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Evaluating the effects of the inclinations of rock blocks on the stability of bimrock slopes

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Abstract. The process of slope stability analysis is one of the most important stages in design of some civil and mining projects. Bimslopes are made from bimrocks (block-in-matrix rocks) where rocky blocks are distributed in a bonded matrix of finer texture. These kind of slopes are often seen in weathered and near-surface depths. Previous studies have shown that VBP (Volumetric Block Proportion) is one of the most significant factors affecting bimrocks strength and consequently the stability of bimslopes. In this paper, the influence of block inclinations on bimslope stability have been investigated. For this purpose, 180 theoretical models have been made with various VBPs, all of them have a specified block size distribution. These bimslopes contain blocks with differing dips relative the slope inclination. Also for each kind of block inclination, 10 different blocks arrangements have been modeled. The Finite Element Method (FEM) was used to analysis the stability of these bimslopes models. The results showed the inclination of blocks has a strong impact on the Safety Factor and stability of bimslopes. When the difference in angle of dip of blocks relative to the slope angle is maximum, the Safety Factor of bimslopes tends to be a maximum compared with the matrix-only state. Furthermore, with increasing VBP of bimslopes stability increases. The graphs obtained from this study could be used for preliminary guidance in the projects design with bimslopes.

Keywords: bimrocks; bimslopes; blocks inclination; numerical modeling; FEM

1. Introduction

The behaviors of purely soil and purely rock masses have been widely analyzed. However, there are common geological environments in which included the rocky blocks are randomly scattered in weaker (sometimes soil-like) matrix masses. Such block-in-matrix rocks (bimrocks) are highly problematic geological masses for construction of engineering applications on/in them due to the complex engineering behavior, even more so than the problems related to working with jointed rock masses (Lindquist 1994, Kahraman and Alber 2006, Bieniawski 1989, Hoek and Brown 1980, Hoek *et al.* 2002). Fig. 1 illustrates an outcrop of bimrocks in Iran, where rock blocks with various dimensions can be seen. Blocks commonly have an irregular shape, often a crude form of ellipsoid, with a major axial dimension larger than the minimum dimension.

Several studies have been conducted to identify bimrocks (Medley 1994, Riedmuller *et al.* 2001, Afifipour and Moarefvand 2014, Tsesarsky *et al.* 2016). But there are still many poorly-understood unknown aspects of bimrocks behavior such as the performance of bimrock masses in slope stability.

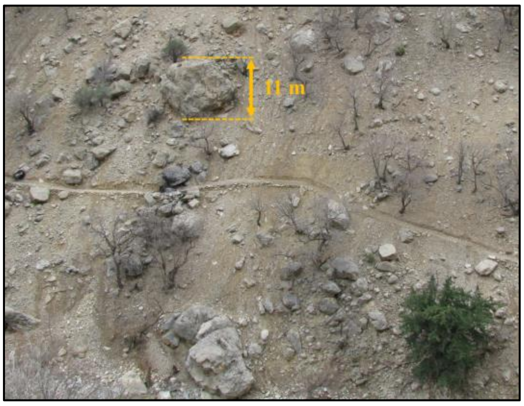

Fig. 1 An outcrop of bimrocks (Seydoon dam site, Iran)

The stability analysis of slopes is one of the important steps in the design of many geotechnical projects. Slope instability and failures occur because of several already well-understood natural factors such as adverse slope geometries, geological discontinuities, weak or weathered slope materials as well as severe weather conditions. But stability assessment of slopes in bimrocks is further complicated by uncertain factors such as inherent spatial variability of soil or rock properties and simplifications in the analysis procedure (Medley 1994). Several statistical

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approaches have been developed to take these uncertainties into account in the performance of slope stability analysis (Napoli *et al.* 2018). Medley and Sanz (2004) have studied about stability of bimslopes using analytical solution and showed with increasing the Volumetric Block Proportion (VBP) in bimrock slopes (bimslopes), the safety factor increased. In this regard, numerical methods can be used to investigate the behavior of bimslopes, which are usually more powerful than analytical solutions for solving complex geotechnical problems. Numerical modeling is a widely used of the technique for the many methods employed for determining the safety factor of slopes (Li *et al.* 2018).

In this paper, the importance of inclinations of blocks on the stability of bimslopes has been investigated. For this purpose, the Finite Element Method (FEM) has been utilized. 180 numerical models with different VBPs (20, 40 and 60%) were made and analyzed.

2. Bimrocks characteristics

Bimrocks are defined as mixtures of rocks composed of geotechnically significant blocks within a bonded matrix of finer texture such as melanges, fault rocks and weathered rocks (Medley 1994). The determination of the mechanical properties of bimrocks, or the more soil-like bimrocks or Soil-Rock Mixtures (S-RM), by standard laboratory tests is a very difficult and challenging task, mostly because it is problematic to obtain undisturbed core and samples of representative dimensions (Sonmez *et al.* 2006, Kahraman and Alber 2006, Xu *et al.* 2011, Xia *et al.* 2017, Yu *et al.* 2018). In bimrocks, various methods can be applied for characterizing the blocks, involving the one-dimensional scanlines method, the two-dimensional image processing technology and the three-dimensional sieving method (Medley 1994, Yue *et al.* 2003, Chen *et al.* 2004, Sonmez *et al.* 2004, Jin *et al.* 2017).

According to previous studies on the bimrocks, the Volumetric Block Proportion (VBP) parameter is one of the most important factors in characterization of these complex formations (Lindquist 1994, Afifipour and Moarefvand 2014, Kalender *et al.* 2014, Zhang *et al.* 2016, Napoli *et al.* 2018). When the VBP ranges from 0.25 to 0.75, the increase in the overall mechanical properties of bimrocks are directly related to the VBP. For VBP more than 0.75, the rock mass can be considered as a "blocky rock mass with infilled joints" (Medley 1994, Lindquist and Goodman 1994).

A sufficient strength and/or stiffness contrast is necessary for a block-in-matrix rock mass to be considered a bimrock (Kalender *et al.* 2014). The generally suggested criteria for bimrocks in terms of stiffness, internal friction angle and Uniaxial Compressive Strength (UCS) are given in Table 1. The strengths of blocks do not significant influence on overall strength of a bimrock. If there is sufficient strength contrast between block and matrix is necessary to force failure surfaces to pass tortuously around blocks (Medley 1994, Lindquist 1994), the overall bimrock strength increases the greater the tortuosity–which is dependent on block shapes, sizes, frequency and size distribution.

Table 1 Strength and stiffness contrasts between blocks and matrix in bimrocks

Criterion	References
(UCSblocks/UCSmatrix) > 1.5	Medley and Zekkos (2011)
(Eblocks/Ematrix) > 2	Lindquist (1994)
(tanϕblocks/tanϕmatrix) > 1.5-2	Medley (1994), Lindquist and Goodman (1994)

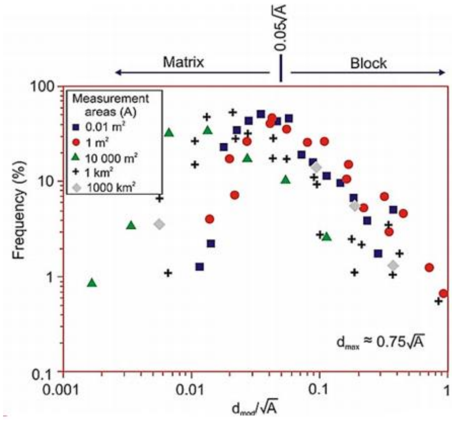


Fig. 2 Normalized block size distribution of Franciscan melange to identify scale independence, After Medley (1994)

The overall mechanical properties of bimrocks are affected by the mechanical properties of the matrix and the blocks, the VBP, the block shapes, the block size distributions and the inclination of blocks (Tsesarsky *et al.* 2016, Xia *et al.* 2017). The boundary strength between block and matrix can be considered as the weakest component in terms of strength (Sonmez *et al.* 2016). Block-in-matrix masses with weak to non-existent contacts strengths denotes "unwelded" blocks on bimsoils (colluvial, tills). Bimrocks generally have some "welding" between the blocks and matrix.

The block size distributions of one kind of bimrocks (Franciscan Complex melanges of northern California) are presented in Fig. 2. In this figure, "A" is the map or plan area of at scales of interest between centimeters and kilometers. The "blocks" of the melanges with dimensions smaller than $0.05\sqrt{A}$ are parts of the matrix. The horizontal axis of Fig. 2 is a normalized parameter: the ratio of maximum observed dimension (d_{mod}) of blocks to $\sqrt{A}$. As seen, the block size distribution of this bimrocks is scale-independent and self-similar (fractal) (Medley 2001). Work performed by Grigull *et al.* (2012) also shows self-similarity of melanges from several locations around the world over scales from millimeters to hundreds of meters. But self-similarity and scale-independence is common for many other comminuted geological materials and has considerable practical value: because of the scale-independence of the block size distributions of the materials, laboratory or in-situ testing programs or analytical investigations at those scales more reasonably model in-site conditions despite the larger block sizes at field scales. In general, for Franciscan melanges: one large block, there will be about 5 blocks with overall dimension about half of the larger block. 25 blocks with sizes about one quarter of the large block size - and so on.

In this study, the block size distribution of Franciscan melange was used to fabricate the theoretical bimslope models.

3. Numerical modeling

Finite Element Method (FEM) by Phase^2 8.0 was used to investigate about the stability of bimslopes. The parameter Areal Block Proportion (ABP) is variable in numerical models and is equal to 20, 40 and 60%. With regard to 2D modeling in this research, it is assumed that the parameter ABP is identical to VBP, although such an assumption may not be generally valid for real bimrocks (Medley 1997, Medley and Sanz 2004).

The height and face angle of the numerical bimslopes were selected as 10 m and 45°, respectively. Different inclinations of the ellipsoid blocks were selected including 0, 30, 60, 90, 120 and 150 degrees (counter-clockwise relative to horizontal). For each kind of blocks inclination, 10 different blocks arrangements have been made. In this regard, the blocks were placed randomly and manually. It is noteworthy that there are some methods for random generation of blocks in bimrocks models, which are more realistic in problems where the blocks have different shapes (Xu *et al.* 2016a, b, Cen *et al.* 2017, Meng *et al.* 2018).

Table 2 presents the properties of the blocks and matrix. In addition, the properties of matrix-block interfaces are shown in Table 3. As seen, the values of strength properties of the interfaces are less than the matrix values. These blocks are considered to be weakly "welded" to the matrix, a necessary condition for bimrocks.

To mesh the numerical models, three noded triangles with fine sizes were employed. Fig. 3 shows three examples of the numerical bimslopes with different VBPs and block inclinations. In this figure, the general geometry, boundary conditions as well as the finite element mesh built for them were illustrated. Based on sensitivity analysis, Mohr-Coulomb criterion was selected for mechanical behavior of the materials, which is the most common model in the context of geomaterials. Besides, interfaces between blocks and matrix were simulated as joint in the software. The critical Strength Reduction Factor (SRF) was determined for all models, which considered is equivalent to the Safety Factor (SF) of slopes in Phase^2 8.0.

4. Results and discussion

As mentioned, 180 different numerical models of bimslopes were analyzed. A plot of maximum shear strain of a bimslope having blocks with a dip of 30° is shown in Fig. 4. As seen, the failure surface is formed through the matrix negotiating around blocks. In all numerical models, the strength contrast between matrix and blocks at the interface between matrix and blocks were the delimiting factors for the development the trajectory of slip surfaces.

The safety factor of the matrix-only slope was equal to 0.88 and all the SFs of bimslopes were normalized using this value. Table 4 presents the statistical parameters of the Normalized Safety Factors (NSF) resulting from the numerical analyses.

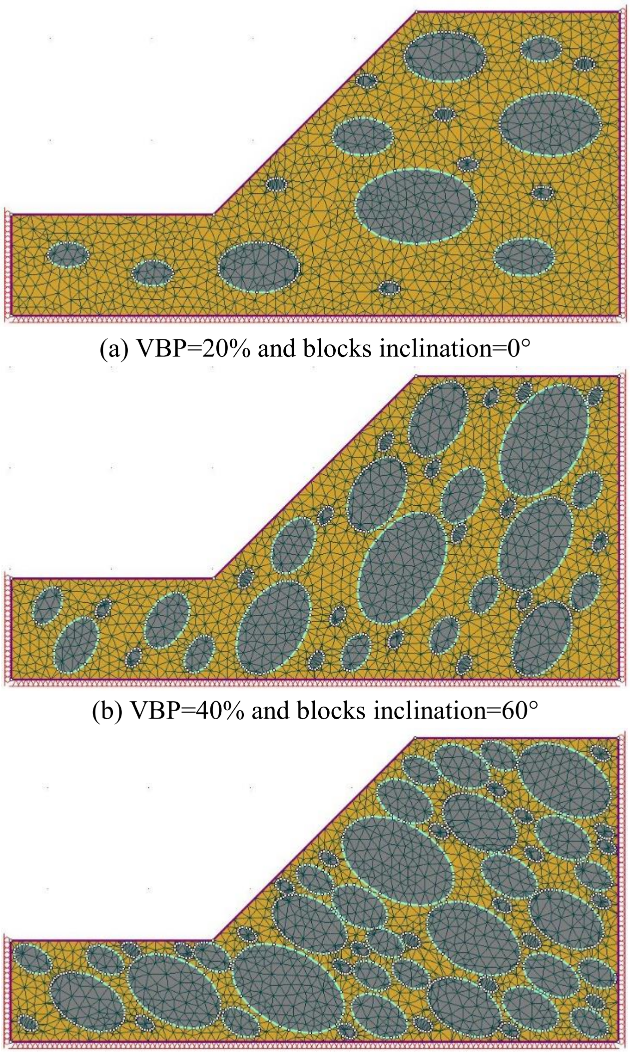
According to literature, the VBP is one the most important factors affecting strength of bimrocks. Fig. 5 demonstrates the results of the bimslope stability analyses

Table 2 Properties of used materials in this study

Parameter	Value	
	Matrix	Blocks
Unit Weight (ton/m3)	1.8	2.3
Cohesion (kPa)	10	1000
Internal friction angle (°)	25	35
Poisson ratio	0.25	0.25
Elasticity modulus (MPa)	30	100

Table 3 Strength properties of matrix-block interface

Parameter	Value
Cohesion (kPa)	8
Internal friction angle (°)	14



(a) VBP=20% and blocks inclination=0°

(b) VBP=40% and blocks inclination=60°

(c) VBP=60% and blocks inclination=150°

Fig. 3 Three examples of numerical bimslopes

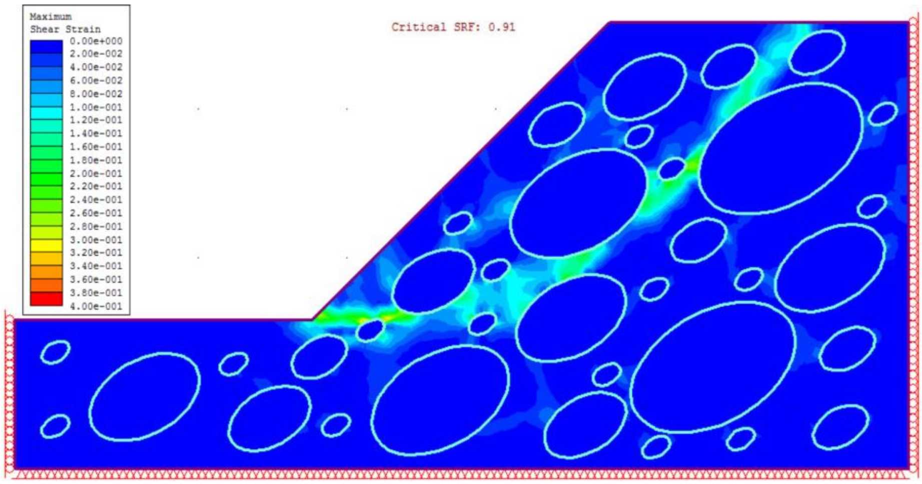


Fig. 4 Maximum shear strain of a bimslope model with VBP of 40% and block dips of 30°

Table 4 Statistical parameters of NSF for various blocks dips and VBPs

VBP=20%						
Parameter	Dip of blocks (°)					
	0	30	60	90	120	150
Minimum	0.97	0.93	0.93	0.99	0.97	0.99
Mean	1.06	0.98	1.02	1.12	1.09	1.10
Maximum	1.18	1.06	1.15	1.22	1.23	1.27
VBP=40%						
Parameter	Dip of blocks (°)					
	0	30	60	90	120	150
Minimum	0.99	0.94	0.95	1.09	1.11	1.15
Mean	1.14	1.02	1.06	1.21	1.21	1.26
Maximum	1.27	1.09	1.14	1.44	1.35	1.40
VBP=60%						
Parameter	Dip of blocks (°)					
	0	30	60	90	120	150
Minimum	1.09	0.92	0.97	1.19	1.31	1.49
Mean	1.38	1.14	1.29	1.46	1.50	1.64
Maximum	1.58	1.41	1.85	1.72	1.67	1.94

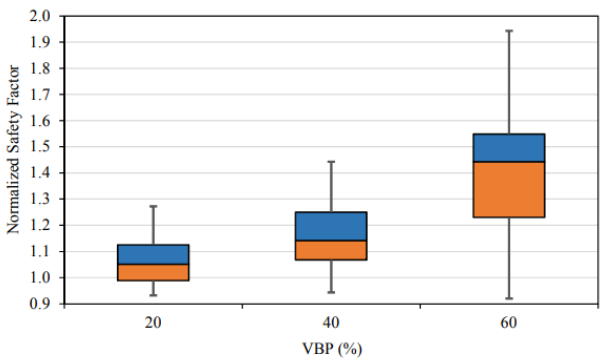
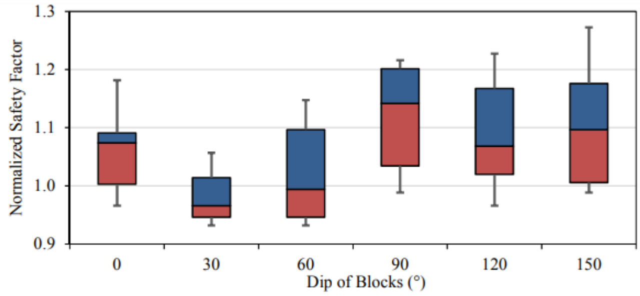
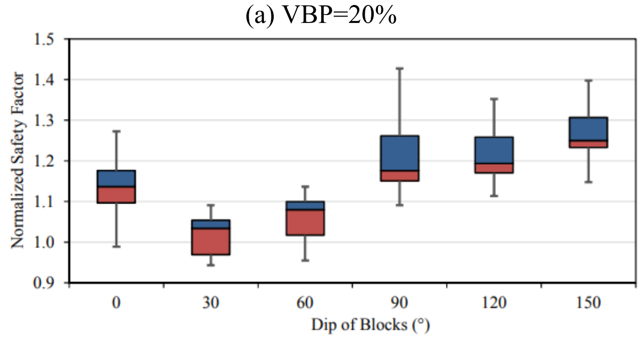


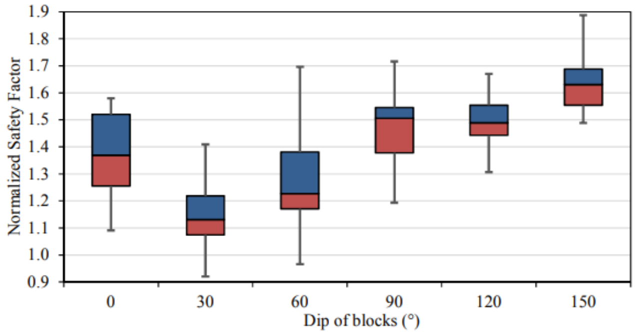
Fig. 5 Normalized safety factor of bimslopes versus various VBPs



(a) VBP=20%



(b) VBP=40%



(c) VBP=60%

Fig. 6 Normalized safety factor of bimslopes for various dips of blocks in different VBPs

for various VBPs. As generally illustrated in this figure, the NSF of bimslopes increased with increasing VBP. A relatively wide range of NSF can be seen for a specific VBP, including SFs less than that of the matrix (NSF less than 1.0), although the magnitude of this range also has an apparent direct relationship to VBP, other influences are

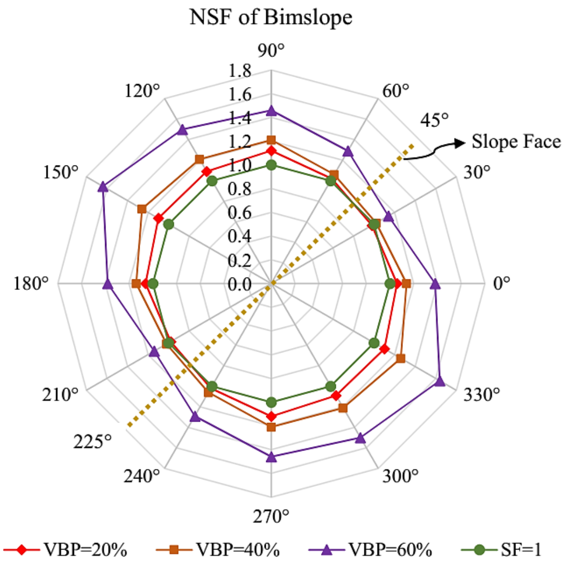


Fig. 7 The mean of NSFs for various blocks dips and VBPs

affect the SF. The arrangement of blocks and especially their inclination as related to the angle of slope faces have a significant effect on stability condition of bimslopes. Consequently: the inherent random arrangement of blocks in bimslopes causes some difficulty for accurate determination of the stability condition.

Box plots of statistical results of NSF versus the related dip of blocks are presented in Fig. 6. Depending on the VBPs, the dip of blocks and arrangements of blocks, the SF of bimslopes varies in a wide range compared to matrix-only slope, having values decreased by 10% and increased up to 90% more. Prominent in the results is the effect of blocks oriented at angles similar to that of the slope itself, such as the 30 and 60 degrees cases. In these cases, the presence of blocks actually weakens the slopes which is an effect similar to the case of jointed rock masses having discontinuities unfavorably inclined out-of-slope. The phenomenon was also observed by Lindquist (1994) in his pioneering investigation into the strength of physical model melanges.

Fig. 7 is presented to clarify the effects of block dips on the stability of bimslopes. In this figure, the radial axis shows the mean of NSF values and values on the perimeter present the dips of blocks.

As mentioned, the face angle of all models is equal to 45 degrees which can be seen in Fig. 7. According to this figure, for VBP<40% when the values of blocks dip are close to face angle (30 and 60 degrees), the presence of blocks has not special effects on SF of bimslopes rather than matrix-only case. Therefore, it can be concluded for VBP<40%, when the dip difference between blocks and face angle is about ±15 degrees, the presence of blocks can be ignored. Therefore, it is at first glance sufficient to analyze the matrix-only slope. However, as shown in Fig. 6, at low block proportions, low block inclinations can result in SFs less than the matrix-only case so prudent design would demand that such cases be investigated rather than simply analyzing the matrix-only conditions.

Increasing the angular difference between blocks and slope faces causes increases in SF of bimslopes compared to the matrix-only case. The maximum of mean NSFs is related to the block inclination of 150 degrees which has the maximum angular difference between the dip and the slope face (105 degrees). It is because of pronounced effect of the exaggerated tortuosity of the slip surfaces negotiating around blocks. Again: it is also clear that in general with increasing the VBP, the NSF increases.

An important point for developing the procedure and results of this research for natural bimslopes in different conditions is the creation of numerical models based on the field geological studies. In this regard, following the steps below can lead to more reliable outcomes:

i. At first, the geometric characteristics of the natural bimslope, and in particular its slope height (L_c, the scaling characteristic dimension) are determined. Based on the height, the threshold size between the blocks and matrix ($0.05L_c$) is specified.

ii. The VBP, the size distribution and the inclination of the blocks are determined based on required investigations on outcrops or boreholes logs of the bimslope.

iii. The strength and mechanical properties of matrix, blocks and block-matrix interface measured by using common geotechnical tests such as direct shear test, uniaxial compressive test and confined compressive test.

With the above information, it is possible to create suitable numerical models for the featured bimslope. Note that if the shapes of the rock blocks are repetitive within the bimslope, it is possible to pick out some specified shapes like ellipse, rectangle, etc. to create blocks for the numerical models. However, random shapes for the blocks may lead to more accurate results (Xu *et al.* 2016a, Meng *et al.* 2018). It is recommended that, in view of the random and complex position of the blocks within the bimslopes in nature, at least five different numerical models with various position of blocks should be generated and analyzed for a desired bimslope.

5. Conclusions

Block-in-matrix rocks (bimrocks) are defined as geological mixtures composed of rock blocks surrounded by weak matrix material. Bimrocks are heterogeneous materials where the arrangement of blocks has a determinant role on stability status. Geomaterials with bimrocks texture are very complicated materials that may cause several challenging problems for civil projects during design and construction phases due to its complex engineering behavior, even more so than with jointed rock masses.

In the last twenty-five years, several studies have been performed on bimrocks and approximately in all of them, Volumetric Block Proportion (VBP) was identified as the most important parameter affecting on behavior and strength of bimrocks. However, more recent studies highlight that there are some other parameters which have significant influence on behavior of bimrocks such as blocks inclination, arrangement of blocks, and strength of interface between blocks and matrix.

In this paper, the effects of VBPs and block inclinations on stability of bimslopes were investigated. For this purpose, numerical modeling by the Finite Element Method was utilized and 180 theoretical models were constructed with various VBPs and block inclinations, although all of them have a specific block size distribution based on that of Franciscan Complex melanges. These numerical models contain a random arrangement of blocks with different dips versus the slope face angle. The dips of blocks were considered as 0, 30, 60, 90, 120 and 150 degrees, where the angle of the slope face was 45 degree. For each kind of block inclination, 10 different blocks arrangements were created. The most prominent outcomes of this research are briefly as follows:

- The slip surface of bimslopes is formed through the matrix negotiating around blocks. According to the previous studies, the weakest component in bimrocks is usually the interface of blocks and matrix.
- The dip of blocks has a significant influence on bimslope stability. Based on analyzed numerical models, the safety factor of bimslopes is changed in a wide range rather than matrix-only slope and its value is decreased to 10% and increased up to 90%.
- In most models, the stability of bimslopes is increased compared to a matrix-only slope. Since the slip surface cannot pass through the blocks, the length of the tortuous surface increases and consequently the overall shear strength of the bimrock increases.
- Generally, the safety factor of bimslopes increased with increasing VBP. When the VBP of a bimslope increases, the slip surfaces tend to a non-circular mode to negotiate around blocks.
- When VBP<40% and the dip difference of blocks and slope face is less than 15 degrees, the blocks have no special effects on stability of bimslopes and the safety factor of bimslope is approximately identical to safety factor of matrix-only slope.
- When the dip difference of blocks and slope face is more than 45 degrees, the safety factor of bimslopes is increased about 10%, 20% and more than 40% compared with the matrix-only state for VBP of 20%, 40% and 60%, respectively.
- According to the results of this research, the safety factor of bimslopes could be estimated by having the SF of matrix-only state, VBP and the inclination of blocks. There are conditions where the SF of a slope (with few blocks oriented with low angular differences between blocks and slope) where it would be tempting to simplify design and analyze the matrix-only case. However: we caution that it is more prudent to analyze the actual conditions rather than take that time-saving short cut.

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