Analyzing slope stability in bimrocks by means of a stochastic approach

ANALYZING SLOPE STABILITY IN BIMROCKS BY MEANS OF A STOCHASTIC APPROACH

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ABSTRACT

Bimrocks (block-in-matrix rocks) are chaotic geological formations defined as heterogeneous mixtures of hard rock blocks encased in a fine-graded matrix. The inherent geometric, lithological and mechanical variability of bimrocks imply a great challenge in their characterization and modeling.
A common practice when planning engineering works in these complex formations is to neglect the contribution of blocks and assign the strength and deformation properties of the weaker matrix to the whole rock mass. However, this assumption can lead to erroneous results and, consequently, to technical problems during construction works.
The aim of this study was to investigate stability of theoretical slopes in bimrocks using a stochastic approach, in order to consider the spatial and dimensional variability of rock inclusions. Many 2D stability analyses were performed on slope models with simple geometries, elliptical block shapes and variable block contents. The results were compared to those obtained in a previous work, where slope stability analyses were carried out on bimrocks with blocks of circular shape.
The findings of this research confirm that rock inclusions play an important role and strongly influence the slope stability of bimrocks. Furthermore, the advantages of using a stochastic approach when working with these heterogeneous materials are highlighted.

1. INTRODUCTION

The term *bimrock* (block-in-matrix rock) was defined by Medley (1997) to be a mixture of rocks "composed of geotechnically significant blocks within a bonded matrix of finer texture". Several geological formations, including melanges, breccias, weathered rocks, conglomerates and agglomerates, can be considered to be bimrocks (Medley, 1994; Haneberg, 2004; Wakabayashi and Medley, 2004). A reliable characterization and modeling of bimrocks is extremely complex due to the inherent spatial, lithologic and dimensional variability of rock inclusions. Hence, geotechnical engineers often plan engineering works in these challenging materials taking into account only the strength and deformation properties of the weaker matrix. However, based on many case histories reported in the literature, such a simplified approach can lead to wrong forecasts, instability problems, unexpected difficulties and delays during construction works (Medley and Zekkos, 2011; Afifipour and Moarefvand, 2014). Recently, a lot of research (laboratory tests, numerical analyses and in situ tests) has been conducted to investigate the mechanical properties of bimrocks, in order to correctly design civil engineering works in these complex formations. The main results of these studies are summarized below:

- bimrocks have scale independent (or fractal) block size distributions (Medley, 1994; Medley and Lindquist, 1995; Medley and Sanz, 2004; Sonmez et al., 2016);
- the block/matrix threshold, i.e. the smallest geotechnically significant block and the largest block size within a volume of bimrock, should be defined according to the scale of engineering interest, termed "characteristic engineering dimension", L_c. It could be the slope height, the specimen diameter, the tunnel diameter, etc. (Medley, 1994; Wakabayashi and Medley, 2004);

- at the selected scale of interest, blocks can be considered all the inclusions with dimensions between $0{,}5\cdot L_c$ (below which rock fragments are considered to belong to the matrix) and $0{,}75\cdot L_c$ (Medley, 1994; Barbero et al., 2006; Medley and Zekkos, 2011);
- the overall strength of bimrocks is affected by many factors. The most important is the Volumetric Block Proportion (VBP), but orientation and spatial location of blocks, matrix strength, block size distributions, block count, block shapes, etc., play an important role, as well (Lindquist, 1994; Irfan and Tang, 1993);
- to be classified as bimrock, a sufficient mechanical contrast between blocks and surrounding matrix must be afforded by the material, so as to force failure surfaces to negotiate tortuously around the blocks. In particular, a minimum friction angle ratio ($\tan\varphi_{block}/\tan\varphi_{matrix}$) of between 1.5 and 2 and a minimum stiffness contrast (E_{block}/E_{matrix}) of about 2 have been suggested in the literature (Medley, 1994; Lindquist and Goodman, 1994; Barbero et al., 2007; Medley and Zekkos, 2011);
- an increase in the strength of bimrocks was registered for VBP between about 25% and 75% (Lindquist, 1994; Medley and Lindquist, 1995). In this range, researchers have observed an increase of both Young's modulus and friction angle, related to the increase in tortuosity of the failure surfaces, and a decrease in the cohesion, due to the poor mechanical properties of the matrix, where deformations develop;
- the presence of blocks (their position, shape and number) within slopes yields to irregular and tortuous sliding surfaces, far different from those obtained in homogeneous materials (Irfan and Tang, 1993; Medley and Sanz, 2004; Barbero et al., 2006). Greater safety factors have been found for higher VBP.

Some authors developed preliminary (simplified) strength criteria, which assume bimrocks to be homogeneous and isotropic masses (Lindquist, 1994; Sonmez et al., 2009; Kalender et al., 2014). Block proportions and matrix strength parameters are necessary in order to define the equivalent mechanical properties of the rock mass.

Lindquist (1994) proposed the empirical strength criterion reported in Eq. (1):

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

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

The approach proposed by Kalender et al. (2014), which takes also into account contact strength between blocks and matrix, is reported in Eqs. (2)-(4).

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

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

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

where α is the angle of repose of blocks, UCS is the uniaxial compressive strength and A is a parameter that can be defined according to both the compressive strength of the matrix and α.

Both the empirical approaches, as stated by the authors themselves, have some limitations and should be applied carefully and only in predesign stages of engineering applications.

2. 2D STABILITY ANALYSIS OF SLOPES IN BIMROCKS

The aim of this study was to evaluate the effects of rock blocks on the stability of theoretical slopes in bimrocks, whose characteristic dimension, Lc, was their height. The slopes had an inclination of 30°, elliptical block shapes (with major axes inclined 90° to the vertical axis) and different block contents. In particular, 25%, 40%, 55% and 70% volumetric block proportions were examined.

To take the spatial and dimensional variability of the inclusions into account, the stochastic approach proposed by Napoli et al. (2017) was applied. In particular, a specific Matlab routine, performing numerical Monte Carlo simulations, was implemented to randomly generate elliptical blocks within the slope models

according to specific statistical rules (Barbero et al., 2012). 15 extractions and, hence, 15 stability analyses were performed for each VBP considered, so as to achieve a statistical validity of the results. 0% VBP configurations (matrix only models) were also analyzed in order to evaluate potential inaccuracies that can be made designing without taking the presence of blocks into account.
Altogether, more than 120 slope stability analyses were carried out using both FEM and LEM methods, with Phase^2 and Slide computer codes (from Rocscience), respectively. Safety factors were evaluated and compared.
Table 1 shows the input parameters that were used in the stability analyses. Both matrix and blocks were assumed to have an elastic-perfectly plastic behavior and to follow the Mohr-Coulomb failure criterion. The empirical approach proposed by Lindquist was also applied, by way of comparison. Table 2 shows the input parameters that were used for analyzing these equivalent homogeneous slope models.

Table 1 – Input parameters for matrix and blocks of heterogeneous slope models

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

Table 2 – Input parameters for equivalent homogeneous materials, according to the Lindquist criterion

	LINDQUIST'S APPROACH			
VBP [%]	(1-VBP)	$c_{bimrock}$ [kPa]	$\Delta\varphi_{matrix}$ [°]	$\varphi_{bimrock}$ [°]
0	1	30	0	24
25	0.75	22.5	0	24
40	0.6	18	4.5	28.5
55	0.45	13.5	9	33
70	0.3	9	13.5	37.5

2.1 FEM analyses

Finite element (FE) slope stability analyses were conducted using the software Phase^2 (vers. 8.0). Six-node triangular elements were used and, in order to avoid stress modelling disturbance, an excavation process was simulated to reproduce the face geometry of the slopes.

Table 3. Average safety factors and standard deviations obtained performing FEM analyses

VBP [%]	**Average SF**	**Standard deviation**
0 (matrix-only)	0.80	-
25	0.79	0.036
40	0.91	0.094
55	1.10	0.144
70	1.41	0.189

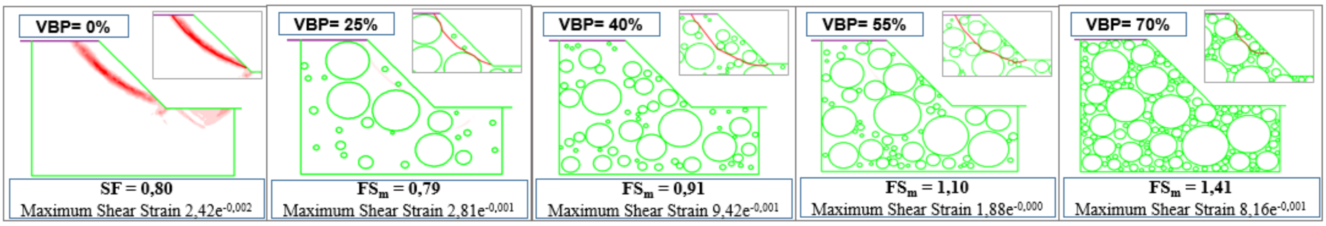

Figure 1. FEM analyses results for one of the bimrock configurations generated for each VBP considered: failure surfaces (in the magnified views), critical safety factors (SRF) and maximum shear strains.

The results, shown in Table 3, indicate that factors of safety increase significantly for higher VBP. This result can be ascribed to the increase of failure surface tortuosity with increasing VBP (Figure 1). Furthermore, the standard deviations reported in Table 3 indicate that a high variability in the results exists, and that it increases with increasing VBP. These results are in good agreement with previous findings reported in Medley and Sanz (2004), Irfan and Tang (1993), Barbero et al. (2006) and Napoli et al. (2017).

2.2 LEM analyses

Limit equilibrium analyses were carried out on the same extended slope models of the FEM analyses using the code Slide (vers. 5.0). The Simplified Bishop method was applied.
As shown in Table 4, a significant increase of the safety factors and standard deviations is achieved for higher VBP values, particularly for both 70% VBP configurations, according to FEM analyses results.

Table 4. Average safety factors and standard deviations obtained performing LEM analyses

VBP [%]	Average SF	Standard deviation
0 (matrix-only)	0.83	-
25	0.90	0.065
40	1.16	0.205
55	1.57	0.279
70	2.24	0.391

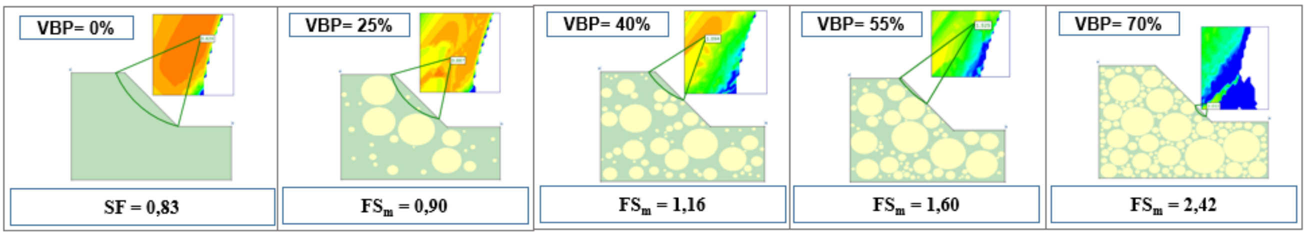

Figure 2 - LEM analyses results for one of the fifteen bimrock configurations generated for each VBP considered: critical surfaces and minimum safety factors (SFs) provided by simplified Bishop's method.

As shown in Figure 2, the tortuosity of failure surfaces is not taken into account, since they have circular shapes. The positions of critical surfaces are affected by the presence of blocks, having greater strength than the matrix. They tend to be, among those analyzed, the ones that encounter the lowest number of inclusions and are all quite superficial. Furthermore, the results are not representative of the real problem and significantly overestimate safety factors (SFs), with respect to FEM results.

2.3 Application of the Lindquist empirical strength criterion

The empirical strength criterion proposed by Lindquist was applied, by way of comparison, on the same slope models previously analyzed. The one proposed by Kalender et al. (2014) was not applicable, since the UCS_{matrix} was less than 0,1 MPa. For 25%VBP, Eq. (1) provided equivalent bimrock cohesion and internal friction angle basically coincident with those of the matrix (as reported in Table 2). Hence, only 40%, 55% and 70% VBP configurations were analyzed.

Table 5 – Safety factors obtained by FEM and LEM analyses applying the Lindquist criterion

	Safety factors – Lindquist criterion	
VBP [%]	LEM Analyses	FEM Analyses
25	-	-
40	0.84	0.94
55	0.92	0.95
70	1.0	1.0

Table 5 compares the SFs obtained performing LEM and FEM analyses. It shows that SFs grow as the VBP increases. This trend is consistent with the one obtained assuming bimrocks to be heterogeneous materials and with previous findings from Napoli et al. (2017), who analyzed slope stability in bimrocks using the same stochastic approach but rock inclusions of circular shape.

However, it is worth pointing out that assuming bimrocks to be homogeneous and isotropic materials does not allow the tortuosity of the slip surfaces to be taken into account and the critical slip surfaces to be correctly identified. This produces an underestimation of the rock volume involved in the instability.

3. COMPARISON OF RESULTS AND CONCLUSIONS

The average SFs, provided by the different approaches applied, are compared and reported in Figure 3.

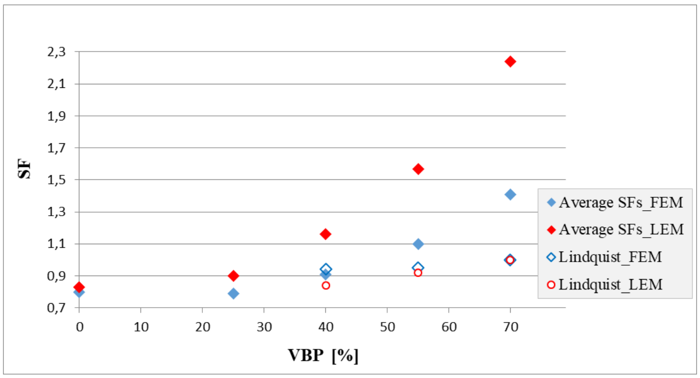

Figure 3 – Average SFs obtained for heterogeneous and homogeneous (Lindquist criterion) bimrock models

The results show that:

– there is a clear trend toward increasing SF with increasing VBP, whatever the analysis performed. This trend, which is more evident for VBP greater than 25%, is in line with the findings of previous studies on slope stability (Irfan and Tang, 1993; Medley and Sanz, 2004; Barbero et al., 2006; Napoli et al., 2017);

– FEM analyses appear to be representative of the real behavior of these materials. As shown in Figure 1, this method allows potential slip surfaces to be correctly identified (Lindquist and Goodman, 1994; Medley and Sanz, 2004; Barbero et al., 2006; Napoli et al., 2017);

– when analyzing heterogeneous geomaterials such as bimrocks, LEM analyses should not be applied using the classic grid search method with circular failure surfaces. Such an approach does not allow the tortuosity of slip surfaces to develop within the matrix. Critical failure surfaces, indeed, are those encountering the lowest number of (stronger) inclusions and are usually located near the slope surfaces. This leads to overestimations of the SFs and to underestimations of unstable volumes involved, that increase with increasing VBP;

– the use of a matrix-only model (0% VBP), which does not take the presence of blocks into account, leads to a significant underestimation of the SFs, especially for high VBP. Furthermore, shapes and positions of failure surfaces are not correctly identified, since their tortuosity is not taken into account. These results are in good agreement with previous studies conducted on bimrocks (Lindquist 1994; Barbero et al. 2006);

– when applying the strength criterion proposed by Lindquist (1994), LEM and FEM analyses provide SFs close to each other (as shown in Table 5 and Figure 3) and quite similar to those yielded by FEM analyses in heterogeneous materials. Anyway, given the limited geometric configurations analyzed, further studies are still required to verify it. Furthermore, since the application of this approach does not allow tortuosity of sliding surfaces to be taken into account (because it assumes bimrocks as homogeneous continuous and isotropic rock masses), it seems to be acceptable if used in predesign stages only (Kalender et al., 2014);

– although further analyses will be performed to validate and generalize the findings of this paper (analyzing different block orientations and shapes, i.e. eccentricity, strength parameters and slope geometries), it appears that both elliptical and circular block shapes, that were analyzed in a previous work by Napoli et al. (2017), influence slope stability of bimrocks in a comparable way. However, failure surfaces obtained in this study show less tortuous paths with respect to those found by Napoli et al. (2017) for bimrocks with circular block shapes.

As illustrated in Table 3 and Table 4, both FEM and LEM results for heterogeneous materials are extremely variable, especially for higher VBP. The difference between the maximum and the minimum SF of slope models with a given VBP ranges from 0,13 ($\Delta SF_{25\%VBP}$) up to around 0,60 ($\Delta SF_{70\%VBP}$). This high variability can be ascribed to the different dimensions and locations of the rock inclusions within the slope models, which strongly affect the positions and shapes of sliding surfaces and the stability of the slopes. These findings, in accordance with previous results found by Napoli et al. (2017), demonstrate that blocks play an important role in slope stability and that their presence should not be neglected. Furthermore, when dealing with such heterogeneous materials, the use of a stochastic approach is highly recommended in order to achieve reliable results.

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