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Analysis of the block-size distribution in the Shale-Limestone Chaotic Complex (Tuscany, Italy)

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ABSTRACT: The Northern Apennine chain in Italy is characterised by scattered outcrops of many oligo-miocenic clay-limestone melanges. The Shale-Limestone Chaotic Complex (SLCC) is one of these melanges and it outcrops in the Valdarno Basin, eastern part of Tuscany.
From a geotechnical point of view the SLCC represents a typical bimrock, made up of a highly sheared and tectonized, scaly-fabric, clayey matrix containing marly-calcareous blocks from a few millimetres to tens of meters in size, randomly distributed.
In this paper focus is given to high artificial slopes (a few hundred meters) of a dismissed pit-mine cut in the SLCC bimrock.
An accurate characterization of the block size distribution in the matrix was carried out by means of photographic surveys on natural and artificial outcrops, that allowed a high number of georeferenced images to be collected.
Images were analyzed with an image processing technique, providing important indications about the block-size distribution in the studied bimrock.

1. INTRODUCTION

The Shale-Limestone Chaotic Complex (hereafter called as SLCC) is a typical melange widely outcropping in the Northern Appennine chain in Italy. It is made up of a highly tectonized clayey matrix containing heterometric, randomly distributed, marly-calcareous blocks in a typical block-in-matrix fabric.

The SLCC forms wide mined slopes in the Santa Barbara dismissed pit-mine (Fig. 1), located near San Giovanni Valdarno, Tuscany.

The slopes, with a total length of 1.5 km and a total height of 180 m, underwent since the beginning of their excavation large mass movements and rotational landslides. The Santa Barbara mine complex is a property of ENEL S.p.A., the largest power company in Italy, which is promoting a research study on the geological and geomechanical characterization of the SLCC in order to properly characterize the mechanical behavior and to assess the stability of the slopes.

Fig. 1. Panoramic view of the SLCC slopes in the Santa Barbara dismissed pit-mine. A1 and A2 are two of the investigated outcrops discussed later in this paper.

This paper presents the first results of this research study, conducted at the Department of Chemical, Mining and Environmental Engineering (DICMA), University of Bologna.

A detailed geological and geomechanical characterization of the SLCC was carried out by means of field surveys and bibliographic research.

The activity is now focusing on the marly-calcareous block-size distribution in the SLCC, according to the bimrocks theory [1, 2, 3, 4, 5, 6]. The investigation was carried out by means of photographic surveys and an image analysis technique.

2. GEOLOGICAL CHARACTERIZATION OF THE SLCC

The SLCC represents one of the many melanges extensively mappable in Tuscany. Tuscan melanges are interbedded in the oligo-miocenic turbiditic formations, like the Macigno of the Tuscan Nappe, and their origin is still under debate in the geological community [7, 8, 9, 10].

Some authors attribute the origin of Tuscan melanges to sedimentary submarine mass movements, like debris-flows and mud-flows [7, 8]. These phenomena generate huge chaotic accumulation of hheterogeneous and heterometric material (i.e. olistostromes) deriving from pre-existing formations. The scaly fabric of the clayey matrix shows that the deposition and diagenesis of the sedimentary body took place in a context of tectonic activity during the formation of the Northern Appennine chain [7, 8, 11]. Tectonic movements caused post-depositional deformations on the melange complex, superimposed on the original sedimentary fabric, which in turn led to the formation of a pervasive fissility and the presence of many shear planes [7, 8, 11, 12].

On the other hand, recent studies [9, 10] interpret Tuscan melanges as tectonic melanges (i.e. tectonosomes), which originated from the dismemberment of pre-existing formations due to the overthrusting of tectonic nappes during the Appenninic orogenetic phases.

2.1. Lithology

The SLCC appears as a dark grey body, highly tectonized, with heterometric marly-calcareous blocks randomly distributed in the clayey matrix with a matrix-supported fabric (Fig. 2).

The following lithological components can be identified:

- Matrix: dark-light grey clay and shale subdivided in centimetric and millimetric thin lenticular laminae by pervasive and polished fissility planes.
- Marly-calcareous blocks: light grey marly-calcareous heterometric blocks, from a few millimeters to tens of meter in size, well graded. Block shapes range from tabular to sub-spherical, with angular to sub-rounded edges. Blocks are randomly distributed in the clayey matrix in a chaotic manner, without preferred orientations.
- Broken-formations: strata or pack of strata characterized by the alternation of limestone and dark pelitic beds, ranging from some meters to twenty meters in size, without lateral continuity in the SLCC rock mass. The distribution of the broken-formations in the melange appears to be random.

2.2. Structural features

The SLCC is characterized by intense and pervasive deformation structures caused by the tectonic history of the formation.

The clayey matrix is characterized by a pervasive fissility which subdivides the matrix in thin sigmoidal and prismatic scales (i.e. scaly-fabric). Two order of scales (scale-in-scale structure [12]) can be identified: the first order is characterized by centimetric to millimetric angular scales originating

Fig. 2. Typical aspect of SLCC exposed in a natural outcrop. The yellow scale reference marked with the white arrow is 1 m long.

from the intersection of two or more discontinuity sets (disjunctive cleavage); the second order is represented by millimetric scales originating from an anastomizing cleavage.

Marly-calcareous blocks and broken-formations are characterized by an intense jointing; tabular blocks are often boudinated [13] and dislocated by local faults.

Clayey matrix and broken-formations are often deformed by mesoscopic disharmonic folds, with inclined or recumbled axis planes. Fold genesis was attributed to a flexural slip deformational mechanism [11, 12].

3. GEOTECHNICAL PROPERTIES OF THE CLAYEY-MATRIX

During the years of mining activity, laboratory tests were carried out at the University of Rome "La Sapienza" [14, 15, 16] in order to characterize the SLCC clayey-matrix from a geotechnical point of view.

Tests were carried out on undisturbed specimens taken with a triple core barrel sampler (Mazier) at a depth ranging from 5 m to 75 m in the SLCC slopes.

The clay has an average saturation rate (S_r) of 0.9, an average void index (e) of 0.28 and a unit weight of volume (γ) of 23.5 kN/m^3 (Fig. 3).

Grain-size distribution and some index properties (CF, W_L, I_P) show a strong dependence on the specimen preparation: the increase of the mechanical disgregation of the material caused a marked increase of the finer size of particles and an increase of clay fraction (CF), liquid limit (W_L) and plasticity index (I_P) (Fig. 3). This phenomena is due to the scaly-fabric of the matrix and due to the hard diagenetic bonds between clay particles.

4. THE SLCC AS A BIMROCK

From a geomechanical point of view the SLCC represents a Structurally Complex Formation (SCF), defined as a geological formation that due to its composition and structure cannot be easily classified from a geomechanical point of view and causes many engineering problems [17, 18].

	CF %	γ kN/m^3	γ_s kN/m^3	W_n %	W_L	I_P	e	S_r
STANDARD A.S.T.M. SPECIMEN PREPARATION	10 - 32 (17)				21 - 35 (28)	5 - 13 (9)		
		21 - 24 (23.5)	27.3 -27.9 (27.5)	3 - 17 (9.0)			0.20 - 0.45 (0.28)	0.8 - 1.0 (0.9)
PROLONGED MECHANICAL DISGREGATION	32 - 41 (37)				31 - 49 (38)	10 - 24 (15)		

Fig. 3. Geotechnical index properties of the clayey-matrix. The increase of the mechanical disgregation of the material caused the variation of some index properties (from [16]).

In the past years, during the activity of the mine, the SLCC was assumed to be an homogeneous mechanical body and all stability analyses were developed adopting the mechanical properties of the matrix [14, 15, 16].

Because this assumption simplifies too much the mechanical behaviour of a melange, recent studies proposed a new geomechanical approach to the problem where a melange-like SCF rock mass is analyzed with the bimrocks (block-in-matrix rocks) theory, first proposed by Medley [1, 2, 3, 4, 5, 6]. According to this theory the melange is assumed to be a body constituted of a block-in-matrix fabric where the size, distribution and volumetric proportion of blocks influences the mechanical properties of the rock-mass [2, 19, 20, 21, 22, 23, 24].

In order to investigate the block size distribution in a bimrock, the 2D block dimensions are taken into consideration and analyzed in terms of the maximum observed dimension (d_{mod}), which is the maximum observable linear dimension of a block in a 2D exposure [1, 2, 4].

Research studies developed for the Franciscan Melange, California, pointed out that the block size distribution in that bimrock is self-similar and scale-independent and that in a log-log diagram the frequencies of measured d_{mod} have a typical trend shown in Fig. 4 [1, 2, 4, 5].

For the purpose of the present study we adopted this approach as a preliminary step in order to investigate the mechanical properties of the SLCC.

The aim of our research in this first stage is to develop a geometrical characterization of the SLCC and to compare the results with the already studied bimrocks.

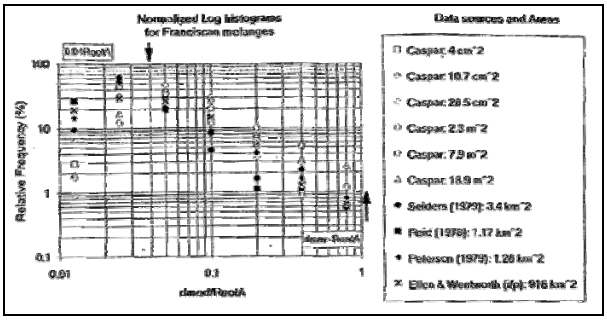

Fig. 4. Log-log diagram of d_{mod} endclasses relative frequency for Franciscan Melange (from [2]).

5. BLOCK SIZE DISTRIBUTION

In order to investigate the grain-size distribution of blocks in the SLCC bimrock, a 2D image analysis technique was adopted and improved for this specific context.

5.1. Photo surveys

A photographic survey on exposed natural and artificial outcrops was carried out.

A digital reflex camera Sony DSC-800 with 8 megapixel resolution was used in order to have a high image resolution and a quick transfer of photographs from the camera to PC for the image analysis process.

Several natural outcrops in the SLCC slope accessible for the photographic survey were mapped. In order to also investigate some areas where there were no suitable natural outcrops, a D10 Caterpillar Dozer was used to remove vegetation and the first weathered strata of soil, creating clear SLCC outcrops.

An aluminium square frame of 2 m x 2 m was assembled in order to have an exact dimensional and angular reference scale for photo images.

For selected outcrops the aluminium reference frame was placed on the ground and moved step by step shooting as many photos as needed to cover the entire exposed surface (Fig. 5).

5.2. Image analysis

All images show a greyscale tonality, characterized by a marked contrast between the predominant dark-grey tone of the clayey matrix ant the light-grey tone of the marly-calcareous blocks.

Images were rectified with Adobe™ Photoshop® by assuming the 2 m x 2 m aluminium frame as angular and dimensional reference scale.

Fig. 5. Example of a photographic shot on a natural SLCC outcrop (the aluminium square reference frame is 2 m x 2 m).

They were then cropped to the aluminium square frame in order to cover the exact area of 4 m^2 (Fig. 6).

Fig. 6. Example of a rectified and cropped image.

An image processing through greyscale transformation, contrast and gray levels threshold filtering was carried out to isolate the blocks from the matrix. A semi-automated script was developed for Adobe™ Photoshop®, giving a binary image where the matrix and the blocks are identified respectively by pure black and pure white (Fig. 7).

Filtered images were then analyzed with an image analysis software (SigmaScan Pro®) in order to collect the maximum observable dimension (d_{mod}) and the area of each block.

5.3. Data analysis

The d_{mod} endclasses approach proposed by Medley [1, 2, 4] was adopted to analyze the distribution of the d_{mod}, choosing a nodal endclass equal to the 4 % of the square root of the analyzed area ($0.04\sqrt{A}$), where A=4 m^2. The nodal d_{mod} endclass for the 2 m x 2 m images is then equal to 8 cm.

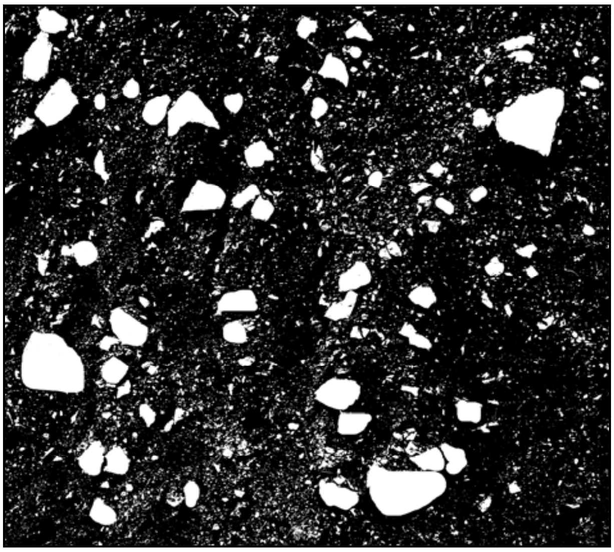

Fig. 7. Example of a filtered image (white areas represent the exposed faces of the blocks).

Other classes were obtained by halving down or doubling up this value of nodal class. Relative frequencies of d_{mod} endclasses were calculated for each filtered image and compared with the other images taken at the same outcrop in a log-log diagram.

Fig. 8 and Fig. 9 show log-log diagram of the d_{mod} endclasses relative frequencies for two of the analyzed outcrops (A1 and A2 in Fig. 1).

Results from different outcrops were compared in order to investigate the relationship among outcrops located in different areas. Fig. 10 shows a log-log diagram of the d_{mod} endclasses relative frequencies for the rectified images relative to outcrops A1 and A2.

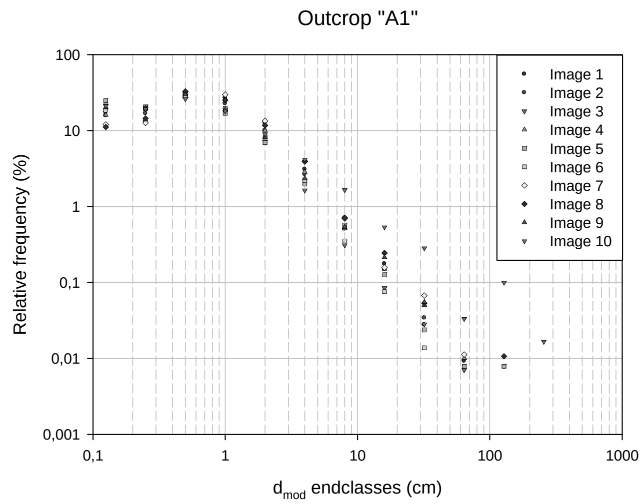

Fig. 8. Log-log diagram of the d_{mod} endclasses relative frequencies for ten filtered images of the outcrop A1.

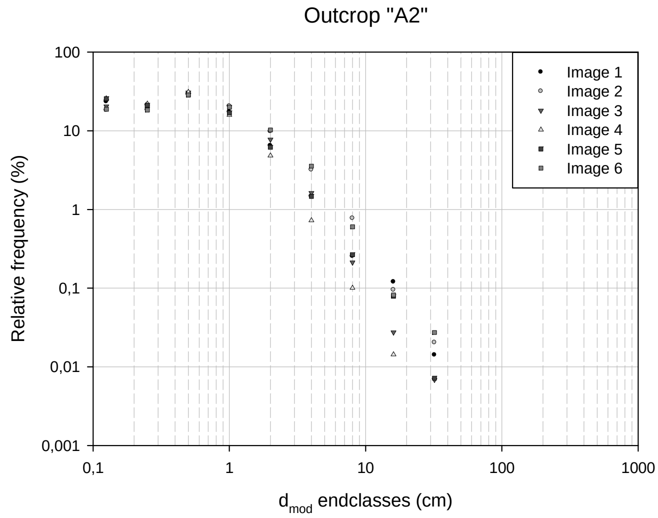

Fig. 9. Log-log histogram of the d_{mod} endclasses relative frequencies for six filtered images of the outcrop A2.

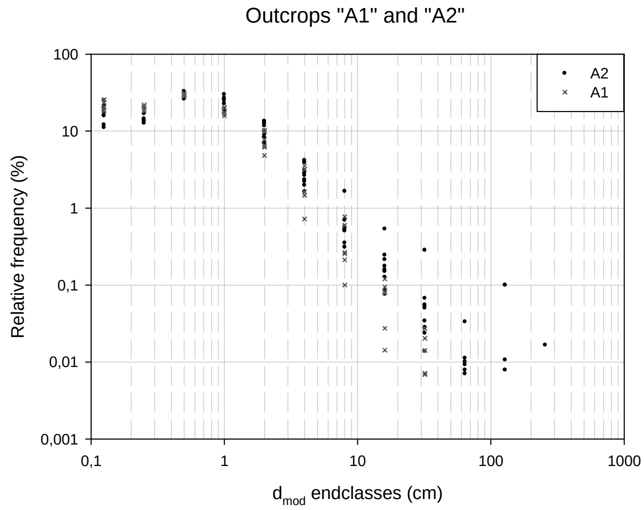

Fig. 10. Log-log diagram of the d_{mod} endclasses relative frequencies for outcrops "A1" and "A2".

6. DISCUSSION

These preliminary analyses, performed on 2 m x 2 m images, show that the frequency distribution of the d_{mod} endclasses:

- does not substantially change for different areas of the same outcrop; therefore at the 2 m x 2 m scale, block size distribution is spatially stationary;
- does not change for different outcrops, indicating that the concept of stationarity can be extended to all the analyzed outcrops;
- has a trend in the log-log histogram which resemble that from previous studies conducted

on the Franciscan Mélange (California) [1, 2, 4, 5]; the diagram is characterized by a well defined peak, a marked descendent limb with increasing in the d_{mod} endclass size and a less pronounced descendent limb towards the smaller d_{mod} one;

- has a peak at a d_{mod} endclass value equal to $0.0025\sqrt{A}$ (0.5 cm); this value is different from that observed in the Franciscan Melanges ($0.05\sqrt{A}$) [1, 2, 4, 5].

7. CONCLUSIONS

In this paper we presented the first results of a research study on the Shale-Limestone Chaotic Complex (SLCC) in the Santa Barbara dismissed pit-mine.

A detailed geological characterization was carried out and the main stratigraphic, lithological and structural features of the SLCC were discussed. The SLCC is a Tuscan melange [7, 8, 9, 10] made up of a scaly-fabric clayey matrix and of marly-calcareous heterometric blocks, randomly distributed in the rock-mass with a matrix-supported fabric.

From a geomechanical point of view the SLCC can be classified as Structurally Complex Formation, and investigated with the theory of the bimrocks [1, 2, 3, 4, 5, 6].

For the purpose of this present study we adopted the bimrocks approach in order to investigate the marly-calcareous block size distribution in the SLCC melange. A photographic surveys campaign in natural and artificial outcrops was carried out and an image analysis technique was used.

The frequency distribution of the maximum observable dimension (d_{mod}) endclasses of blocks computed for the processed 2 m x 2 m square images appears to be self-similar and in a log-log diagram it shows the same trend and magnitude among images of the same outcrop and for different outcrops.

These results also agree with previous studies developed for the Franciscan Melange, California [1, 2, 4, 5]; some differences will be investigated in more detail with further research.

Future surveys will focus on larger (by aerial photographs) and smaller scales of image analysis in order to overcome the constrain related to a single scale of analysis and to verify if the block size distribution in the SLCC is scale-independent.

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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. Medley, E., and E.S. Lindquist. 1995. The engineering significance of the scale-independence of some Franciscan melanges in California, USA. In *Proceedings of the 35th US Rock Mechanics Symposium*, Reno, 907-914. Rotterdam: Balkema.
3. Medley, E. 1997. Uncertainty in estimates volumetric proportions in melange bimrocks. In *Proceedings of International Symposium on Engineering Geology and the Environment*, *Athens, 23-27 June 1997*, eds P.G Marinos et al, 267-272. Rotterdam: Balkema.
4. Medley E. 2001. Orderly Characterization of Chaotic Franciscan Melanges. *Felsbau Rock and Soil Engineering-Journal for Engineering Geology, Geomechanics and Tunneling*. 19: 4,20-4,21.
5. Medley, E. 2002. Estimating Block Size Distributions of Melanges and Similar Block-in Matrix Rocks (Bimrocks). In *Proceedings of 5th North American Rock Mechanics Symposium (NARMS)*, *Toronto, July 2002*, eds. R. Hammah et al, 509-606. University of Toronto Press.
6. Medley, E. 2007. Bimrocks Article Part 1: "Introduction". *Newsletter of HSSMGE*. 7: 17-21.
7. Castellucci, P. and F. Cornaggia. 1980. Gli olistostromi nel Macigno dei Monti del Chianti: analisi stratigrafico-strutturale. *Mem. Soc. Geol. It.* 21: 171-180.
8. Abbate, E., M. Sagri and V. Bortolotti. 1981. Excursion No.5: Olistostromes in the Oligocene Macigno Formation (Florence area). Introduction: An approach to Olistostrome interpretation. In *International Assiciation of Sedimentologists, 2nd European Regional Meeting, Excursion guidebook, Bologna, 1981*, eds. F. Ricci Lucchi, 165-185. Bologna: Tecnoprint.
9. Boccaletti, M., M. Bonini, G. Moratti and F. Sani. 1996. Tectono-sedimentary evolution of the post-nappe basins in the Northern Apennines. In *Proceedings of the Interim Colloquium R.C.M.N.S., "Relations tectono-sédimentaires dans les bassins Néogènes de la*

Méditerranée Occidentale", Rabat, 7-8 April 1994, eds. Notes et Mémoires Service Géologique Maroc, 387: 177-193.

10. Bonini, M. 1999. Basement-controlled Neogene polyphase cover thrusting and basin development along the Chianti Mountains ridge (Northern Apennines, Italy). *Geological Magazine*, 136: 133-152.

11. Castellarin, A., G.A. Pini, G. Crestana and E. Rabbi. 1986. Caratteri strutturali mesoscopici delle Argille Scagliose dell'Appennino Bolognese. *Memorie di Scienze Geologiche*, 38: 459-477.

12. 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.

13. Ramsay, J.G. 1967. *Folding and fracturing of rocks*. McGraw Hill, NY.

14. D'Elia, B., D. Di Stefano, F. Esu and G. Federico. 1986. Slope movements in Structurally Complex Formations. In: *Proceedings of the International Symposium on Engineeering in Complex Formations, Beijing, 3-7 November 1986*. Science Press, XIV: 430-436.

15. D'Elia, B., D. Di Stefano, F. Esu and G. Federico. 1988. Deformations and stability of high cuts in a structurally complex formation: Analysis and prediction. In: *Proceedings of the 5th international symposium on landslides, Lausanne, 10-15 July 1988*, 699-604. Rotterdam: Balkema.

16. D'Elia, B. 1991. *Convenzione Università degli Studi di Roma "La Sapienza" ed ENEL Centro di Ricerca Idraulica e Strutturale (CRIS): Ricerca Sperimentale Sul Comportamento Meccanico delle Argille Scagliose Toscane – Rapporto Finale*. Università Degli Studi di Roma "La Sapienza", unpublished paper.

17. A.G.I. 1977. Some Italian Experiences on the mechanical characterization of Structurally Complex Formations. In *Proceedings of International Symposium "The geotechnics of Structurally Complex Formations, Capri, 1977*. 2: 91-106.

18. A.G.I. 1979. Some Italian experiences on the Mechanical Characterization of Structurally Complex Formations. In *Proceedings of International Congress on Rock Mechanics, Montreaux, 1979*. 1: 827-846.

19. Lindquist, E. 1994. *The Strength and Deformation Properties of Melange*. Dept of Civil Engineering, University of California, Berkley, PhD diss. UMI Diss. Svc., Ann Arbor, MI.

20. 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.

21. Goodman, R.E. and C.S. Ahlgren. 2000. Evaluating the safety of a concrete gravity dam on weak rock-Scott Dam. *Journal of Geotechnical and Geoenvironmental Engineering*, 126: 429-442.

22. Kim, C., C. Snell and E. Medley. 2004. Shear Strength of Franciscan Complex Melange as Calculated From Back-Analysis of a Landslide. In *Proceedings of the 5th International Conference on Case Histories in Geotechnical Engineering, New York, 13-17 April 2004.*

23. 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

24. Sonmez, H., H. Altinsoy, C. Gokceoglu and E.W. Medley. 2006. Considerations in Developing an Empirical Strength Criterion for Bimrocks". In *Proceedings of Asian Rock Mechanics Symposium Singapore, 6-10 November 2006.*