ARMA 11-259

An integrated geostatistical-geomechanical approach for the characterization of a bimrock

Coli, N., Berry, P., Bruno, R. and Boldini, D.

Department of Civil, Environmental and Material Engineering (DICAM), University of Bologna, Bologna, Italy

This paper was prepared for presentation at the 45th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, June 26–29, 2011.

ABSTRACT: Bimrocks are structurally complex formations made up by a fine-grained matrix including heterometric hard-rock fragments which deeply influence their mechanical behavior. A new approach for characterizing the morphological and spatial variability of rock fragments in bimrocks is introduced, based on the geostatistical analysis of bimrock outcrop pictures through a single-scale variogram analysis of the rock fragment indicator variable $I_B(x, y)$. The analysis indicated the presence, all over the field, of a nested structure characterized by three or four common elementary variogram models, each taking into account the variability of a specific size range of the rock fragments. A first attempt was also made in order to investigate the possible correlations between the bimrock strength parameters, obtained through in-situ non-conventional shear tests (BimTests), and the geostatistical indexes, which quantify specific spatial and morphological properties of the fragments, by means of a Cross-Covariance study of non-isotopic regionalized variables (ReV).

1. INTRODUCTION

Bimrocks [1] are structurally complex formations characterized by a fine-grained soil, the “matrix”, which includes, in a typical block-in-matrix fabric, hard-rock fragments of variable dimensions. The presence of rock fragments above a critical threshold size, namely the block/matrix (B/M) threshold, deeply influences the mechanical behaviour of bimrocks [2, 3, 4, 5, 6, 7]. The B/M is not an absolute property of bimrocks but is related to a specific engineering scale of interest (i.e. several B/M can be identified depending on the working scale of the problem under investigation). Due to their complex structure, an exhaustive mechanical characterization of bimrocks requires some special investigations to be carried out. In particular a non-conventional in-situ large size test (namely BimTest) was developed by the Authors in order to properly take into account the presence of rock fragments and their interactions with the soil matrix [8]. The main advantage of BimTest is that that the shear plane is free to develop inside the specimen, thus allowing for an increase in tortuosity of the shear plane, leading to an increase in the bimrock shear strength compared to that of the only clayey matrix.

However, the in-situ characterization through BimTests could result in a quite expensive and time-consuming task, especially when large volumes of the formation are involved. For this reason, the possibility to integrate the mechanical tests with an indirect method of characterization was investigated. The analysis aimed at correlating the strength parameters with 2D geostatistical indexes obtained through a single-scale variogram analysis of the rock fragment indicator variable $I_B(x, y)$, performed on digital pictures of outcrop exposures. The present study was carried out on a wide slope located in a dismissed open-pit mine in Tuscany, Italy, characterized by a wide exposure (about 345.000 m^2) of an Oligo-Miocenic olistostrome of the Tuscan Nappe. The formation is constituted by a dark-grey clayey matrix containing rock fragments of micritic and arenitic limestone [9] (Fig. 1).

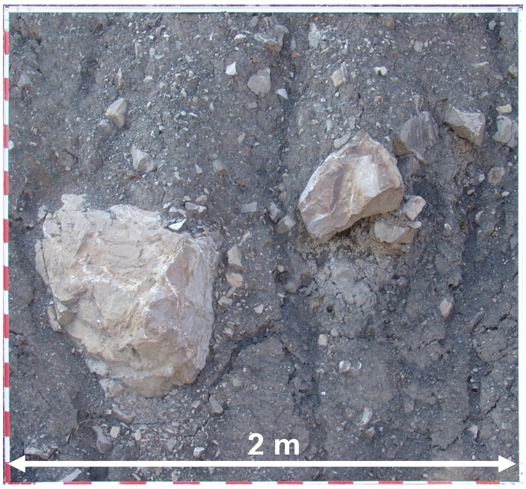

Fig. 1. The investigated bimrock: clayey matrix with calcareous hard-rock inclusions.

2. THE BIMTEST

Six BimTests were performed over the investigated area, on specimens of 0.3 m^3 (80x80x50 cm) [8]. The performed tests indicated that friction angle is well correlated to the volumetric content of calcareous fragments (VBC) inside the specimens, while cohesion shows a sudden drop above a critical VBC threshold of 20-25 % (Fig. 2, Fig. 3).

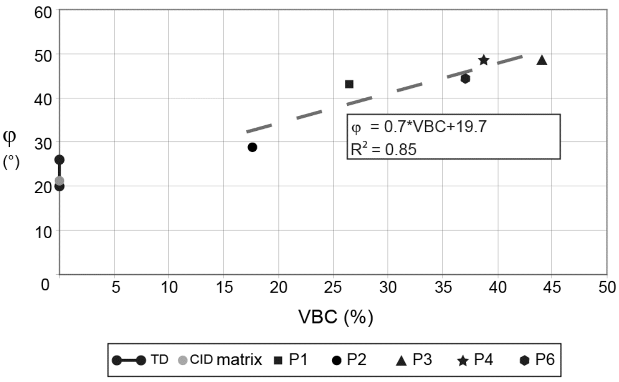

Fig. 2. Correlation between VBC and friction angle. The effective friction angle relative to the only clayey matrix is also showed (from [8]).

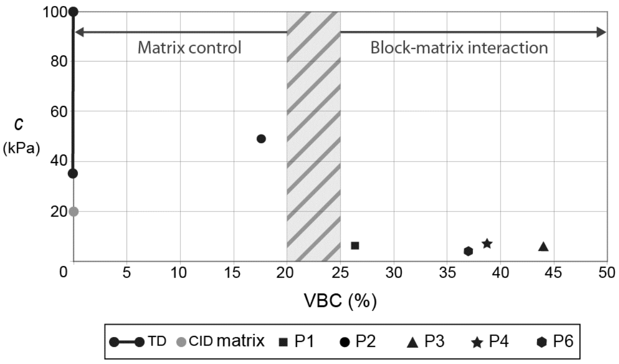

Fig. 3. Correlation between VBC and cohesion. The effective cohesion relative to the only clayey matrix is also showed (from [8]).

3. IMAGE SAMPLING AND PROCESSING

The image sampling was performed on natural outcrop exposures, by choosing a sampling window of 2 m square frame (4 m^2), which is comparable with the BimTest specimen size. According to the adopted Stratified Sampling Technique the investigated domain, relative to the bimrock outcrop exposure (345.000 m^2), was subdivided into 68 square cells each one covering 1.5% of the total investigated area, and sampling picture was taken at random position inside each cell. Pictures were then digitally scaled in order to maintain the exact angular proportion of the 2 m x 2 m window [10].

Since the main difference between calcareous fragments and the matrix are due to grey tone intensity changes, binary images where obtained from the digital pictures by applying a supervised maximum entropy segmentation algorithm [11, 12]. Binary images $g(x, y)$ can thus be interpreted as a realisation of an indicator variable function $I_B(x, y)$ describing the presence or absence of calcareous fragments defined as Set A (Fig. 4).

$$I_B(x,y) = \begin{cases} 0 & g(x,y) = 255 & (x,y) \notin A \\ 1 & g(x,y) = 0 & (x,y) \in A \end{cases}$$

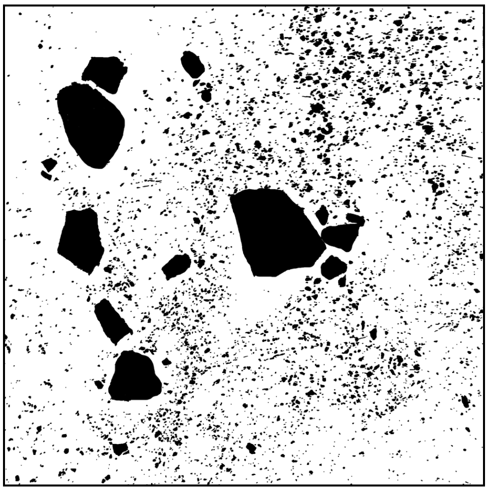

Fig. 4. Binary image obtained from the digital segmentation of a bimrock outcrop picture (the black features represent the calcareous rock fragments). It can be interpreted as the realization of the indicator variable $I_B(x, y)$.

4. GEOSTATISTICAL ANALYSIS

In the first level of the geostatistical analysis, the rock fragment spatial variability at the working scale of the 4 m^2 sampled window was investigated, by modeling the 2D spatial variability of the $I_B(x, y)$.

In the second level of the geostatistical study new variables (i.e. the model indexes) were defined by modeling each one of the 4 m^2 sampled windows at the working scale of the whole domain.

4.1. 1st level analysis: elementary nested models

The 2D spatial variability of the $I_B(x, y)$ was modeled by calculating experimental variograms on the binary images along the directions of 0° and 90°, assuming lags (h) ranging between 0.005 m and 1 m [13]. The experimental variograms were then fitted by nested structure models by means of GEOST-M, a Visual Basic macro library, developed by DICAM for Microsoft™ Office®. The nested models take into account the omnidirectional spatial variability and they show the possible presence of geometrical anisotropy, when they assume different ranges along different directions, while maintaining a constant sill.

The analysis of nested structures indicated that variogram are always characterized by three common elementary models, with constant range and variable sills (Fig. 5):

- Spherical model at small scale, always isotropic, with a constant range of 8 mm
- 1st exponential model for medium scale variability, always isotropic, and with a practical range between 11 and 15 mm
- 2nd exponential model for large scale variability, with a practical range between 30 and 300 mm, which can show a significant geometric anisotropy

Some of the nested models also showed a slight periodicity which was described with a hole effect model.

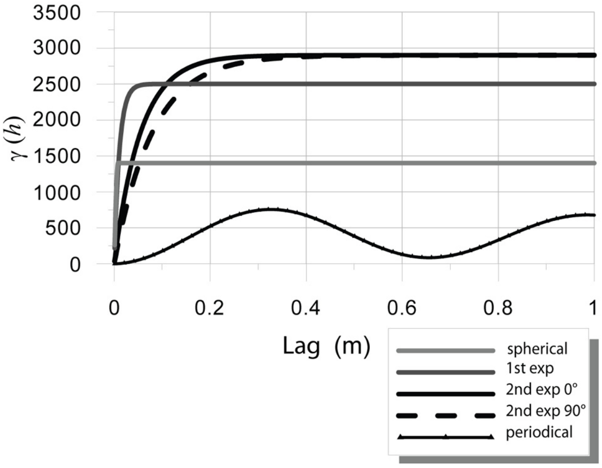

Fig. 5. Elementary nested models. Example of the elementary nested models describing the spatial variability of the I_{B} (x, y) at different scales within the 4m^2 sampling window.

4.2. 2nd level analysis: model indexes

The indexes (range, sill, anisotropy, periodicity) of the nested structures describe the variability of I_{B} (x, y) and can be correlated with the spatial and morphological properties of rock fragments $\in A$:

- the range a is correlated with the average size of fragments
- the sill C_{tot} is linked to the percentage of calcareous lithology on the image, since the variance of the indicator is defined as $\sigma_I^2 = p(1-p)$, where p is the proportion of Set A
- the variogram geometrical anisotropy is correlated with the anisotropy of the iso-oriented shape of fragments
- the periodicity T is a function of the average local distance between the fragments and therefore it is only evident when, at the scale of investigation, they are arranged according to a regular pattern

As a consequence, the following considerations can be drawn (Fig. 6):

- the spherical model takes into account the shape and spatial variability of the calcareous fragments below the B/M threshold, which was defined as 1 cm for the present working scale [8]. Even if at this working scale these fragments have no influence on the strength properties, we decided to not discard them from the variogram analysis because their influence on the total I_{B} (x, y) variability could not be a-priori excluded.
- the 1st exponential model refers to the variability of small fragments, close to the B/M threshold, with an average size of about 1 cm
- the 2nd exponential model expresses the variability of medium-large fragments, with an average size between 3 cm and 30 cm

The geometrical anisotropy, when present, is related to the 2nd exponential model, thus to the medium-large rock fragments, while it is not visible for the small fragments. The periodical/hole model is seldom observed and it usually has a low impact on total variability, which can be explained due to a predominant chaotic spatial arrangement of fragments.

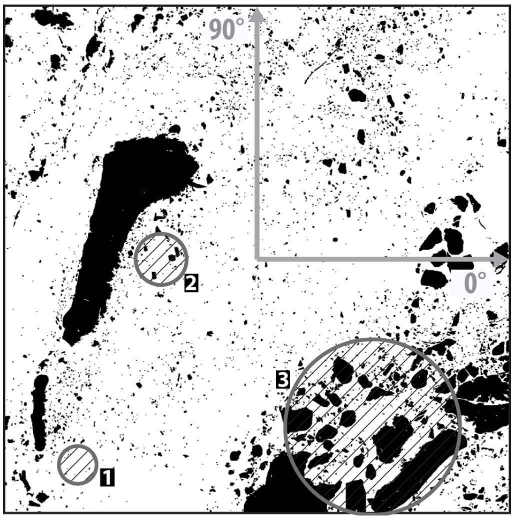

Fig. 6. The spatial variability of specific size-range of rock fragments are described by the elementary models: 1) spherical model; 2) 1st exponential model; 3) 2nd exponential model.

4.3. Cross-covariance and correlation with strength parameters

An extensive campaign of in situ testing raises some problems related to the costs, time, and practical technical difficulties. As a consequence, beside the physical tests, a quick and less expensive indirect method of characterization can be very helpful. For this reason the geostatistical indexes obtained through the non-destructive image analysis were attempted to be correlated to the BimTest strength parameters: if a correlation exist, in fact, the non-destructive indexes can be used as a valid support for the mechanical characterization of the bimrock under investigation.

Since the strength and image data are non-isotopic (the tested specimens were unavailable at the time the pictures were collected), any attempt to study their possible correlation must be carried out by using a geostatistical tool, like the spatial Cross-Covariance (C^*_{12}), that makes it possible to investigate the correlation of two non-isotopic variables. The spatial cross-covariance for the origin ($h \to 0$), in fact coincides with the classical covariance between two random isotopic variables, and it can be roughly inferred by:

$$C^*_{12}(\boldsymbol{h} \to 0) \cong C_{12}(0) = E[Z_1(x)Z_2(x)] - m_1 m_2 = \sigma_{12} \quad (1)$$

The BimTests strength parameters were chosen to represent the first regionalized variable (ReV), $z_1(x) = c(x)$, $\varphi(x)$, while the variogram total sill C_{tot} of the $I_B(x, y)$, which is linked to the 2D percentage of the calcareous lithology, represent the second ReV, $z_2(x) = C_{\text{tot}}(x)$.

The cross-correlograms, $\rho_{12}(\boldsymbol{h})$, were used for an easier interpretation of the cross-correlation analysis, since they represent a dimensionless measure of the spatial cross-covariance $C_{12}(\boldsymbol{h})$. For the $\rho_{12}(\boldsymbol{h})$ calculation, a base lag $\boldsymbol{h}$ of 30 m was found to be the best compromise in order to study the small distances (smaller lags) and at the same time to work on a statistically meaningful number of $z_1(x)$-$z_2(x)$ pairs. The ρ^*_{12} relative to φ - C_{tot} (Fig. 7) shows, for $\boldsymbol{h} \to 0$, a clear positive correlation, while for c - C_{tot} (Fig. 8) the correlation is negative. Since C_{tot} is linked to the rock percentage, it can be related to the physical VBC inside the specimens. The positive φ – VBC and negative c – VBC correlation [8] are in agreement with the behaviour showed by the cross-correlograms ρ^*_{12} for $\boldsymbol{h} \to 0$.

5. FINAL REMARKS

The geostatistical indexes (range a, sill C, period T), obtained through the variogram analysis of the rock fragment indicator variable $I_B(x, y)$ at the scale of the 4 m^2 sampling window, resulted to quantitatively and synthetically express the main properties of the morphological and spatial variability of rock fragments.

The preliminary Cross-Covariance study highlighted the likely presence of a meaningful correlation, at the multi-metric scale, between the non-isotopic variables strength parameters and C_{tot}.

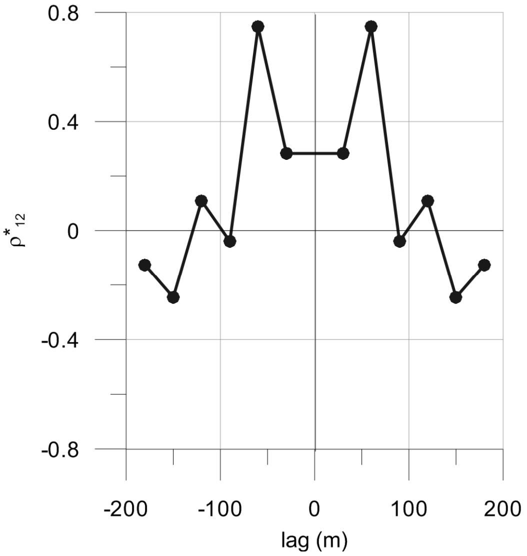

Fig. 7. Cross-correlogram between friction angle and total sill (base lag = 30 m). For lag → 0 the cross-correlogram shows a positive correlation ($\rho^*_{12} \geq 0.3$).

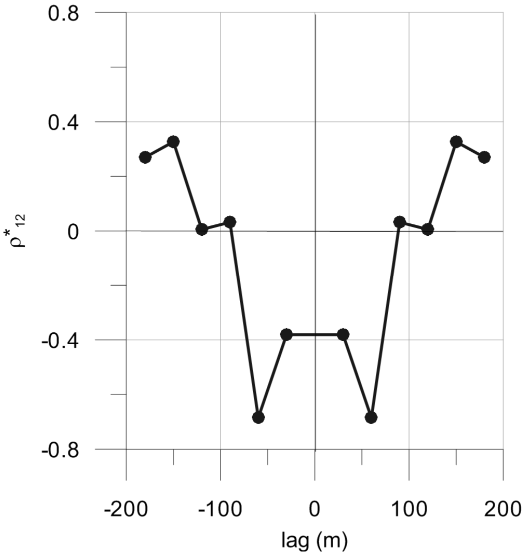

Fig. 8. Cross-correlogram between cohesion and total sill (base lag = 30 m). For lag → 0 the cross-correlogram shows a negative correlation ($\rho^*_{12} \leq -0.38$).

Due to the low number of strength data, however, the overall presence of a spatially structured variability cannot be postulated on the basis of the only experimental ρ^*_{12}, even if the existence of a positive/negative correlation at the small scale (<100 m) appears to be verified.

Even if the indexes refer to 2D block properties, whilst bimrock mechanical behaviour is governed by 3D properties, these experimental correlations can be of great advantage for the modeling of spatial and scale variability of bimrock strength in support of the in-situ tests. Moreover they can also be very useful for a preliminary mapping of the relative strength variations across the investigated area.

The experimental correlations presented in this paper must be intended as a preliminary result which needs to be validated with further studies:

- laboratory tests and correlation between isotopic strength-images variables
- multiscale analysis

REFERENCES

1. Medley, E. 1994. *The engineering characterization of melanges and similar block_in_matrix rocks (bimrocks)*. Dept of Civil Engineering, University of California, Berkley, California, PhD diss., UMI Diss. Svc., Ann Arbor, NI.
2. Lindquist, E. and R.E. Goodman. 1994. Strength deformation properties of a physical model melange. In *Proceedings of the 1st North American Rock Mechanic Symposium, Austin, Texas, 1994*, eds. P.P. Nelson and S.E. Laubach, 843-850. Rotterdam: Balkema.
3. Sonmez, H., C. Gokceoglu, E. Tuncany, E. Medley and H.A. Nefeslioglu. 2004. Relationships Between Volumetric Block Proportions and Overall UCS of a Volcanic Bimrock". *Felsbau Rock and Soil Engineering- Journal for Engineering Geology, Geomechanics and Tunneling*, 22: 5,27-5,34 September 2004
4. Sonmez, H., C. Gokceoglu, E. Medley, E. Tuncay and H.A. Nefeslioglu. 2006. Estimating the Uniaxial Compressive Strength of a Volcanic Bimrock. *Int. J. Rock Mech. Min. Sci.* 43: 554-561.
5. Xu, W.J., R.L. Hu and R.J. Tan. 2007. Some geomechanical properties of soil–rock mixtures in the Hutiao Gorge area, China. *Geotechnique* 57 (3): 255–264.
6. Pan, Y.W., M.H. Hsieh, M.H. and J.J. Liao. 2008. Mechanical Properties of virtual block-in-matrix colluvium. In *Proceedings of ARMA 2008 - American Rock Mechanics Association, 42nd U.S. Rock Mechanics Symposium, San Francisco, June 28– July 5, 2008.*
7. Sonmez, H., K.E. Kasapoglu, A. Coskun, C. Tununsluoglu, E.W. Medley and R.W. Zimmerman. 2009. A conceptual empirical approach for the overall strength of unwelded bimrocks. *ISRM Regional Symposium "Rock Eng. In Difficult Ground Conditions, Soft Rocks and Karst", Dubrovnik, Croatia, 29-31 October 2009.*
8. Coli, N., P. Berry and D. Boldini. 2011. In situ non-conventional shear tests for the mechanical characterisation of a bimrock. *Int. J. Rock Mech. Min. Sci.* 48: 95-102.
9. Pini, G.A. 1999. *Tectonosomes and olistostromes in the argille scagliose of the Northern Appennines, Italy*. Geological Society of America, Special Paper, 335: 1-69.
10. Coli, N., P. Berry, D. Boldini and P. Castellucci. 2008. Analysis of the block-size distribution in the Shale-Limestone Chaotic Complex (Tuscany, Italy). In *Proceedings of ARMA 2008 - American Rock Mechanics Association, 42nd U.S. Rock Mechanics Symposium, San Francisco, USA, June 28– July 5, 2008.*, ARMA 08-233, 7pp.
11. Kapur, J.N., P.K. Sahoo and A.K.C. Wong. 1985. A New method for gray-level thresholding using the entropy of the histogram. *Computer Vision, Graphics, and Image Processing* 29, 273-285.
12. Sahoo, P.K., S. Soltani and A.K.C. Wong. 1988. A survey of thresholding techniques. *Computer Vision, Graphics, and Image Processing* 41 (2), 233-260.
13. Bruno, R. and M. De Lucia. 2004. Decreasing Variograms of Lithology-Indicator Variable. In *Proceedings VII International Geostatistics Congress*, Banff, Alberta – Canada, October 2004.