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The relict landslide in bimsoils in downtown Genova, Italy: a new modeling approach

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Abstract. Stability problems occurring in geological units with a block-in-matrix fabric are often analyzed with deterministic approaches and/or assuming block-in-matrix rocks/soils (bimrocks or bimsoils) to be homogeneous equivalent geomaterials. However, recent studies have demonstrated that since these formations are characterized by a great (dimensional, spatial and lithological) variability, reliable results can only be obtained if a stochastic approach accounting for different block arrangements and dimensions is used.

This paper extends and improves a previous study from Minuto and Morandi (2015) to evaluate the stability of a relict landslide in bimsoil located in downtown Genova (Italy), where a deterministic approach and the traditional limit equilibrium method were used. In this work, different slope models with elliptical blocks of variable eccentricity, size and positions are generated by means of a stochastic approach and are analyzed with the FEM code RS2. Moreover, since the slope can be considered to be a bimsoil, interfaces between the blocks and matrix are introduced in order to better simulate the lower strength at the block/matrix contacts. The numerical analyses of the slope reveal that shallow failure surfaces have a higher probability of occurrence as compared to the deep failure surfaces considered by Minuto and Morandi (2015). Furthermore, lower safety factors are obtained when a block-matrix interface strength smaller than that of the matrix (i.e., a bimsoil) is simulated.

1. Introduction

The stability assessment of slopes with a block-in-matrix internal arrangement is a challenging task because of the inherent variability of the soil-rock properties. As widely documented in the literature, many factors affect the stability of such heterogeneous geomaterials, defined as bimrocks/bimsoils (block-in-matrix rocks/soils) [1]: the volumetric block proportion (VBP), the geometric properties of the rock blocks (i.e. shape and inclination), their size and position, the block-matrix interface strength, etc. [2–5]. Therefore, in order to take all these characteristics into full account and perform an accurate stability assessment, stochastic instead of deterministic analyses should be used [6–8].

In this regard, the work presented in this paper extends a study by Minuto and Morandi [9]. The authors analyzed the stability of a portion (toe) of a relict landslide in bimsoil located in a densely urbanized area, downtown Genova (Italy) by means of a deterministic approach and the Limit

Equilibrium (LEM) method. The slope is constituted by a variable thickness colluvium material (clayey gravels with sand and interspersed boulders) underlain by the Flysch bedrock (mainly succession of limestone-marls). Standard direct shear tests were carried out on the undisturbed finer material (i.e. fine matrix) to obtain the effective strength parameters. From these tests, the cohesion (c') and friction angle (φ') were found to be equal to 10 kPa and 27°, respectively. Since the matrix contained also a significant amount of coarse material, these strength parameters were considered to be too conservative and not representative of the whole slope. In addition, the SPT soundings were not considered reliable, reaching a very high N_{SPT} values or refusal, due to the high coarse fraction. Accordingly, the friction angle from the direct shear tests was increased according to literature findings about the effect of coarse fraction in colluvium materials; as a rule of thumb, with a coarse fraction content $\geq$30% a $\Delta\varphi$ increment of 4° for every 10% coarse fraction increment can be assumed [3]. Hence, for an average gravel content of 50%, φ' was increased by 8° with respect to that of the fine matrix and, therefore, the overall φ' of the coarse matrix was assumed to be 35° (Table 1).

Table 1. Mechanical properties assigned to the matrix and blocks in the different slope configurations analyzed [9].

Slope configuration	Geotechnical properties	
	c' (kPa)	φ' (°)
Homogeneous - Fine matrix	10	27
Homogeneous - Coarse Matrix	10	35
Heterogeneous - 15% VBP	10	35
Heterogeneous - 30% VBP	5	37

From the interpretation of six borehole drillings, the authors estimated a VBP between 15% and 30%. Given this variability and considering potential errors in the estimation of this parameter, Minuto and Morandi analyzed two heterogeneous slope configurations with a block content of 15% and 30% VBP. According to the literature [3], the c' and φ' values of the homogeneous model (i.e. coarse matrix) were modified in order to take the presence of the blocks into account (Table 1). Rectangular shaped blocks were used to model the slope, according to observations of the slope area. The two homogeneous matrix-only models (composed of fine and coarse debris only) were also analyzed, by way of comparison. In terms of a potential risk related to the collapse of the slope, the shallow slip surfaces were neglected.

The results found showed that the fine and coarse matrix-only models had a safety factor (SF) value of 0.99 and 1.28, respectively, while a SF increase of 12% and 23% (i.e., SF equal to 1.44 and 1.49, respectively) was yielded by the heterogeneous slopes with 15% and 30% VBPs, respectively, as compared to the coarse matrix model. This outcome confirmed that the classical and simplified approach of using the strength parameters of the weaker matrix only can be excessively conservative.

In this paper, a new modeling approach is proposed to extend the previous study [9] and overcome its main limitations. These limitations are the use of both a deterministic approach and LEM method, particularly when blocks are added to the slope model, as well as the absence of block-matrix interfaces, which significantly affect the mechanical behavior of unwelded block-in-matrix materials (i.e., bimsoils [10]). Interface elements should indeed be used when simulating bimsoils [11], while they are not necessary when dealing with welded block-in-matrix materials (i.e., bimrocks [1]). Therefore, in this work Finite Element (FEM) analyses are carried out considering the block-matrix interfaces (i.e. bimsoil slopes). However, in order to better compare the results, the same slope models are analyzed also without the interfaces (i.e. bimrock slopes). Moreover, the stochastic approach proposed by Napoli et al. [4,12] is applied in order to take the spatial and dimensional variability of the rock blocks into account, and obtain statistically-based results.

2. FEM analyses

As discussed above, the stability of this portion of the relict landslide was investigated in this paper by means of a stochastic approach. Specifically, ten slope models with different rock blocks characteristics were generated and analyzed for each VBP considered (15% and 30%). Elliptical blocks with eccentricities varying between 0.4 and 0.9 were used to simulate the blocks, which had random positions, sizes and orientations within the slope. This block shape was preferred to the rectangular used by Minuto and Morandi (2015) in order to avoid meshing problems near the edges. The FEM analyses were performed with the RS2 code from Rocscience. Finally, since the material composing the slope can be classified as a bimsoil, implying that the blocks in the matrix are loosely packed, an interface between the matrix and rock blocks was also introduced in this research and further analyses were carried out. According to the literature, a strength lower than that of the matrix was assigned to these elements.

2.1 Geometrical and mechanical parameters of the slope models

The c’ and φ’ values assigned to the matrix and blocks composing the slope were obtained from the study of Minuto and Morandi (2015), as shown in Table 1.

The geomaterial properties assigned to the matrix and blocks (i.e., Young modulus, E_0, Poisson ratio, ν, and shear modulus, G_0) were instead derived from a downhole test performed by Minuto and Morandi. By looking at the profile of the downhole test (Figure 1) it was practical to divide the slope into three layers: the first from 0 to 16 m depth, the second from 16 to 34 m depth, and the last from 34 to 40 m depth.

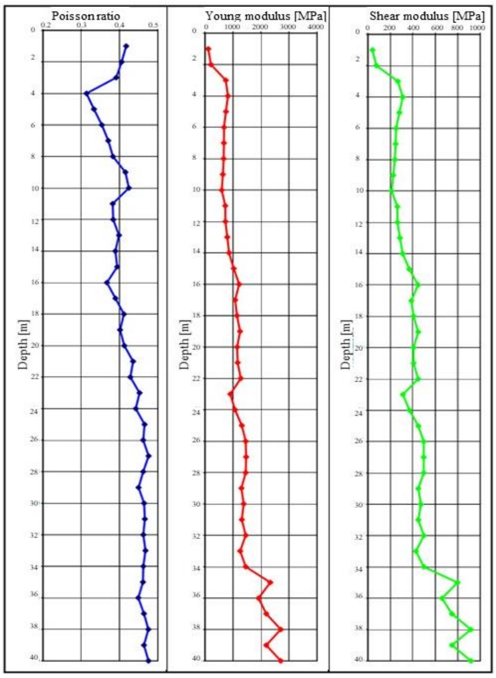

Figure 1. Result of the downhole test. On the left is the profile of the Poisson ratio, in the middle the profile of the Young modulus and on the right is the profile of the shear modulus.

Different matrix properties were assigned to the three layers, as shown in Table 2 and Figure 2b. Since the results shown in Figure 1 were not related to a homogeneous matrix but to a complex geomaterial composed of matrix and rock blocks, the minimum values of E_0, ν and G_0 were identified and assigned to the matrix.

Table 2. Matrix properties, considering different depths.

Parameter	Layers of material		
	1-16 m	16-34 m	34-40 m
E (MPa)	700	1300	2300
ν (-)	0.32	0.37	0.4
γ (kN/m^3)	18	18	18

From the ground investigations performed by Minuto and Morandi (2015), the bedrock was found almost 40 m below the ground surface. The GSI value for the rock mass ranged between 40-60, the uniaxial compressive strength (UCS) and the Elastic Modulus (E) for the intact rock were assumed between 50-60 MPa and 45 GPa, respectively. An elastic perfectly plastic constitutive law and the Hoek-Brown strength criterion were used for both the blocks and the bedrock. The final parameters used are summarized in Table 3.

Table 3. Mechanical properties used for bedrock and rock blocks in the FEM models.

Material Properties	Bedrock	Rock blocks
E (GPa)	18	45
ν (-)	0.3	0.3
γ (kN/m^3)	27	27
UCS (MPa)	60	60
m_i/m_b	1.084	9
s	0.007	1

This work extended the study of Minuto and Morandi (2015) since it also consisted in introducing an interface between the rock blocks and matrix, in order to model the slope as a bimsoil. An elastic perfectly plastic constitutive law was assigned to the interfaces, which had $c' = 0$ kPa and $\varphi' = 35°$. These contact elements were introduced using the “joint” command in RS2.

For the field stress, a gravitational stress distribution was used, which is reasonable in slope stability analyses. The horizontal stress ratio was selected as 1, implying a hydrostatic initial stress. The Shear Stress Reduction technique (SSR) was enabled and a SSR search area was defined to reduce the computational time. Figure 2 shows the model setup in RS2 along with different materials, piezometric level, rock blocks, boundary conditions and SSR search area.

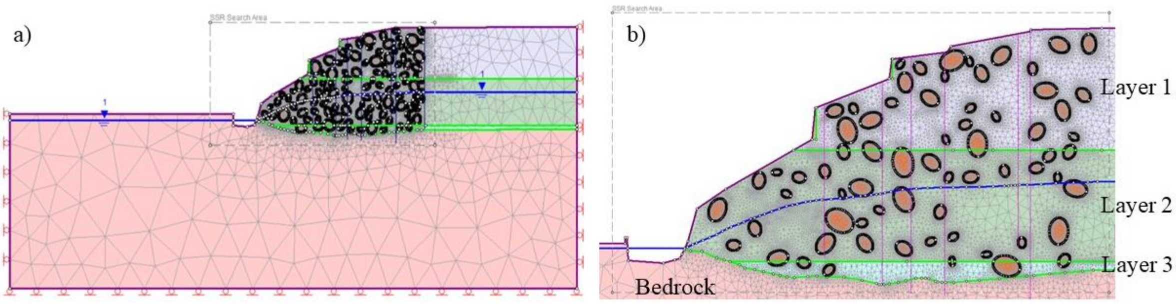

Figure 2. a) model setup for one of the 30% VBP models in RS2; b) magnified view of the model slope with the indication of the material layers.

2.2 Results

First, the previous LEM results [9] obtained for the homogeneous slope model (i.e., coarse matrix) were validated numerically. The results obtained (safety factor and failure surface shape and position) are shown in Figure 3. They compare well with those obtained in the previous LEM analysis if the shallow (and most critical) failure surfaces are neglected and only deep failure surfaces are considered. In fact, as stated before, no evidence of instabilities were detected on site.

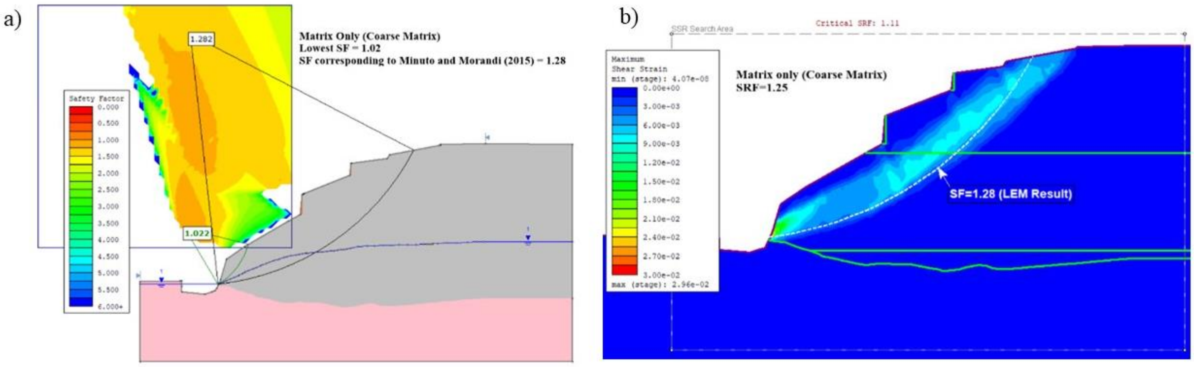

Figure 3. LEM and FEM models of the coarse matrix-only model for the validation of the previous study of Minuto and Morandi (2015). a) a deep failure surface obtained by Slide® is shown; b) the deep failure surface obtained by RS2® is shown.

Then, the heterogeneous models without the interfaces (i.e. bimrock models) were analyzed in order to compare the FEM results with those of Minuto and Morandi (2015).

The critical Strength Reduction Factor (SRF) of the ten different configurations with 15% VBP ranged between 1.02 and 1.17, with a mean value of 1.08 and a coefficient of variation of 0.031. The mean SRF value is almost the same as for the coarse matrix-only model. The presence of the blocks has not changed the safety factor much, but the failure surfaces have different paths depending on the distribution and dimension of the blocks. It is worth pointing out that the minimum SF are, again, related to shallow failure surfaces, while Minuto and Morandi (2015) only took deep failure surfaces into account. Hence, in order to compare the results correctly, deeper failure surfaces were investigated, by navigating in RS2 through the SRF values in the maximum shear strains window of results. Figure 4 shows the progression of the failure surface for one of the 15% VBP models analyzed.

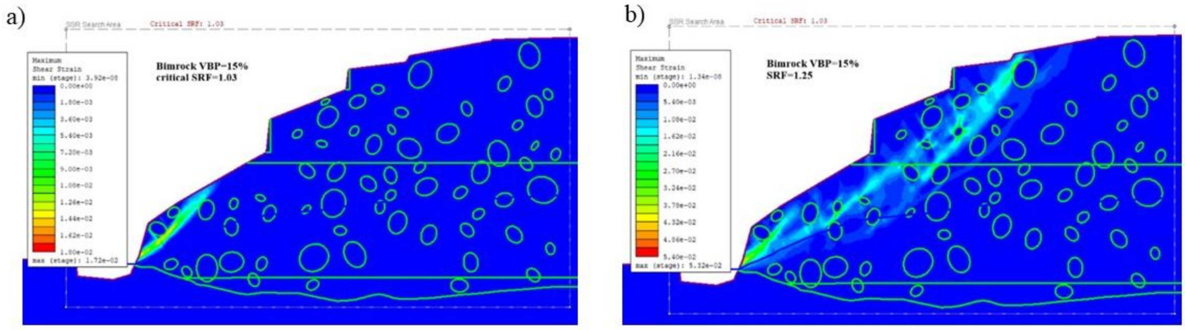

Figure 4. Maximum shear strains of one of the 15% VBP models. a) maximum shear strains corresponding to a shallow failure surface with critical SRF of 1.03; b) progression of failure surface, showing a deep failure surface at SRF=1.25.

For the 30%VBP models, the critical SRF values ranged between 1.12 and 1.28, with a mean value of 1.19 and a coefficient of variation of 0.042. An increase of 10% is observed in the average value of the SRF as compared to the matrix-only model. When the progressive failure surfaces are observed, a deeper failure surface is encountered at SRF values of around 1.27 to 1.37. The progression of the failure surface for one of the 15 models analyzed is shown in Figure 5.

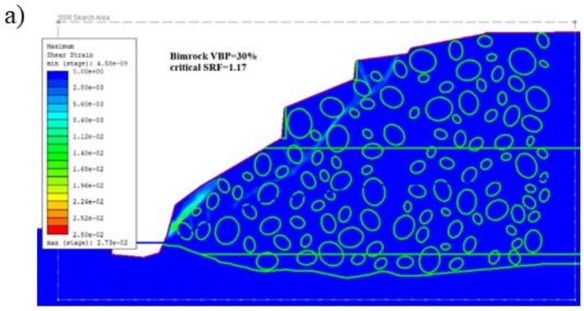

Figure 5. Maximum shear strains of one of the 30% VBP models. a) maximum shear strains corresponding to a shallow failure surface with critical SRF of 1.17; b) progression of failure surface, showing a deep failure surface at SRF=1.37.

Although statistically based and, therefore, more reliable than those of Minuto and Morandi (2015), these FEM analyses were not considered sufficiently adequate to allow the real in-situ conditions to be modelled. In fact, given the loosely packed material composing the slope, an interface between the matrix and rock blocks was introduced to simulate a bimsoil. When introducing the interfaces, (i.e. bimsoil slope analyses) a decrease in the average values of the SRF was observed as compared to bimrock models with the same VBP. For 15% and 30%VBP models, the average SRF values decreased by almost 3% and 6%, respectively. The shape and position of the failure surfaces of the bimsoil slopes was generally the same of the corresponding bimrock models.

A comparison of the SRF obtained for both the 15% and 30% VBP bimsoil and bimrock models are shown in Table 4.

Table 4. Comparison of the SF values obtained for both the bimrock (without interface elements) and bimsoil (with interface elements) slopes.

Model configuration	15% VBP		30% VBP	
	Bimrock	Bimsoil	Bimrock	Bimsoil
1	1.08	1.06	1.21	1.16
2	1.04	1.07	1.17	1.07
3	1.05	1.07	1.16	1.10
4	1.12	1.07	1.21	1.15
5	1.07	1.05	1.13	1.08
6	1.10	1.01	1.16	1.12
7	1.14	1.06	1.25	1.16
8	1.11	1.11	1.12	1.03
9	1.03	0.94	1.23	1.19
10	1.10	1.09	1.28	1.18
Mean	**1.08**	**1.05**	**1.19**	**1.12**
Std. Deviation	**0.034**	**0.045**	**0.050**	**0.050**
Coefficient of variation	**0.031**	**0.043**	**0.042**	**0.045**

3. Comparison with the LEM results

The results of Minuto and Morandi (2015) related to the matrix-only configuration were first validated numerically and comparable results were obtained. The comparison between FEM and LEM analyses shows some coherence for deep failure surfaces for both fine and coarse homogenous matrix-only models. This is because the LEM results obtained from the previous study considered only deep failure surfaces.

The heterogeneous configurations (i.e., 15% and 30% VBP models) also showed comparable deep failure surface positions. A good correspondence between the safety factor values of LEM and FEM analyses is shown for the 15% VBP models, whereas a significant difference was found for the 30% VBP models. In this last case the value of the SRF corresponding to the deep failure surfaces is rather lower than that obtained by Minuto and Morandi (2015). The reason could be that the authors have assumed a deeper failure surface, as they manually drawn a possible failure surface around the rock blocks.

The comparison of the SF obtained in this research and in the previous study of Minuto and Morandi (2015) is shown in Table 5. The SF values obtained for the bimsoil slopes are also listed, since these analyses are considered more representative of the real slope behavior.

Table 5. Comparison between LEM results from Minuto and Morandi (2015) and FEM results obtained in this research. The results obtained for the bimsoil slopes are also shown.

Model Type	**SF_LEM**		**SF_FEM**	
	Shallow-Deep failure surfaces (Lowest-Higher SF)	Deep failure surfaces of Minuto and Morandi (2015)	Critical SRF Shallow failure surfaces (Lowest SF)	Deep failure surface (Higher SF)
Fine matrix	0.85-0.98	0.99	0.85	0.99
Coarse matrix	1.02-1.28	1.21/1.28	1.11	1.25
15% VBP (bimrock)		1.20/1.44	1.08 (mean)	~1.25 (mean)
30% VBP (bimrock)		1.49	1.19 (mean)	~1.37 (mean)
15% VBP (bimsoil)			1.05 (mean)	~1.16 (mean)
30% VBP (bimsoil)			1.12 (mean)	~1.22 (mean)

4. Discussion and conclusions

FEM numerical analyses and the use of a stochastic approach have complemented the outcomes of the LEM study from Minuto and Morandi (2015), with reference to deep failure surfaces.

The results obtained show that shallow failure surfaces have a higher probability of occurrence (i.e., lower safety factors) as compared to deeper ones. This study also highlights the significant effect of the rock blocks within the slope, and confirms previous research that suggest to use a stochastic approach to account for different orientation, position, shape, and size of the blocks.

Similar SFs were obtained for the homogeneous (coarse matrix) and 15% VBP bimrock models. This outcome suggests that, for low block contents, the mechanical behavior of block-in-matrix materials is not affected by the presence of the stronger blocks. On the contrary, the failure surface positions and shapes change if heterogeneous instead of (simplified) homogeneous configurations are considered, and are deeper if rock blocks are located at the toe of the slope. For higher VBPs, an increase in the SF is observed as compared to the homogeneous (matrix-only) model. This increase is of about 10% passing from 15% to 30% VBP.

Given the unwelded characteristic of the geomaterial composing the slope, block-matrix interfaces (with a strength lower than that of the matrix) were added to the slope models analyzed previously, and further FEM analyses were carried out. The SFs yielded by these bimsoil slopes were lower than those of the bimrock slopes. For higher VBP values the difference between the SF values of bimrock and bimsoil analyses increases. Such a difference is greater than 6% for the 30% VBP models. This outcome, while expected, confirms the necessity to clearly classify the slope material as a bimrock or bimsoil during site investigations, in order to carry out more reliable simulations. It is worth pointing out that the mechanical properties assigned to the interfaces have a high impact on the stability analysis results. However, since these parameters are difficult to be defined practically, further research is needed in order to shed light on such a complex issue.

References

[1] Medley E W and Zekkos D 2011 Geopractitioner approaches to working with antisocial mélanges *Mélanges: Processes of Formation and Societal Significance - Geological Society of America Special Paper 480* vol 42, ed J Wakabayashi and Y Dilek pp 261–77

[2] Medley E W and Sanz Rehermann P F 2004 Characterization of Bimrocks (Rock/Soil Mixtures) With Application to Slope Stability Problems *Eurock 2004 & 53rd geomechanics colloquium* (Salzburg, Austria)

[3] Irfan T Y and Tang K Y 1993 *Effect of the coarse fractions on the shear strength of colluvium. Geo Report 23.*

[4] Napoli M L 2021 3D slope stability analyses of a complex formation with a block-in-matrix fabric *Challenges and Innovations in Geomechanics. IACMAG 2021. Lecture Notes in Civil Engineering, Vol. 126* (Turin: Springer) p 7

[5] Huang X, Wei Y, Ai W and Jiang P 2021 Stability analysis of soil - rock slope (SRS) with an improved stochastic method and physical models *Environ. Earth Sci.* **80** 1–21

[6] Khorasani E, Amini M, Hossaini M and Medley E 2019 Evaluating the effects of the inclinations of rock blocks on the stability of Bimrock slopes *Geomech. Eng.* **17** 281–7

[7] Napoli M L, Barbero M and Scavia C 2021 Effects of block shape and inclination on the stability of melange bimrocks *Bull. Eng. Geol. Environ.*

[8] Montoya-Araque E A, Suarez-Burgoa L O and Medley E W 2020 Application of the tortuous surface method to stochastic analysis of bimslope stability *Bull. Eng. Geol. Environ.*

[9] Minuto D and Morandi L 2015 Geotechnical Characterization and Slope Stability of a Relict Landslide in Bimsoils (Blocks in Matrix Soils) in Dowtown Genoa, Italy. *Eng. Geol. Soc. Territ. Landslide Process.* **2** 1083–8

[10] Sonmez H, Ercanoglu M, Kalender A, Dagdelenler G and Tunusluoglu C 2016 Predicting uniaxial compressive strength and deformation modulus of volcanic bimrock considering engineering dimension *Int. J. Rock Mech. Min. Sci.* **86** 91–103

[11] Schmüdderich C, Prada-Sarmiento L F and Wichtmann T 2021 Numerical analyses of the 2D bearing capacity of block-in-matrix soils (bimsoils) under shallow foundations *Comput. Geotech.* **136**

[12] Napoli M L, Barbero M and Scavia C 2019 Slope stability in heterogeneous rock masses with a block-in-matrix fabric *Rock Mechanics for Natural Resources and Infrastructure Development- Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering, ISRM* (Foz do Iguassu, Brazil) pp 3482–9