BRIEF LECTURE NOTES

ANTICIPATING AND ADDRESSING THE CHARACTERIZATION, DESIGN AND CONSTRUCTION PROBLEMS OF FAULT ROCKS, MELANGES, and OTHER BIMROCKS

A SHORT COURSE FOR ENGINEERING GEOLOGISTS AND GEOTECHNICAL ENGINEERS

Photo: Ed Medley

Relatively little is known about engineering geological characterization and geomechanical properties of complex brittle fault rocks and tectonic melanges, although these troublesome block-in-matrix rocks are common throughout the world. This Short Course will introduce engineering geologists and geotechnical engineers to techniques useful for the characterization, design and construction of tunnels in fault rocks and melanges. The course is topical given that several tunnels and excavations are currently in design, or are proposed for construction, in fault rocks and melanges in Turkey and worldwide.

The Course will also provide background useful to geo-professionals interested in characterizing melanges, fault rocks and similar block-in-matrix rocks for excavations and other earthworks.

The Short Course will be presented by Dr. Edmund Medley, an internationally recognized consultant and researcher in the engineering geological characterization of geological complexity and tunnel design/construction in fault rocks and melanges. Dr Medley will draw on materials presented in other Short Courses presented in California, Taiwan and Thailand by Dr Medley and his colleagues Professor Wulf Schubert and the late Professor Gunter Riedmueller (both of the Technical University of Graz, Austria). For portions of the Course Dr. Sönmez, Dr. Gökceoğlu and Dr Ulusay Hacettepe University will share important recent findings from their research on bimrocks.

COURSE OUTLINE

The 1-1/2 day Short Course will be composed of an approximately ½ day field trip to review local bimrocks, followed by a full day of lectures.

Day 1 Tuesday June 22, 2004

- Characterization and classification of fault rocks, melanges and other bimrocks
- Investigation of bimrocks (block-in-matrix rocks), engineering geology field practice, outcrop studies, and drill core logging
- Tunneling through fault zones and melanges
- Evaluation of the strength of bimrocks
- Fuzzy based approach for predicting UCS of the Ankara Agglomerate (Dr. Gokceoglu)
- A generalized approach for predicting the UCS of bimrocks (Dr. Sonmez)
- Questions, Answers and Discussions

Day 2 Wednesday June 23, 2004

- Seminar 1: A Simple Lecture on Geological Complexity: How to Characterize Melange and Other Bimrocks (Dr. Medley)
- Seminar 2: A brief overview on geoengineering properties of melanges in the vicinity of Ankara and Çorum, and examples from some melange-associated problems (Dr. Ulusay)
- Afternoon Field Trip to the Middle Anatolia Melange
- Closing comments (Prof. Dr. Ulusay)

BIOGRAPHY of Dr. Edmund Medley

Dr. Edmund Medley is a Principal Engineer in the Menlo Park, California, office of Exponent Failure Analysis Associates where he performs forensic investigations of the geotechnical and geological aspects of failures of structures, engineered ground and natural terrain. He attended primary and secondary school in the UK, and moved to Canada in 1969, where he prospected for several years before earning a degree in Geological Engineering from the University of British Columbia in Vancouver, Canada. His graduate degrees are in Civil Engineering (Geotechnical) from the University of California at Berkeley.

Dr. Medley has broad experience in geological and geotechnical engineering, geophysics and mineral exploration. He specializes in the site investigation and subsurface characterization of spatially and mechanically variable heterogeneous soils and rocks such as mélange, breccias, colluviums and glacial tills. He has worked in remote regions of Canada, and also in Hawaii, California, Papua New Guinea, Iran and the United Kingdom. Dr. Medley is licensed as both a professional engineer and a professional geologist in the US, Canada and the UK. He is a member of several professional and learned organizations including the ASCE, AEG, IAEG, USCOLD, British Institution of Civil Engineers, and the Geological Society of London.

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OUTLINE OF LECTURES

NOTE: The handouts attached to this outline but may not be in the order presented the lecture.

MELANGES: GENERAL INFORMATION

A geological definition of melange: *A body of rock mappable at a scale of 1: 24,000 or smaller and characterized both by the lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmented matrix of finer grained material.* (*Glossary of Geology*, Bates and Jackson, 1987; and Raymond, 1984.)

- **Mélange** is the French for ***"mixture".*** There is no conformance in the use of the acute accent "é", and it may be neglected. The word "melange" first used by Greenly (1919) for "Autoclastic Mélange" of Gwna Melange of Wales, reintroduced in 1941 by Edgar Bailey of the United States Geological Survey, and popularized by Kenneth Hsü in 1968, in his description of the chaos of the Franciscan Formation in Morro Bay, California[1].
- Melanges are found in over 70 countries, usually in mountainous areas near recent or ancient tectonic subduction zones. Melanges are found in Europe, but are famously exemplified by the Franciscan Complex of California
- The formation of melanges is a controversial topic, confused by the fact that melanges and chaotic melange fabrics are known by many synonyms*: argille scagliose*, scaley clay, sedimentary chaos, block clay, crush breccia, crush conglomerate, mega-breccia, chaotic structure, complex formations, lenticular fabric, tectonic mixtures, stratal disruption, friction carpets, varicolored clays, olistostromes, sheared serpentinites, and *wildflysch* (amongst many others).
- **NOTE:** the geological dictionary definition of melange above is **not** a satisfactory definition for an engineer since it excludes bodies that could be mapped at scales of less than 1:24,000, which may be of interest to geotechnical engineers. Consequently, an alternative definition of melange could be as follows: *At the **scale of engineering interest**, a **melange** is a chaotic rock mass composed of competent blocks of various sizes and lithologies, embedded within a weaker, usually argillaceous, matrix.*

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[1] For an informative history, see K. Hsü, 1985; *A basement of melanges: A personal account of the circumstances leading to the breakthrough in Franciscan research*; Geol. Soc. America, Centennial Special Vol. 1, p.47-64

2. BIMROCKS (BLOCK-IN-MATRIX ROCKS)

Melanges included in the geological spectrum of fragmented rocks (Laznicka, 1988). There are over 1000 geological terms for block-in-matrix and fragmented rocks. The abundance of terms, and geological implications of those terms, is confusing for the average engineer, so a simple and non-genetic term was devised**: Bimrocks**: (**block-in-matrix** rocks), **defined as** ***mixtures of rocks composed of geotechnically significant blocks, within a bonded matrix of finer texture***

geotechnically significant blocks requires:

1. **a mechanical superiority** of blocks over matrix (strength considerations), e.g.:
   ratio $\phi_{block}/\phi_{matrix} > 1.2$ (for instance, but not extensively researched!!!)

2. **a size range of blocks (which** influences bimrock mechanical properties)
   e.g.: if block size characterized by **d** then **a bimrock** has a range of blocks that at the scale of engineering interest, as scaled by a ***characteristic engineering dimension*** (***ced),*** conforms to:

$$0.05ced \le d \le 0.75ced$$

for example, if ced = 100m, then blocks < 5 m are assigned to matrix; and blocks > 75 m, are considered blocky rock

3. **a volumetric proportion** of blocks influences bimrock mechanical properties, so the block volumetric proportion (V_v) of a bimrock is:

$$25\% \le V_v \le 75\%,$$

or, if V_v $V_v \le 25\%$ treat the material as matrix, and if $V_v > 75\%$, treat material as block rock

- **Bimrocks similar to melanges** include: olistostromes: (chaotic deposits formed from submarine debris flows), Sheared serpentinites (mono-lithologic block-in-matrix chaos); Serpentinite melange (poly-lithologic blocks within sheared serpentinite matrix) and possibly; tillites, fault breccias and fault gouges (*see work of Professor Riedmüller*); blocky rocks with wide, weathered discontinuities, decomposed granites, and other saprolites, pyroclastics, etc.

3. ENGINEERING SIGNIFICANCE OF BIMROCKS

- Bimrocks have:
    - extreme spatial variability (chaos) which hinders exploration and sub-surface characterization
    - wide ranges in mechanical variability (strength, stiffness, deformation)
    - great hydrogeological variability

- heterogeneous materials abound, and the lessons learned from a study of bimrocks is useful for understanding how to characterize geological chaos of materials other than bimrocks.

- If nothing else, a study of bimrocks teaches one:

    - not to use the terms “inter layered rock” indiscriminately

    - not to shrug one’s shoulders at chaos and take the easy way by assuming the worst properties of the rock mass are representative

    - not to disregard the construction difficulties faced buy the excavation or tunneling contractor

- "chaos" => weakness of matrix leads to usual engineering assumption that the strength of the rock mass can be taken to be the strength of the weaker matrix.

- Question**: is this assumption always valid?**

- Answer: *Not in all situations, hence motivation for lectures!*

4. SCALE-INDEPENDENCE OF SOME FRANCISCAN MELANGES

Melanges and bimrocks look similar at many scales; ie: for some given area of melange, sub-areas will have block arrangements that will appear to be replicas of the parent area at many scales of observation. In a study of Franciscan of scales ranging from cms to tens of kms, the following was done (Medley, 1994) for outcrop studies many scales of Area (A)**,**

- **individual. block sizes were characterized by** d_{mod} **(max. observed dimension) of block, or simply** d
- **block size histograms were plotted as log-log histograms ("fractal distributions")**
- **sizes of blocks measured from particular areas (A) were normalized by** √A
- **The block side distributions of Franciscan melanges found to be similar, once normalized by √A of the measurement areas, and the block frequencies plotted as relative numerical frequencies**

Log histograms plot as power law relations: slope of linear plots are fractal dimensions.

Other bimrocks and fragmented rocks appear to have block size distributions that obey power law or possibly exponential law.

- **IMPLICATIONS OF SCALE-INDEPENDENCE OF FRANCISCAN MELANGES (AND OTHER BIMROICKS?)**

- The peak (d_{peak}) of the normalized log-histograms occurs at approx. $0.05\sqrt{A}$
- Maximum largest block (d_{max}) is equivalent in size to $\sqrt{A}$
- Hence, we can write both $d_{peak} \cong 0.05\ d_{max}$, and $d_{peak} \cong 0.05\ \sqrt{A}$.
- More likely largest block is about $0.7\sqrt{A}$
- These rules define the block size smaller than which block counts are unrepresentative (blocks appear to be too small to discriminate accurately at the scale of observation). **In other words, d_{peak} is a block/matrix threshold size.**

- **Blocks are found at all scales, and cannot be avoided or ignored**. Blocks defined within matrix at one scale are blocks at other scales. Testing and representative characterization and geotechnical analysis **must** incorporate blocks.

- Because blocks will be found at all scales, a block/matrix threshold **at the scale of engineering interest must be established**. Above this threshold size, blocks will be geotechnically significant at that particular scale of engineering interest, which is described by a *characteristic engineering dimension.* Based on analysis and empirical work, a reasonable block/matrix threshold size can be defined as **0.05ced.** (ced is also known as $\mathbf{L_c}$) Below this size, blocks are assigned to the matrix. But blocks demoted at one scale may be blocks in their right at larger scales (smaller ced). Similarly, the **maximum block size** is defined as **0.75ced,** above which blocks are termed *blocky rock.*

- Below the threshold size, again at the scale of interest, the blocks are assigned to the matrix. Once the scale of engineering interest changes, so must the block/matrix threshold. (For instance, changing from the scale of the lab specimen, in which blocks may be a few mm long, to the scale of the outcrop, where blocks may be tens of cms long, means the blocks of the lab specimen are now assigned to the matrix).

- Characteristic engineering dimensions (**ced**) are lengths that are descriptive of the geometry of the engineering problem under consideration. Possible ceds for various situations may be:

- ced for triaxial specimen: specimen diameter
- ced for tunnel: tunnel diameter
- ced for spread footing: footing width
- ced for landslide analysis: thickness of failure plane
- ced for excavation: $\sqrt{A}$ of excavation area

- It requires judgment to decide if the block/matrix threshold is:
    - **0.05 $\sqrt{A}$** (possibly an initial estimate or after reconnaissance mapping)
    - **0.05d_{max}** (where the largest local block is known following fieldwork)
    - **0.05ced** (where some critical geotechnical geometry is known)

- **Scale independence of rock masses allows studies at tractable scales: results from model studies are appropriate for scale-independent rock masses, or even rock masses that show scale independence of the range of engineering interest (normally centimeters to 100s of meters).**

- The melanges of the Franciscan Formation in California appear to have a scale independent block size distribution characterized by a log-log linear relationship of the form $\mathbf{N_i = 2^{2.3}\ N_{i+1}}$ or; the number of blocks in one size class, N, is about 5 times the number of blocks in the following size class (based on size classes that serially double, such as 1-2m; 2-4m; 4-8m;….).

6. OVERALL BIMROCK STRENGTH

- Matches results of previous work with soils in Hong Kong work (laboratory, slope stability back analyses, analytical studies) by Irfan and Tang (1992)

- results from physical model melanges of Dr. Eric Lindquist and Prof Richard Goodman; see also recent work by Dr. Harun Sonmez and colleagues, Medley & Sanz, 2004.

- results from Lindquist work:
    - ☐ Bimrock frictional strength is simply and directly related to block volumetric proportion: the greater the proportion of blocks, the greater the bimrock strength due to the effects of tortuosity of failure surfaces having to negotiate the edges of blocks
    - ☐ Bimrock cohesion decreases with increasing block content because there are more block/matrix contacts, and block/matrix contacts are the weakest component of a bimrock
    - ☐ Bimrock deformation depends on the orientation of blocks as well as block volumetric proportion. Rock masses with blocks oriented parallel to normal loads are stiffer than masses with blocks oriented perpendicular to normal loads.

- **Biggest problem with the findings:** If strength depends on block volumetric proportion (a 3-dimensional attribute) HOW to determine such proportions for a rock mass given that geological engineers use only 2-dimensional (mapping) or 1-dimensional (drilling) techniques**?**

- **So, need techniques to estimate block volumetric proportion....**

7. ESTIMATION OF BLOCK VOLUMETRIC PROPORTIONS

- Stereology law states that, **given enough sampling:**

L_L (block linear proportion) = A_A(block areal proportion) = V_V(block volumetric proportion)

- We seek to estimate volumetric proportion by linear proportion
- In geological engineering, linear sampling is generally by drilling and coring (scanlines)
- How much total scan line required to estimate volumetric prop.: >**$10*d_{max}$**
- BEWARE the **uncertainty** resulting from our assumption that linear proportion = volumetric proportion. We must adjust our estimate to account for **uncertainty**.

8. UNCERTAINTY IN ESTIMATION OF BLOCK VOLUMETRIC PROPORTION

- Repeat: $L_L = A_A = V_V$ is true **only when there is enough sampling.**
- Even when working with uniform rock masses, we can rarely do the amount of drilling and sampling we would like to perform; so how do we estimate uncertainty?
- One approach is empirical and quasi-statistical using physical models.
- Physical models constructed of clay and plasticene blocks in plaster of Paris. Four models fabricated with known maximum block size, known block volumetric proportions, known size distribution and controlled block orientations. Models sliced into 10 slices. Each slice photographed, and 10 model borings drawn on each photograph. Lengths of bring/block intercepts (chords) measured for each boring. Block linear proportion of each boring calculated, for 100 such linear proportions for each model, or four exhaustive data sets for each model. Subsets of borings taken randomly for 2,4, 10, 20 and 40 at a time for 40 iterations.
- Statistical analysis showed:
  - ☐ If all borings used, the calculated block linear proportion was same as known block volumetric proportion
  - ☐ However, when less borings used (ie total length of borings), the total linear proportions varied from the known block volumetric proportion as a function of both total length of borings and the actual block volumetric proportion.
- Approximate relationships were derived and related to "Uncertainty" (Coefficient of Variation, or Standard Deviation/Mean).
- In practice**, uncertainty** is the error between the truth and our estimate of the truth: in the case studied, it is the difference between the calculated block linear proportion (our estimate of the truth) and the block volumetric proportion (the truth).
- In practice, one would apply the uncertainty to the calculated block linear proportion conservatively (ie estimated block volumetric proportion is LESS than calculated block linear proportion) where one is interested in estimating the **Strength** of the bimrock.
- But in the case of estimating for purposes of excavation construction, the uncertainty is **added** to the calculated block linear proportion (ie: the estimated block volumetric proportion is higher than the linear proportion as a contingency toward contractual harmony).

9. BLOCK SIZE DISTRIBUTIONS:

- Compare well graded weight-based PSD (Particle size distribution) for till and 3DBSD (3D-Block size distribution.

- Differences 3D-Block size distribution (3DBSD), 2DBSD (measured from cross-sections and outcrops), Chord Length Distribution (CLD) (measured from borings) and numerical frequency.

- Problems related to sampling: block vol. proportion, block orientation, class intervals, total length of sampling.

- **Beware uncertainty in estimates of block size distributions from chord length distributions**

10. UNCERTAINTY IN ESTIMATES OF BLOCK SIZE DISTRIBUTIONS

- Understanding of the problem is possible by a study of plasticene/plaster of Paris physical models (described above). Known 3D block size distributions compared to chord length distributions (CLD) based on lengths of intercepts between model borings and blocks.
- Results are less encouraging than for study of block volumetric proportion:
- In general:
- the sizes and proportions of the larger blocks are underestimated
- sizes and proportions of smaller blocks are greatly overestimated
- the size class of the largest block (d_{max}) may be determined
- Regardless of how much drilling one will do, one can never generate a true 3-dimension Block Size Distribution from a 1-dimensional Chord Length Distribution.

- So, what how can we estimate BSD**?** One approach is an iterative one proposed by Medley and Lindquist (1995): using generalized and scale independent BSD for Franciscan melanges (i.e.: the number of blocks in one size class, N, is about 5 times the number of blocks in the preceding size class; based on size classes that serially double, such as 1-2m; 2-4m; 4-8m;….), as described in section above for Scale-Independence of Franciscan melanges. With a trial number and trial average block size, and assumed block geometry, a trial block size distribution is created. The total volume of the blocks in the trial distributions is used to attempt to match the estimated block volumetric proportion based on the drilling intercepts. In the case that these two estimates do not match, adjustments must be made to the starting number of large blocks, or the size of the largest blocks.

- Estimates can also be made by attempting to adjust the chord length distribution of the basis of observed field dimensions of blocks, and the size of the maximum block possible for the investigated area ($\sqrt{A}$ or d_{max}) .

- There is a great need for more research in developing dependable approaches to estimating block size distributions.

See Medley, 2002 and Haneberg (in press) for recent work on 3D Block size distributions from 1D data (such as drill core)

11. OTHER ASPECTS OF ENGINEERING CHARACTERIZATION OF MELANGES AND SIMILAR BIMROCKS

Understanding engineering properties of a bimrock demands skills of both the geologist and the engineer, and requires determination of:

- **block lithology**
- **matrix lithology**
- **block sizes (requires blocks size descriptor : dmod in 1D, 2D, 3D)**
- **block shapes**
- **block orientations (relative to principal stresses, engineering problem)**
- **block discontinuities**
- **block strength (why: for excavation and tunneling contractors)**
- **matrix fabric**
- **matrix strength**
- **block/matrix contacts**

12. SUMMARY AND CONCLUSIONS

- **Bimrocks are mixtures of competent and relatively incompetent rocks**
- Melanges are examples of bimrocks
- Process of formation of melanges and other bimrocks =>geotechnical inheritances

- **What is the overall geomechanical behavior of a mixture?**
- **Conventional approach is to design for the weak component only**
- **Conventional approach is OK for vol. proportion < 25 percent**
- **For volumetric proportion> 25 percent, add in some strength from contribution of blocks**
- **Blocks introduce higher ϕ because of tortuosity of failure surfaces**
- **Blocks result in lower cohesion because of increase in weak surfaces**
- **Blocks => stiffer mixture (depending on orientation blocks/stress)**
- **How to estimate block volumetric proportion from drill holes and mapping? Principals of Stereology state vol. prop = areal prop = linear prop.**

  Hence, assume the linear proportion is equivalent to the volumetric proportion and measure linear proportion of blocks
  Must select characteristic engineering. dimension for problem

- **Need to decide on block/matrix threshold, d_{peak}**
- **d_{peak} is 5 percent of characteristic engineering dimension or $0.05*d_{max}$**
- **(d_{peak} is also $0.05\sqrt{A}$ for a rough estimate)**
- **Require** minimum **ten times d_{max} for sufficient line (core) length**

Adjust estimates of block volumetric proportion for uncertainty

- **Estimate of BSD is useful for construction excavation, tunneling etc., but beware the considerable uncertainty.** A CLD is not equal to a BSD **regardless of the amount of drilling one does!**

- Careful characterization of matrix fabric, block discontinuities required

Do not describe bimrocks as “inter layered” or “interbedded”

13 . CASE HISTORY EXAMPLES OF WORKING WITH MELANGES (See Medley, 1994 PhD (PDF) Case Histories for more detail

A Lone Tree Slide Landslide, Marin County, California

- Location, background information
- Selection of characteristic engineering. dimension and block/matrix threshold size
- volumetric block proportion
- lithology proportions and BSD: construction implications
- estimating BSD for construction purposes

B Richmond Tunnel, San Francisco, California

- Location, background information, geology
- Use of $\sqrt{A}$
- Selection characteristic engineering dim
- Core data and volumetric proportion: significance for TBM
- Block lithologies: significance
- BSD: significance for TBM

C Scott Dam, Lake County, California

NOTE: The research on melange bimrocks summarized in this lecture was prompted by engineering problems in characterizing the strength of the melange bedrock at the foundation of Scott Dam in northern California. See **Also Goodman & Ahlgren, 2000**

- Location, background information, geology
- previous geotechnical work: sliding failure: FS = 0.6
- selection of characteristic engineering dimension and block/matrix size
- estimation of volumetric proportion
- use of strength models to estimate design ϕ ($c \approx 0$)
- influence of block fabric
- uncertainty in volumetric block proportion
- adjustment of bimrock rock mass strength used for design

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SOME REFERENCES ON MELANGES, BIMROCKS, BIMSOILS, AND STEREOLOGY *refer also to "bimrock papers" PDFs*

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