Investigation of block geometrical properties of the Shale-Limestone Chaotic Complex bimrock of The Santa Barbara open pit mine (Italy)

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ABSTRACT: The exhausted Santa Barbara open pit mine (Tuscany, Italy) has some high slopes excavated in the Shale-Limestone Chaotic Complex Formation (SLCC). The slopes suffer large gravitational sliding movements. From a geotechnical point of view the SLCC can be classified as a typical block-in-matrix rock (bimrock), made up of a gray scaly-fabric clayey matrix including heterometric calcareous blocks. Since the geometrical dimensions of blocks influences the mechanical behaviour of a bimrock, an accurate study was carried out in order to determine these properties by means of indirect non-destructive characterisations: image analysis and geostatistical approach to the data. The volumetric ratio between blocks and the matrix is also investigating by means of in-situ large sized sieving tests.

1 INTRODUCTION

The exhausted Santa Barbara open pit mine (Tuscany, Italy), owned by the main electric power company in Italy (ENEL S.p.A,) extracted lignite as a fuel for the Santa Barbara thermoelectric power plant.

The mining activity led to the excavation of a wide slope (with a maximum height of 200 m and a planar extension of about 1300 m x 400 m) in the Shale Limestone Chaotic Complex (SLCC) (Figure 1). Since the beginning of its excavation the slope underwent rotational landslides and diffuse instability phenomena.

The SLCC is a typical mélange of the Northern Apennines mountain belt and it is made up of a mixture of a highly sheared scaly-fabric clayey matrix and calcareous blocks ranging from a few millimetres to tens of metres in size (Figure 2). From a geotechnical point of view the SLCC represents a typical bimrock (block-in-matrix rock) (Medley 1994, Medley & Lindquist 1995, Medley 2002, Medley 2007) characterised by competent blocks floating in a weaker clayey matrix.

During the mining activity several research studies were carried out in order to study the stability behaviour of the slope (D’Elia et al. 1986, D’Elia et al. 1988, D’Elia 2006). In all these analyses the SLCC was considered a homogeneous body made up only of the clayey matrix, without taking into consideration the influence of calcareous blocks on the mechanical behaviour of the bimrock.

Figure 1. The mine slope of the Santa Barbara open pit mine cut in the SLCC bimrock.

Figure 2. Typical aspect of the SLCC. Image edge is 2 m in size.

Since the geometry of blocks (grain-size distribution, shape, orientation and volumetric proportion) has proven to influence the mechanical behaviour of bimrocks (Lindquist 1994, Lindquist & Goodman 1994, Goodman & Ahlgren 2000, Kim et al. 2004, Sonmez et al. 2004, Sonmez et al. 2006), this study aims to investigate the influence of the geometrical properties of calcareous blocks on the mechanical behaviour of the SLCC bimrock, in order to further predict the movements of the slope.

Digital images of SLCC outcrops were taken in the field and analysed by means of advanced image analysis techniques, in order to investigate block size-distribution and shape.

A geostatistical approach was also adopted (experimental semivariograms and variographic maps) in order to investigate the shape and spatial distribution of blocks and to identify the possible directions of anisotropy.

Finally, in-situ large sized sieving tests were carried out to investigate the volumetric ratio between blocks and the clayey matrix.

2 THE IMPORTANCE OF BLOCK GEOMETRICAL PROPERTIES FOR BIMROCKS

Bimrocks are characterised by a fine-grained matrix including heterometric rock blocks, in a typical block-in-matrix chaotic structure. Typical bimrocks are mélanges, olistostromes and tectonosomes (Pini 1999).

From a geomechanical point of view, the strength of the matrix is at least one half lower than that of blocks, leading to a high mechanical contrast at the blocks/matrix interfaces (Lindquist 1994, Lindquist & Goodman 1994, Sonmez et al. 2006). One of the main factors affecting bimrock strength is the percentage by volume of blocks within the matrix, in the range of 25% - 75%. As a consequence the shear surfaces which may develop into the rock mass are forced to develop in tortuous paths with an increasing resistance (Medley & Sanz 2004).

Also the shape and orientation of blocks influence the overall mechanical properties: when the average direction of block major axes is oriented at about 30 degrees with respect to the direction of the maximum principal stress, the bimrock reaches the minimum strength (Lindquist & Goodman 1994).

These properties are very important for slope stability, because a marked anisotropy in block orientation may lead to a preferred direction of weakness. When blocks have an overall out-of-slope orientation there is a decrease in slope stability; on the other hand, when blocks are oriented at high angles to the slope, there is an increase stability due to the increase of failure plane tortuosity (Medley & Sanz 2004).

Furthermore, block shape influences the tortuosity of failure surfaces: for example elliptical blocks were found to have the worst effect on slope stability when the direction of the major axis coincides with the direction of shearing (Kim et al. 2004).

3 BLOCK GEOMETRICAL PROPERTIES

A great number of pictures of SLCC natural outcrops were collected in order to investigate geometrical properties of SLCC calcareous blocks by means of advanced 2D image analysis techniques.

3.1 *Photographic surveys*

The investigated area was divided into 100 squares of 72 m x 72 m, which were considered as the elementary sampling areas for the photographic surveys.

Pictures of SLCC outcrops were taken only for the sampling squares where available outcrops were present, for a total number of 55 pictures (one picture per square).

GPS and portable GIS software were used during the photographic survey in order to have in real time the georeferenced position and spatial orientation of each photo.

A Sony DSC-800 digital camera with 8 megapixels resolution was used.

The scale of image investigation was restricted to a 4 m^2 representative area encompassed by an aluminium square frame of 2 m x 2 m (Figure 3a). The aluminium frame was placed on the ground in order to have an exact dimensional and angular reference scale.

Once the pictures were downloaded on the PC, they were ortho-rectified and cropped to the aluminium square frame (Figure 3b). Cropped images have a resolution of 1 pixel/mm allowing for the detection of features with a physical dimension up to 1 mm.

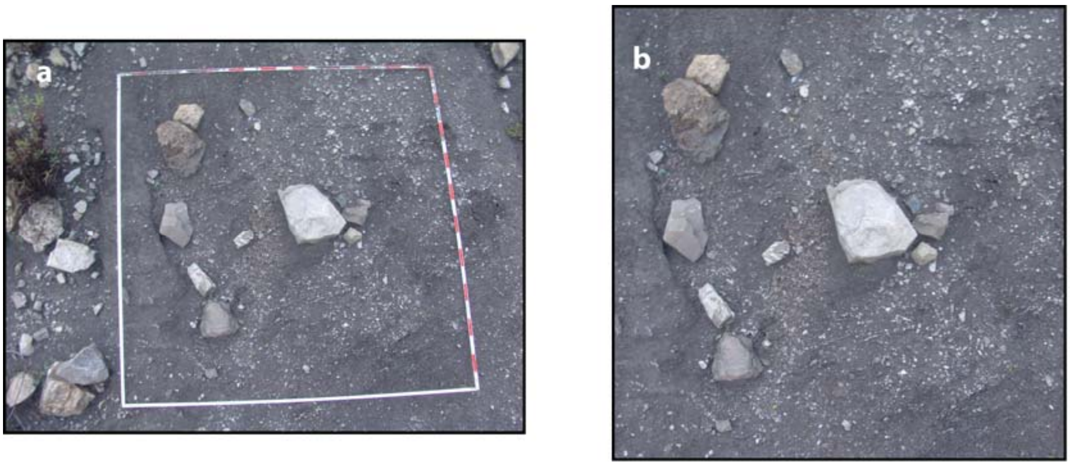

Figure 3. Picture of an SLCC outcrop: a) original picture shot in the field; b) the same image cropped and ortho-rectified to the 2 m x 2 m aluminium square frame.

3.2 *Image analysis*

SLCC images show an overall grey tonality characterised by a predominant dark grey uniform background of the clayey matrix and the light grey tones of calcareous blocks.

Because blocks and matrix are distinct only by a grey-level intensity contrast, it was possible to discard the colour information and convert all the images in 8-bit monochromatic greyscale.

The overall block/matrix intensity contrast, and the high gradients of grey intensity variation along blocks edges, allowed us to apply a segmentation to the input image in order to isolate the blocks from the matrix. Segmentation was performed by applying a threshold to the grey level histogram of the input image producing a binary output image where all pixels with an intensity value lower than the threshold value are set to 1 (pure white) and pixels with an intensity value higher than the threshold are set to 0 (pure black) (Sahoo et al. 1988, Coster & Chermant 2001, Gonzalez & Wood 2002).

Thresholding can be performed with numerous techniques. In the present work we used the Simple Thresholding and the Maximum Entropy Threshold techniques, which, after several experimental comparative tests (IsoData, Otsu, Mixture Modeling, Minimum Error), resulted to be the most suitable for the characteristics of processed images.

Simple Thresholding is a decisional method and it is performed by studying the variations of image grey intensity histograms: bimodal distributions and concavities in the histogram shape indicate good positions to place the threshold value.

Maximum Entropy Threshold is an automated histogram-based algorithm which attempts to define the optimal threshold by maximizing the entropy equations associated with the probability distributions of grey levels.

Once images were binarized, further processing was required in order to remove some artifacts that the thresholding process may have introduced. Mathematical morphology filters were used in order to fill holes within features and to remove isolated pixels (image dust) (Serra, 1982).

Figure 4 shows the binary and filtered image of Figure 3.

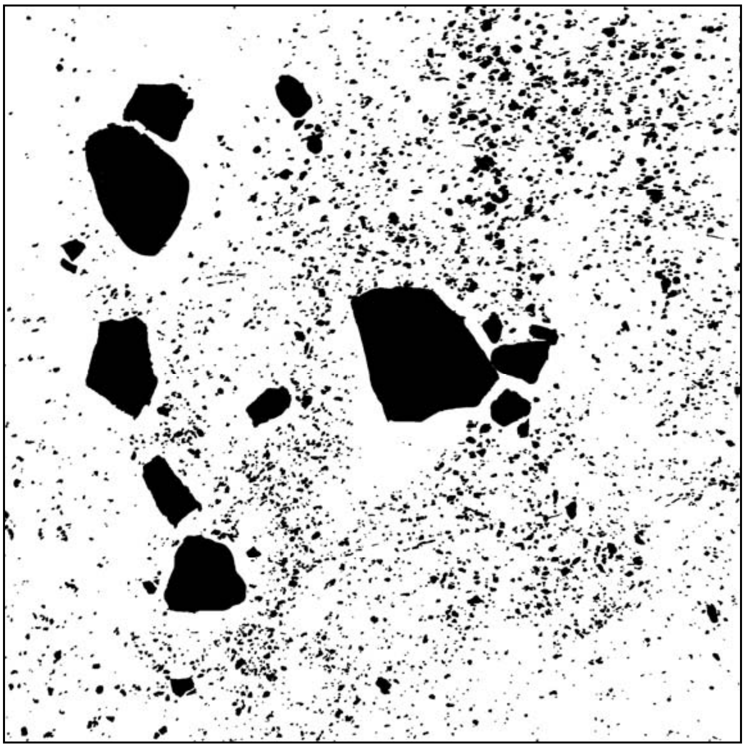

Figure 4. Example of a binarized and filtered output image. Calcareous blocks are represented by the foreground black features isolated from the white background (clayey matrix).

Cropped images were then calibrated to the actual spatial scale of 2 m x 2 m.

A Region of Interest (ROI) recognition algorithm was used in order to evaluate the geometrical properties of foreground black features, thus of calcareous blocks.

The Major and Minor axes (Feret's diameter) were measured for every black feature detected in the processed images, allowing us to collect a great number of data about block geometry. Each processed image, in fact, counts an average of 4000 black features, which corresponds to as many calcareous blocks.

3.3 *Data analysis*

The maximum observable dimension approach proposed by Medley was used in order to investigate the grain-size distribution of blocks. Maximum observable dimension represent the longest vector within a block measured in two-dimensions and it corresponds to the Major axis.

The Major axis size distribution of blocks were analysed by choosing a nodal endclass equal to 4% of the square root of the analysed area ($0.04\sqrt{A}$) where A=4 m^2 (Medley, 1994; Medley and Lindquist, 1995). The nodal endclass for the 2 m x 2 m images is 8 cm. Other classes were obtained by halving or doubling the nodal endclass value. According to the detected blocks Major axis the minimum endclass is 0.5 cm and the maximum 128 cm.

Relative frequencies of Major axes were plotted on log-log histograms. Results for different images where compared in order to investigate the variability of the block size distribution (Figure 5).

Size distributions show a common trend for all the analysed images characterised by a marked increase in frequency with the decrease of Major axis size.

In the endclass range of 1 cm to 128 cm the Major axis size distribution can be described with an inverse power-law relationship with a 2D fractal dimension D ranging from 1.2 to 1.9 (Figure 6).

Moreover, block size distribution has a peak at the endclass value equal to $0.005\sqrt{A}$.

The block shape ratio was also investigated by correlating the Major and Minor axis (Figure 7), resulting in a very good correlation in all the analysed images and an average shape ratio ranging from 0.4 to 0.65, with a well defined modal value of 0.55 (Figure 8).

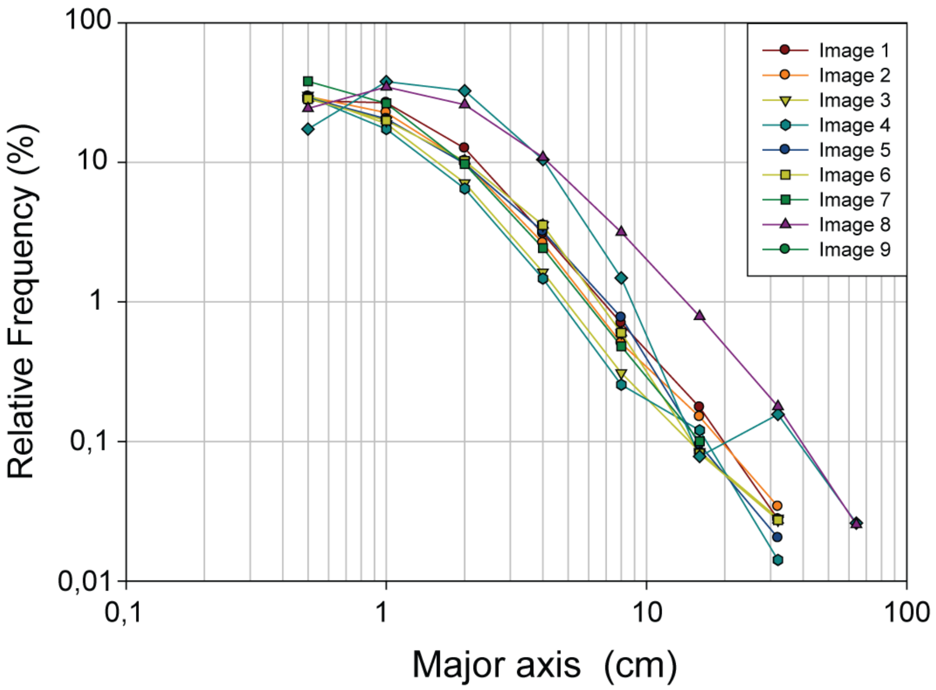

Figure 5. Distribution of block Major axes (MA) of nine analysed images.

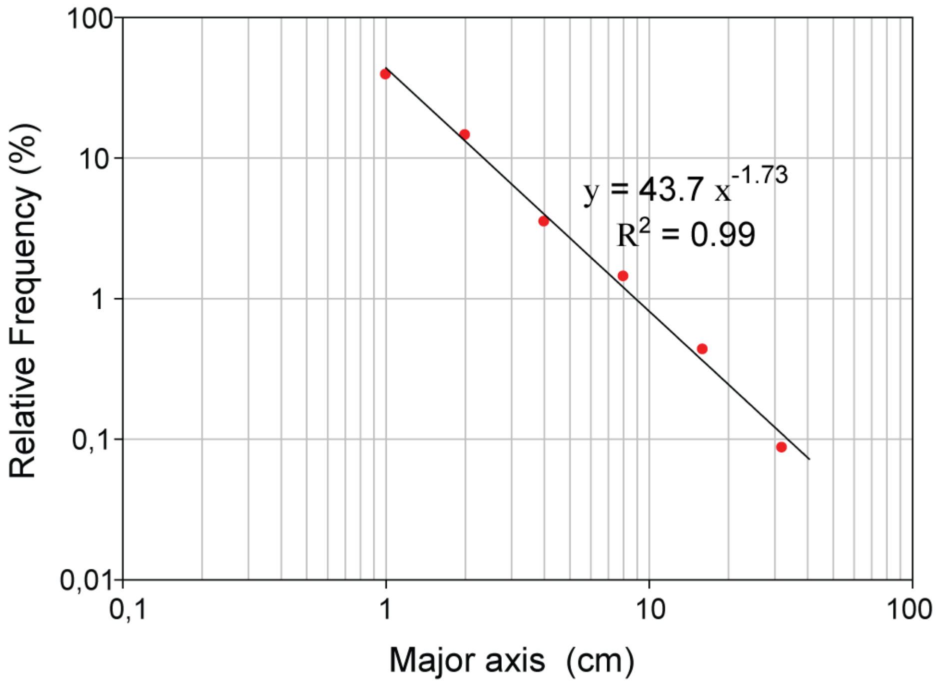

Figure 6. MA distribution with regression power curve of one image. The absolute value of the power law exponent represents the fractal dimension D (in this case $D = 1.73$).

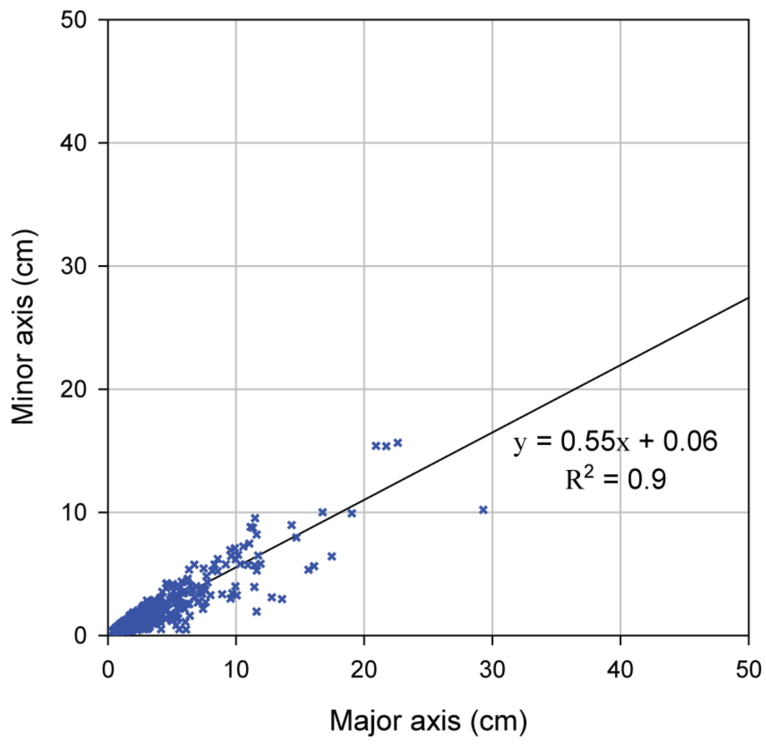

Figure 7. Block Major and Minor axes correlation for a SLCC image.

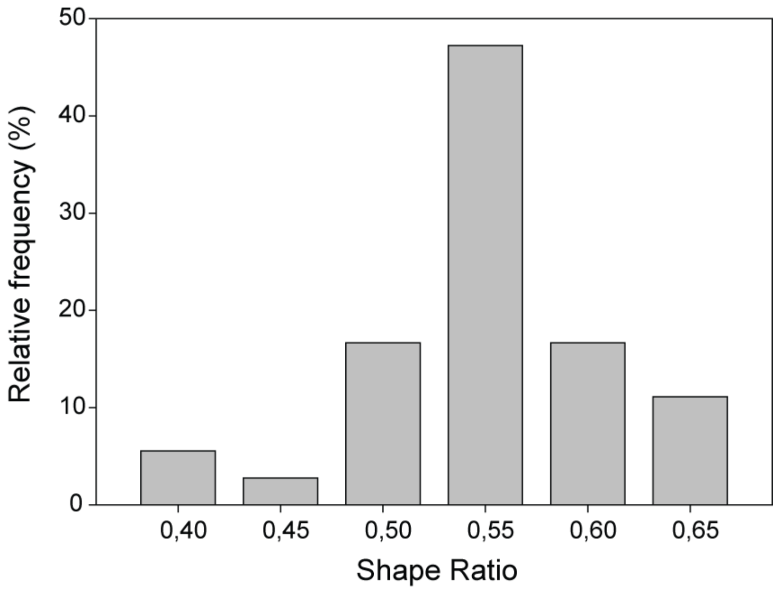

Figure 8. Frequency histogram of block shape ratios.

4 GEOSTATISTICAL ANALYSIS

Geostatistical techniques, beside other properties, have also the capacity to identify the directions of anisotropy of a regionalized variable.

Gray intensity values of image pixels represent a regionalized variable $h(x, y)$ and, from a geostatistical point of view, it can be interpreted as a realization of a random function $H(x, y)$, which, for binary image, can only assume the discrete values of 0 and 1.

Experimental semivariograms can be calculated for binary SLCC images. Since experimental semivariograms define the degree of spatial variation of the regionalized variable $h(x, y)$ in a specific direction *X*, if the semivariograms are different in the various direction an anisotropy of the block spatial distribution is present.

SLCC images were converted in point vector maps and experimental semivariograms were calculated in the direction of 0°, 30°, 60°, 90°, 120° and 150° from +*x* direction (Figure 9), assuming directional distance classes between values of 0.005 m and 1 m.

Figure 10 shows the experimental semivariograms of the binary image in Figure 9 calculated along the directions of 0° and 90°. In this case semivariograms show a nested structure composed by a short scale variability mostly isotropic and a medium scale variability showing a slight anisotropy. In Figure 10 the semivariogram model for the direction 0° is also showed, modeled by a spherical semivariogram with a range of 0.03 m and an exponential semivariogram with a practical range of 0.1 m.

The first structure takes into account the shape and spatial distribution of the small size fraction of blocks, whereas the second structure explains the shape and spatial variability of the larger blocks.

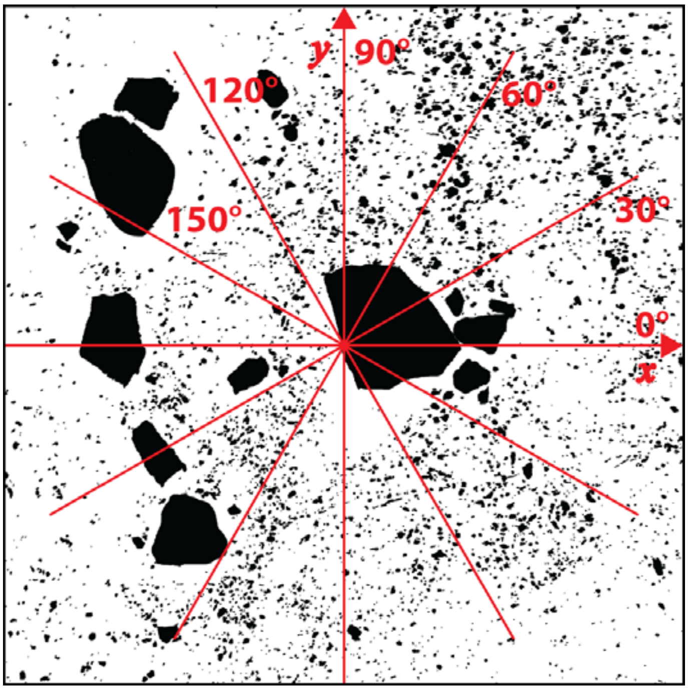

Figure 9. Directions where the experimental semivariograms were calculated.

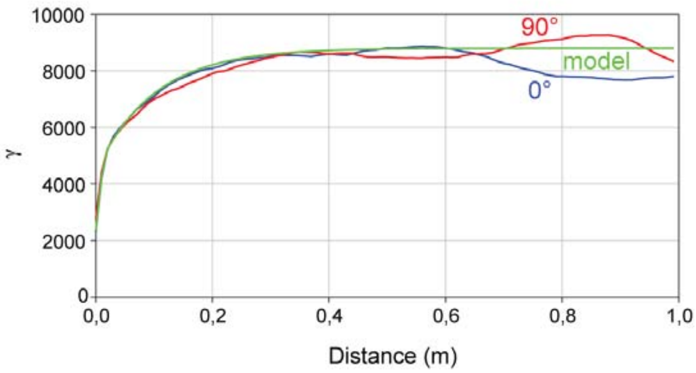

Figure 10. Experimental semivariograms calculated along the directions of 0° (blue line) and 90° (red line), and semivariogram model along the direction of 0° (green line) of the binary image in Figure 9.

Variographic surfaces (VS) were also calculated in analysed images. A VS is a map with the origin in the centre of the input image, characterised by a pre-defined number of cells which represent directional distance classes. Each cell has a value equal to the semivariogram value for that vector distance. Therefore, VS are particularly suitable in order to identify spatial anisotropy (Figure 11).

From the analysis of semivariograms and variographic surfaces some important information about the spatial assessment of blocks were inferred.

The shape and spatial distribution of blocks, at the scale of investigation, vary from an isotropic to a layered pattern with some marked preferred directions of anisotropy.

Directions of anisotropy differ from image to image and it is not possible to identify main preferred orientations common to all the analysed images all over the entire slope.

An exhaustive variogram modeling is currently under development with the aim to find common parameters (elementary structures, range values) distinctive for the investigated bimrock.

We can reasonably assume that the anisotropic pattern of the shape and spatial distribution of blocks may locally influence the mechanical properties of the bimrock at the investigation scale of 2 m x 2 m.

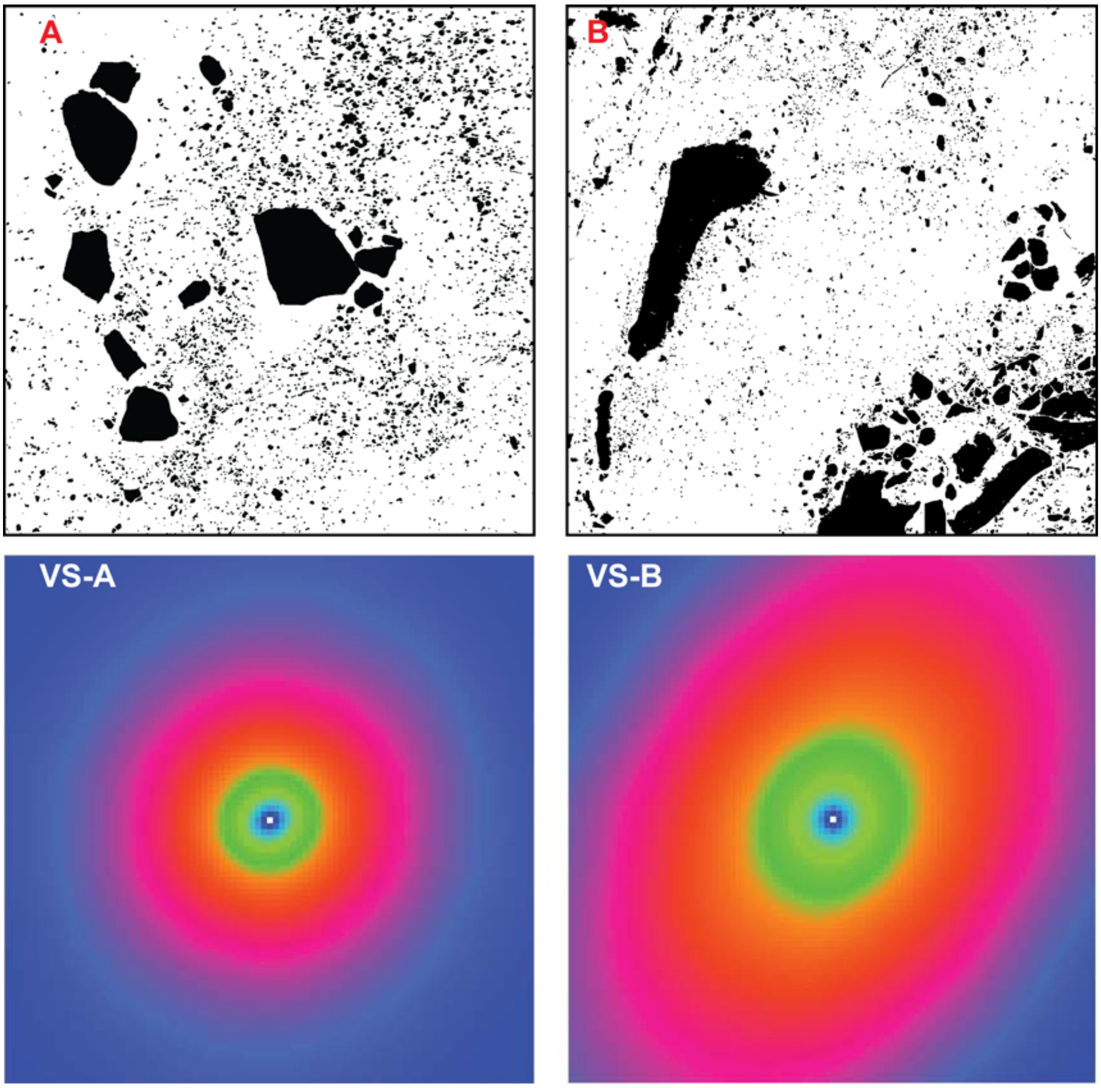

Figure 11. Comparsion of two VS relative to different input binary images (A, B). VS-A does not show any major direction of anisotropy while in VS-B an evident anisotropy can be identified along the direction of 45°.

5 IN SITU SIEVING TESTS

In situ large sized sieving tests were performed in order to investigate the volumetric block proportion of calcareous blocks within the clayey matrix for bulk samples.

A special sieve apparatus was developed in order to sieve samples of 1 m^3 of material. The apparatus is a cubic cage with 1 m edge (Figure 12), lateral faces are made up of a square iron grid with a spacing of 7 cm. This spacing represents 5% of the characteristic engineering dimension L_c, which is the diagonal length of the investigated 1 m^3 cubical bulk volume (Medley 1994, Medley 2002). The upper face of the cage is open to allow infilling of the excavated material.

Due to the large volume of material involved, the sieving procedure is very complicated and it involves a lot of logistics. A total number of 15 sieving tests were carried out, with a random stratified localisation over the investigated area.

Once the sieve cage was filled with SLCC material, the finer particles (below the 7 cm sieve grid size) were washed out by means of an intense water flow (Figure 12b).

The sieve cage with only the blocks was then immersed into a water tank with a specific volume. The difference of water volumes before and after the immersion of the cage leads to the evaluation of volumetric percentage of blocks in the bulk sample of 1 m^3.

The average value of the volumetric percentage of the blocks within the matrix resulting from the sieving tests is equal to 33%.

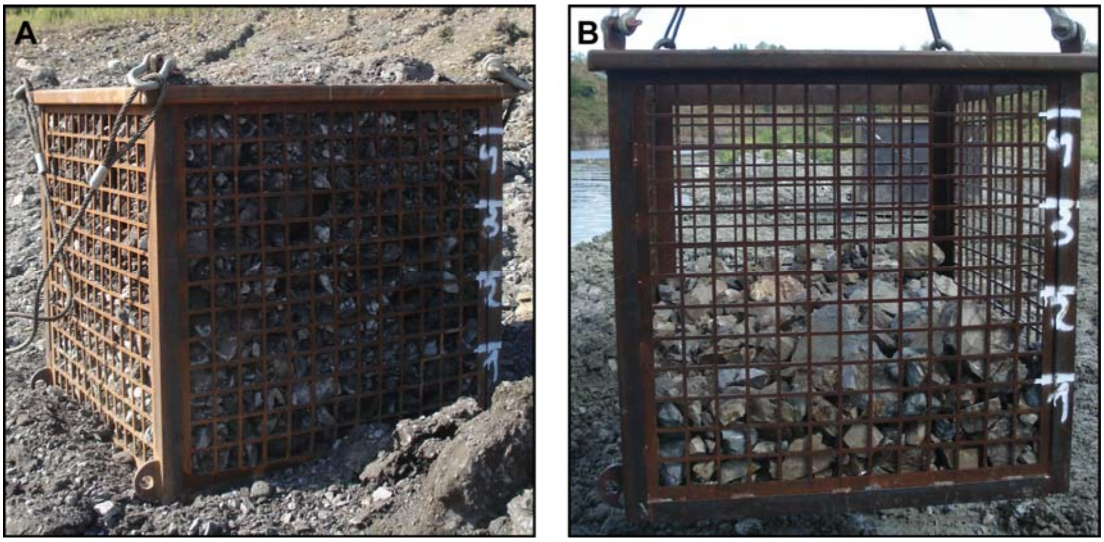

Figure 12. The cubic sieve cage used for the evaluation of the volumetric percentage of blocks. A) The basked filled with 1 m^3 bulk sample of SLCC; B) The sample after finer particles (< 7 cm) were washed out.

6 CONCLUSIONS

In this paper we presented the research study conducted at the Department of Chemical, Mining, and Environmental Engineering (DICMA), University of Bologna. The investigation was aimed at identifying the block geometrical properties of the Shale Limestone Chaotic Complex (SLCC) of Santa Barbara disused open pit mine..

Since the mechanical behaviour of a bimrock is deeply influenced by the geometrical properties of blocks, the aim of the present study is to characterise the geometrical properties of SLCC blocks.

An indirect non-destructive characterisation was carried out on 2 m x 2 m photographic images of SLCC outcrops by means of advanced image analysis and geostatistical techniques.

Image analysis by image binarization was used in order to investigate the size distribution of the block major axes and the block shape ratio.

The size distribution of Major axes appears to be self-similar at the scale of investigation and it can be described as an inverse power-law relationship with a 2D fractal dimension D ranging from 1.2 to 1.9. These data are in agreement with previous studies developed for the Franciscan Melange, California (Medley 1994, Medley & Lindquist 1995, Medley 1997, Medley 2001, Medley 2002).

The size distribution shows a peak for the endclass value equal to $0.005\sqrt{A}$ (1 cm); this value is different from that observed in the Franciscan mélange where it is equal to $0.05\sqrt{A}$.

Block shape ratio was also investigated resulting in a an overall shape ratio ranging from 0.4 to 0.65 with a modal value of 0.55.

Experimental semivariograms and variographic surfaces were calculated in order to identify preferred directions of anisotropy of block shape and spatial distribution. The analysis evidenced both isotropic and anisotropic patterns at the scale of investigated samples. Layered patterns, however, do not show a common principal direction of anisotropy all over the whole slope.

The evaluation of volumetric block proportion within the clayey matrix was investigated by means of in-situ sieving tests on 1 m^3 bulk samples, using a special sieving apparatus developed for the purpose of the study. Sieving tests gave an average volumetric percentage of blocks within the matrix of 33%.

Further researches will focus on the geostatistical correlation between the volumetric percentage of blocks, derived from the in-situ sieving tests, and some of the representative parameters obtained by the image analysis study.

We expect that a good correlation exists, so that the volumetric percentage of blocks can be estimated all over the entire slope area by means of multivariate geostatistics.

The investigated block geometrical properties will be also correlated with the mechanical properties of the SLCC bimrock, which are currently under investigation by means of laboratory tests and in-situ non conventional large shear tests.

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