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ORIGINAL PAPER

Effects of block shape and inclination on the stability of melange bimrocks

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Abstract

A wide range of heterogeneous geological units composed of strong rock blocks enclosed in a bonded matrix of fine texture exists worldwide. Such geomaterials belong to geotechnically complex formations and are often referred to as *bimrocks* (block-in-matrix rocks) or *bimsoils* (block-in-matrix soils), as a function of their matrix characteristics and the interface strength between the matrix and blocks. Stability problems occurring in such complex geomaterials have been analysed almost exclusively by means of deterministic approaches and with the aim of investigating the effects of variable block contents on their mechanical behaviour. However, bimrocks and bimsoils can present very different internal block-in-matrix arrangements and properties according to their forming process and, consequently, significantly dissimilar mechanical behaviours. Therefore, the aim of this paper was to statistically investigate and compare the stability of theoretical slopes in the most widespread bimrock formations, i.e. sedimentary and tectonic melanges. These formations are characterised by substantial differences in their rock inclusion geometry. To this aim, a great number of 2D slope models were generated to enclose blocks with variable shapes, dimensions, arrangements, inclinations and contents. To obtain statistically based results, fifteen configurations were analysed for each block content and geometrical configuration considered. The results obtained indicate that block shapes and orientations significantly affect the stability of slopes in bimrocks only when the block contents are greater than 40%. Moreover, it is demonstrated that blocks inclined 0° to the horizontal provide the most tortuous and irregular failure surfaces and, consequently, the highest safety factors.

Keywords Block-in-matrix · Slope stability · Block shape · Block inclination · Volumetric block proportion · Tortuosity

Introduction

The term *bimrocks* (block-in-matrix rocks) was coined by Medley in 1994 to generically indicate mixtures of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture (Medley 1994). In this definition, the words "geotechnically significant" indicate that a sufficient mechanical contrast between the blocks and matrix must exist and that block sizes and content must contribute to the overall strength of the geomaterial at the scale of engineering interest, L_c (Medley 2001, 2007a). This parameter may variously indicate the diameter of a specimen or that of a tunnel, the height of an unstable slope or can be an indicator of an outcrop size.

Subsequently, following Medley's line, the term *bimsoils* (block-in-matrix soils) was also introduced to designate geologic units with rock blocks embedded in a soil-like matrix (Medley and Goodman 1994; Kalender et al. 2014; Sonmez et al. 2016). With respect to bimrocks, where blocks are bonded with the matrix and their contacts have the same shear strength as the matrix, bimsoils are characterised by unwelded block-matrix contacts.

Different complex geomaterials with a block-in-matrix (BIM) internal arrangement exist worldwide, such as sedimentary and tectonic melanges, conglomerates, agglomerates, breccias and glacial tills (Lindquist 1994; Gokceoglu 2002; Kahraman et al. 2008; Dong et al. 2013; Sonmez et al. 2016). Due to the great variability of their mechanical

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properties, the characterisation and modelling of these formations are extremely challenging tasks. Consequently, as documented in the literature, geological and geotechnical mischaracterisations caused many engineering works carried out in and on BIM materials to suffer technical problems, safety risks and costly consequences (Glawe and Upreti 2004; Medley 2007a, b).

In order to investigate the factors influencing the overall mechanical behaviour of these complex formations, much research has been conducted in the last decades. The results of these studies have shown that the strength, deformability and failure mode of these geomaterials mainly depend on the volumetric block proportion (VBP), when this parameter falls between 25 and 75% (Lindquist and Goodman 1994; Sonmez et al. 2004, 2006; Barbero et al. 2012; Coli et al. 2012; Afifipour and Moarefvand 2014; Napoli et al. 2018a, 2021; Napoli 2021). Moreover, the importance of taking blocks into account in the planning, designing and construction phases of any engineering work has also been underlined.

The strength of bimrocks and bimsoils has been mainly related to the VBP. However, several authors have also pointed out the importance that other parameters, such as the shape and orientation of the blocks, have on the mechanical response of these complex formations (Lindquist 1994; Lindquist and Goodman 1994; Li et al. 2013; Kalender et al. 2014; Guerra et al. 2016). However, further research must be performed in order to fully understand how these parameters may influence the behaviour of BIM geomaterials. In fact, these heterogeneous formations may present extremely variable geometrical characteristics of the blocks, as a result of different processes of formation. A striking example is given by the comparison between the most widespread bimrocks: tectonic and sedimentary melanges (Fig. 1). While the blocks in the former have an elongated shape, and are aligned with the main shear and/or fault zone, sedimentary melanges are characterised by a random distribution of irregularly shaped blocks within the matrix (Button and Riedmueller 2002; Button et al. 2004; Moritz et al. 2004; Festa et al. 2010; Aalto 2014). Hence, it is reasonable to assume that they also have extremely dissimilar mechanical behaviours.

To date, however, the problem has received scant attention in the research literature, especially in the field of slope stability. Previous studies on this topic have demonstrated that the overall mechanical behaviour of these complex formations is mainly affected by their VBP, and that the presence of stronger rock inclusions adds strength to BIM geomaterials by inducing the development of tortuous failure surfaces around the blocks (Irfan and Tang 1993; Lindquist 1994; Medley 1994, 2004). Hence, when dealing with slope stability problems almost all researchers focused their attention on exploring the effects of variable block contents on the mechanical response of such geomaterials. The analyses have been carried out almost exclusively by means of deterministic approaches and with limit equilibrium methods (LEM) (Irfan and Tang 1993; Kim et al. 2004; Medley and Sanz Rehermann 2004; Adam et al. 2014; Minuto and Morandi 2015), and only more recently by using finite element (FEM) modelling (Napoli et al. 2018a, b; Khorasani et al. 2019b, a).

When the LEM approach is used, a common practice is to manually draw possible failure surfaces negotiating around the blocks and evaluate the relative SFs, as was the case in Irfan and Tang (1993), Medley and Sanz Rehermann (2004), Minuto and Morandi (2015) and Guerra et al. (2016). Several authors (Guerra et al. 2016; Napoli et al. 2018a; Montoya-Araque et al. 2020) have pointed out that, when performing slope stability analyses in heterogeneous geomaterials, the LEM cannot be applied using the classic grid search method with circular failure surfaces. In fact, these failure surfaces, which intersect the stronger blocks, are not representative of the real problem and generally lead to higher safety factors and unreliable positions of the failure surfaces.

A valuable contribution to the LEM modelling is represented by the recently developed pyBIMstab software (Montoya-Araque and Suarez-Burgoa 2019), which performs 2D stability analyses with the LEM approach either for heterogeneous or homogeneous geomaterials. This open-source application software uses the optimum pathfinding algorithm named A* (A star) to automatically generate tortuous failure surfaces when a BIM material is analysed (Montoya-Araque and Suarez-Burgoa 2018). The

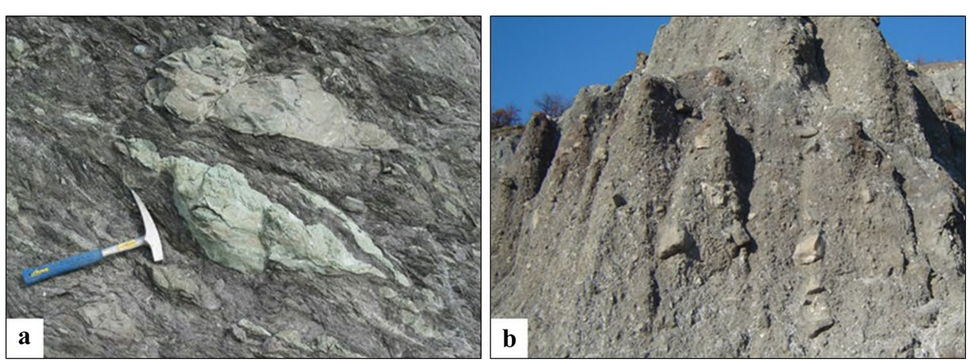

Fig. 1 An example of: **a** a tectonic melange; **b** a sedimentary melange (Festa et al. 2010)

potential of this tool is that it allows the subjectivity of tracing tortuous surfaces by hand to be avoided.

The main findings of the studies mentioned above show that stability increases with increasing VBP and that both the position and shape of failure surfaces are strongly affected by the presence of the rock inclusions. However, as recent works have highlighted, deterministic approaches present several limitations. In fact, the uncertainty in the results that may be caused by different block arrangements and dimensions, as well as the occurrence of block-poor (or block-rich) zones within the geomaterial, can only be taken into account if a stochastic approach is used (Napoli et al. 2018a; Khorasani et al. 2019b, a; Montoya-Araque et al. 2020).

More rigorous, statistically based FEM analyses were carried out by a few authors, who investigated the effects of VBPs on safety factors (SFs), volumes involved and failure surfaces tortuosity of slopes in bimsoils (Khorasani et al. 2019b, a) and bimrocks (Napoli et al. 2018b, a). In order to take the inherent variability of bimrocks and bimsoils into account, these authors analysed ten configurations for each VBP considered. The findings of these studies confirm that a significantly higher level of stability is obtained for higher VBPs, which was ascribed to the increase in the tortuosity of the failure surfaces. On the other hand, when the VBPs fell between 20 and 25%, it was also observed that the presence of the blocks can sometimes produce a negative contribution to the stability of BIM slopes (i.e. SFs lower than those obtained with the matrix-only models). Moreover, a significant variability in the results was provided by the different configurations analysed for each VBP, which increased for higher block contents. This effect was attributed to the variable sizes and locations of the rock blocks within slope models with the same VBP. These outcomes highlight the potential of performing stochastic rather than deterministic analyses and demonstrate that stochastic analyses are essential for prudent geotechnical design.

The 2D FEM analyses carried out by Khorasani et al. (2019a) were also aimed at evaluating the effect of different block inclinations on the stability of slopes in bimsoils. The authors found that when the inclination of the blocks was closer to that of the slope, the lowest SFs were obtained and that for VBPs lower than 40% the presence of these rock inclusions provided no significant strength increase with respect to the 0% VBP model. On the contrary, the highest SFs were obtained when the inclination of the elliptical blocks deviated the most with respect to the slope face.

In this paper, an extensive study was carried out to statistically investigate the influence of different geometric parameters of the rock inclusions on the stability of theoretical slopes in different BIM formations, by means of 2D Finite Element (FEM) analyses. Given the wide diffusion of melanges, sedimentary-chaotic and tectonic melanges were chosen to simulate the BIM materials composing the slopes. These geological units are characterised by dissimilar shapes, eccentricity and orientations of the blocks, and are the most widespread BIM geomaterials. Since the rock blocks considered have regular shapes (i.e. circular, elliptical), the FEM approach was used instead of other advanced methods, such as the numerical manifold method (Yang et al. 2019; Wu et al. 2020). In order to take the inherent variability of bimrocks into account, fifteen configurations were generated for each set of geometric input parameters considered, for a total of 600 slope models, so as to achieve statistically based results.

Slope stability analyses in sedimentary and tectonic melange bimrocks

Melanges are the most widespread and intractable of bimrocks and, for this reason, have been extensively studied by many authors from all over the world (Medley 1994; Püstow 2001; Button et al. 2004; Kim et al. 2004; Moritz et al. 2004). Geologists have defined these formations as “mappable bodies (at 1:25,000 or smaller scale) of internally disrupted and mixed rocks, with exotic lithologies included as discrete masses (i.e. blocks) in a pervasively deformed finer grained matrix, without restriction to any particular lithological unit” (Raymond 1984; Cowan 1985; Festa et al. 2010). Different processes may lead to the formation of melanges: the adjectives “tectonic”, “sedimentary”, “diapiric” and “polygenetic” (i.e. formed by the interplay and superimposition of tectonic, sedimentary and/or diapiric contributions) are therefore used to indicate their origin (Festa et al. 2020).

To date, no previous study has been carried out to compare the mechanical response of melanges presenting dissimilar BIM fabrics which result from different geological forming processes.

In light of the above, in this paper, the statistical approach proposed by Napoli et al. (2018a), and implemented in a Matlab code, was used to compare the stability of theoretical slopes in sedimentary-chaotic and tectonic melanges.

A great number of 2D Finite Element (FEM) analyses were carried out assuming that the geomaterial has different VBPs and block orientations and shapes (circular/slightly elliptical for the sedimentary melange and elliptical for the tectonic melange).

The matrix-only approach, which does not take the presence of blocks into account, was also applied, by way of comparison.

Characteristics and properties of the melange slope models

The bimrock models analysed had a slope height (corresponding to the L_c) equal to 50 m, a slope inclination equal to 45°, the typical melanges fractal block-size distribution

Table 1 Geometrical configurations considered and number of simulations performed. Sedimentary melanges are modelled by using circular (e = 0) and elliptical blocks with e = 0.5, while tectonic melanges are modelled by using elliptical blocks with e = 0.87

Shape	Eccentricity (e)	Orientation (i)	Number of simulations performed				
			0%VBP	25%VBP	40%VBP	55%VBP	70%VBP
Circular	0	-		15	15	15	15
Elliptical	0.5	0°		15	15	15	15
Elliptical	0.5	30°		15	15	15	15
Elliptical	0.5	60°		15	15	15	15
Elliptical	0.5	90°		15	15	15	15
Elliptical	0.5	Random	1	15	15	15	15
Elliptical	0.87	0°		15	15	15	15
Elliptical	0.87	30°		15	15	15	15
Elliptical	0.87	60°		15	15	15	15
Elliptical	0.87	90°		15	15	15	15

(Medley 1994), block dimensions in the range 5–75% L_c, different block shapes and VBPs equal to 25%, 40%, 55% and 70%. Circular and elliptical rock inclusions were modelled to simulate (i) sedimentary melanges, characterised by sub-rounded blocks, and (ii) tectonic melanges, composed of elongated blocks aligned with the main shear and/or fault zone. Specifically, three eccentricity values, *e*, were assigned to the blocks to simulate the different melanges ($e = 0$, 0.5 for sedimentary melanges and $e = 0.87$ for tectonic melanges). Moreover, five orientations to the horizontal, *i*, ($i = 0°$, 30°, 60°, 90°, random) were assigned to the elliptical blocks to represent variable on-site conditions. A random inclination was used to model only sedimentary melanges, since tectonic melanges very rarely present a chaotic arrangement of the rock inclusions.

The slope models were created by using a new Matlab routine, modified from that developed and described in detail in Napoli et al. (2018a) for the generation of circular blocks. The code is based on the classical random sequential addition (RSA) procedure. Specifically, the Matlab routine generates blocks with random sizes and positions within the slope models, according to specific statistical rules, VBPs, eccentricities and orientations. Moreover, block overlapping and block-external boundary intersections are avoided. Although improved algorithms have been proposed recently in the literature to more efficiently place rock inclusions within bimrock models (Chen et al. 2018), the code used in this paper has an extremely low computational cost. In fact, only a few seconds are required to generate the models, even when high VBPs are considered.

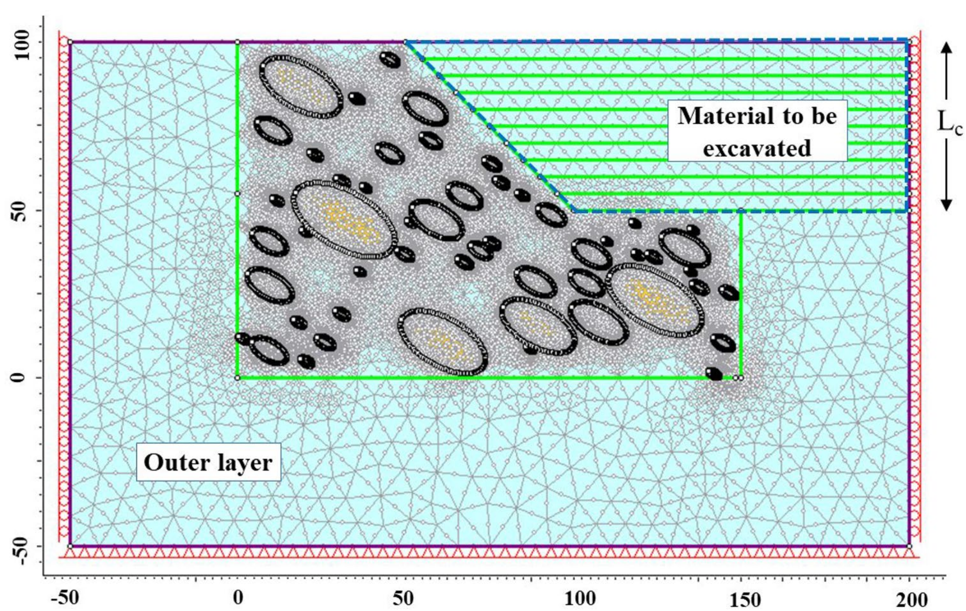

Fig. 2 Example of a tectonic melange with 40% VBP, block eccentricity = 0.87 and block inclination = 30° (clockwise)

Table 2 Input parameters for the matrix and blocks

	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

A total of 601 2D slope stability analyses were carried out with the FEM code RS2 from Rocscience. In fact, as shown in Table 1, for each VBP and geometrical configuration considered, 15 bimrock slope models were generated so as to achieve a statistical validity of the results.

An example of a tectonic melange model slope is given in Fig. 2. Both vertical and horizontal translations were restrained at the bottom boundary, while the vertical boundary was restrained laterally, but was free to move vertically.

A ten stages excavation process was used to reproduce the face geometry of the slope, in order to avoid stress modelling disturbance. As shown in Fig. 2, the bimrock models were modified to include an outer homogeneous layer with the same properties of the matrix, in order to avoid boundary effects. Six-node triangular elements, with higher density around the rock blocks, were used to mesh the models. Both the matrix and blocks were assumed to have an elastic-perfectly plastic behaviour and to obey the Mohr–Coulomb failure criterion. The input parameters used in all the analyses are listed in Table 2. These parameters were chosen in order to assure a sufficient mechanical contrast between competent blocks and weaker matrix, in accordance with the literature (Medley 2001, 2007a; Medley and Sanz Rehermann 2004; Wakabayashi and Medley 2004).

Results

The results obtained are listed in Table 3 in terms of average normalised safety factors (SF_N) and standard deviations (σ). The SFs were normalised by dividing them by the SF of the matrix-only model to generalise the findings. An example is given in Table 4.

For the sake of clarity, the average normalised SFs are partially presented in Fig. 3 and Fig. 4. Figure 3 shows the average SF_N of slopes with circular and elliptical blocks with $e = 0.5$ (i.e. sedimentary melange slopes with sub-rounded blocks). Figure 4 shows the average SF_N of slopes with elliptical blocks with the major axis equal to twice the minor axis (i.e. $e = 0.87$, simulating tectonic melange slopes). The average SF_N provided by all the analyses are shown in the graph in Fig. 5.

These results confirm previous findings from the literature, which highlight that the presence of the blocks provides little geomechanical advantage for low VBP values (i.e. 25% VBP) with respect to the matrix-only model, while for higher rock contents the SFs increase significantly (Lindquist 1994; Medley and Sanz Rehermann

Table 3 Results of the analyses. σ indicates the standard deviation obtained from the 15 analyses carried out for each VBP and geometrical configuration considered, while SF_N indicates the SF normalised with respect to the SF of the 0% VBP model

Circular blocks—$e = 0$										
VBP [%]	σ	SF_N								
25	0.053	1.03								
40	0.058	1.01								
55	0.083	1.11								
70	0.171	1.37								
Elliptical blocks—$e = 0.5$										
	$i = 0°$		**$i = 30°$**		**$i = 60°$**		**$i = 90°$**		**$i =$ random**	
VBP [%]	σ	SF_N	σ	SF_N	σ	SF_N	σ	SF_N	σ	SF_N
25	0.064	1.00	0.030	1.01	0.108	1.05	0.075	1.03	0.051	1.01
40	0.067	1.05	0.050	1.03	0.096	1.02	0.050	1.05	0.060	1.02
55	0.143	1.21	0.044	1.09	0.074	1.07	0.080	1.07	0.075	1.09
70	0.188	1.55	0.133	1.28	0.143	1.18	0.187	1.25	0.163	1.39
Elliptical blocks—$e = 0.87$										
	$i = 0°$		**$i = 30°$**		**$i = 60°$**		**$i = 90°$**			
VBP [%]	σ	SF_N	σ	SF_N	σ	SF_N	σ	SF_N		
25	0.044	1.01	0.079	1.06	0.099	1.05	0.060	1.04		
40	0.039	1.05	0.108	1.07	0.041	1.04	0.049	1.03		
55	0.062	1.10	0.104	1.12	0.053	1.07	0.076	1.08		
70	0.153	1.38	0.079	1.17	0.095	1.30	0.104	1.29		

Table 4 Normalised SFs and average normalised SFs, SF_N, obtained for the 15 configurations with elliptical blocks with $e=0.5$ and 25% VBP

SF_matrix	SF_bimrock	Normalised SFs (SF_bimrock/SF_matrix)	Average normalised SF (SF_N)
	0.93	1.00	
	0.88	0.95	
	0.86	0.92	
	0.89	0.96	
	1.00	1.08	
	1.06	1.14	
	0.82	0.88	
0.93	0.91	0.98	1.00
	1.00	1.08	
	0.96	1.03	
	0.93	1.00	
	0.91	0.98	
	0.88	0.95	
	1.00	1.08	
	0.95	1.02	

2004; Napoli et al. 2018a, 2019; Khorasani et al. 2019b). As shown in Fig. 6 and Fig. 7, both shear strains and failure surfaces are far different from the matrix-only model. They pass tortuously around the blocks, demonstrating that the highest strength depends on the increase of failure surface tortuosity with increasing VBP. This behaviour is more evident the higher the VBP values, and is affected by the dimension, shape and position of the blocks. As a consequence, higher VBPs produce more variable unstable volumes, since the instability can be both shallower or deeper than that of the matrix. This variability is reflected in the higher standard deviations yielded by the slope models with 70% VBP listed in Table 3.

However, one of the most striking findings to emerge from the results obtained is that if a preferred orientation of the clasts exists this seems to affect the stability of slopes in bimrocks for VBP higher than 40% only (Fig. 5). In fact, for VBPs equal to 25% and 40% the (slight) increase of the average SFs cannot be correlated to specific geometric characteristics of the blocks (eccentricity and orientation) but only to the higher block content.

On the other hand, it is apparent from Fig. 5 that, for VBPs equal to 55% and 70%, when the major axes of the elliptical rock blocks are inclined 0° to the horizontal, whatever the eccentricity, the highest SFs are obtained. It is important to highlight that this inclination deviates greatly from that of the slopes, which is 45°, and produces more tortuous failure surfaces with respect to the other geometrical configurations analysed (Fig. 7). On the other hand, when the rock inclusions are inclined at angles similar to that of the slope, less tortuous failure surfaces are obtained. The positive effect of a higher tortuosity on the stability of the melange slopes is clearly shown in Fig. 7. In this figure, all the failure surfaces of the models with elliptical blocks and eccentricity $e=0.5$ are compared, considering the two inclinations that yielded the maximum and minimum average SF_N, $i=0°$ and $i=60°$, respectively. From the inspection of this figure, it is apparent that less variable and tortuous failure surfaces are obtained when $i=60°$, which have yielded average SF_N up to about 23% lower than $i=0°$ configurations (for VBP = 70%).

Moreover, sedimentary melange slopes with rounded blocks and slightly elliptical blocks with a random orientation (i.e. configurations with $e=0$, and with $e=0.5$ and $i=$random) also provide high SFs with respect to the other geometrical configurations.

All the other slope models analysed (e.g. $e=0.87$ and $i=30°$, $e=0.87$ and $i=60°$, etc.) present an evident positive

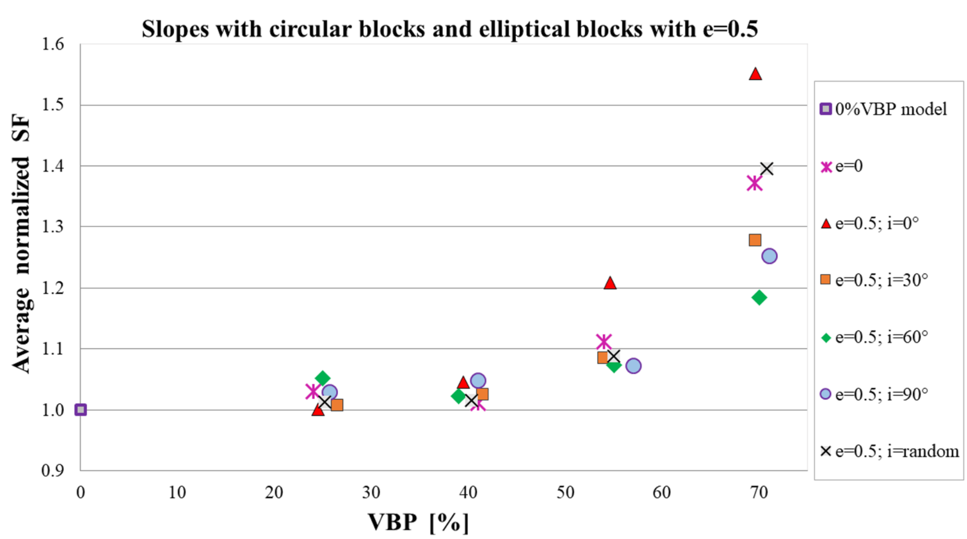

Fig. 3 Average normalised SFs as a function of the VBP for the slopes with blocks with $e=0$ and $e=0.5$ (sedimentary melange slopes). Some normalised SFs are slightly shifted to the left/right to avoid graphical overlapping

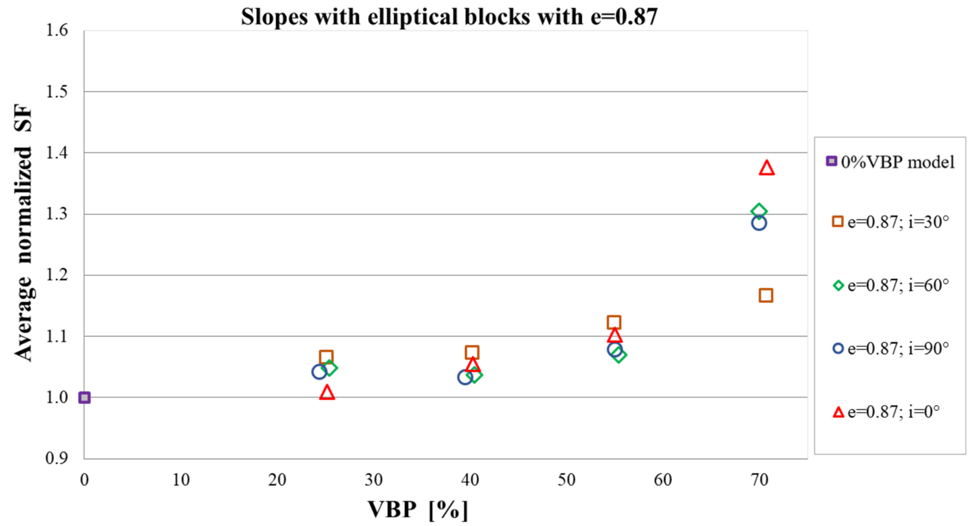

Fig. 4 Average normalised SFs as a function of the VBP for the slopes with blocks with $e=0.87$ (tectonic melange slopes). Some normalised SFs are slightly shifted to the left/right to avoid graphical overlapping

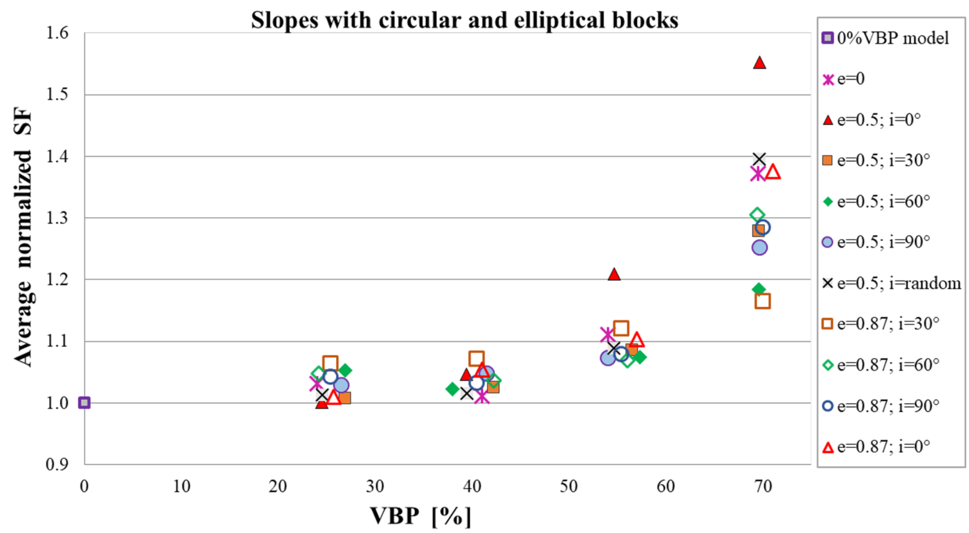

Fig. 5 Average normalised SFs as a function of the VBP for all the slopes analysed. Some normalised SFs are slightly shifted to the left/right to avoid graphical overlapping

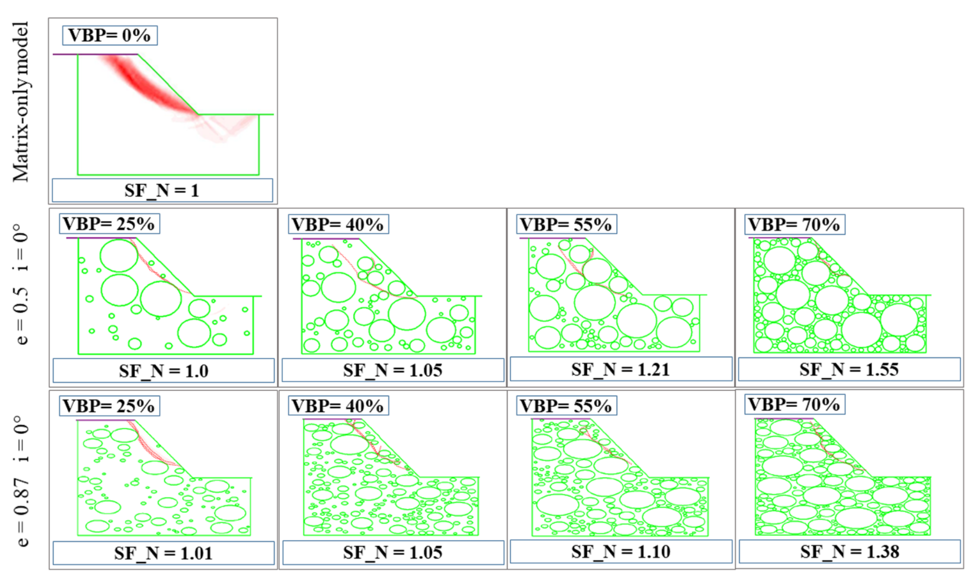

Fig. 6 Location of maximum shear strains obtained for one of the 15 bimrock configurations generated with elliptical blocks inclined 0° to the horizontal, for each VBP considered. The average normalised SFs are also indicated. The matrix-only model result is also shown by way of comparison

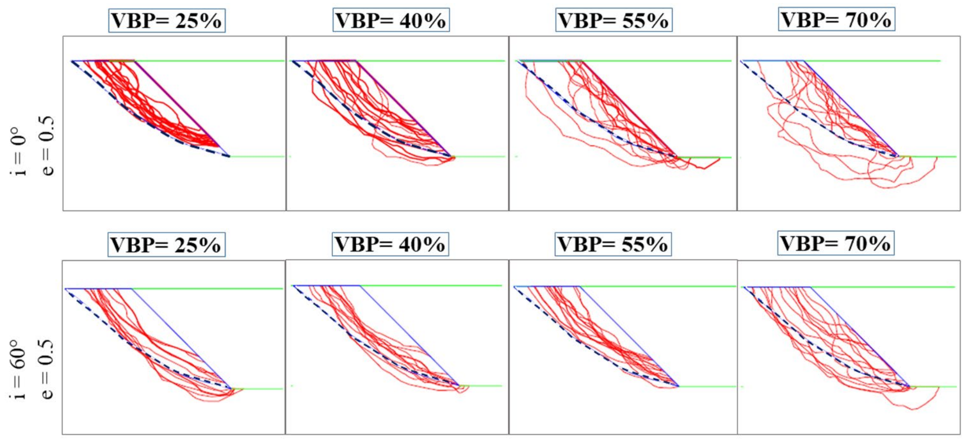

Fig. 7 Superimposition of the 15 failure surfaces obtained for each VBP considered from the bimrock configurations having blocks with $e = 0.5$ and $i = 0°$ and 60°. The matrix-only model result is also shown with the dotted line, by way of comparison

correlation between the normalised SFs and block contents in the range 55–70% VBPs. However, their SF increase is less marked with respect to the abovementioned configurations and cannot be clearly attributed to the geometrical characteristics of the blocks.

Discussion and conclusions

The overall mechanical behaviour of bimrocks and bimsoils has been experimentally and numerically demonstrated to be mainly affected by their block content. In this regard, almost all the researchers who have investigated slope stability have focused their attention on exploring how the strength and failure mode of such geomaterials are affected by the presence of the blocks and their content and arrangement. However, there has been no detailed investigation of the effects of other rock block properties (e.g., inclination and eccentricity) on the stability of slopes in bimrocks.

BIM formations encompass a wide range of heterogeneous geological units, which can have extremely different block characteristics according to their forming process. Hence, the main goal of this research was to compare the overall mechanical behaviour of bimrock slopes constituted by different geometries and properties of the rock inclusions. Specifically, variable block shapes and orientations were used to simulate the two melanges, which are the most widespread bimrocks. In particular, the stability of the sedimentary melanges, composed of sub-rounded blocks, and tectonic melanges, characterised by elongated blocks, was extensively investigated by means of a stochastic approach. To this aim, a new modified version of the Matlab code proposed by Napoli et al. (2018a), performing Monte Carlo simulations, was developed. The code was used to generate a total of 600 bimrock models containing blocks with circular/elliptical shapes, random sizes and positions, different inclinations and eccentricities, and VBPs in the range from 25% up to 70%. A 0% VBP slope was also analysed to compare the results. The modelling was carried out with the FEM code RS2 from Rocscience.

In this study, the effects of the block shape and orientation were found to significantly affect shear strains, safety factors, failure surfaces and unstable volumes for VBPs higher than 40% only (Fig. 5), while for the lowest block contents analysed less marked differences were obtained with respect to the matrix-only model results.

The highest SFs were obtained for bimrock slope models with VBPs equal to 55% and 70%, when elliptical rock blocks were inclined 0° to the horizontal, whatever their eccentricity. This inclination, which deviates greatly from that of the slopes, produced more tortuous and irregular failure surfaces (with respect to the other geometrical configurations analysed). This had a positive effect on the stability of the melange slopes. On the contrary, rock inclusions inclined at angles similar to that of the slopes yielded less tortuous failure surfaces (i.e. less irregular unstable volumes) and, consequently, lower SFs.

Although the other geometrical configurations analysed produced an evidently positive correlation between the average SFs and VBPs, especially for VBPs greater than 40%, the SF increase was less evident and appeared to be unaffected by the specific geometrical characteristics of the blocks.

It is also interesting to note that, in general, the sedimentary melange slopes provided higher SFs than the tectonic melange slopes. Moreover, particularly high SFs were obtained from the configurations with rounded blocks and randomly orientated slightly elliptical blocks (i.e. sedimentary-chaotic melanges). However, it is worth pointing out that for the sake of simplicity and in order to compare the results, the same mechanical properties were assigned to the matrix and blocks of both the sedimentary and tectonic melanges, which may represent a possible limitation of this study. Another limitation of this study is that plane strain conditions were assumed for both the matrix and blocks by analysing 2D bimrock configurations instead of more realistic 3D models. However, as

Table 5 Student's *t*-test results

VBP	Average SFs	σ_X	C.L. = 95% (α = 5%)	
			Confidence interval	
25%	0.932	0.064	0.97	0.9
40%	0.973	0.067	1.01	0.94
55%	1.125	0.143	1.21	1.04
70%	1.443	0.188	1.55	1.34

demonstrated by Napoli (2021), potential mistakes resulting from 2D rather than 3D analyses should be found to lie on the side of safety.

Overall, the results of this modelling indicate that, when working with such heterogeneous materials, careful geological studies must be performed in order to obtain the necessary information to generate slope models with representative block shapes and orientations, especially when high VBPs are expected.

Another important finding of this work is that a significant variability in the results was obtained from the 15 models analysed for each configuration considered (standard deviations listed in Table 3), especially when melanges with high block contents were simulated. This outcome confirms previous findings from the literature, which have recommended the use of a stochastic rather than a deterministic approach to analyse slope stability in bimrocks and bimsoils (Napoli et al. 2018a; Khorasani et al. 2019a; Montoya-Araque et al. 2020). A statistical test was also performed to justify the use of 15 configurations. In particular, a two tailed *t*-test was performed for the case elliptical blocks ($e = 0.5$). A confidence level (C.L. = 1-α, where α is the significance value) of 95% was used, with a critical t value ($t_{1-\alpha/2} = t_{0.975}$) of 2.13, corresponding to n = 15 degrees of freedom. As shown in Table 5, the test can be accepted because, for each VBP, the average SF lies between the upper and lower limits ("Confidence interval"), which are also close to each other.

It could be interesting in future to investigate the stability of other bimrock formations, by considering other mechanical properties of the matrix, further block shapes and orientations and different block-matrix contact strengths.

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Declarations

Conflict of interest The authors declare no competing interests.

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