support

Gallery	Case	Ground		Shotcrete		Convergence (mm)
		c(MPa)	(φº)	c(MPa)	(φº)	
G-865	1	0.1	25	8.2	40	Instable
	2	0.2	20	8.2	40	Instable
	3	0.6	20	8.2	40	153
	4	0.6	20	10.5	30	140
G-740	5	0.4	20	8.2	40	Instable
	6	1.0	25	8.2	40	69
	7	1.0	25	10.5	30	61
	8	1.0	25	11.14	25	65
	9	1.5	25	10.5	30	42

From the conducted simulations, it can be established that the properties of the rock mass for the G-865 gallery are c = 0.6 MPa and φ = 20º, while for the G-740 gallery they are c = 1 MPa, φ = 25º. On the other hand, it is observed that the properties of the shotcrete that ensure the measured convergences are c = 10.5 MPa and φ = 30º.

5.2. Analysis with FLAC2D

The objective of this modelling is to obtain the behaviour of the convergence and the radius of plastic zone as a function of the properties of the ground and of the support variables.

5.2.1. Effect of the geotechnical properties of the rock mass

Taking into account that the galleries can cross different lithologies and that only a section of them can be characterised by means of back-analysis, the intention is to evaluate the influence of slight changes in the cohesion and friction with respect to the values found. The employed range of values for the cohesion is 0.4 MPa – 0.8 MPa and for the friction is 15º-25º.

For the study, a code based on the classic Mohr-Coulomb theory is elaborated. This code allows obtaining the characteristic curves that represent the cohesion and the friction depending on the convergence and the measurement radius in the simulated gallery in each plastic zone (Alejano et al., 2012). The evaluation of the deformation moduli is made from the available estimates of the HVL-94 index. This index gauges the parameters in a different way front the classification of Bieniawski and takes into account ground factors, such as shale and sandstone power, persistence of discontinuities, and presence of folds (Vázquez-Silva, 2014).

Figure 3 shows the variation of the convergence and the radius of plasticization for a cohesion that varies between 0.4 and 0.8 MPa and a value of friction equal to 20º for a gallery without support (continuous line), and with a support pressure of 1.1 MPa (discontinuous line), which is equivalent to 10% of the pressure in situ (about 11 MPa). The first simulation, without support, represents an extreme situation in which the support fails. From the figure 3 it is deduced that when the failure occurs, the convergence varies between 150 and 400 mm, while the radius of plasticization moves between 9 and 16 m. If a support that holds when a pressure of 1.1 MPa is applied, the convergence is reduced by 15% while the radius of plasticization is reduced by 40%.

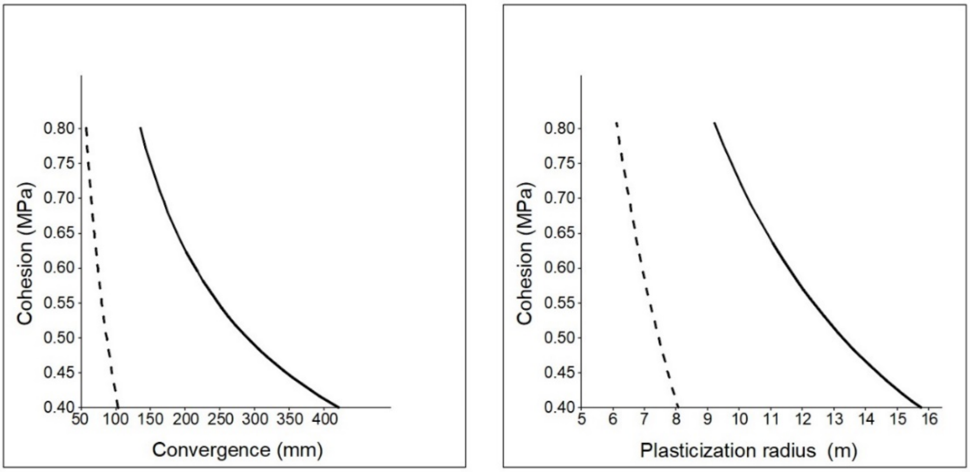


Fig. 3. Relation between cohesion and convergence (left) and between cohesion and radius of plasticization (right) for a friction equal to 20º

The same analysis for a constant value of cohesion equal to 0.6 MPa and values of friction between 15° and 25° produces similar results. Without support, the convergence reaches values of between 150 and 500 mm and the radius of plasticization between 8 and 19 m. When a support pressure of 1.1 MPa is applied the values of convergence are between 50 and 150 mm and the radius of plasticization between 6 and 11 m.

5.2.2. Effect of the geometrical properties of the support

In this case the shotcrete has been simulated by means of beam elements. The different aspects analysed are:

- Influence of the length of the bolts on convergence. The study is conducted with bolts of 16 mm in diameter and a spacing between them of 1 m. The length of the bolts varies between 2.5 and 5 m. The result is a decrease in the convergence values from 230 mm to values lower than 180 mm for the support scheme with the bolts of 5 m in length. For all the lengths, the radius of plasticization is around 10 m.
- Influence of the spacing between bolts on convergence. The study is conducted with bolts of 3 m in length and 16 mm in diameter. The results show that as the spacing increases, the convergence also increases to values greater than 250 mm with bolts spacing of 1.5 m.
- Influence of the diameter of the bolts on convergence. The analysis is carried out with bolts spacing of 1 m and a length of 3 m. The results show that an increase in the diameter of the bolts produces a very fast decrease in the value of convergence down to bolt diameters of 25 mm. Bellow this diameter the effect on convergence is less. An analysis of the maximum tensile stress supported by the bolts as a function of their diameter corroborates this effect. There is a significant increase in the load they bear when the diameter increases from 16 to 25 mm (from 0.500 to 0.900 MN), but an increase in the diameter from 25 to 32 mm only produces an increase of 10%.
- Influence of the shotcrete on convergence. The study shows the small influence that a change in the thickness of the shotcrete has on the convergence. The study is carried out for thickness between 6 and 12 mm and bolts 3 m in length, 16 mm in diameter and with a spacing of 1 m among them.

From the analysis, the variables that have more influence on the convergence are the diameter of the bolts (to 25 mm) and their spacing. Their length, at least in the interval of lengths between one and two times the radius of the gallery (and for radii of plasticization around 10 m), or the thickness of the shotcrete, have little effect.

5.2.3. Effect of installing time of the different elements of the support

The importance of the time in which the different elements of one support are installed is known. Regardless, accurately describing the influence of the time factor, which would require the use of dynamic codes, is more complex. In order to assess this influence, one compound support is analysed in two different circumstances: when the bolts and the shotcrete are set up at the same time and when the support is set up in two steps (the bolts are previously set up and then the shotcrete is applied). In this case the shotcrete is simulated when the ground has already been relaxed by 30%, taking into account the decompression rate suggested by Panet models on the face.

Figure 4 shows the state of plasticization and the deformed magnified curve for the two circumstances, bolts and shotcrete set up at the same time (Fig. 4a), and bolts and shotcrete set up in two steps (Fig. 4b). In the figure the support is not represented in order to clarify the image. A greater deformation in the first case is noted because a large portion of the load is held up by the shotcrete that can be broken by tensile stress.

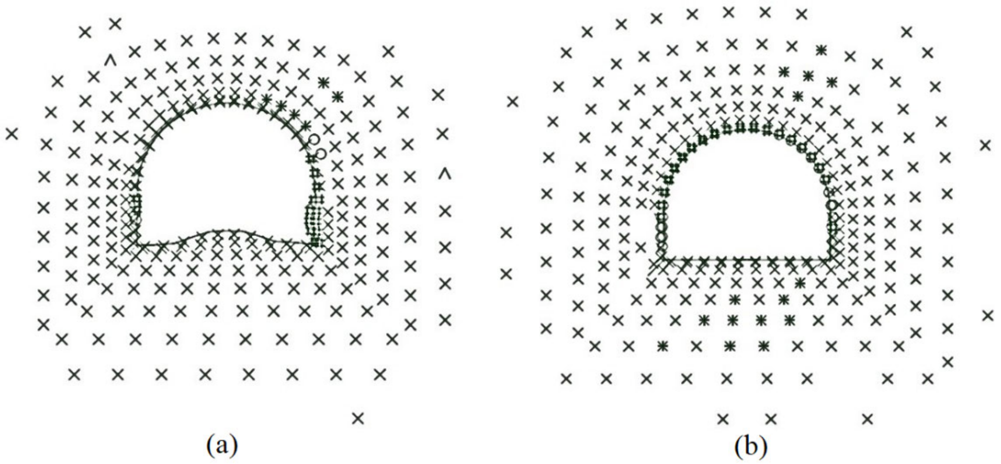


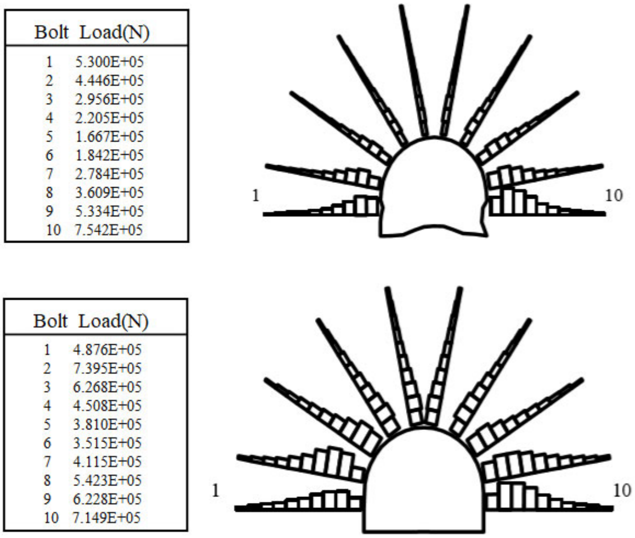
Fig. 4. Plastic radius (a) when the bolts and the shotcrete are set up at the same time, (b) when the bolts and shotcrete are set up in two steps

The analysis of the convergences indicates that in the top of the sides of the gallery the support set up at the same time generates values of convergence almost double that of those obtained with the support set up in two steps. The explanation for this is obtained with the analysis of the load on the bolts (Fig. 5). In the case of the support installed in two steps (Fig. 5 bottom), the crown bolts hold up a load almost twice as high. Therefore, it is necessary to install, with enough time, the layer of shotcrete to give the bolts time to load. If not, part of the load of the bolts is over the shotcrete, which can give rise to cracks of tensile stress and, therefore, to the failure of the support.

5.2.4. Results of the back analysis

From the previous analysis a new support is designed to be formed by one layer of shotcrete with a thickness of 6-8 cm and a mesh of 11 Swellex radial bolts with a length of 3.5 m, a diameter of 25 mm, a 1 m of space between them, and a minimum breaking load of 240 kN. In addition, in the top part of the sides another layer of shotcrete with a thickness of 6 cm is applied (Fig. 6).

However, at the beginning of the exploitation works, cracks and deformations are noted. This fact leads to a new analysis that allows designing and optimizing a new support capable of responding adequately not only to the particular conditions of the rock mass (tectonization, depth), but also to the loads caused by nearby work.



Bolt	Load(N)
1	5.300E+05
2	4.446E+05
3	2.956E+05
4	2.205E+05
5	1.667E+05
6	1.842E+05
7	2.784E+05
8	3.609E+05
9	5.334E+05
10	7.542E+05

Bolt	Load(N)
1	4.876E+05
2	7.395E+05
3	6.268E+05
4	4.508E+05
5	3.810E+05
6	3.515E+05
7	4.115E+05
8	5.423E+05
9	6.228E+05
10	7.149E+05

Fig. 5. Load over the bolts when the bolts and the shotcrete are set up at the same time (top) and when the bolts and shotcrete are set up in two steps (bottom)

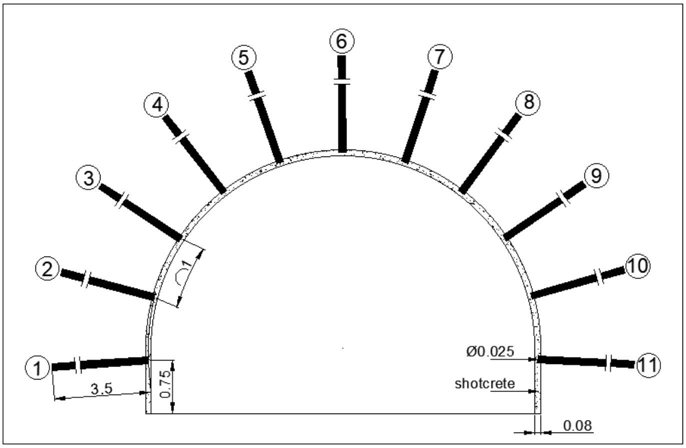


Fig. 6. Geometric properties of the second support

6. Analysis of the exploitation under the influence of surrounding works

With the purpose of analysing the influence of the mining work on the behaviour of the support, a two-dimensional model of the rock mass is elaborated, including the model of gallery-support. The properties of the materials employed in the analysis are shown in table 4. These are the results of the previous studies and the instrumentation campaing.

TABLE 4

Geotechnical properties and support properties

Property	**Value**
Horizontal / vertical stress ratio (in situ)	0.8
Density of the rock mass	2200 kg/m^3
Young's module of the rock mass	4 × 10^9 Pa
Shear deformation module of the rock mass	1.739 × 10^9 Pa
Poisson's coefficient of the rock mass	0.15
Cohesion of rock mass	0.4 × 10^6 Pa
Friction of the rock mass	20º
Density of the coal	1500 kg/m^3
Volumetric deformation module of the coal	1 × 10^9 Pa
Shear deformation module of the coal	3 × 10^8 Pa
Cohesion of the coal	2 × 10^5 Pa
Friction of the coal	25º
Density of the shotcrete	3000 kg/m^3
Young's module of the shotcrete	2 × 10^{10} Pa
Poisson's coefficient of the shotcrete	0.25
Compression strength of the shotcrete	1 × 10^7 Pa
Young's module of the bolt	200 × 10^9 Pa
Tensile strength of the bolt	3 × 10^5 Pa

The simulated work sequence is described below:

1. Phase of sublevel caving up to the level immediately above the analysed galleries (G-865 and G-740). As the galleries are still far from the work, there is hardly any influence in these regions.
2. Opening of G-865 gallery with delayed support: placement of bolts and application of shotcrete (Fig. 7a). The analysis of the load supported by the bolts indicates that the bolts of the sides, close to the sublevel caving of the higher levels, hold up a smaller load. This is due to the modification of the tensional state by the mining work itself. The maximum effort that the shotcrete supports in this phase is 1.373 × 10^4 N.
3. Sublevel caving up to G-865 gallery (Fig. 7b). At this moment, the influence of the mining work on the plasticization and the efforts held up by the support of the gallery is clearly noticed. In this phase the layer of shotcrete is supporting an inadmissible load of 1.431 × 10^7 N and the bolts are practically at the limit of their tensile strength 3 × 10^5 Pa.
4. Opening of the G-740 gallery with delayed support: placement of bolts and application of shotcrete (Fig. 7c). In this case, the newly opened gallery is not yet affected by the mining work. At this moment, the bolts reach a maximum load of 3 x 10^5 N while the shotcrete reaches 6.3 x 10^4 N.
5. Sublevel caving up to the level of G-740 gallery (Fig. 7d). At this moment when the sublevel caving reaches about 500 m in depth, the plasticized region around the G-740 gallery presents an inadmissible radius, as the compression effort on the shotcrete reaches a value of 1.631 × 10^7 N.

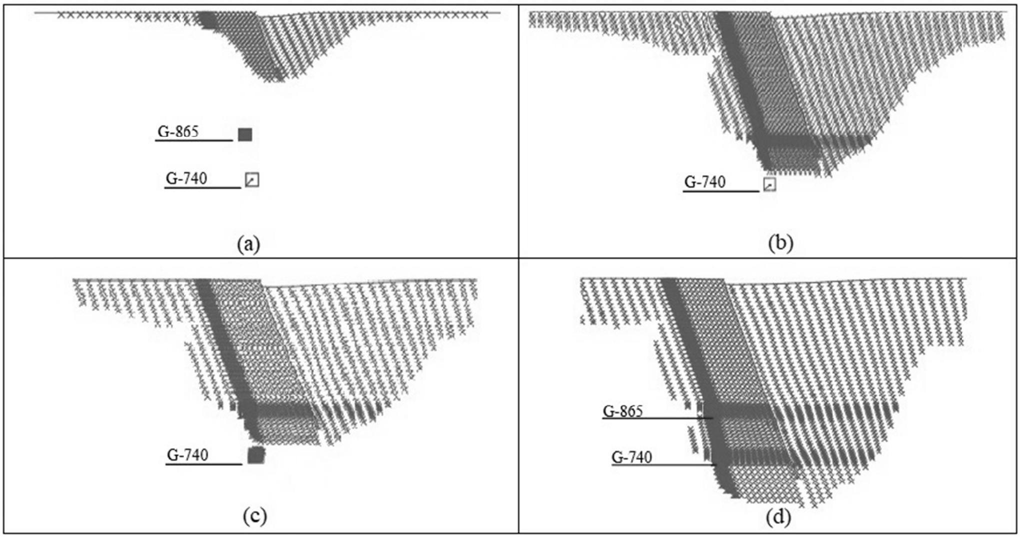


Fig. 7. Simulated work sequence. (a) Opening of G-865 gallery. (b) Sublevel caving up to G-865 gallery. (c) Opening of the G-740 gallery. (d) Sublevel caving up to the level of G-740 gallery

Figure 8 shows the evolution of the displacement vector in the G-865 gallery in the different phases of the modelling process:

- When the gallery has not yet been excavated and the sublevel caving is at the level of the gallery immediately above, it is observed that the direction and magnitude of the displacement vector (in the region where the G-865 gallery will be excavated) clearly points towards the sutured area with a value around 12 mm (Fig. 8a).
- When the gallery is excavated and supported, and the sublevel caving is at the previous level, the displacement vector converges towards the G-865 gallery prevailing the effect of the opening against the effect of the sublevel caving (Fig. 8b). At this point, the displacement is multiplied by 20, reaching 244 mm.
- When the sublevel caving reaches the level of the gallery itself, the displacement vector again „follows“ the mining work and the displacement increases approximately 30% reaching 331 mm (Fig. 8c).
- Finally, when the sublevel caving is at 500 m in depth, at the level of the G-740 gallery, the displacement vector again changes direction and increases almost 100% (Fig. 8d). Probably at this point in the process, the support has ceased to be effective, both quantitatively and qualitatively. The effect of the exploitation of a layer of such dimensions is, therefore, much greater than expected. Also swellings of more than 30 cm appear in floor.

The explanation of this phenomenon could be the key to achieve a correct support. If it is assumed that the support of the gallery pushes in an equal way along the contour of the gallery section and that the tensional state is isotropic, the behaviour of the support would be adequate. But if the gallery is sucked out by the mining work, the pressure that the support incurs on the nearest side to the mining work favours the sucking, while the pressure that the support incurs on the farthest side to the mining work opposes the former.

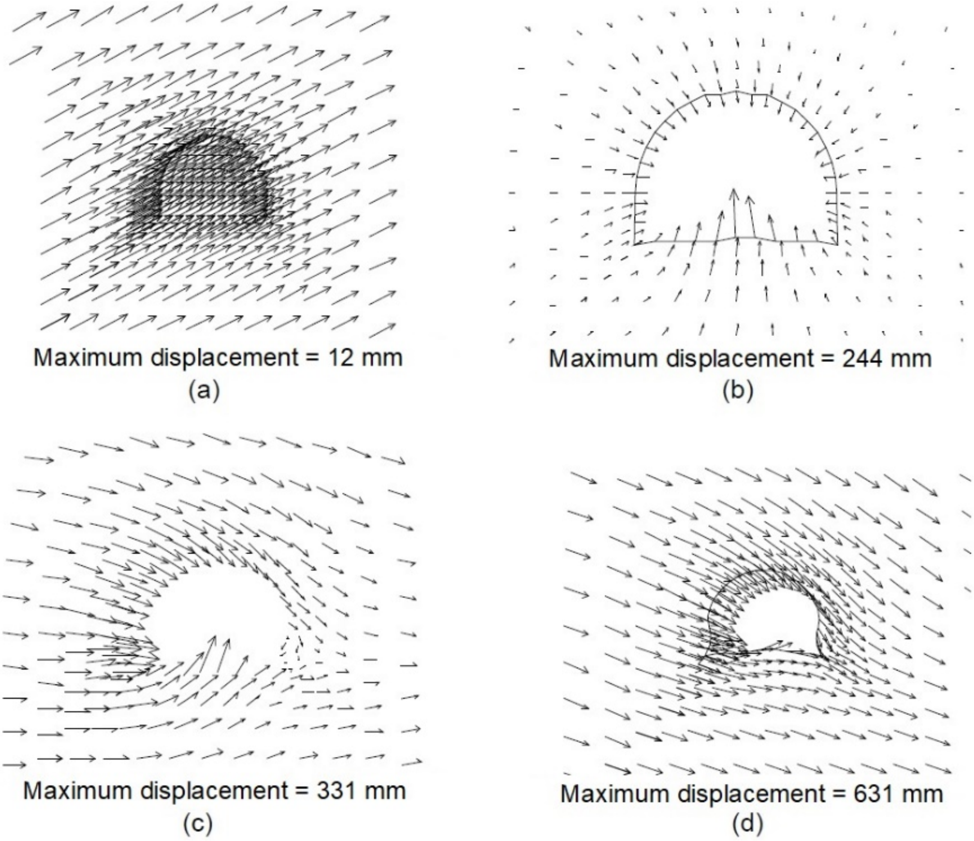


Fig. 8. Global view of the changes in the direction of the displacement vector around the section of the G-865 gallery in different phases of the modelling process

The shape of the efforts, recorded on the support throughout the modelling process, seems to confirm this. When the gallery is opened and the convergence takes place towards its inside, the support behaves well. But when the mining work sucks the gallery, the bolts of the nearer side to the mining work are discharged, those of the farther side to the mining work are overloaded and the shotcrete must support inadmissible compression stresses in this farther side to the mining works.

7. New support

Due to the influence that the works of sublevel caving have on the behaviour of the galleries, yieldable steel arches type Ω are employed in the support construction (Fig. 9).

These profiles have been adopted due to their robustness, that is, the elastic section moduli on the principal axes of the Ω sections are very similar, meaning that they behave well with respect to bi-axial loads. Table 5 shows the technical data for the Ω 21 sections and the clamps.

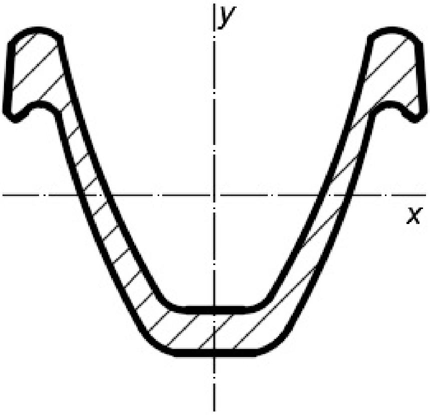


Fig. 9. Cross section shape of Ω section or V section depending on the countries

TABLE 5

Physical and geometric properties of the Ω sections and the clamps

Ω 21 Section	Weight	21 kg/m
	Area	27 cm^2
	Moment of inertia in x (Ixx)	341 cm^4
	Moment of inertia in y (Iyy)	398 cm^4
	Elastic section modulus in x (Wxx)	61 cm^3
	Elastic section modulus in y (Wyy)	64 cm^3
	Yield strength	≥330 × 10^6 Pa
	Tensile strength	≥540 × 10^6 Pa
Clamp	Weight	4.17 kg
	Tightening torque	245-294 Nm

For modelling the yieldable steel arches, a part of the mesh is generated in finite differences (Fig. 10). In this way, it is possible to apply a clamping pressure to the frames and one part of the frame slides on the other.

To analyse the influence that mining works have on the support, the same phases used in the previous study have been employed (Fig. 7).

1. Sublevel caving up to the level immediately above the analysed galleries (G-865 and G-740). As the galleries are still far from the work, there is little influence in these regions.
2. Opening of G-865 gallery. Once the section is open, the metal frame is installed and the model reaches equilibrium. The plasticizing radius is equal to 8 m. The work of sublevel caving is still not enough to influence the support. The convergences are 50 mm in the sides and 44 mm between the crown and the floor. The magnitude of the pressures on the frame, in this phase, is 18 MPa in the crown and floor, and 11 MPa in the sides. The magnitude of the displacements in the tightening points of the frame is 24 mm.
3. Sublevel caving up to G-865 gallery. At this moment, the influence of the mining work on the plasticization is clearly noticed. The convergences are 150 mm, that is, they have

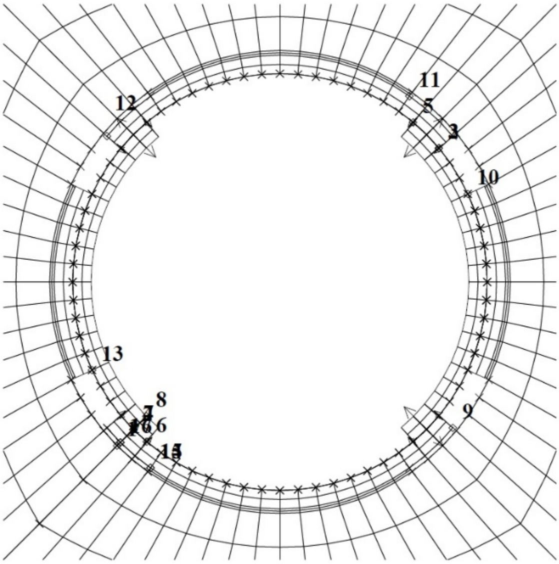


Fig. 10. Model in finite differences for metallic frames

tripled. The pressure in the right side, the closest to the work, is 24 MPa and the pressure in the floor is 14 MPa. The maximum magnitude of the displacements in the tightening points of the frame is 96 mm, in the lower point of the left side, and 49 mm in the crown. On the other hand, it has lost the symmetry previously maintained due, undoubtedly, to the proximity of sublevel caving.

4. Opening of the G-740 gallery. In this phase the plasticized zone adopts an elliptical shape with its major axis clearly oriented towards the work of sublevel caving. The maximum convergence in this gallery is 198 mm between the crown and the left side. The minimum convergence is 153 mm between the crown and the floor. The maximum pressure on the frame occurs on the crown and has a value of 7.5 MPa. The minimum pressure takes place on the right side, closest to the mining works, and its value is 1.7 MPa. From these data, a great difference can be seen between the opening of the G-865 gallery and the opening of the G-740 gallery. The lower pressure, which is now recorded in the frame, is due to the fact that the damage zone is much larger and, therefore, the pressure exerted by the ground decreases. However, the convergences are three times higher than those recorded in the opening of the G-865 gallery. Displacements in the frame also tripled.
5. Sublevel caving up to the level of G-740 gallery. The maximum convergence in the G-740 gallery is 338 mm and the minimum convergence is 296 mm. The pressures in G-865 gallery increase to 59 MPa in the right side and 54 MPa in the left side. In G-740 gallery the highest pressure is in the sides, in the order of 30 MPa.

The final displacements in the G-865 gallery reach values of 120, 84, 165 and 201 mm in the floor, crown, left side and right side respectively. The difference in the displacement values indicates the loss of symmetry due to the mining works. The displacements in the frame of the G-740 gallery are 255, 172, 220 and 240 mm in the same points.

8. Conclusions

From the work carried out, the following conclusions can be drawn:

- The classification indexes are not adequate to characterise the tectonized rock masses and under the influence of mining works, upholding (Małkowski et al. 2016).
- The data collected with the instrumentation allows evaluating the behaviour of different types of support, in addition to a back analysis conducted in order to obtain the real properties of the ground more precisely.
- Numerical models show that lone galleries are stable, even without support. However, bolts and shotcrete are required to obtain acceptable convergences.
- The diameter of the bolts and their spacing are the variables with more influence on convergence, while the length or the thickness of the shotcrete have little effect on it.
- The most significant decrease in convergence is obtained by increasing the bolting diameter to 25 mm.
- As the rigidity of the shotcrete is much greater than the rigidity of the bolts, the effect of the shotcrete support is long term. So, it is necessary to install the support in two steps: first install the bolts and once they are loaded project the shotcrete.
- In mining exploitations, it is necessary to take into account the order of the operations, with the goal of analysing the behaviour of the support accurately. When the effect of sublevel caving on the galleries is analysed, it is found that the use of shotcrete and bolts as unique support is not suitable.
- The steel yielding support is the most suitable support for galleries affected by mining works due to its major flexible behaviour.
- The magnitudes of convergence, pressure and displacements experienced by the steel yielding support are admissible, unlike those obtained with the support consisting of bolts and shotcrete.
- The increase in the distance between galleries and sublevel caving zones improves the behaviour of the support, but it does not resolve the anisotropic behaviour of the surrounding rock mass.
- In the near future, in anisotropic stress field around the gallery, asymmetric support schemes can be considered.

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