Slope stability in heterogeneous rock masses with a block-in-matrix fabric

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ABSTRACT: Heterogeneous rock masses composed of strong rock blocks embedded in a weaker matrix belong to complex formations and are often referred as BIMRocks (Block-In-Matrix-Rocks). The high variability of such rock bodies (spatial, dimensional and lithological) and the extraordinary problematic determination of their geomechanical properties make both the planning and the modelling of engineering works in and on these geomaterials extremely challenging.
The aim of this study is to investigate the stability of theoretical slopes in bimrocks. In order to determine how rock inclusions may influence the overall behaviour of these rock units, different block orientations and several Volumetric Block Proportions (VBP) are considered. To take the inherent spatial and dimensional variability of the blocks into account, many heterogeneous slope models are generated for each block orientation and VBP examined. In order to do this, a stochastic approach is used, which provides for an acceptable statistical validity of the results.

1 INTRODUCTIONS

The term *bimrock* (block-in-matrix rock) was coined by Medley (1997) to denote a mixture of rocks “composed of geotechnically significant blocks within a bonded matrix of finer texture”. A great number of heterogeneous rock bodies, such as melanges, breccias, weathered rocks, conglomerates and agglomerates, can be considered to be bimrocks (Medley 1994, Haneberg 2004, Wakabayashi & Medley 2004). These widespread rock units are extremely complex to identify, characterize and model due to both their inherent stratigraphic, lithologic and geohydrological non-uniformity and to the spatial and dimensional variability of the competent rock inclusions embedded in the softer matrix. As a consequence, engineering works in these challenging materials are often planned taking into account only the strength and deformability properties of the weaker matrix, which means neglecting the contribution of blocks to the overall bimrock strength. However, as demonstrated by many case histories reported in the literature, such a simplified approach can cause wrong forecasts, technical problems and delays during construction works (E. W. Medley & Zekkos 2011, Afifipour & Moarefvand 2014, Pilgerstorfer & Schubert 2014). Over the last decades a considerable amount of research (laboratory tests, numerical simulations and in situ tests) has been carried out all over the world with the aim of identifying any specific characteristics of these heterogeneous rock bodies and the major factors affecting their geomechanical behavior. According to these studies, the main characteristics associated with these geomaterials are reported below:

- bimrocks have scale independent (or fractal) block size distributions (Medley 1994, Medley & Lindquist 1995, Medley & Sanz Rehermann 2004, Sonmez et al. 2016);
- the block/matrix threshold, above which the influence of the rock inclusion becomes significant, should be defined according to the “characteristic engineering dimension”, L_c, repre-

senting the scale of the problem at hand. It could be the slope height, the tunnel diameter, the specimen diameter, etc. (Medley 1994, Wakabayashi & Medley 2004);
- blocks can be considered all the rock particles with dimensions greater than $0{,}5 \cdot L_c$ (below which rock fragments are considered to belong to the matrix) but smaller than $0{,}75 \cdot L_c$ (Medley 1994, Medley & Zekkos 2011);
- to be classified as bimrock, a sufficient block-matrix mechanical contrast is required to generate tortuous failure surfaces negotiating around the blocks (Medley 2001, 2007a, b, Napoli et al. 2018a);
- an increase in the strength of bimrocks has been registered for Volumetric Block Proportion (VBP) between about 25% and 75% (Lindquist 1994, Medley & Lindquist 1995);
- the overall strength of bimrocks is mainly affected by their VBP. Nevertheless, orientation, shape and spatial location of blocks, matrix strength, block size distributions, block count, etc., play also an important role (Irfan & Tang 1993, Lindquist 1994, Sonmez et al. 2016);
- the presence of blocks (their position, shape and number) within a slope strongly affects its failure surface, which develops irregularly and tortuously, especially for higher VBP. This result is far different from the one yielded by a stability analysis of a homogeneous geomaterial (Irfan & Tang 1993, Medley & Sanz Rehermann 2004, Barbero et al. 2006, Guerra et al. 2016, Napoli et al. 2017, 2018a, b).

Furthermore, several authors proposed preliminary strength criteria, which assume bimrocks to be homogeneous and isotropic rock masses (Lindquist 1994, Sonmez et al. 2009, Kalender et al. 2014). To define the equivalent mechanical properties of the geomaterial, both the VBP and the matrix strength parameters are required. Lindquist (1994) proposed the empirical strength criterion reported in Equation 1 below:

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

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

The aim of this study was to investigate the stability of theoretical slopes in heterogeneous rock masses with a block-in-matrix fabric, by means of numerical analyses. In order to determine how rock inclusions may influence the overall behaviour of bimrocks, different block orientations and several VBP values were considered. To take the inherent spatial and dimensional variability of the blocks into account, many heterogeneous slope models were generated for each block orientation and VBP examined. In order to do this, a stochastic approach was used, which provides for a sufficient statistical validity of the results.

2 SLOPE STABILITY ANALYSES IN BIMROCKS

2.1 *Slope models generation*

The theoretical slope models examined in this paper have all the same geometric characteristics, such as height and slope ratio, and are composed of iso-oriented rock inclusions embedded in a softer matrix. The stronger blocks have an elliptical shape and an eccentricity equal to 0.5. In order to investigate how slope stability is affected by the presence of the blocky material, bimrock models with different block contents and orientations were considered. In particular, heterogeneous models with rock particle orientations, *i*, of 0°, 30°, 60° and 90° (with respect to the horizontal axis) and 25%, 40%, 55% and 70% VBP were analysed. Moreover, to take the inherent spatial and dimensional variability of bimrocks into account, a specific Matlab routine, performing Monte Carlo simulations, was implemented. The Matlab code generates elliptical blocks with random axes lengths and positions within the rock mass geometry, according to specific statistical rules and given rock contents and orientations (Napoli et al. 2018a). To achieve a statistical validity of the results, fifteen extractions (generating fifteen bimrock configurations) and, hence, fifteen numerical simulations were carried out for each VBP and for each orientation considered. The Shear Strength Reduction technique, which gradually decreases the shear strength of the bimrock slope materials, was used in order to determine the critical

(Strength Reduction) factor at which failure occurs (SRF), i.e. the safety factor (SF) of the slope.

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, were also applied by way of comparison. In particular, the matrix-only model (0% VBP configuration) and the Lindquist approach were applied.

Altogether, more than 240 2D Finite Element (FE) analyses were carried out using the RS[2] code, from Rocscience. As shown in Figure 1, in order to avoid stress modelling disturbance, an outer layer having the same characteristics of the matrix was included in all the slope models and a ten stages excavation process was simulated to reproduce the face geometry of the slopes. Six-node triangular elements, with higher density around the rock inclusions for the heterogeneous bimrock models, were used to create the mesh.

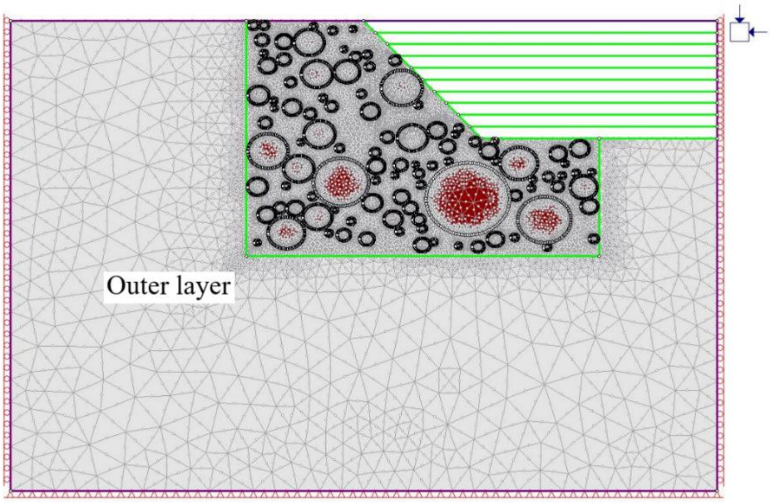

Figure 1. An example of slope model including the bimrock slope with 40% VBP and blocks randomly generated and oriented parallel to the horizontal (i=0°), the outer layer and the excavation process.

2.2 *Input parameters*

Table 1 summarizes the input parameters that were used in the stability analyses for the heterogeneous and the matrix-only models. Both the matrix and blocks were assumed to have an elastic-perfectly plastic behavior and to obey the Mohr-Coulomb failure criterion.

Table 1. Input parameters for matrix and blocks of heterogeneous and matrix-only slope models.

	E	ν	γ [kN/]	c	φ
	[GPa]	[-]	[kN/m^3]	[kPa]	[°]
Matrix	0.04	0.25	22	30	24
Blocks	5.1	0.22	27	600	40

Table 2 shows the input parameters that were used for analyzing equivalent homogeneous slope models according to the empirical approach proposed by Lindquist (1994). Since for VBP values less than 25% this approach provides the same bimrock strength parameters of the matrix, new analyses were performed for 40%, 55% and 70% VBP models only.

Table 2. Input parameters for the equivalent homogeneous slope models, according to the Lindquist criterion (1994).

VBP [%]	(1-VBP) [-]	$c_{bimrock}$ [kPa]	$\Delta\varphi_{matrix}$ [°]	$\varphi_{bimrock}$ [°]
40	0.6	18	4.5	28.5
55	0.45	13.5	9	33
70	0.3	9	13.5	37.5

2.3 *Finite element analyses results*

As previously mentioned, fifteen configurations for each VBP and each orientation considered, i.e. 240 heterogeneous bimrock models, and a homogeneous only-matrix (0% VBP) model were analyzed. Safety factors (SF), standard deviations and failure surfaces were evaluated and compared (Tab. 3 and Fig. 2).

Table 3. Safety factor obtained for the matrix only model (0% VBP) and average safety factors and standard deviations obtained for the different VBP and block orientations, i, analyzed.

	i = 0°		i = 30°		i = 60°		i = 90°	
VBP [%]	Average SF	Standard deviation	Average SF	Standard deviation	Average SF	Standard deviation	Average SF	Standard deviation
0	0.92	-	0.92	-	0.92	-	0.92	-
25	0.93	0.064	0.93	0.030	1.03	0.108	1.01	0.075
40	0.97	0.067	0.94	0.050	1.00	0.096	1.03	0.050
55	1.12	0.143	1.00	0.044	1.05	0.074	1.05	0.080
70	1.44	0.188	1.18	0.133	1.16	0.143	1.23	0.187

As shown in Table 3, whatever the block orientation, SF increase significantly for higher VBP. This result can be related to the increase of failure surface tortuosity with increasing VBP (Fig. 2). On the other hand, for a given VBP, greater SF are generally obtained for bimrock configurations having block orientations of 0° and 90°, which seem to be the ones that most affect the tortuous development of failure surfaces.

Furthermore, the standard deviations reported in Table 3 indicate that a high variability in the results exists, especially for higher VBP values. Such a variability can be associated with the different block dimensions and positions within the slope models having the same orientation and block content. These results are in good agreement with previous findings reported in Medley & Sanz Rehermann 2004 (2004), Irfan & Tang (1993), Barbero et al. (2006) and Napoli et al. (2018a, b).

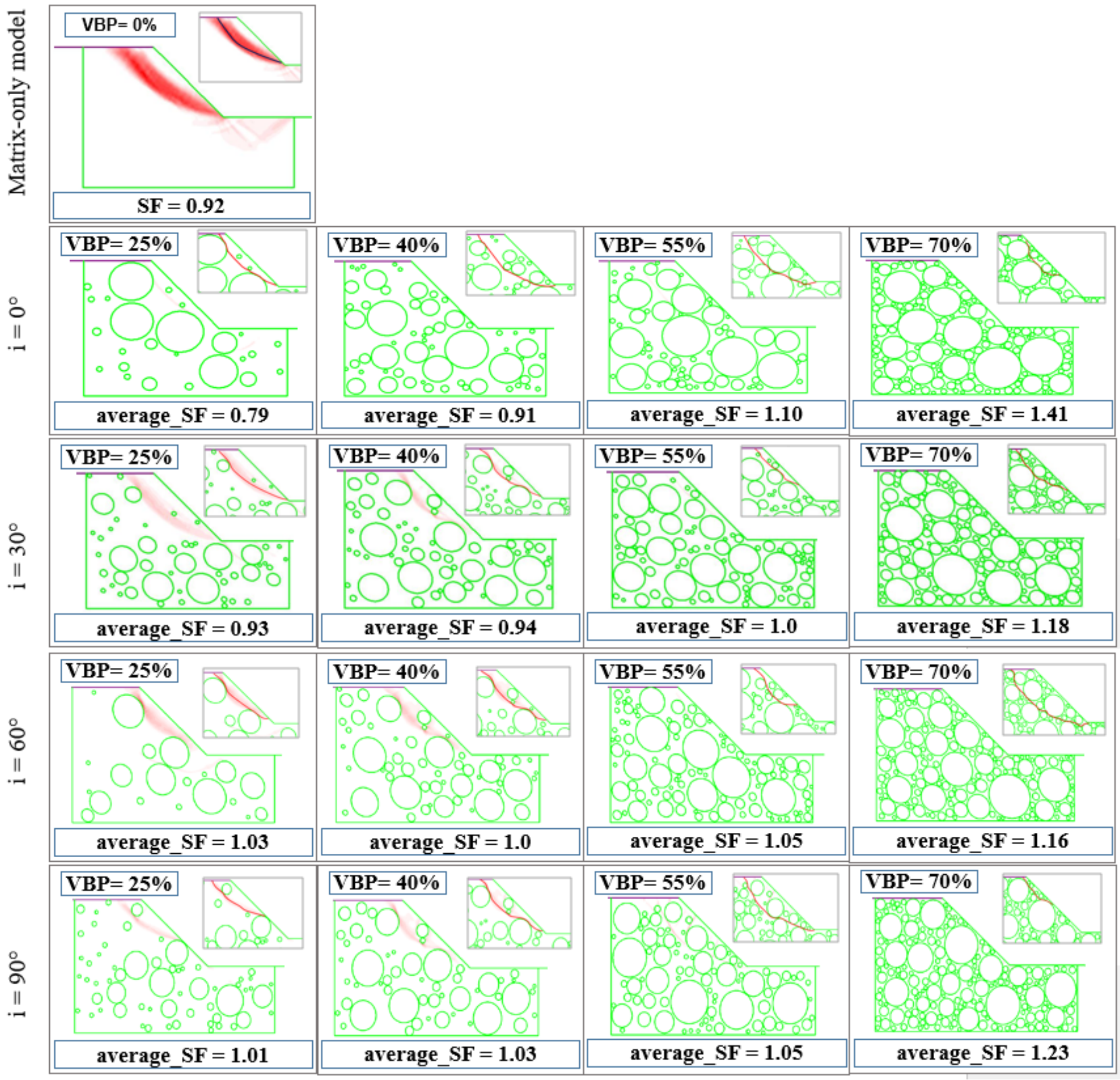

Figure 2. Results for one of the 15 bimrock configurations generated for each VBP and orientation, i, considered: average safety factors and failure surfaces (in the magnified views).

2.4 *Application of the Lindquist approach*

The empirical strength criterion proposed by Lindquist was applied, by way of comparison, considering the same slope models previously analyzed. However, only 3 configurations were analyzed, considering 40%, 55% and 70% VBP. In fact, for VBP values below 25%, Equation 1 provides the same mechanical properties (cohesion and internal friction angle) of the matrix for the equivalent bimrock. Moreover, the Lindquist approach does not take block orientation into account.

Table 4 shows the SF obtained from the analyses. The results corresponding to 0% and 25% VBP are reported in brackets for completeness, since they coincide to the ones of matrix-only model already analyzed in Section 2.3. The SF yielded by the empirical approach are consistent with the ones provided by the heterogeneous models previously examined, since they grow as the VBP increases, although in a less marked way.

Table 4. SF obtained applying the Lindquist criterion.

VBP [%]	SF [-]
(0)	(0.92)
(25)	(0.92)
40	0.94
55	0.96
70	1.00

3 COMPARISON OF RESULTS

The average SF provided by the different approaches applied were normalized by dividing them by the SF obtained for the matrix-only (0% VBP) model. The results, reported in Figure 3, show that there is a clear trend toward increasing SF with increasing VBP, although a certain variability occurs for the different orientations analyzed. This is in line with the findings of previous studies on slope stability (Irfan & Tang 1993, Medley & Sanz Rehermann 2004, Barbero et al. 2006, Napoli et al. 2018a, b), which highlight that the mechanical behavior of these heterogeneous rock masses is strongly influenced by the presence of rock inclusions and their content, positions and dimensions. Rock blocks also affect the position and shape of failure surfaces, which are forced to negotiate tortuously around them (Lindquist 1994, Medley 2001). Moreover, it seems that if a preferred orientation of the clasts exists, this may influence the stability of slopes in bimrocks. In particular, from this research it can be seen that higher SF are provided when the major axes of rock blocks are inclined 0° and 90° to the horizontal. It is worth pointing out that these two values are those that deviate more from the inclination of the slopes, which is 45°.

From Figure 3 it is also evident that the use of a matrix-only model, which does not take the presence of blocks into account, leads to a significant underestimation of the SF, especially for VBP equal to 55% and 70% and for block orientations equal to 0° and 90°. Furthermore, as shown in Figure 2, the shape and position of the failure surface cannot be correctly identified using this simplified approach, since tortuosity is not taken into account. These results are in good agreement with previous studies conducted on bimrocks (Lindquist 1994, Medley & Sanz Rehermann 2004, Barbero et al. 2006, Napoli et al. 2018b).

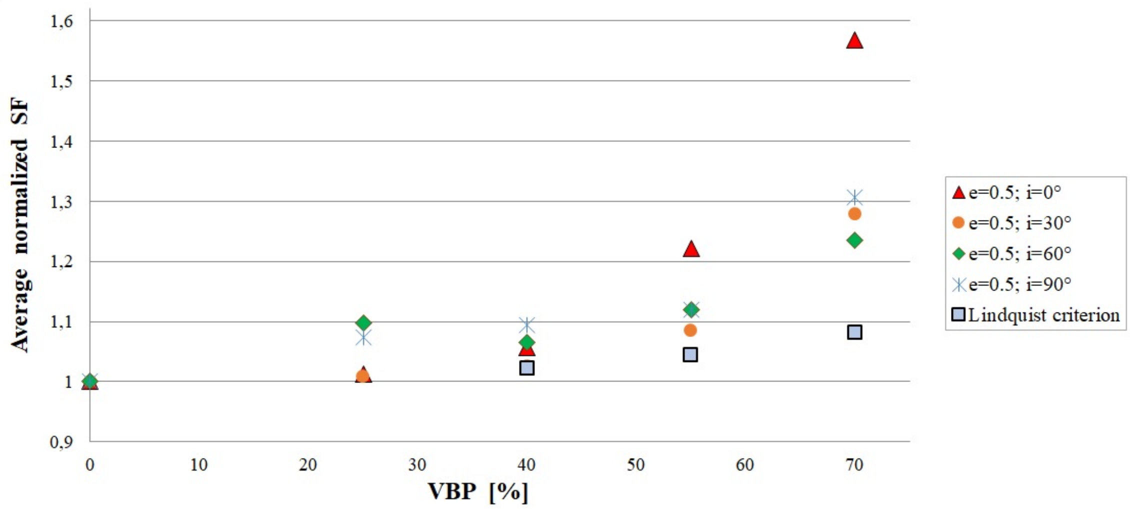

Figure 3. Average normalized SF obtained for heterogeneous and homogeneous (Lindquist criterion) bimrock models.

Finally, when applying the empirical strength criterion proposed by Lindquist (1994), slope models with higher VBP exhibit greater SF. However, as shown in Figure 3, this trend is much less pronounced than that observed for heterogeneous slope models, particularly for higher VBP. Hence, great underestimations of SF may derive from the application of this criterion. Furthermore, since this approach assumes bimrocks as homogeneous continuous and isotropic rock masses, the tortuosity of the sliding surface cannot be taken into account and, consequently, the shape and position of the failure surface (and, thus, the volume involved in the instability) is not representative of the real problem.

4 CONCLUSIONS

This work investigates the effects of the presence of rock blocks and of their content and orientation on the stability of slopes in bimrocks and the reliability of designing on the basis of the strength and deformability properties of the matrix only, as often happens in practice.

More than 240 bidimensional slope stability numerical analyses were performed on bimrock models with variable VBP values and block orientations. For each parameter considered, fifteen bimrock configurations were generated using a stochastic approach performing numerical Monte Carlo simulations, with the aim of taking spatial and dimensional variability of rock inclusions into account. Furthermore, the empirical strength model proposed by Lindquist, which assumes bimrocks to be equivalent homogeneous, continuous and isotropic masses, was applied by way of comparison.

The results yielded by the FE analyses demonstrate that the presence of rock blocks strongly affects the mechanical behavior of bimrocks, leading to greater slope stability (SF) and tortuous failure surfaces as the VBP increases. This indicates that designing neglecting the presence of the blocks may lead to underestimations of the SF as well as to wrong forecasts (unrealistic positions and shapes of slip surfaces). These outcomes are in good agreement with previous findings from the literature. Anyway, this research also highlights that a significant variability in the SF of heterogeneous slope models with the same VBP and block orientation exists. The difference between the maximum and the minimum SF of the fifteen configurations with the same VBP ranges, on average, from 0.24 ($\Delta SF_{25\%VBP}$) up to 0.56 ($\Delta SF_{70\%VBP}$). This behavior can be ascribed to the different position and dimension of blocks within the slope models, which may influence the shear strain concentrations and, consequently, the stability of the slopes. There is compelling evidence that deterministic analyses cannot take this variability into account. Conversely, the use of a stochastic approach seems to be more appropriate to study these heterogeneous formations, since it makes it possible to perceive the variability in the results.

Moreover, if a preferred orientation of the clasts exists, this may also influence the stability of slopes in bimrocks. In particular, it seems that higher SF are provided when the major axes of rock blocks deviate considerably from the inclination of the slopes.

Finally, the Lindquist approach produces greater SF for higher VBP values. However, this trend is less evident than that obtained for the heterogeneous slope models. Moreover, this method does not take the orientation of the blocks into account, produces failure surfaces that are not representative of the real problem (since tortuosity is not considered) and leads to severe underestimations of the SF for VBP above 40%. Hence, it seems to be acceptable if used in predesign stages only.

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