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A stochastic approach to slope stability analysis in bimrocks

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A B S T R A C T

The aim of this paper is to investigate slope stability in bimrocks using both finite element (FEM) and limit equilibrium (LEM) methods. More than 90 2D stability analyses were performed on slope models with the same geometry and with block proportions varying between 0% (matrix-only) and 70%. A stochastic approach was introduced in order to consider the inherent spatial and dimensional variability of rock inclusions. To this aim, a specific Matlab routine, performing numerical Monte Carlo simulations, was implemented. The code generates populations of 2D blocks with random sizes and positions within the slope models, according to specific statistical rules and given block contents. To achieve a statistical validity of the results, ten extractions and, hence, ten stability analyses were performed for each block proportion considered. Two empirical strength criteria available in the literature were also applied to the bimrock slope models by way of comparison. These criteria assume bimrocks to be homogeneous and isotropic masses with strength parameters that depend on their block contents and matrix strength. The effects of block proportions on safety factors, volumes involved and failure surfaces tortuosity provided by the different methods are discussed in detail. The findings of this study strongly suggest that bimrocks should be treated as heterogeneous materials, in order to avoid potential inaccuracies caused by neglecting the presence of blocks at the design stage. Furthermore, the benefits of using a stochastic rather than a deterministic approach to perform slope stability analyses in these heterogeneous materials is highlighted.

1. Introduction

The term *bimrock* (block-in-matrix rock) was defined by Medley[1] to be a mixture of rocks "*composed of geotechnically significant blocks within a bonded matrix of finer texture*". The expression "geotechnically significant blocks" means that there is sufficient mechanical contrast between blocks and weaker matrix, and that size distributions and volumetric proportion of blocks influence the rock mass properties at all scales of engineering interest.[2–6]

The definition of bimrock has no geological connotation[1,7–13] and encompasses a wide range of geologic and widespread materials including mélanges, colluvial materials, sheared serpentinites, agglomerates, breccias, lahars, decomposed granites, weathered rocks, fault rocks, landslide debris, etc.[3,4,9,11,14–19]

Given the great spatial, lithological and mechanical variability of these rock/soil mixtures,[5,11] geotechnical engineers often neglect the contribution of blocks to the overall bimrock strength, choosing instead to plan their work using the strength and deformation properties of the weaker matrix only.[4,7,8,20–25] However, as proved by many case histories reported in the literature, such a simplified assumption can lead to serious technical problems, ground failures and delays during many engineering works, ascribed to mischaracterizations and incorrect results obtained in the planning phases.[6,8,11,14,23,25–27]

Much research has been carried out in the last few decades to define systematic approaches to properly characterize bimrocks, select the appropriate strength and deformation parameters and perform suitable numerical simulations, in order to correctly carry out civil engineering works in these complex formations.[28–32]

On the basis of laboratory test results on artificial bimrocks, some authors developed preliminary strength criteria which assume bimrocks to be homogeneous and isotropic masses with equivalent mechanical properties that can be defined according to their block proportions and matrix strength parameters.[13,16,33]

Other authors analyzed the effects of explicitly taking blocks into account when analyzing slope stability in heterogeneous formations using a deterministic approach.[3,34,35] They highlighted peculiar results yielded by this kind of modeling, significantly different from those obtained when analyzing these materials as homogeneous.

The aim of our work was to investigate slope stability in bimrocks according to a new stochastic approach. This approach was introduced to explicitly take into account the presence of rock blocks and their spatial and dimensional variability. Both FEM and LEM analyses were

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performed on slope models with a simple geometry and variable volumetric block proportions (VBP). The blocks were generated according to statistical rules and located randomly within the slope models. With the aim of improving the statistical validity of the results, ten configurations were analyzed for each VBP considered. A VBP value of 0%, corresponding to a matrix-only model slope, was also analyzed in order to investigate possible inaccuracies during the design stage of engineering works. In fact, rock inclusions are often neglected in this phase.

Furthermore, two empirical strength criteria available in the literature were applied to compare results obtained using homogeneous models rather than a (more complex) heterogeneous one.

2. Main characteristics of bimrocks

Bimrocks have scale independent (or fractal) block size distributions.[4,5,11,22,32,36] A negative power law can be used to describe the relationship (on a log-log plot) between block frequencies and sizes. The exponent of the negative power law is the fractal dimension (*D*), which means that for *n* blocks of a specific size class there are n^D blocks within the previous one.[9,10,12,20,37–39] For Franciscan melanges, a 2D fractal dimension between 1 and 2, leading to a 3D fractal dimension ranging between 2 and 3, was generally found.[1]

Because of the scale independency, blocks are found at any scale of engineering interest.[13,25] Hence, both the threshold between blocks and matrix, i.e. the smallest geotechnically significant block, and the largest block size within a volume of bimrock should be determined taking the scale of observation into account, by a “characteristic engineering dimension”. Slope height, specimen diameter, footing width, tunnel diameter, etc. can be considered possible characteristic engineering dimensions (L_c). Once L_c is defined, blocks are limited to be between about 5% ($0.05L_c$, below which they are considered to belong to the matrix) and 75% of that dimension ($0.75L_c$, above which they are considered to belong to blocky rock masses).[1,3,5,9,11,13,22,25]

To be classified as bimrock, the material must present enough mechanical contrast between hard blocks and surrounding matrix so as to force failure surfaces to negotiate tortuously around the blocks.[22,33] To satisfy this condition, a minimum stiffness contrast (E_{block}/E_{matrix}) of about 2 and a minimum friction coefficient contrast ($tan\varphi_{block}/tan\varphi_{matrix}$) of between 1.5 and 2 were proposed in the literature for melanges and similar bimrocks.[1,9,11,13,21,22,36,37]

Several authors performed numerical simulations[15,24,37,38,40,41] and laboratory and in situ tests on different bimrocks.[10,17,18,21,24,26,29,30,32,33,39,42,43] They highlighted that failure zones propagate irregularly within the matrix and that the overall mechanical properties of bimrocks depend on many factors, i.e. *VBP*, orientation and spatial location of blocks, matrix strength, block size distributions, block count, block shapes, etc. In particular, an increase in the overall strength of bimrocks was registered for *VBP* between about 25% and 75%. In this range, researchers observed a gradual increase of both Young's modulus and friction angle, which was correlated with the increased tortuosity of the failure surfaces, and a decrease in the cohesion. This decrease was associated with the poor mechanical properties of the matrix, where deformations tend to develop.[21,44] Below *VBP* values of about 25%, the mechanical properties of bimrocks tend to correspond to those of the matrix. Above *VBP* values of about 75%, the overall strength of bimrocks approaches that of the rocky blocks.[2,26,30,45]

Other authors investigated the effects of explicitly taking blocks into account when modeling slope stability in heterogeneous formations. Barbero et al.[35] highlighted that the presence of blocks within slope models yielded to sliding surfaces with irregular positions and shapes, different from those obtained for homogeneous materials. Medley and Sanz Rehermann[3] found that the factor of safety increased with increasing volumetric block proportions (*VBP*). Irfan and Tang (1993) determined that changing in both blocks orientation and volumetric block proportion (*VBP*) yielded to significant differences in the safety factors of theoretical slopes in Hong Kong coarse colluvium. These findings are in good agreement with the evidences provided by numerical and experimental analyses on bimrock specimens, clearly suggesting the importance of explicitly taking the presence of blocks into account in the planning phase of civil engineering projects.

3. Available empirical approaches to define bimrocks strength parameters

On the basis of available field data and experimental test results on many artificial bimrocks, some authors developed preliminary strength criteria, assuming bimrocks to be homogeneous and isotropic masses.[13,16,33] Lindquist,[33] who studied melanges in detail, proposed the following empirical strength criterion:

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

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

Kalender et al.,[13] on the basis of their laboratory tests together with well documented findings from the literature,[16,18,33,42] developed a preliminary approach to predict the strength parameters ($\varphi_{bimrock}$, $c_{bimrock}$ and $UCS_{bimrock}$) of bimrocks:

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

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

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

where α is the angle of repose of blocks, *UCS* is the material uniaxial compressive strength, and *A* is a parameter that can be defined according to both the compressive strength of the matrix and parameter α. The novelty of such a method is that it takes into account contact strength between blocks and matrix and its possible effects on the overall strength of bimrocks.

However, further studies are still required to improve the knowledge on this topic since, as highlighted by the authors themselves, these empirical approaches present severe limitations and should be applied carefully and in predesign stages only.[13,16]

4. 2D slope stability analysis in bimrocks

The aim of the study reported in this paper was to evaluate the effects of block proportions on the stability of theoretical slopes in bimrocks. To this purpose, a large number of 2D slope stability analyses were carried out. Both FEM and LEM approaches were used on simple slope models, whose height corresponds to the characteristic engineering dimension L_c.[45] The slopes had an inclination of 30° and different block contents. In particular, 0% (matrix only), 25%, 40%, 55% and 70% areal block proportions were examined. Since they were 2D models, the areal block proportions were assumed to be equivalent to the *VBP*, although such an assumption is not generally valid for real bimrocks.[3,46]

To take the inherent spatial and dimensional variability of the inclusions into account, a specific Matlab routine was implemented to randomly generate blocks within the slope models. For each *VBP* considered, ten extractions (i.e. ten bimrock configurations) and, hence, ten stability analyses were performed so as to achieve a statistical validity of the results.

A 0% VBP configuration was also analyzed in order to evaluate potential