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Tunnelling in bimunits with different block-matrix characteristics: a preliminary numerical study

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ABSTRACT: The aim of this paper is to investigate the different mechanical responses of a deep circular tunnel excavated (virtually) in different bimunits (block-in-matrix units), which include a wide range of heterogeneous geological deposits. The three main categories identified and analysed are hard-bimrocks, soft-bimrocks and bimsoils, with block contents ranging from 25% to 55%. For this purpose, 2D finite element simulations are carried out. Special attention is paid to the simulation of the block-matrix contacts, which depend on the bimunit category.

1 INTRODUCTION

The design of tunnels is a fundamental area of geotechnics and geomechanics that presents many challenges. Among the others, accurately predicting the interaction between the ground and the tunnel lining is often a difficult task. The development of various numerical models has made significant progress in simulating in-situ observations. However, additional efforts are needed to improve the robustness of these approaches, especially for complex formations such as bimunits (block-in-matrix units), which include a wide range of heterogeneous geological deposits, such as mélanges, glacial tills, agglomerates and conglomerates.

When modelling such complex geomaterials, it is common practice to assume that the block-matrix contacts are as strong as the matrix material. However, this assumption (i.e. no block-matrix interface elements or displacement compatibility) is only representative of some bimunits belonging to 'hard bimrocks'. It should be noted that three macro-categories of bimunits have been identified according to their main compositional characteristics and that, although they all have a block-in-matrix internal arrangement, their geotechnical behaviour is significantly different depending on their block-matrix contact characteristics. The three identified macro-categories are: bimrocks, soft bimrocks and bimsoils (Napoli et al. 2022).

In the field of tunnelling, previous simulations carried out to simulate underground excavations in hard bimrocks show that blocks play a key role in the rock mass behaviour during excavation (Napoli et al. 2021; Pustow 2001). In fact, shear stresses, displacements and plastic zones are strongly influenced by the presence and characteristics of the stronger blocks in the vicinity of a tunnel (Button et al. 2002; Dhang 2016). Furthermore, the differences in response with excavation progress are also related to the different block positions and variably extended block-poor zones near the tunnel (within bimrock models with the same Volumetric Block Proportions, VBP), which influence the stresses and shear strain concentrations and consequently the stability of the rock mass. The inhomogeneity of stresses and displacements around the tunnel can strongly influence the stress state induced in the tunnel lining, which will be anisotropic and consequently affect its design.

In light of the above, the objective of this paper is to investigate the different mechanical responses of deep circular tunnels excavated (virtually) in a hard bimrock, soft bimrock and bimsoil, with block contents ranging from 25% to 55%. For this purpose, 2D finite element simulations

are carried out through RS2 code from Rocscience. The reference model is inspired by a previously published study in order to compare the results. In addition, the effect of neglecting the presence of blocks and considering only a homogenized massif on the lining load is discussed.

2 BLOCK-IN-MATRIX UNITS (BIMUNITS)

2.1 *Bimunits categories*

Bimunits have been studied for several years and different classifications have been proposed (e.g. Medeley 1994, Sonmez et al. 2009, Kalender et al. 2014). As explained above, the three main categories of bimunits are considered in the present work:

- *Hard bimrocks,* formed under very high temperature/pressure conditions, are well lithified/consolidated units, with blocks fully bonded to the matrix.
- *Soft bimrocks,* consist mainly of poorly consolidated/lithified sedimentary units, characterized by a water-sensitive matrix.
- *Bimsoils,* loose/uncemented heterogeneous deposits, also defined in the literature as soil-rock mixtures, rock-soil aggregates and unwelded bimrocks.

2.2 *Assumptions for bimunits simulation*

As explained above, bimunits consist of two main materials: the matrix (1) into which rigid and stronger blocks (2) are inserted. These blocks vary in size and shape, and their arrangement within the host rock or soil matrix depends on the geological history of the formation. Given the inherent variability and the uncertainties related to the characterization of the geometrical properties of the rock blocks, a common approach is to consider them to be circular or elliptical in shape. And to simulate different configurations (i.e. through the resort to a stochastic approach) (e.g. Khorasani et al. 2019, Napoli, 2021, Napoli et al. 2021).

An important point to consider is the behaviour of the matrix-rigid block interfaces. In fact, the block-matrix contact depends on the category of bimunit, and although some efforts have been made to better characterise this interaction in different bimunits (e.g. Sonmez et al. 2006a and 2006, Khorasani et al. 2019), it is still a task that needs to be studied in more detail.

3 2D NUMERICAL MODEL IMPLEMENTATION

3.1 *Characteristic properties of bimunits studied*

Following the same approach as Napoli et al. (2021), the rocks and blocks were defined in the 2D FEM model by obeying the Mohr-Coulomb failure criterion and following an elastic-perfectly plastic behaviour. For the soft bimrocks and bimsoils, a first approach is considered by changing the parameter values of each matrix, as summarised in Table 1.

Table 1. Bimunits properties used for simulation

Bimunits	Parameter	Matrix	Blocks
Hard Bimrock	E (MPa)	8000	40000
	υ	0.3	0.3
	γ (kN/m^3)	27	27
	c (MPa)	1.5	11
ϕ	(°)	36	50
Soft Bimrock	E (MPa)	4000	40000
	υ	0.3	0.3
	γ (kN/m^3)	24	27
	c (MPa)	0.4	11
ϕ	(°)	32	50
Bimsoil	E (MPa)	400	40000
	υ	0.3	0.3
	γ (kN/m^3)	22	27
	c (MPa)	0.04	11
ϕ	(°)	28	50

As explained by Medley (2001), the mechanical parameters of the matrix and blocks chosen for hard bimrocks have a sufficient mechanical contrast between rock and blocks ($E_{block}/E_{matrix} > 2$ and $\tan \phi_{block}/\tan \phi_{matrix} > 2$). Moreover, a linear elastic model is assumed for the lining, with E = 30 GPa and υ = 0.2.

In a first attempt, and based on the assumptions made in the literature, for the simulation of the three types of bimunits, the main assumptions considered for the interaction between the matrix and the rigid blocks are:

- *Hard bimrocks*. The strength of the contact interface between matrix and blocks is assumed to be approximately equal to the strength of the matrix (i.e., $c_{interface} = c_{matrix}$ = 1.5 MPa and $\phi_{interface} = \phi_{matrix}$ = 36°).
- *Soft bimrocks*. The strength of the matrix/block contact interface is assumed to be approximately half the strength of the matrix (i.e., $c_{interface} = c_{matrix}/2$ = 0.2 MPa and $\phi_{interface} = \phi_{matrix}$ = 32°).
- *Bimsoils*. The matrix/block contact interface is assumed to be dominated by frictional contact only. In a first attempt and for simplicity, the angle of friction is assumed to be equal to that of the matrix (i.e., $c_{interface}$ = 0 MPa and $\phi_{interface} = \phi_{matrix}$ = 28°).

3.2 *Model of reference*

We refer here to the numerical model developed in the previous work of Napoli et al. (2021). A deep tunnel with a circular cross-section of radius R = 5 m is excavated in a heterogeneous rock mass with an isotropic initial stress state (σ_0). Previous work has considered σ_0 values ranging from 1.65 MPa (25% VBP model) to 1.74 MPa (70% VBP model), to account for the presence of the rock blocks. In the present work, σ_0 is assumed to be 1.7 MPa for the sake of simplicity when comparing different case studies.

As explained by Napoli et al. (2021), to avoid boundary effects the model includes an outer layer of 50 m on each side (Figure 1). An elastic behaviour and the same mechanical properties of the matrix were assigned to this extended part of the geometry. To ensure high mesh quality, a non-uniform mesh size was created, denser near the blocks. Simulations are carried out through RS2 code from Rocscience.

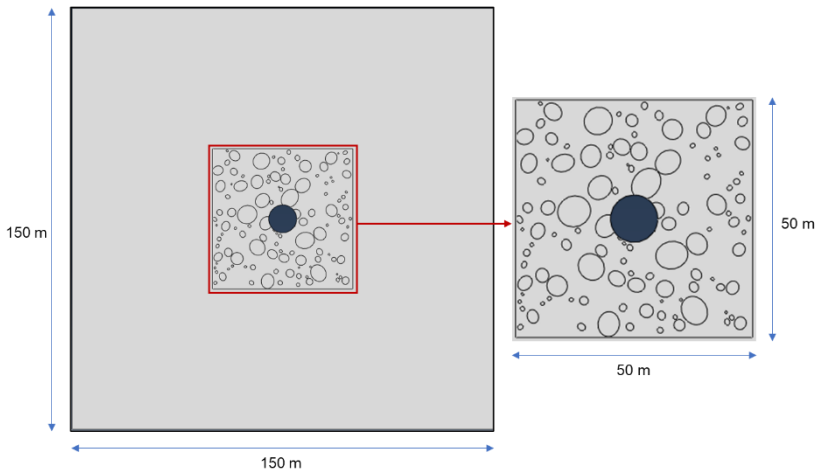


Figure 1. Reference numerical model. Case study of VBP = 25 %.

Different stages have been simulated to reproduce progressive underground excavation. The well-known convergence-confinement method (Panet 1995, Panet & Sulem 2022) was used, which simulates gradual excavation by progressively reducing a fictitious stress acting on the tunnel boundary. The support is placed at a deconfinement rate λd, which represents the deconfinement occurring at a distance (d) of the lining installation from the tunnel face.

The objective of the present work is to compare the behaviour observed for tunnels excavated in different bimunits. A reference model of 25% VBP is considered, and the main results are discussed in section 4.2. Then, in order to investigate how the rock block content (i.e., VBP) affects the lining load, a comparison is made between different bimunits. These results are discussed in detail in Section 4.3.

4 RESULTS AND DISCUSSION

4.1 *Overview on tunnel excavation in hard bimrocks with different Volumetric Block Proportions (VBPs) and distributions.*

In the previous work proposed by Napoli et al. (2021), the presence of rock inclusions during excavation in hard bimrock was investigated using different VBPs. To take into account the inherent spatial and dimensional variability of the blocks, a stochastic approach was applied to generate and analyse 10 heterogeneous tunnel configurations for each VBP considered (from 25 to 70%). A comparison with the commonly-used homogeneous equivalent approach was also carried out. The main results showed that:

- The use of a pure matrix model, neglecting the presence of blocks, leads to homogeneous yield zones and stress distributions that are unrealistic.
- The presence of the rock blocks has a high influence on the bimrock behavior. For higher values of VBP, displacements around excavation are lower. Neglecting the presence of blocks leads to large overestimations of both displacements and plastic zone extension and shape.
- A variability of the displacements around the tunnel is observed, depending on the different block distribution in the near zone. An interesting result is that a higher VBP induces less data scattering.

Therefore, the decision to ignore the contribution of the blocks to the overall bimrock strength, and instead to design using only the strength and deformation properties of the weaker matrix, appears inappropriate and overly conservative.

4.2 *Tunnel excavation in different bimunits*

In order to study the influence of the blocks during the excavation in different bimunits, a comparison is first carried out taking into account the three different categories presented in section 3 and an additional formation called "initial matrix", which is a massif with the characteristics of the hard bimrock matrix without blocks.

As explained before, the excavation sequence is simulated by progressively reducing a fictitious stress acting on the tunnel boundary. Figure 2 shows the displacements obtained considering a deconfinement rate, λd, equal to 0.8 for a model with a VBP = 25%. This rate of deconfinement is taken into account by assuming that the lining is being installed at this time. It is observed that in the hard bimrock formation the displacements around the perimeter of the excavation are the lowest. The presence of the blocks, in line with the results of previous works from the literature, contributes to the strengthening of the rock mass around the structure. A higher quantity of blocks (i.e. a higher VBP value) results in lower displacements. On the other hand, the displacements of the other two bimunits analysed (soft bimrock and bimsoil), as expected, are higher than those of the "initial matrix" model because of the softer matrix.

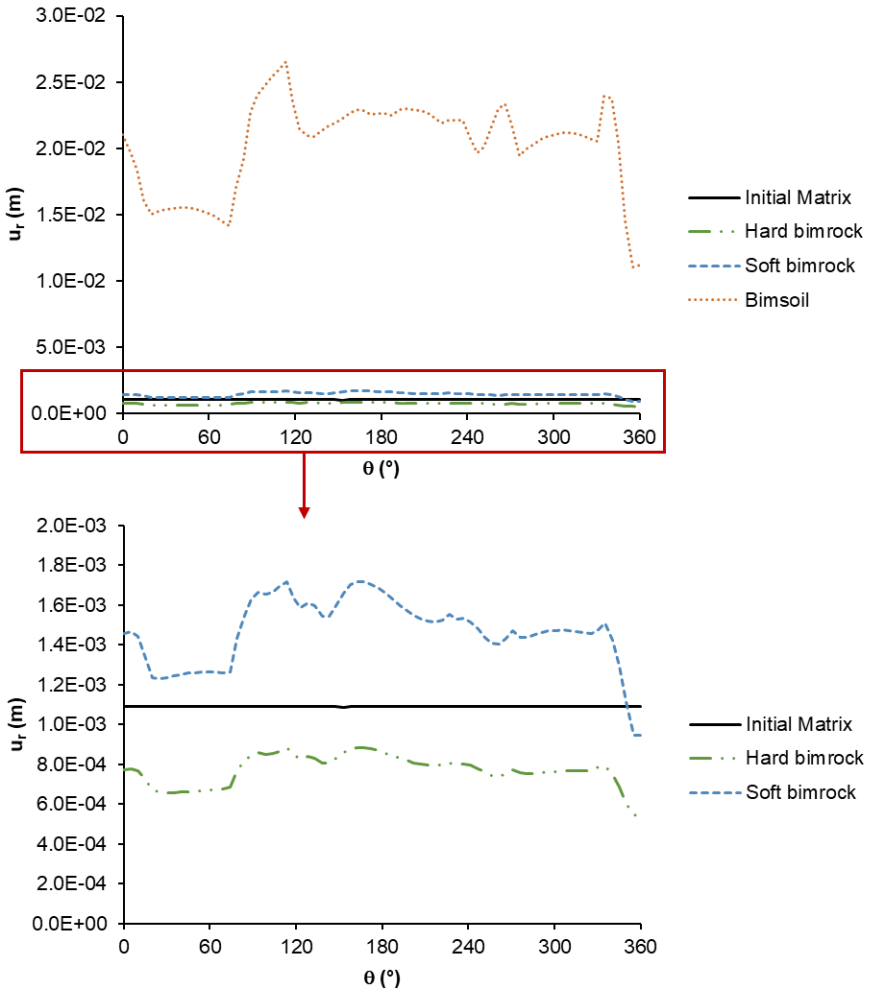


Figure 2. Radial displacements around the tunnel perimeter at a deconfinement rate of λd=0.8, for tunnels excavated in different bimunits.

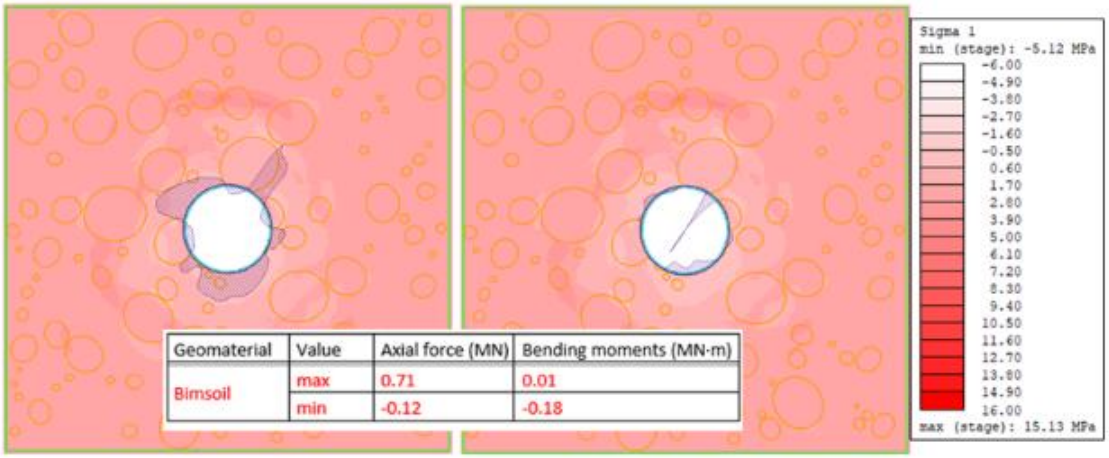
An interesting point to highlight is that lower displacements are observed in the zones around the perimeter of the tunnel, where the rock blocks are very close to the tunnel wall. In addition, some peaks are observed which are related to the contact zones between the matrix and the blocks. It is observed that these peaks are more pronounced for the soft bimunit tunnel, with the bimsoil presenting the highest changes. These results can be related to the assumption used for the simulation of the block-matrix contact interfaces in the bimsoil, which were assumed to be dominated by frictional contact only, with a friction angle considered equal to that of the soil matrix.

4.3 *Influence on lining distribution load*

To study the effect on the load transferred from the blocks to the lining, a comparison was made between the different bimunits. For the sake of simplicity, the lining was installed at the same deconfinement rate (λd=0.8) for all bimunits and the lining characteristics remained similar.

Figure 3 shows the internal bending moments and axial forces obtained for the case of a tunnel excavated in a bimsoil with VBP = 25%. It can be seen that the support is subjected to a load that is no longer uniform over its entire circumference and that the distribution of this load is highly dependent on the distribution and size of the blocks in the vicinity of the tunnel. In fact, as observed in the lower part of the tunnel, where the presence of blocks is less pronounced, the behaviour is similar to that observed in the zones where only the matrix is present. In addition, based on the results obtained, it seems that where a part of the matrix soil is between two rigid blocks

(e.g. in the right vault part of the tunnel), sudden changes in the load on the lining are observed, which may affect the behaviour of the structure over time.



Geomaterial	Value	Axial force (MN)	Bending moments (MN·m)
Bimsoil	max	0.71	0.01
	min	-0.12	-0.18

Figure 3. Bending moments and axial forces on the lining installed around an excavation in bimsoil unit with a VBP = 25 %. Blocks are represented by orange lines.

The results obtained open up new perspectives for the study, which are currently being studied:

- an interesting point to analyse is the influence of the density and also of the size of the blocks (in relation to the size of the tunnel opening) in the zone close to the tunnel contour (e.g., from the tunnel wall to 2D of the distance around the tunnel);
- for the sake of comparison in this preliminar work, the choice of lining installation was kept at the same deconfinement rate. However, the distance of the lining installation will depend on the characteristics of the excavated massif and will also play a key role in the loading of the lining;
- another interesting point to further study is the minimum size of the blocks around the tunnel beyond which the homogenisation of the geomaterial is no longer representative of the behaviour of the host massif and the interaction between the bimsoil/bimrock and structure is not really accessible in real conditions.
- also of interest would be to investigate whether a lining with yieldable elements, which can be placed between the massif and the lining or inside the lining around the perimeter (e.g., yieldable concrete wedges), could help to better distribute the load that will be transferred to the lining.

5 CONCLUSIONS

This paper investigates, based on 2D finite element simulations, the mechanical responses of a deep circular tunnel excavated in different bimunits (block-in-matrix units), namely: hard bimrocks, soft bimrocks and bimsoils. Special attention is given to the simulation of the block-matrix interfaces, which depend on the bimunit category. Therefore, based on the literature, the main assumptions considered for the interaction between the matrix and the rigid blocks have been modified according to each bimunit analysed. From considering the strength of the matrix/block contact interface to be approximately equal to the strength of the matrix in hard bimrocks, to a matrix/block contact interface dominated by frictional contact only, as in the case of bimsoils.

The main results show that the decision to ignore the contribution of the blocks to the overall strength of the bimunit and instead to design using only the strength and deformation properties of the weaker matrix, or to consider a homogenised matrix, may appear inappropriate. In fact, the final load transferred to the lining cannot be well estimated in terms of magnitude (in most cases overestimated) and/or distribution around the tunnel (the lining is loaded heterogeneously). This underlines the importance of not neglecting the blocks and the inhomogeneity of the ground when designing the lining.

In the future, this work will be extended to further investigate a wide range of conditions in bimunit tunnels. Specifically, different geotechnical and geometrical properties will be assigned to the new bimunit formations, and different support systems (with and without yielding elements) and installation distances will be analysed.

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