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(Article begins on next page)

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Maria Lia Napoli*, Monica Barbero, Claudio Scavia

Department of Structural, Geotechnical and Building Engineering,
Politecnico di Torino, C.so Duca degli Abruzzi 24, Torino 10124, Italy
** Corresponding author. E-mail address: maria.napoli@polito.it*

ABSTRACT

Heterogeneous rock masses composed of strong rock blocks embedded in a weaker matrix belong to complex formations and are often referred to as bimrocks (block-in-matrix-rocks). Due to the high spatial, dimensional, geo-hydrological and lithological variability of such rock bodies, a common geotechnical engineering design practice is not to consider the presence of the blocks and assign the strength and deformability properties of the weaker matrix to the whole rock mass. However, over the last decades, several case histories and many relevant studies on bimrocks have demonstrated that neglecting the presence of the blocks can produce wrong forecasts, which often lead to serious technical problems and severe economic repercussions during the construction of engineering works on and in these complex formations.

The aim of this study is to investigate the stability of a deep circular tunnel excavated in a heterogeneous rock mass with a chaotic block-in-matrix fabric. In order to determine how the presence of rock inclusions may influence the overall behavior of the bimrock during the excavation, different Volumetric Block Proportions (VBPs) are used. To take the inherent spatial and dimensional variability of the blocks into account, many heterogeneous tunnel configurations are generated for each VBP considered by means of a stochastic approach. The analyses are performed using the Finite Element code RS2.

Moreover, in order to highlight potential inaccuracies caused by neglecting the presence of the blocks at the design stage, simplified approaches commonly used by geopractitioners, which assume bimrocks to be homogeneous equivalent geomaterials, are also applied by way of comparison.

KEYWORDS

Bimrocks, heterogeneous rock masses, tunneling, stochastic approach, FEM

1 INTRODUCTION

Bimrocks (block-in-matrix rocks) are complex, heterogeneous and often chaotic formations composed of competent rock blocks embedded in a matrix of finer and often sheared texture. [1–3]

These geomaterials are widespread all over the world and encompass many geological rock units such as melanges, agglomerates, conglomerates, breccias, fault rocks, etc.. [4–10] Due to the high spatial, dimensional, geo-hydrological and lithological variability that characterize these rock formations, the determination of their geomechanical properties is extraordinary problematic. [11–15] As a consequence, geotechnical engineers often plan their work neglecting the contribution of blocks to the overall bimrock strength, choosing instead to design on the basis of the strength and deformation properties of the weaker matrix only. [2,16–18] However, as documented by several case histories reported in the literature, such a simplified assumption can cause mischaracterizations and wrong forecasts in the planning phases, leading to unexpected technical problems and delays during the construction of engineering works on and in these complex formations. [6,18–24]

Many research studies (laboratory and in situ tests, as well as numerical simulations) conducted on this topic over the last decades have demonstrated that the behavior of bimrocks is largely controlled by the size, shape, position, orientation and content of the blocks within the rock mass. Laboratory tests have been performed by many authors on artificial bimrock specimens since 1994 to study the effects that block proportion and orientation have on the mechanical properties of melanges. [3,7,17,25–28] A few authors have also performed laboratory tests on real bimrock specimens [13,29,30] developing empirical approaches for the determination of their uniaxial compressive strength and elastic modulus on the basis of the Volumetric Block Proportion (VBP). These works have also revealed that blocks strongly influence the mechanical behavior of such geomaterials if rock inclusions represent at least 20% of the total rock mass volume.

Moreover, in situ large scale direct shear tests have been carried out on different rock-soil mixtures. [5,31–33] These experiments have demonstrated that the strength parameters of a bimrock are correlated to the VBP and that the presence of rock inclusions controls the development, position and shape of failure surfaces.

Numerical simulations of laboratory tests on bimrocks with different VBPs have also been carried out in order to study the mechanical behavior and failure pattern of these complex geomaterials.[10,34–38]

Furthermore, slope stability in heterogeneous formations has been investigated using both deterministic and stochastic approaches. [22,39–43] The main findings of these studies show that safety factors increase with increasing VBP and that both the position and shape of failure surfaces are strongly affected by the presence of the blocks.

The aim of this paper was to examine how the presence of rock inclusions can affect the stability conditions of a bimrock during the excavation of a deep tunnel. In fact, to the authors' knowledge, very few works have been carried out on this specific topic. In particular, a theoretical circular tunnel was supposed to be excavated in a chaotic melange with variable VBPs. In order to generate the numerical models, a specific Matlab routine, performing Monte Carlo simulations, was implemented. The Matlab code generates elliptical blocks with random dimensions, orientations and positions within the rock mass, according to specific statistical rules and given rock contents. For each VBP considered, ten extractions (generating ten bimrock configurations) and, hence, ten numerical simulations were carried out by means of Finite Element (FE) analyses, to achieve a statistical validity of the results.

A VBP value of 0%, corresponding to a matrix-only model, was also analyzed in order to investigate potential inaccuracies and inconsistencies arising from the simplified design approach (which neglects the presence of rock inclusions at the design stage), which is often used by geopractitioners.

Furthermore, two empirical strength criteria available in the literature were applied to compare the results obtained using homogeneous models rather than a (more complex) heterogeneous one.

2 TUNNELING IN BIMROCKS

Excavating tunnels in difficult ground conditions (e.g. soft rocks, fault zones, mixed face conditions, weathered or fractured rock masses, and many others) often leads to critical situations such as wall/face instabilities, breakdown or failure of excavation machine components, uncontrolled over-excavations, heavy loading on preliminary supports and final linings, water inflows, cutter wears, boreability problems, etc.. [21,44–47] All these aspects may have a significant impact on the logistic of tunnel constructions, with serious delays, safety problems and cost increments. [48–50]

To date, to the authors' knowledge, not much research on tunneling in bimrocks has been carried out.

A 2D Finite Element analysis has been performed by Pustow [51] in order to investigate stress redistributions and critical states during the "Spital" underground excavation (Austrian Alps) in a melange with lenticular inclusions (i.e. tectonic melange). The author analyzed seven models, five with a single block of variable dimension and position (from 7 m to 70 m) arranged at the left sidewall of the tunnel, a matrix supported melange and a block supported melange. The results show that the blocks are characterized by stress concentrations if in contact with each other, and that block dimensions affect their distribution. Moreover, due to the increase of the rock mass strength, the radial displacements around the tunnel decrease. Experiences gained during the construction of the Spital and Steinhaus tunnels are also reported in other papers. [21,45]

Moritz et al. (2004) have illustrated their experience with a shallow tunnel excavated in heterogeneous formations located in the Eastern Alps of Austria. One of these geologic units is a tectonic melange with a block-in-matrix fabric. The material is characterized by smaller blocks embedded in a soft and weathered matrix, consisting of cataclastic phyllites. The authors highlight how important is a continuous updating of observed ground conditions during underground excavations (observational method) in these complex geomaterials. In particular, the evaluation and interpretation of 3D displacement monitoring data can be used for on-site short term prediction of the rock mass structure and quality. [50]

Adam et al. (2014) worked on the city bypass tunnel of Waidhofen an der Ybbs (Austria), where difficult ground conditions were encountered due to the presence of a tectonic melange and creeping slopes. In particular, various tunneling methods were applied on the basis of the overburden and rock mass properties. Moreover, a sophisticated monitoring system was installed in order to face the complex geological and morphological situation. [47] The analyses have been performed on an equivalent homogeneous material applying the empirical approach proposed in 1994 by Lindquist [3] and reported in Eq. (1):

$$\tau_p = c_{matrix}(1 - \mathrm{VBP}) + \sigma \tan(\varphi_{\mathrm{matrix}} + \Delta\varphi_{\mathrm{matrix}}(\mathrm{VBP})) \quad (1)$$

where τ_p is the equivalent mass shear strength, c_{matrix} is the cohesion of the matrix (assumed to decrease with increasing VBP), $\varphi_{\mathrm{matrix}}$ is the internal friction angle of the matrix and $\Delta\varphi_{\mathrm{matrix}}$(VBP) is the increase of the internal friction angle, assumed by Lindquist to be, above 25% VBP, equal to 3° for every VBP increase of 10%.

Marinos et al. (2014) proposed a new Geological Strength Index (GSI) chart for heterogeneous rock masses such as flysch and a range of geotechnical parameters for 11 flysch types, according to their siltstone-sandstone proportion and tectonic disturbance. Moreover, the authors provided specific recommendations for temporary support measures in underground excavations through the different flysch types, based on their geotechnical behavior and critical failure mechanism. [52]

Colmenares et al. (2017) worked on the Bogota-Villavicencio road, a very important connection between the Colombian capital and the eastern plains. Difficult ground conditions, characterized by a highly heterogeneous geology, favored the occurrence of multiple landslides over time. These instabilities have required many interventions since 1995, including underground excavations. Tunnel designs were mainly developed using the methodology proposed by the Austrian Society of Geomechanics. The approaches proposed by Medley and Lindquist [53] were followed to determine the ground properties and select the constitutive model, on the basis of rock contents and laboratory test results carried out on the matrix. Numerical simulations were also performed to design and back analyze the excavation processes during construction works. [54]

All these studies concerning tunneling in complex formations with a block-in-matrix fabric highlight that appropriate ground investigations and numerical analyses must be performed, adequate construction and support methods must be used and appropriate monitoring systems are required in order to allow a safe tunnel construction.

3 2D SIMULTATIONS OF TUNNEL EXCAVATION IN BIMROCKS

The aim of this study was to investigate how different block proportions may affect the stability of a deep circular tunnel excavated in a heterogeneous rock mass with a chaotic block-in-matrix fabric, by means of numerical simulations. To this purpose, these simulations were carried out using different VBPs. In particular, 25%, 40%, 55% and 70% VBPs were examined. To take the innate spatial and dimensional variability of the blocks into account, the stochastic approach proposed by Napoli et al. (2018) [41,42] was applied. In particular, a Matlab routine was appositely implemented to randomly generate and locate elliptical blocks within the rock mass. For each VBP considered, ten tunnel configurations were created with the Matlab code.

A 0% VBP configuration was also analyzed in order to evaluate potential inaccuracies that geopractitioners could make when designing on the basis of the strength and deformation properties of the matrix only.

Moreover, numerical simulations were also carried out following both the Lindquist (1994a) and Kalender et al. (2014) empirical approaches. These approaches assume bimrocks to be equivalent homogeneous and isotropic materials.

Altogether, the excavation of more than forty bimrock tunnels was simulated using the Finite Element Method (FEM) in two-dimensional conditions.

The matrix and blocks mechanical parameters that were used in the analyses are reported in Table 1. Both materials present sufficient mechanical contrast ($E_{block}/E_{matrix} > 2$ and $\tan\varphi_{block}/\tan\varphi_{matrix} > 2$), as suggested by many authors. [1,7,17,24,35,55–57] They were assumed to obey the Mohr-Coulomb failure criterion and to follow an elastic-perfectly plastic behavior.

3.1 GENERATION OF TUNNEL CONFIGURATIONS

In order to model the spatial and dimensional variability inherent in bimrocks, a specific Matlab routine, performing Monte Carlo simulations, was appositely implemented. The code generates elliptical rock inclusions with eccentricity equal to 0.5, and random dimensions and orientations. It also locates the blocks randomly within the rock mass, according to given geometric boundaries, VBPs and statistical block size distribution parameters. [36] The size of the blocks is strictly dependent on the characteristic engineering dimension, L_c, set equal to 10 m, corresponding to the diameter of the tunnel. [2,58] To maximize the code performance, blocks placing is made from the largest to the smallest one. [41] Moreover, the Matlab code verifies that blocks do not interpenetrate each other, otherwise it would have no physical meaning. To this reason, it was set a minimum distance between two blocks equal to 5 cm.

For the four VBPs considered (25%, 40%, 55% and 70%VBP), ten bimrock configurations were created.

The main Matlab code output consists of a text file containing, for each tunnel configuration, a list of the coordinates of both the center and the vertex of the semi-major axis and the length of the semi-minor axis of each ellipse, representing a block.

An example of the final geometry obtained with this process is shown in Fig. 1.

3.2 FINITE ELEMENT ANALYSES

Finite Element (FE) analyses were conducted using the 2D FEM software RS2 (vers. 9.0) from Rocscience. Six-node triangular elements were used to mesh the models.

Sensitivity analyses were carried out to evaluate the influence of external boundaries, geometry and mesh density. In particular, with the purpose of avoiding boundary effects, bimrock models were modified to include an outer layer $5L_c$ long (i.e. 50 m) on each side (Fig. 2). An elastic behavior and the same mechanical properties of the matrix were assigned to this extended part of the geometry of the bimrock models. To guarantee a high mesh quality, a non-uniform mesh size, denser near the blocks, was created (Fig. 3). Moreover, local mesh refinements were adopted where necessary.

A constant and isotropic field stress was assigned to the models, assuming an in situ state of stress (p_0) depending on the VBP. In particular, an increasing equivalent unit weight was assigned to the rock mass for higher block contents, obtaining p_0 values ranging from 1.65 MPa to 1.74 MPa. Furthermore, 12 excavation stages (the first in elastic conditions and without the presence of the tunnel) were simulated to reproduce the progressive underground excavation. The convergence-confinement method was used, which simulates the ongoing excavation by means of a progressive reduction of the stresses acting on each node located on the tunnel boundary. Each stage corresponds to a stress reduction of 10%p_0. An elastic perfectly plastic behavior was adopted for both the matrix and blocks belonging to the bimrock model, assigning the mechanical characteristics reported in Table 1.

As previously mentioned, an only-matrix model and ten bimrock configurations for each VBP considered, i.e. forty heterogeneous tunnel models, were simulated. Displacements and characteristic curves, stresses and yielded zones were analyzed in detail with particular reference to points R.S., C. and L.S. of the crown and the sidewalls, respectively (Fig. 3), under no support pressure either at the wall or at the face.

The results obtained indicate that for increasing VBP values displacements undergo an evident reduction with respect to those of the matrix (Fig. 4 and Fig. 5).

For the left sidewall (point L.S.), for example, the average maximum radial displacements (provided by the 10 simulations analyzed for each VBP considered) are 0.94 m, 0.87m, 0.44m and 0.14 m for the 25%, 40%, 55% and 70% VBP models, respectively, against the 1.57 m obtained with the matrix-only model (Table 2).

According to previous literature findings, the presence of blocks with a low VBP provides relatively little geomechanical advantage compared to the matrix-only model. [1,3] However, the position, orientation, dimension and number of the blocks located near the tunnel strongly affects the results. As shown in Fig. 4 and Fig. 5, the radial displacements at the crown and sidewalls provided by the ten 25% VBP configurations presented the greatest data dispersion. On the other hand, for increasing rock contents a remarkable less data scattering is registered (Fig. 4, Fig. 6 and Table 3). In fact, the standard deviations of the radial displacements registered at the crown (point C.) and sidewalls (points R.S. and L.S.) provided by the 10 tunnel models analyzed for each VBP are greatly reduced passing from 25% to 70% VBP bimrock models, e.g. the right sidewall standard deviations are reduced from 0.26 (for 25% VBP configurations) to 0.07 (for

70% VBP configurations). This outcome can be ascribed to the different block positions, dimensions and orientations as well as to block-poor zones of variable extension and location (within bimrock models having the same VBP), more evident for lower VBPs, which influence the rock mass behavior.

Moreover, Fig. 6 shows the variability and the non-uniformity of the radial displacements around the tunnel for the ten configurations analyzed for each VBP, due to the random location of the blocks within the rock mass. This also induces non-uniform stresses that have to be taken into account when designing the tunnel lining.

In order to better visualize the effects of the excavation on the different rock masses (from the 0% to the 70% VBPs), Fig. 7 and Fig. 9 illustrate the increasing in displacements with decreasing internal pressure (i.e. advancing tunnel face) on both tunnel sidewalls and crown. In particular, for each VBP considered, a variation band of radial displacements provided by the 10 tunnel models is shown. The upper and lower limits of each band were obtained by adding and subtracting from the average radial displacement the associated standard deviation. From these figures it is clear that blocks play a key role in the stability of the tunnels. For higher VBP values, in fact, the displacement bands depart from the red curve, which represents the displacements associated with the matrix-only model. Moreover, the greater the VBP the less thick the band, which indicates that a less data scattering is provided by the 10 models analyzed.

Stresses and yielded zones are also affected by the presence of the rock inclusions, especially by those located close to the tunnel (Fig. 10, Fig. 11, Fig. 12), and are considerably different from the uniform matrix-only results. Fig. 10 and Fig. 11 show that the blocks are characterized by stress concentrations, the distribution of which greatly depends on the block dimensions. In particular, higher stresses are observed in the blocks of greater dimension located in the vicinity of the tunnel, as well as at the block-matrix contacts. This result is in line with previous research.[51]

As illustrated in Fig. 12, the extension of the yielded zones greatly reduces for higher VBPs. It also varies from model to model with the same rock content, according to block sizes, locations and orientations. It is worth pointing out that plasticity occurs within the matrix only. As a consequence, the length of the plastic radius varies around the tunnel depending on the presence of the blocks.

As shown above, different stress distributions, yielded zones and displacements are provided by each tunnel configuration, even by those having the same VBP. This variability suggests the necessity of performing numerical simulations in these complex geomaterials according to a stochastic approach, which may avoid mistakes resulting from either only considering a homogeneous rock mass or just performing a deterministic analysis. In fact, since real block positions and dimensions cannot be predicted, a stochastic approach may be useful at the design stage to predict possible unfavorable conditions during the excavation works. Moreover, when the observational method is implemented during the construction process, the displacement measured at a given point should be compared and ought to be within the computed range of displacements obtained with the stochastic approach. However, since many uncertainties exist when dealing with bimrocks, an observational method together with appropriate and continuous monitoring systems must always be used.

3.3 APPLICATION OF THE EMPIRICAL STRENGTH CRITERIA

In order to compare the results reported in Section 3.2 with those provided using equivalent homogeneous models, the empirical strength criteria proposed by Lindquist [3] and Kalender et al. [7] were applied to the tunnel models considered.

The equivalent bimrock cohesion and internal friction angle were evaluated, for all the previously analyzed VBP values, according to Eq. (1) for the Lindquist criterion and according to the following Eqs. (2-4) for the Kalender criterion (see Table 4). The other input parameters (E, ν, γ) were assumed to be equal to those assigned to the matrix and reported in Table 1.

$$\varphi_{bimrock} = \varphi_{matrix}[1 + \frac{1000\left[\frac{\tan(\alpha)}{\tan(\varphi_{matrix})} - 1\right]}{1000 + 5^{\left(\frac{100-VBP}{15}\right)}}\left(\frac{VBP}{VBP+1}\right)] \quad (2)$$

$$UCS_{bimrock} = [(A - A^{\frac{VBP}{100}})/(A-1)]UCS_{matrix} \ , \qquad 0{,}1 \leq A \leq 500 \quad (3)$$

$$c_{bimrock} = UCS_{bimrock}[1 - \sin(\varphi_{bimrock})]/[2\cos(\varphi_{bimrock})] \quad (4)$$

where α is the angle of repose of blocks, assumed as equal to 45°, *UCS* is the material uniaxial compressive strength and *A* is a parameter that can be defined according to both the adhesion strength between the matrix and blocks and parameter α, determined as equal to 4.

As shown in Fig. 13 and Fig. 15, the strength criterion proposed by Lindquist (1994a) yields conservative results, especially for lower VBP values. For the 25% and 40% VBP models, results are remarkably similar to those provided by the matrix-only model, although more conservative. In particular, the maximum radial displacements are 2.09 m and 1.69 m, respectively, greater than 1.57 m obtained with the matrix-only model.

Better conditions are provided by 55% and 70% VBP models, where the maximum radial displacements are 1.37 m and 1.25 m, respectively.

The results obtained using the Kalender et al. (2014) empirical approach are less conservative than both the matrix-only and the Lindquist models (Fig. 14). In fact, the maximum radial displacements are 1.39 m, 1.06 m, 0.94 and 1.03 m for 25%, 40%, 55% and 70% VBPs, respectively. However, especially for VBPs greater than 40%, they differ considerably from the results provided by the heterogeneous models, leading to an erroneous estimation of the mechanical response of the bimrock to the excavation process (Fig. 15).

Moreover, it is worth pointing out that the use of both the empirical criteria implies neglecting the presence of blocks and analyzing a homogeneous material. This assumption results in unrealistic final outcomes, since uniform stress distributions, plastic zones and radial displacements are obtained. However, the non uniformity shown by the heterogeneous models cannot be neglected, because it takes primary importance in the design of the tunnel lining. Hence, these simplified approaches seem to be acceptable if used in predesign stages only.

CONCLUSIONS

This work investigates the effects of the VBP on the stability of deep circular tunnels excavated in a complex formation with a block-in-matrix fabric and the reliability of designing on the basis of the strength of the matrix only, as often happens in practice.

More than 40 2D numerical analyses were performed on different bimrock models, using the FEM code RS2 from Rocscience. Block dimensions, orientations and positions within the rock masses were randomly obtained using a stochastic approach performing numerical Monte Carlo simulations. For each VBP considered, ten bimrock configurations were generated with the aim of taking spatial and dimensional variability of rock inclusions into account. Furthermore, the empirical strength models proposed by Lindquist (1994a) and Kalender et al. (2014), which assume these geomaterials to be equivalent homogeneous, continuous and isotropic rock masses, were applied by way of comparison.

The results obtained provided the following principal findings.

The use of a matrix-only model, neglecting the presence of blocks, leads to homogeneous yielded zones and stress distributions which are unrealistic, since they are strongly affected by the presence of the rock inclusions (e.g. yielded zones develop tortuously within the matrix), as demonstrated in previous research. Moreover, severe overestimations of both displacements and plastic zone extension and shape are provided. This overestimation becomes steadily more evident as the VBP increases. Therefore, the choice of ignoring the contribution of blocks to the overall bimrock strength, choosing instead to design using the strength and deformation properties of the weaker matrix only, appears to be inappropriate and over conservative (i.e. uneconomical).

When analyzing bimrocks using the strength criterion proposed by Lindquist (1994a), the analyses provide conservative results, remarkably similar to those of the 0% VBP model. In particular, for a low VBP, some points around the tunnel showed even higher convergences than the matrix-only model. More stable conditions are provided by 55% and 70% VBP models, although these are considerably different from those yielded by the heterogeneous tunnel models.

The results obtained using the Kalender et al. (2014) empirical approach are less conservative than both the matrix-only and the Lindquist models. However, especially for VBP greater than 40%, they too provide results which differ considerably from those of the heterogeneous configurations.

All the same, it is worth pointing out that the use of these two empirical criteria implies neglecting the presence of blocks and analyzing an equivalent homogeneous material. This assumption results in many uncertainties in the final outcomes, as highlighted by previous findings [41,42], since they underestimate the mechanical behavior of the bimrock. Hence, they seem to be acceptable if used in predesign stages only. Moreover, it is worth mentioning that ignoring the presence of the blocks can also lead to delays and unexpected technical problems during many engineering works, with possible significant economic repercussions. [6,18–24]

On the other hand, the simulations carried out for the heterogeneous models demonstrate that blocks play a key role in the behavior of bimrocks during underground excavation processes. Shear stresses, displacements and plastic zones are in fact strongly affected by the presence of blocks located near the tunnel, as well as by their dimensions. Moreover, yielded zones develop tortuously within the matrix according to previous literature findings. The FEM analyses on these models demonstrate that even for a VBP equal to 25% the presence of blocks may induce quite significant variations in the strength of the rock mass. This variation becomes more evident for greater VBP values. However, very different results are yielded by the ten models with lower VBP values. This behavior can be ascribed to the different block positions and variably extended block-poor zones near the tunnel (within bimrock models having the same VBP), which influence stresses and shear strain concentrations and, consequently, the stability of the rock mass. The non uniformity of stresses and displacements around the tunnel can strongly influence the state of stress induced in the tunnel lining, which affects its design. This problem is not taken into account with the equivalent homogeneous models.

There is compelling evidence that deterministic analyses cannot take these particular characteristics into account. Conversely, a stochastic approach seems to be more reliable to study these complex formations, since it makes it possible to predict possible unfavorable conditions during the excavation works, perceiving the variability in the results. The assumptions made during the design phase and the numerical analysis results both have to be verified during construction. In particular, when applying the observational method, actual ground displacements at a given point should be compared and ought to be within the computed range of displacements obtained with the stochastic approach. However, since many uncertainties exist when dealing with bimrocks, an observational method together with appropriate and continuous monitoring systems must always be used.

It is worth pointing out that the main limitation of this study is that plane strain conditions were assumed for both the matrix and blocks by analyzing 2D bimrock configurations instead of more realistic 3D models.

Hence, in order to investigate the implications that this assumption could have produced on the results found in this paper, a future work will be to carry out statistical analyses of 3D tunnel stability in the same bimrock formations and compare the results.

ACKNOWLEDGMENTS

The authors would like to acknowledge Eng. Paolo Dadone for his contribution to this paper.

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LIST OF TABLES

LIST OF FIGURES

Fig. 10. Minimum principal stress for the matrix-only model and for one of the ten configurations analyzed for each VBP considered

Fig. 11. Maximum principal stress for the matrix-only model and for one of the ten configurations analyzed for each VBP considered

Fig. 12. Yielded zones for one of the ten tunnel configurations analyzed for each VBP considered (from left to right: 25%, 40%, 55% and 70% VBPs)

Fig. 13. Internal pressure versus radial displacements at the right sidewall (point R.S.) – Lindquist (1994a) criterion

Fig. 14. Internal pressure versus radial displacements at the right sidewall (point R.S.) – Kalender et al. (2014) criterion

Fig. 15. Comparison between the empirical approaches of Lindquist (1994a) and Kalender et al. (2014) and the heterogeneous models