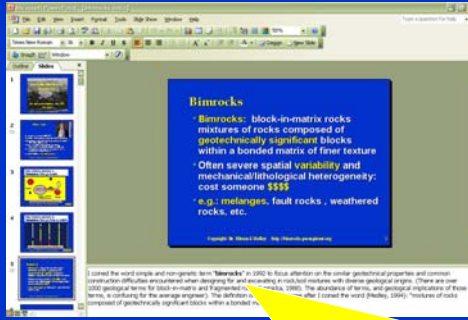


HINT: To read Notes



To read Notes: save PowerPoint file; View presentation in Normal View (Slide Edit mode); and expand the Notes pane, OR: View presentation in Notes Page mode.

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About Me



- Prospector in Canada 1969-1973
- Education: Geological and Geotechnical Engineering
- Geological and Geotechnical Engineering Consultant 1978-1991; 1995-current
- Senior Consultant, Geological Engineering, Geosyntec Consultants, Oakland, California
- Prof. Registered Geologist and Engineer in USA, Canada, and United Kingdom
- Contact Details: emedley@geosyntec.com

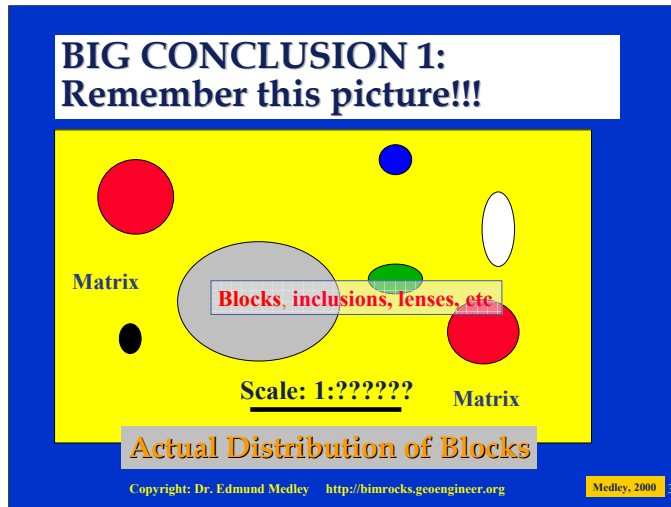
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BIOGRAPHY of Dr. Edmund Medley, PE, CEG

Dr. Edmund Medley, PE, CEG, F.ASCE is a Senior Consultant in the GeoEngineering practice of Geosyntec Consultants, Oakland, California, USA (www.geosyntec.com). 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 melange, 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 has experience evaluating geotechnical/geological engineering vulnerabilities and the causes of civil engineering failures, and has provided testimony for attorneys, insurance companies, contractors and municipal clients. Projects include investigation of major landslides, rock fall hazards, expansive/collapsing soils, tunnel failures, coastal erosion, sinkholes and other ground movements in the USA and overseas. He is licensed/registered/chartered as both an engineer and a geologist in the USA, Canada and the United Kingdom

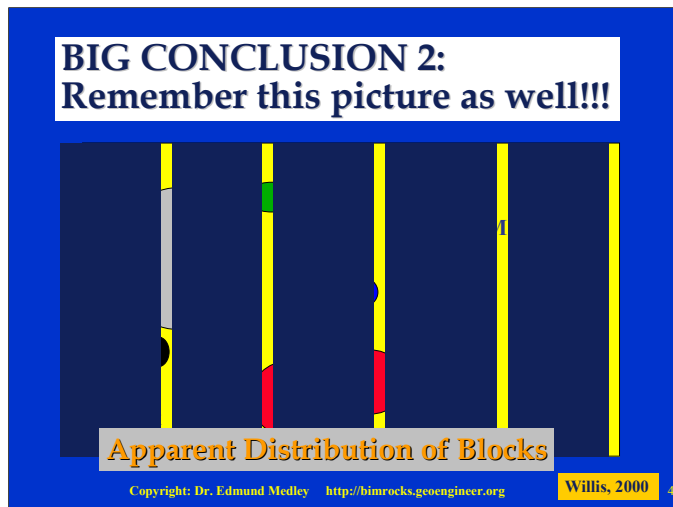
Dr. Medley has contributed to over 30 professional publications. He has presented more than 100 lectures, and taught several Short Courses. He has appeared in TV documentaries featuring the investigation of the 1995 Sea Cliff Incident in San Francisco. He is member of the Editorial Boards of *Felsbau* and the *International Journal of GeoEngineering Case Histories*, and has been a peer reviewer for several professional papers.

EDUCATION: University of California at Berkeley: 1994: Ph.D., Geotechnical Engineering with Minors in Geology and Ocean Engineering, University of California at Berkeley; 1991: M.S., Geotechnical Engineering, University of California at Berkeley; 1978: University of British Columbia: B. Applied Sc., Geological Engineering, Geotechnical Engineering Option with concentrations in Fluvial Geomorphology, Ocean and River Engineering, and Oceanography.



Here is a simple picture to show the fabric of a complex geological mixture, one of two pictures which summarizes an important message I present on this website.

Complex geological mixtures are ubiquitous. Think of isolated blocks, blobs, lenses, inclusions, zones (or whatever) with certain physical, chemical, geophysical, geological (again, or whatever) properties contained within a surrounding field (or matrix) of contrasting properties. Examples include glacial tills with boulders and cobbles embedded in clays; groundwater lenses within unsaturated strata; mineral ore deposits within uneconomic host rock; contaminated soil zones within uncontaminated soil, and so on.



But what we see by drilling and mapping is considerably less, as shown in this slide. Most important still: when working in bimrocks we must resist the temptation to draw straight lines between our boring contacts and mapped outcrops!!

To understand better how little we actually see of underground conditions, **try this simple exercise**: put your hands in front of your face leaving a narrow gap to look through. Now take several “slit image” mental photographs of your surroundings. Imagine now that you transmitted those images to a colleague and asked her/him to reconstruct your surroundings from the images. Difficult, right? Well, it is the same difficult problem that geologists and geotechnical engineers must solve all the time. But realize how wrong we can be before we start believing our geological characterizations based on our interpretations of borings.

Bimrocks

- **Bimrocks:** block-in-matrix rocks mixtures of rocks composed of **geotechnically significant** blocks within a bonded matrix of finer texture
- Often severe spatial **variability** and mechanical/lithological heterogeneity: **cost someone \$\$\$\$**
- **e.g.: melanges, fault rocks, weathered rocks, etc.**

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I coined the word simple and non-genetic term “**bimrocks**” in 1992 to focus attention on the similar geotechnical properties and common construction difficulties encountered when designing for and excavating in rock/soil mixtures with diverse geological origins. (There are over 1000 geological terms for block-in-matrix and fragmented rocks (Laznicka, 1988). The abundance of terms, and geological implications of those terms, is confusing for the average engineer). The definition of “bimrocks” came after I coined the word (Medley, 1994): “mixtures of rocks composed of geotechnically significant blocks within a bonded matrix of finer texture”.

To be **geotechnically significant**, blocks in bimrocks require:

1. **a mechanical superiority** of blocks over matrix (strength considerations), e.g.:

$$\text{ratio } \phi_{\text{block}}/\phi_{\text{matrix}} > 1.2 \text{ (for instance, but not extensively researched!!!)}$$

2. **a size range** which influences bimrock mechanical properties

e.g.: if block size is 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 (Lc)**) conforms to:

$$0.05 Lc \leq d \leq 0.75 Lc$$

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

3. **a volumetric proportion** of blocks which influences bimrock mechanical properties.

Based on the work of Lindquist (1994) a reasonable range of block volumetric proportion (**Vv**) for a bimrock is:

$$25\% \leq Vv \leq 75\%,$$

Or: if $Vv \leq 25\%$ treat the material as matrix (and analyze as a “soil”) and if $Vv > 75\%$, treat material as blocky rock (or rock mass with wide, in-filled joints).



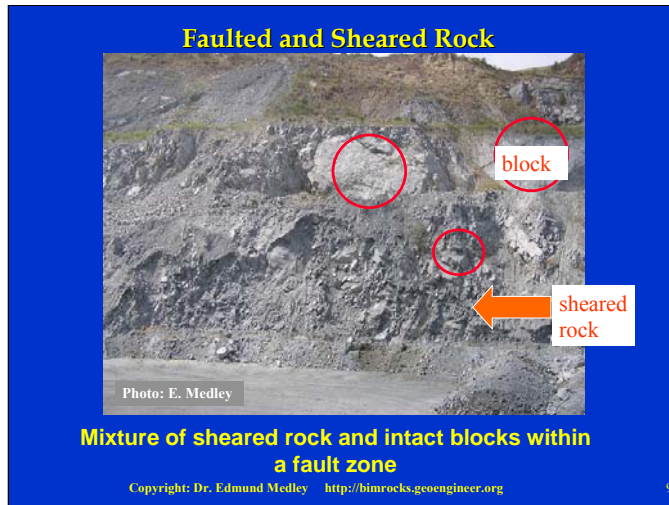
Bimrocks have extreme spatial variability (chaos) which hinders exploration and sub-surface characterization; wide ranges in mechanical variability (strength, stiffness, deformation); and great hydrogeological variability. The chaos of bimrocks causes considerable trouble, especially as a result of poor characterizations.



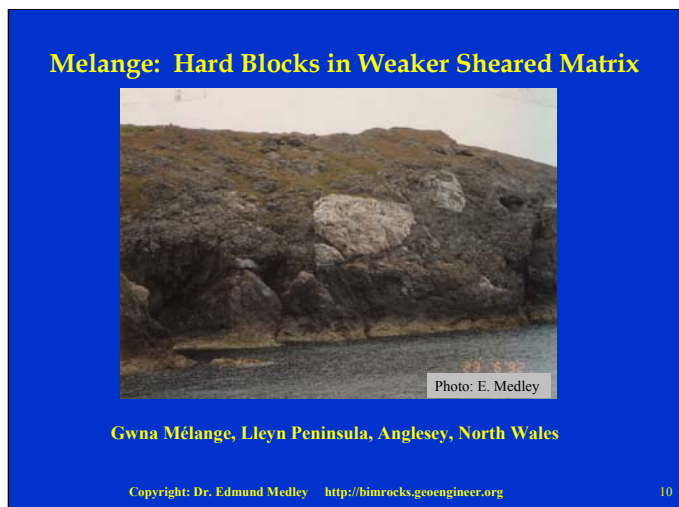
Hard blocks of fresher granite (corestones) surrounded by soil-like sandy “*gruss*”, which is completely weathered granite. The size distribution of the blocks is governed partly by the original size distribution of blocks (bounded by variably spaced rock joints) and partly by the state of weathering. It would be wrong to characterize this weathered rock as “soil with boulders” since the boulders may be several 10s of meters in size.



A typical shear zone in a rock mass produces a block-in-matrix fabric that is often scale independent over several scales of engineering interest (centimeters to hundreds of meters). In other words: the appearance of the zone is often the same whether viewed at through a microscope or looked at from the air. This image is of a ductile shear zone (DSZ) developed in a gneiss containing pod-like bodies of pegmatite, Broken Hill, NSW Australia: see: <http://www.newcastle.edu.au/department/gl/ro/str/st4.htm>



A highly sheared and fragmented rock mass within a major fault zone more than a 1 km wide. Blocks range from centimeters to hundreds of meters in size.



Gwna Mélange at Tryn-moen-moel, a headland on the Lleyn Peninsula of Anglesey, North Wales; near the birth place of the term “autoclastic mélangé”. The word “mélangé” in a geological context was first used by Edward Greenly (1919)[1] for the Gwna Melange of Wales. The word was 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 then-called Franciscan “Formation” in Morro Bay, California[1]. I paid homage to Greenly’s outcrops at this and other shrines when I started my research. My mother was Welsh and I was brought up in North Wales, so with great much pleasure I made a pilgrimage to the several remote sites Greenly mapped. However, there was some discomfort for my patient wife Julie who waited for me on steep wind-whipped cliffs, while I ran around joyfully amongst the blocks and the baaa-ing sheep.

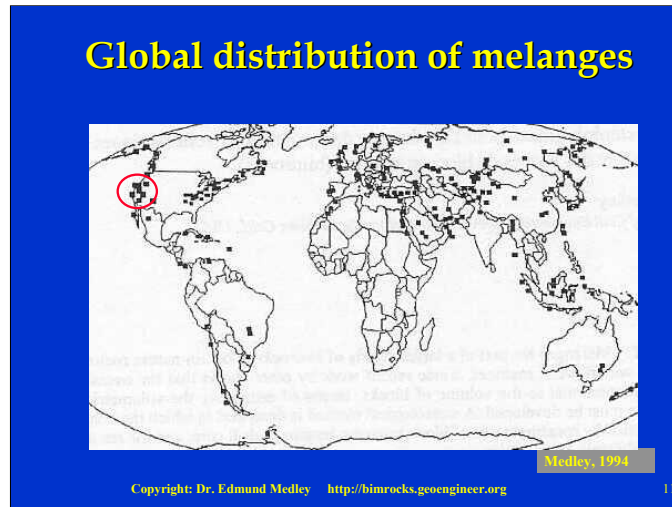
Mélange is the French for “*mixture*”. By the way: “melange” is spelt correctly. There is no conformance in the use of the acute accented e as in “é”, and it may be neglected. Yes, I know that the word is French (*mélange*, pronounced *may-LAWN-juh*) but few people in the United States know how to write or pronounce words that have letters with squiggles and dashes over them. So, to make it easier for them and myself, I spell it melange, no “é”. I pronounce the word **mell-AHN-juh**, but go ahead and pronounce the word which ever way you want.

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.)*

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.*

[1] Greenly, E, 1919, The Geology of Anglesey Memoir, Geological Survey of Great Britain, 2 vols.

[2] For an informative history of melange, 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

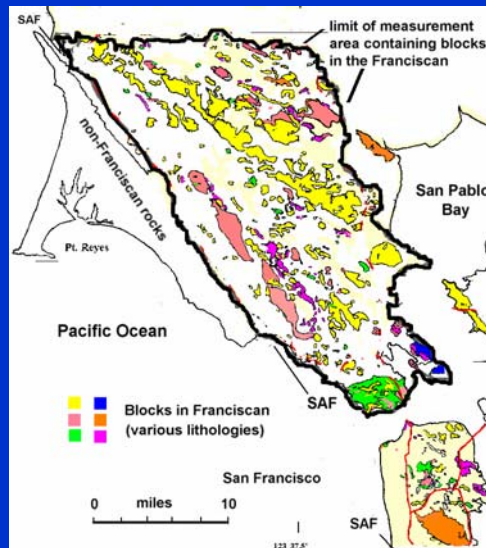


Melanges are found in over 70 countries, usually in mountainous areas near recent or ancient tectonic subduction zones. Melanges are famously exemplified by the Franciscan Complex of California (red circle) which is the “type locality” for melanges.

Melanges form as off-scraped deposits in the subduction zones. There are still considerable geologic debates about the formation of melanges. Indeed, in 1994, I counted over 2000 technical papers on the geologic aspects of melanges. 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*, scaly 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).

While learning all these geological terms from many geological papers, I discovered that there were only a handful that addressed the engineering aspects of melanges. Nevertheless, melanges are extremely troublesome to geotechnical engineers.

Franciscan Complex melanges



Franciscan Complex in Marin County, California

From Medley, 1994;
after Ellen and
Wentworth, 1995

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This map shows the Franciscan Complex in Marin County, just north of San Francisco.



A melange in Greece; photograph by the late Professor Gunter Riedmueller, GGG, Graz, Austria. Blocks of limestone protrude through sheared shale along proposed alignment of new highway in Greece. Photograph reproduced permission of Gruppe Geotechnik Graz.

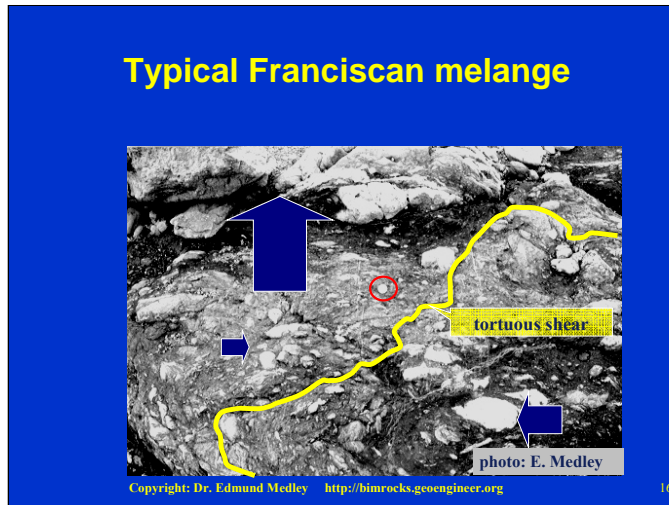


Large block of graywacke sandstone and surrounding block-rich shear zone of shale within melange of the Franciscan Complex, Caspar Headlands, Mendocino County, California. It is common for erosion-resistant blocks to protrude as headlands along the coastline and rivers in the melange bodies of the Franciscan complex of Northern California. Such blocks also have a buttressing effect on slopes.



Typical Franciscan Complex melange at Caspar Headlands, near Mendocino, California.

The smiling pony-tailed geotechnical engineer is Dr. Eric Lindquist, PE who, under the guidance of Professor Richard E Goodman, pioneered the research into the fundamental geomechanical properties of physical model Franciscan melanges during his PhD research at the University of California at Berkeley in the early 1990s.



Typical Franciscan Complex melange at Point Delgada, Northern California. Scale shown by 25 cent coin in center (red circle). Blue arrows show typical blocks: always a very few large blocks and increasing numbers of smaller blocks. Matrix is pervasively sheared shale, with shears invariably negotiating around blocks in a tortuous fashion. Shearing may be pervasive: over 800 shears per meter have been counted in Franciscan Complex melanges. (See: (M. E. Savina, 1982: "Studies in bedrock lithology and the nature of downslope movement", University of California, Berkeley, California; PhD dissertation, 298 p.)

Another Example



Franciscan Complex melange, Trinidad Beach, Humboldt County, California

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Franciscan melanges can contain blocks with many lithologies: sandstones, siltstones, intact turbidite sequences, cherts, greenstone, limestone, exotic metamorphics like blueschists and eclogites. The juxtaposition of such a variety of rocks is one of the prime indicators of melanges.

block/matrix contacts are weakest

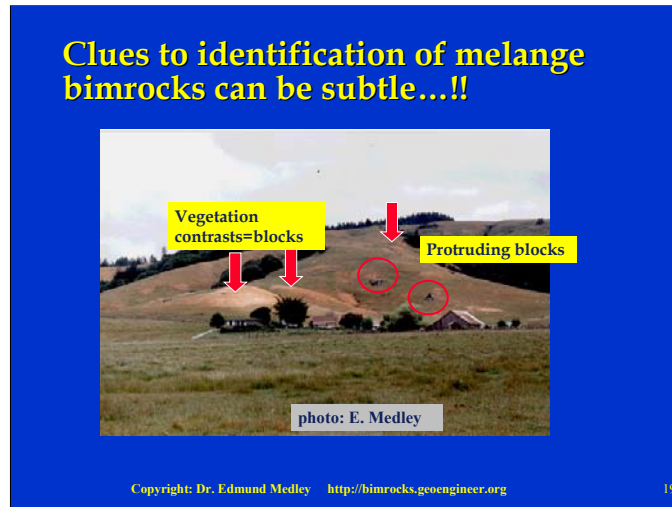


photo: E. Medley

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The weakest component in a melange is generally the block/matrix contact.



Geomorphology of melange terrain is characteristic in areas of Northern California underlain by Franciscan complex melanges. Blocks protrude from otherwise smoothly rolling hills. Where blocks underlie the surface at shallow depths, vegetation contrasts may reveal them. In spring, sandy soil above graywacke blocks (which are the most common in the Franciscan) dry quicker than clayey soils above shaley matrix, and grass turns browner sooner in spring. The mottled appearance is very marked on air photos taken during springtime.

USEFUL REFERENCES: Melanges and Similar Bimrocks

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 3. **Horton, J. Wright, and Rast, Nicholas, 1989:** (editors): Mélanges and Olistostromes of the US Appalachians; Special Paper 228, Geological Society of America, Boulder, Colorado; 276 p.
 4. **Hsü, K., 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
 5. **Laznicka, P., 1988:** Breccias and coarse fragmentites: Petrology, environments, associations, ores; vol. 25 of Developments in Economic Geology; Elsevier, New York, 832 p.
 6. **McCall, G.J.H., 1983:** (editor): Ophiolitic and related melanges, Benchmark Paper in Geology No. 66, Hutchinson Ross Publishing Company, Stroudsburg, Pennsylvania.
 7. **Medley, E.W., 1994a:** The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.
 8. **Raymond, L.A., 1984:** (editor): Melanges: their nature, origin and significance; Special Paper 198, Geological Society of America, Boulder, Colorado; 170 p.
 9. **Riedmüller, G., F. J. Brosch, K. Klima & E. Medley, 2001:** Engineering geological characterization of brittle fault rocks and classification of fault rocks. Feldsbau, J. of Engineering Geology, Geomechanics and Tunnelling. 19 (4/2001): 13-19.
 10. **Savina, M. E., 1982:** "Studies in bedrock lithology and the nature of downslope movement", University of California, Berkeley, California; PhD dissertation, 298 p.)
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For highlighted references: see "Resources" page on <http://bimrocks.geoengineer.org>

Cowan, D.S., 1978; Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Bull. Geol. Soc. America, v.89, p.1415-1423.

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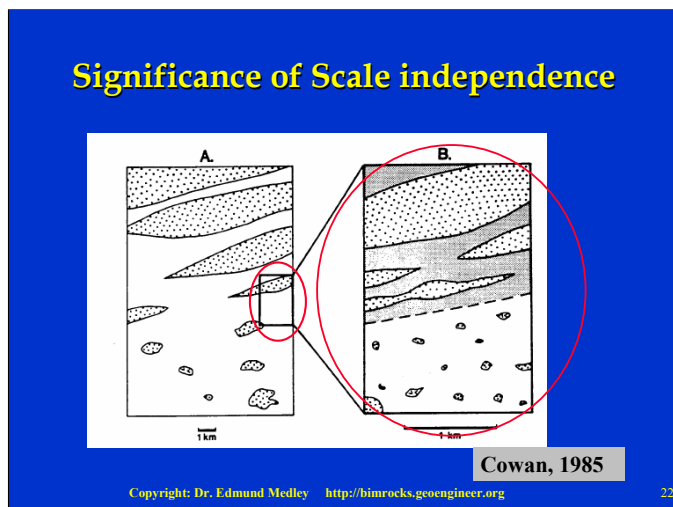
**Significance of Scale Independence
in Block Size Distributions of
Franciscan Melanges**

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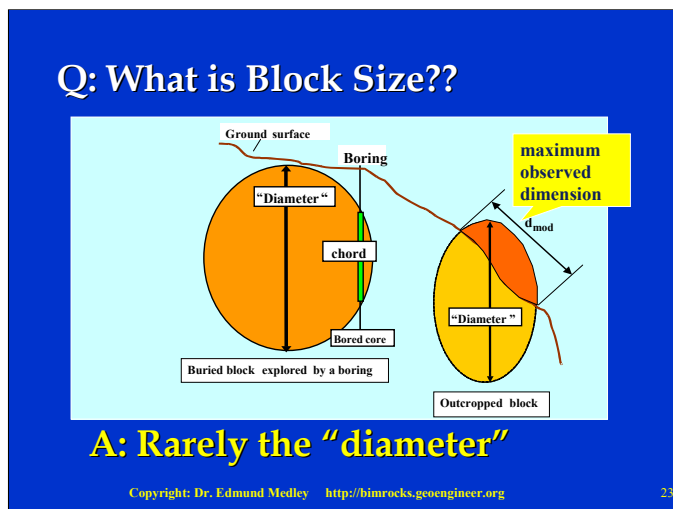
The title is a mouthful, I admit....

Melanges look similar at many scales of interests; from the scale of millimeters to kilometers. Many other bimrocks also show block fabrics that appear similar over the range of scales of engineering interest (laboratory to site scales). There are some important implications to scale-independence as is shown in the next few slides, which highlight findings from studies of Franciscan melanges. But the findings are applicable to many other bimrocks too.



Melanges and bimrocks look similar at many scales; i.e: 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. So: it is important to discriminate the blocks from the matrix in bimrocks. In the picture here, it seems clear enough: the blocks are the big bits of rock and the matrix is every thing else. But what if we now step closer to an outcrop? At the changed scale of interest is the heterogeneous mixture of blocks and matrix now “homogeneous”?

The next few slides explore this question.



Before exploring scale-independence, we should look briefly at the issue of “**block size**”.

We often say that a boulder, block or rock fragment is some “size”, such as “5m diameter”. However, it will generally be incorrect to make those statements if the only basis for our estimate is drilling or geological mapping.

The left image of this slide shows a buried block with a “true diameter”. The block is intersected by a drilled boring and the length of the intersection is measured. This length is a “chord”. It should be clear that if there are (for example) 100 possible chords through the block, only 1 will be the actual diameter. Indeed it is a matter of geometric probability that the chords will generally NOT be the diameter and so drilled exploration will almost **always** underestimate the “size” of the block.

The same is true when mapping a block outcropping at the ground surface.

However, we can measure the “maximum observed dimension” (d_{mod}) (or simply d) of the block.

The extent of inaccuracy in our estimates of block sizes and block size distributions based drilling or mapping is explored later in the presentation.

“size” = d_{mod}

Measuring block sizes (and size distributions) in 2-dimensions

Outcrop scale of interest

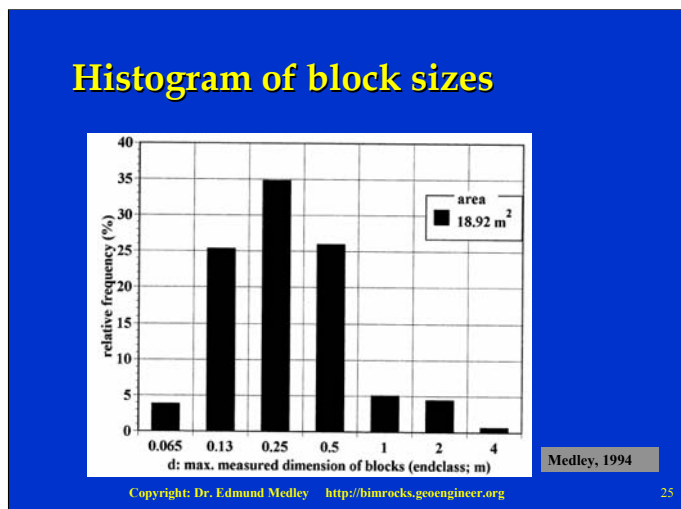
$A < 1 \text{ m}^2$

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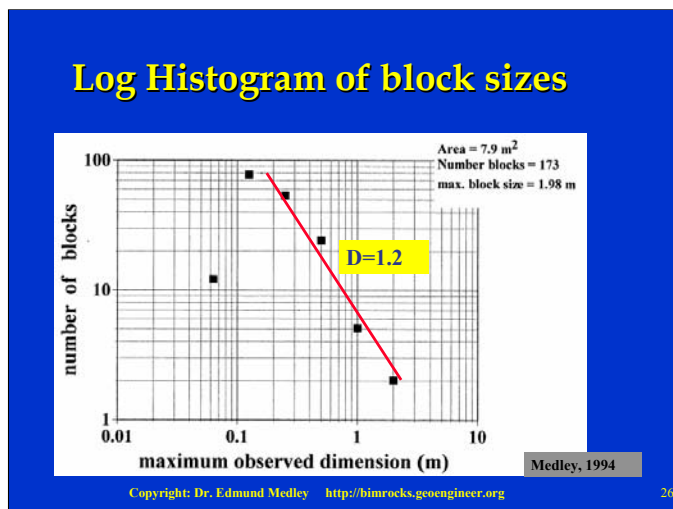
The graphics show a photograph (top) of an outcrop of Franciscan Melange. The image below is the result of image analysis of the photograph.

The scale is 5 feet long (1.5 m). The longest dimension of all the blocks visible in the outcrop can be measured, by hand if need be, or else more conveniently using image analysis software. The apparent maximum length for one block is shown by the yellow bar. The “size” of the blocks is thus characterized by many d_{mod} .

The area of interest can also be measured: **A**. The area is an indicator of the scale of measurement, in this case, $A < 1 \text{ m}^2$.

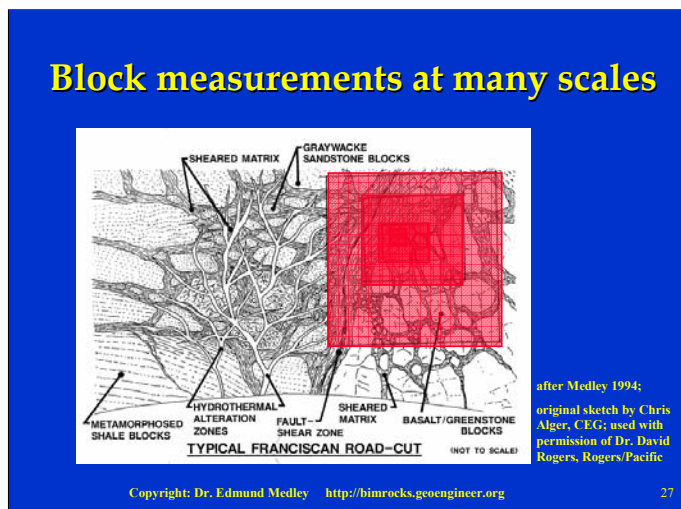


Suppose one measures all the “d” lengths that one can see in the outcrop, or the photograph. Then a histogram can be constructed, much like the one above. Note that the “x” axis shows size “classes” that double in range to the rightward (0.5 1, 2, 4, 8, etc..) . Note also that the “y” axis is “relative frequency”, which is the proportion of blocks in a certain “d” class relative to the total number of blocks counted, expressed as a percentage.



This slide shows a different way of showing the data. The d classes are on a logarithmic scale (which is actually bad practice given that the logarithmic value should be dimensionless.) Rather than relative frequency (as in the previous slide), this plot shows the absolute number of blocks in each d class, also plotted logarithmically. The plot is called a "Log Histogram". The best fit line of the "descending limb" of the plot is the slope, and is also the Fractal Dimension.

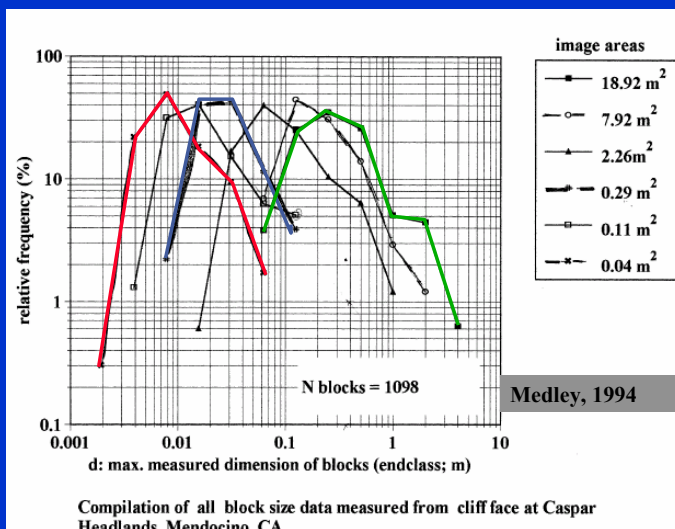
The left limb, or "ascent limb", shows just a few blocks. The apparent low number is a consequence of the smallness of the blocks. Because they are difficult to see compared to larger blocks, it is easy to miss them, and hence many do not get counted. Such under-counting is called "censoring" of the data.



Now suppose that you are looking at an outcrop and perform several measurement exercises of the same outcrop but at different scales.

For example you could take a photograph standing tens of meters from the outcrop and then gradually step toward the outcrop taking additional photographs as you move closer in. You would then make separate measurements of the “d” of the blocks in each of the photographs. You will find that as you move in, blocks that you could not see when you were further away will be discernable as you move in. Of course, the areas of measurements also diminish as you move closer, given that, say, you are taking photographs of a fixed size.

Log Histograms at several scales

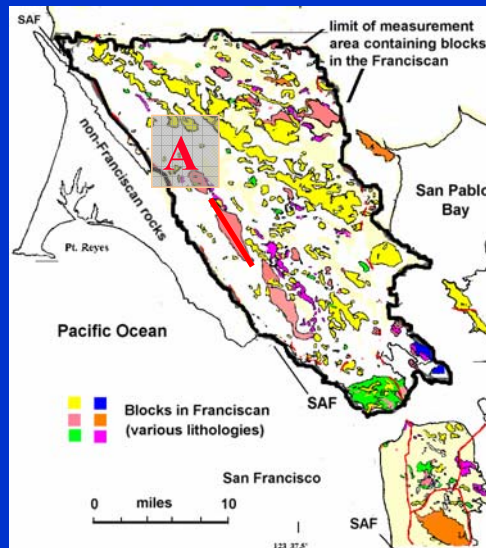


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This plot is a compilation of the log histograms for block $d_{\text{mod}s}$ (or \mathbf{d}) of an outcrop as measured from photographs taken at different scales. Notice the marked similarity of the plots top each other. Note also that blocks that are censored (under-counted; like the left limb of the green plot), because they are too small. However, these are measurable as the scale changes larger (leftward) and the blocks become discernable at the larger scales. There are 3 ranges in magnitude of scale, from millimeters to meters.

Franciscan Complex blocks in maps



Regional map
scale of interest:
Franciscan
Complex in
Marin County,
California

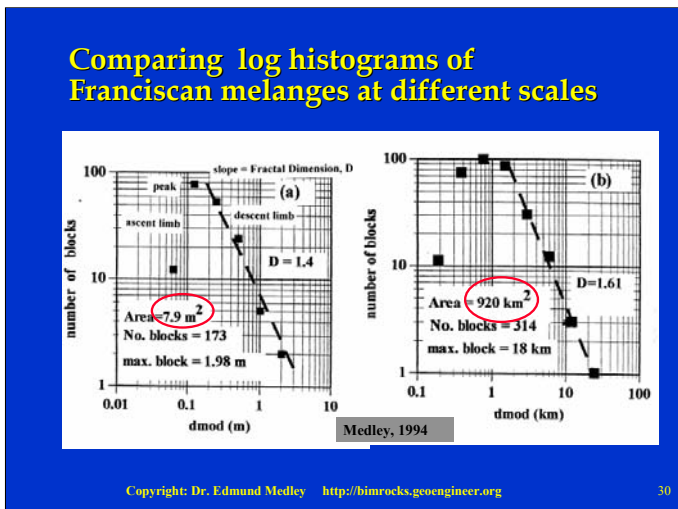
A~1000 km²

From Medley, 1994;
after Ellen and
Wentworth, 1994

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This is a copy of a previous slide, showing the Franciscan Complex as mapped by Steve Ellen and Carl Wentworth of the US Geological Survey, in Menlo Park, California. Dr Ellen was kind enough to allow me access to the preliminary geological map before it was published. I measured the d_{mod} (e.g.: red bar) of the mapped blocks within the area bounded by the thick black line, which is much of the area of the county. The A(rea) is about 1000 km².

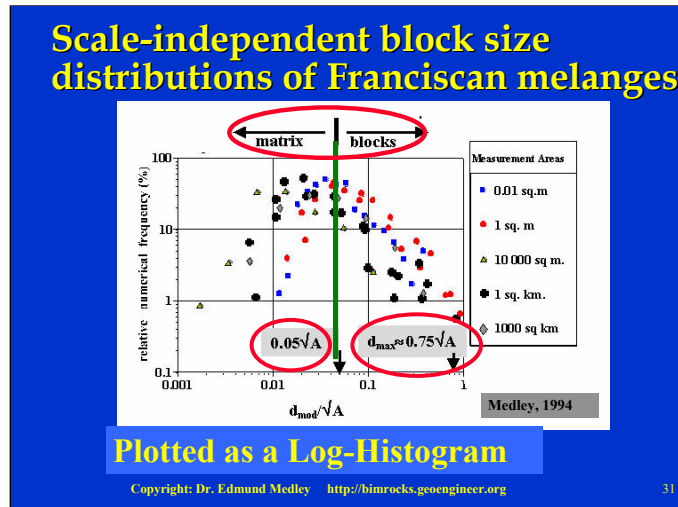


Here are two log histograms.

The left one is a plot of block “d” measurements of the outcrop shown in the previous slides. Note that the maximum d (d_{mod}) measured in the photograph is 1.98 m. The Area (A) is 7.9 m² and the fractal dimension D, is 1.4.

The right plot is one showing data measured of blocks mapped in Franciscan Complex of in entire the county of Marin, shown if the previous slide. The maximum d (d_{mod}) for the right plot is 18 km and the fractal Dimension is 1.61. Observe how similar the shapes of the twp plots are despite the extreme difference in scale.

A pattern is developing. Do you see how similar to each other are the block size distribution log histograms that we are looking at??



This plot is a compilation of plots of measurements of block d_{mod} from maps and photographs at many scales, including the outcrop and map in previous slides.

In order to compare the many plots, the “x” axis represents the dimensionless ratio (d_{mod}/\sqrt{A}) in which block d_{mod} values are divided by the square root of the measurement area containing the blocks. The “y” axis is dimensionless relative frequency of the blocks. Note that the range of measurement areas ranges over many orders of magnitude.

The plot is a very important one for the following reasons:

1. The peak (d_{peak}) of the normalized log-histograms at any scale measured occurs at approx. $0.05\sqrt{A}$, or:

$$d_{\text{peak}} \cong 0.05 \sqrt{A}.$$

2. The maximum largest block (d_{max}) at any scale measured is equivalent in size to \sqrt{A} (ie: at $d_{\text{mod}}/\sqrt{A} = 1$, $d_{\text{mod}} = A$). In fact, nearly all the blocks are less than about $0.75\sqrt{A}$, so:

$$d_{\text{max}} \cong 0.75\sqrt{A}$$

The first rule defines the range in block size smaller than which block counts are unrepresentative (blocks are too small to discriminate accurately at the scale of observation). In other words:

$$d_{\text{peak}} \cong 0.05 \sqrt{A} \text{ is a block/matrix threshold size.}$$

Blocks smaller than the threshold are considered part of the matrix at the scale of interest considered.

This plot is remarkable in many ways. Firstly, the normalized plots are very similar to each other, despite the great range in scales of observation. The curves combine into a relatively consistent constellation of points. So: the block size distributions are relatively similar despite that blocks sized ranged in sizes between sand and mountains. In other words, **blocks will be found at all scales of observation (at least in the Franciscan Complex melanges observed), and cannot be ignored!** Furthermore, smaller samples of Franciscan melange are “models” of larger scale rock masses. Much can be learned by looking at outcrops and testing small specimens that will be applicable to larger volumes of rock mass. Such is not generally true in the rock engineering of more tractable rocks!

Blocks in Franciscan Melange

- Blocks range in size between mountains and sand and will **always be found**
- Characterization **must** take blocks into account
- Block size distributions are scale independent **and** fractal (**power law**)
- Need a characteristic dimension to scale the rockmass to the scale of engineering interest (L_c)

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The plot on the previous slide shows that **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**. *Characteristic engineering dimensions* (L_c) are lengths that are descriptive of the geometry of the engineering problem under consideration. Think of them as scaling lengths analogous to photographing your Significant Other or a coin or camera lens cap on rock outcrops.

Possible L_c for various situations may be:

- L_c for triaxial specimen: specimen diameter
- L_c for tunnel: tunnel diameter
- L_c for spread footing: footing width
- L_c for landslide analysis: thickness of failure plane, height of slope
- L_c for excavation: Height of cut; \sqrt{A} of excavation area
- L_c for site reconnaissance: \sqrt{A} of project area, estimate of dimension of largest block (d_{max})

Use these guidelines at any scale of interest

- **smallest blocks are:**
 $0.05L_c$ or $0.05 \sqrt{A}$ or $0.05d_{\max}$
- **largest block is:**
 $0.75L_c$ or $0.75 \sqrt{A}$ or $0.75d_{\max}$

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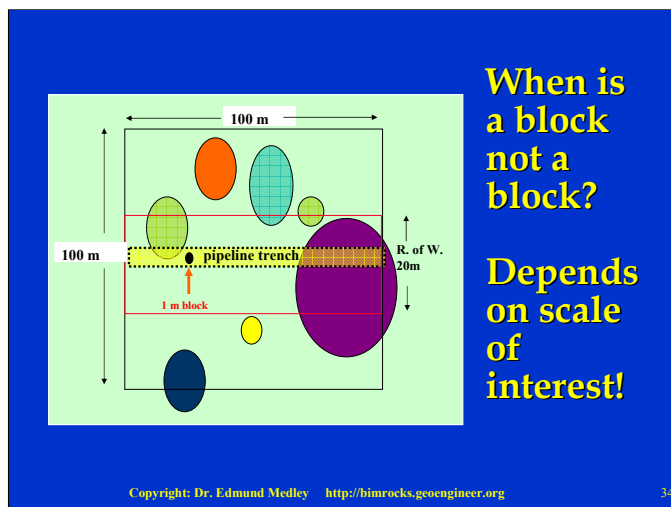
Based on analysis (see log histograms in previous slides) and empirical work, a reasonable block/matrix threshold size can be defined as $0.05L_c$. Above this threshold size, blocks will be geotechnically significant at any particular scale of engineering interest. Below the block/matrix threshold size, blocks are assigned to the matrix, and are too small to make any geomechanical contribution, (although they will be very numerous).

But blocks demoted at one scale may be blocks in their right at larger scales (smaller L_c). Similarly, the **maximum block size** is defined as $0.75L_c$, above which limit blocks are termed **blocky rock**.

However, \sqrt{A} is actually a scaling dimension, and can be used as L_c . Indeed, if one knows reasonably well what the very largest block dimension (d_{\max}) is, that size also is a scaling dimension.

Comparing the guidelines in the previous slides, it can be seen that there are many ways to describe the block/matrix threshold at any scale of interest: $0.05L_c$, $0.05 \sqrt{A}$; and $0.05d_{\max}$.

Similarly, the largest reasonable block can be defined as: $0.75L_c$, $0.75\sqrt{A}$ and $0.05d_{\max}$.



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 centimeters long, means the blocks of the lab specimen are now assigned to the matrix).

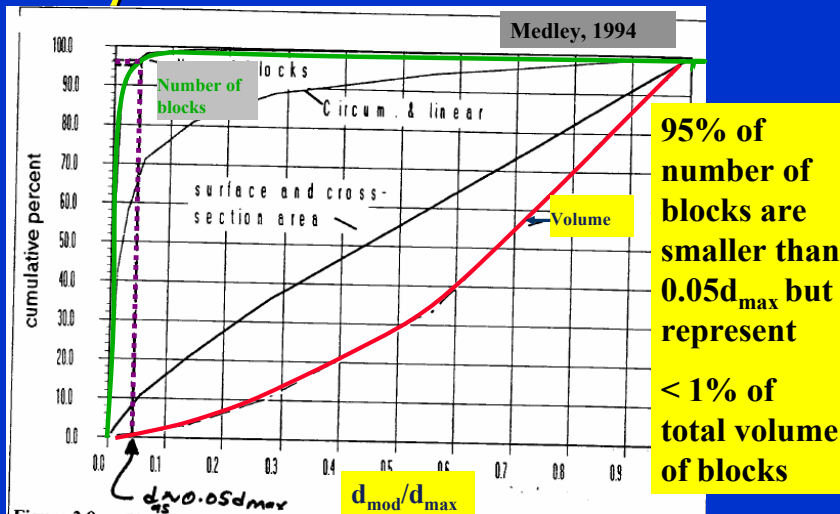
This sketch illustrates the effect of changing of scales of interest on block/matrix thresholds:

Imagine that one is interested in a project area some 100 m by 100 m square which is underlain by a melange of the Franciscan Complex. The scale of the whole project site is thus characterized by a characteristic dimension (L_c) best described as \sqrt{A} , which here is 100m. Hence at the site scale of interest, the block/matrix threshold is $0.05\sqrt{A}$, or 5m; and the largest reasonable block is $0.75\sqrt{A}$ or 75m. So, at the scale of the whole site, any blocks smaller than 5m are assigned to the matrix, and blocks larger than 75m are blocky rock. All blocks in the sketch are valid except for the 1m block (arrowed).

Imagine now that a road is planned through the site. The road has a right-of-way width of 20m. For excavation and design purposes, our scale of interest is now changed to the road and the right of way width of 20m becomes the characteristic dimension, L_c . At this scale the block/matrix threshold of $0.05L_c$ is 1m and the largest reasonable block is $0.75L_c$ or 15m. At this scale, the large purple block on the right side is now blocky rock. For excavation purposes, it can be analyzed using conventional rock engineering approaches. The 1m block (arrowed) is now a block although it was assigned to the matrix at the site scale. **But at the even smaller scale of a pipeline trench** aligned below the road, the 1 m block is clearly a significant obstruction. And at the scale of a bulldozer blade or an excavation scraper, the 1m block is similarly potentially troublesome for an earthwork contractor if the potential presence of blocks was unanticipated.

As shown in the log histograms: Blocks should be anticipated at all scales of interest in Franciscan melanges! For many other bimrocks, blocks should also be anticipated over the range of scales of engineering interest between the laboratory scale of centimeters, to site scales of 100s of meters.

Another reason to select the 5% block/matrix threshold



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Another reason for selecting the 5% threshold is shown in the graphic here. For a melange with a block size distribution that is “Franciscan”, there will be countless small blocks. Even though the left limb of the block histograms suggests that there are few blocks smaller than $0.05L_c$, in actuality there are many more but they are too small to see or count. This exclusion of data is called “censoring”.

The plot is for a population of ellipsoid-shaped blocks with minor axes intermediate axes=0.5 the maximum axes. The green plot shows that 98% of the **number** of block are **smaller** than the block/matrix threshold at $0.05d_{max}$ but the **volume** of those myriad blocks represents less than 1 percent. In other words, they make no difference to the mechanical behavior of the mixture.

USEFUL REFERENCES: Scale Independence

1. **Cowan, D.S., 1978**; Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San Simeon, California: Bull. Geol. Soc. America, v.89, p.1415-1423.
2. -----, **1985**; Structural styles in Mesozoic and Cenozoic melanges in the western Cordillera of North America; Bull. Geol. Soc. of America, v.96, p. 451-462.
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4. **Medley, E.W. and Lindquist, E.S., 1995**; The engineering significance of the apparent scale-independence of some melanges of the Franciscan Complex, California, in Proc 35 th US Rock Mechanics Conference, (South Lake Tahoe, California).

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Medley, E.W. and Lindquist, E.S., 1995; The engineering significance of the apparent scale-independence of some melanges of the Franciscan Complex, California, in Proc., 35th US Rock Mechanics Conference, South Lake Tahoe, California.



I am frequently asked: “What is the strength of bimrocks?” Well: these few slides following will not answer that question but they give a summary of how Dr Eric Lindquist and Professor Richard Goodman researched the question, and will provide some guidelines for others to answer the question themselves....

So, YES: bimrocks ARE chaotic...

But Practitioners should **NOT** say:
"those rocks are too chaotic, let's
design for the weak matrix..."

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So, all this scale-changing stuff means that bimrocks are too confusing and too chaotic to be of bother to the geologists and geotechnical engineers? Why not design for the weak matrix and be conservative? **Isn't this assumption always valid?** Answer: *Not in all situations, hence motivation for these slides!*

But by all means design for the weak component if you wish. But in doing so, the you may give away geomechanical advantage. More importantly, a focus on the "weak" matrix may result in the presence of the blocks being ignored during design. But the contractor will not be able to ignore them during construction, and the Owner may not be able ignore the extra change order costs when presented with them.

There is also a danger that once the bimrock is "homogenized" to a "soil" the discontinuities, shears other rock mass structural fragilities will also be forgotten.

**Strength and deformation properties of
Melange Bimrocks**

- Strength and deformation properties of melanges are independent of block strengths (Lindquist and Goodman, 1994)
- **Overall strength is directly related to volumetric block proportion**
- Blocks adds friction, stiffen the mixture and reduce cohesion
- Must perform geotech tests with blocks in specimens

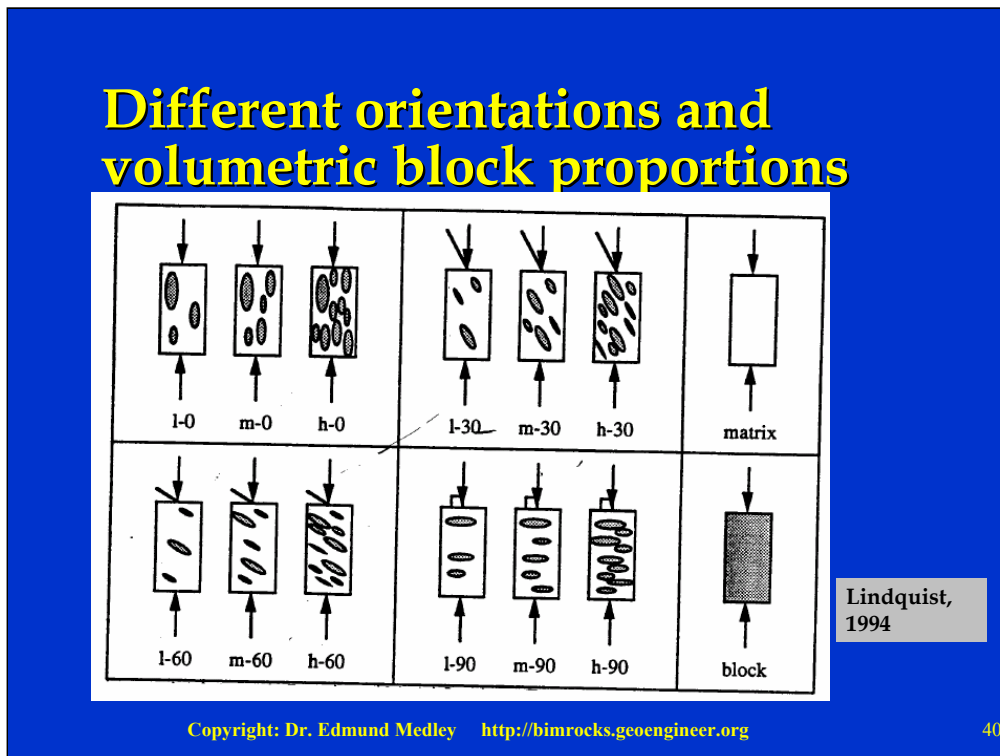


Dr. Eric Lindquist, 1992

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The following slides review the geomechanical aspects of melange bimrocks. Many of the points made here are applicable to other bimrocks too. The work is based on the fundamental studies of Dr. Eric Lindquist, PE, who was my colleague during our PhD research supervised by Professor Richard E. Goodman at the University of California at Berkeley in the early 1990s. (The picture of Dr. Lindquist above is a smaller version of the previous slide showing typical Franciscan complex melange.)

One of the most important findings of Dr Lindquist's and Professor Goodman's work was that the overall strength of a physical model melange was simply and directly related to the volumetric proportion of blocks. That seems pretty obvious, but prior to the Lindquist/Goodman research, there was no clear demonstration of that relationship. Indeed, soil mechanics literature has generally indicated that in a mixture of clay and sand, the overall behavior of the mixture is dominated by the clay. So: design for the weak stuff!! But at the scale of a bulldozer blade excavating a bimrock; or a TBM boring a tunnel, there is of course a big difference between neglecting any contribution of sand in a sand/clay mixture compared to neglecting blocks 10s of meters in size in a melange! You **cannot** ignore the blocks, even if you decide not to account for their presence in the overall strength.



Lindquist,
1994

Dr. Lindquist fabricated over 120 specimens of 150 mm diameter composed of physical model melanges. He tested them in a Hoek triaxial cell. The specimens were made with a weak matrix composed of a bentonite/cement mortar with inclusions of paraffin wax lamina (to model shears). He fabricated thousands of model disc shaped blocks and for each specimen had volumetric block proportions of about 30%, 50% or 75%, with block size distributions that matched the overall size distribution of Franciscan melange (a distribution much as shown in log-histograms in the previous slides).

Blocks were placed in the matrix with generally consistent range of orientations (0 degrees, 30 degrees, 60 degrees and 90 degrees relative to the vertical axis of loading). So, with controlled block size distributions, block orientations, block shapes, and volumetric block proportions, the specimens were tested in triaxial compression at several confining loads, to yield the trends shown in the following slides.

Increase in friction angle with volumetric block proportion

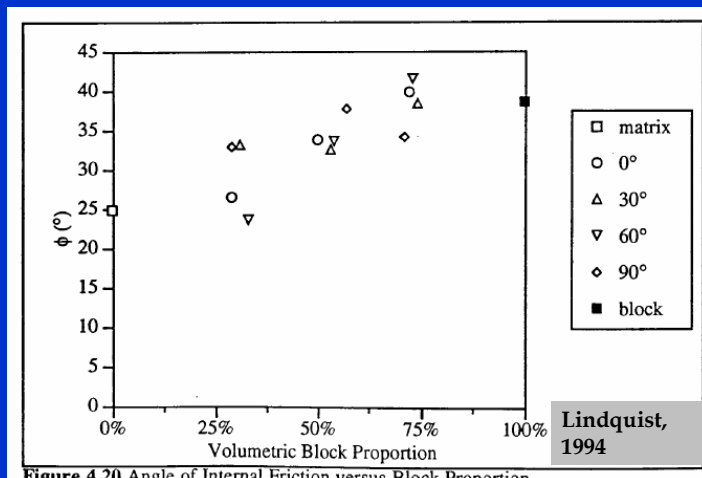


Figure 4.20 Angle of Internal Friction versus Block Proportion

Lindquist, 1994

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This plot shows the relationship between volumetric block proportion and friction angle. Matrix friction was about 25 degrees and block friction 37 degrees. Clearly: as volumetric block proportion increases, frictional strength increases.

Decrease in cohesion with volumetric block proportion

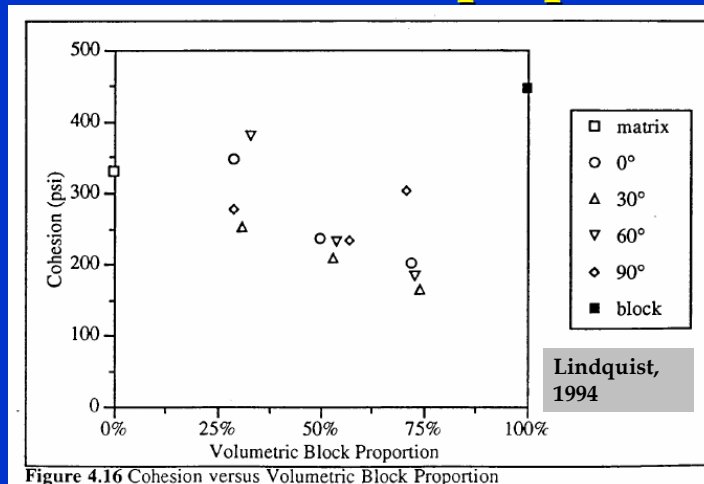
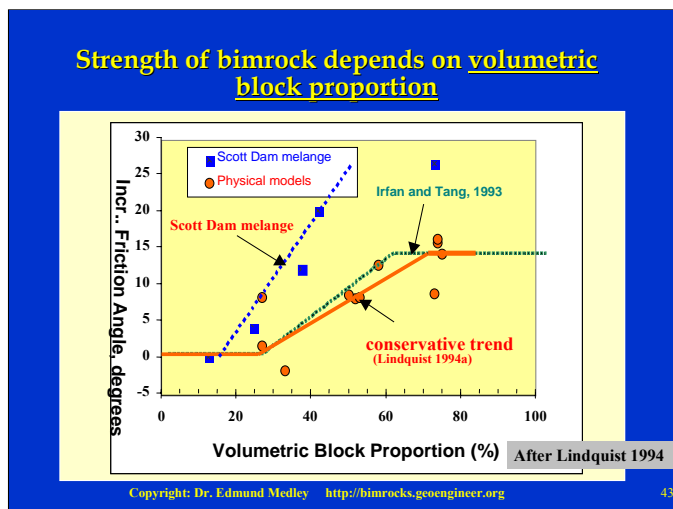


Figure 4.16 Cohesion versus Volumetric Block Proportion

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... and for increasing volumetric block proportions cohesion decreases. Cohesion tends to decrease and stiffness increases (depending on block orientations). Cohesion decreases because with increasing block proportion, there is also an increase in the number of block/matrix contacts. Since those contacts are the weakest element in the mixtures, overall cohesion is reduced.



This slide is a compilation of relationships between volumetric block proportion and frictional strength. The “y” axis shows the increases in friction angle of the overall melange mass additional to the frictional strength of just the matrix material.

The primary relation (“Conservative trend, Lindquist 1994a”) is based on the work of Dr. Eric Lindquist.

During my research, I was lucky enough to be helped by the Geotechnical Engineering Office of Hong Kong, who provided a summary of their own research into a decade long study of the overall strength of colluvium containing very large boulders (Irfan and Tang, 1993). A summary plot of their findings is shown on the figure here. It is remarkable that their data matches those of Dr Lindquist so closely, for materials that are so disparate in origin.

Dr. Lindquist’s work showed that up to about 25% volumetric block proportion the presence of blocks adds little to the overall melange strength. Hence such block-poor mixtures may be analyzed as soils or weak rocks. Beyond 75% there is little further addition in strength because at about that proportion, blocks start to touch each other. Such block-rich mixtures are similar to blocky rock containing wide in-filled joints, and as such they may be analyzed by conventional rock engineering methods.

Between 25% and 75% there is a marked increase in overall frictional strength with increasing volumetric block proportion. The increase may be as much as about 15 degrees.

Testing of actual melanges obtained from near Scott Dam, in northern California, showed dramatically different results than those of Lindquist (1994) or Irfan and Tang (1993). The contribution from the presence of blocks starts to occur at low volumetric block proportion, and there is greater incremental frictional strength.

(For much more information, review the thesis and papers by Dr. Lindquist which are included in the Resources page of this website.)

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Strength of Melanges and Similar Bimrocks

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2. **Glawe, U. and Upreti, B.N., 2004**, B.N. Better understanding the strengths of serpentinite bimrock and homogeneous serpentinite, Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling, v. 22 no. 5 (5/2004)
3. **Irfan, T.Y and Tang K.Y., 1992**; An engineering geological characterization of colluvium in Hong Kong; Technical Note TN 4/92, Geotechnical Engineering Office, Govt. of Hong Kong (publication is not freely available, except by special request).
4. -----, **1993**; Effect of the coarse fraction on the shear strength of colluvium; GEO Report No. 23, Geotechnical Engineering Office, Hong Kong; 21p.
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6. -----, **1994b**; The mechanical properties of a physical model melange, in Proc. 7th Congress of the Int. Ass. Eng. Geol. (Lisbon, Portugal); A.A. Balkema, Rotterdam.
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8. **Sönmez, H., Gokceoglu, C., Tuncay, E., Medley, E.W. and Nefeslioglu, H.A., 2004**, Relationship Between Volumetric Block Proportions and Overall UCS of a Volcanic Bimrock, Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling, v. 22 no. 5 (5/2004); pp 27-34.
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Irfan, T.Y and Tang K.Y., 1992; An engineering geological characterization of colluvium in Hong Kong; Technical Note TN 4/92, Geotechnical Engineering Office, Govt. of Hong Kong (publication is not freely available, except by special request).

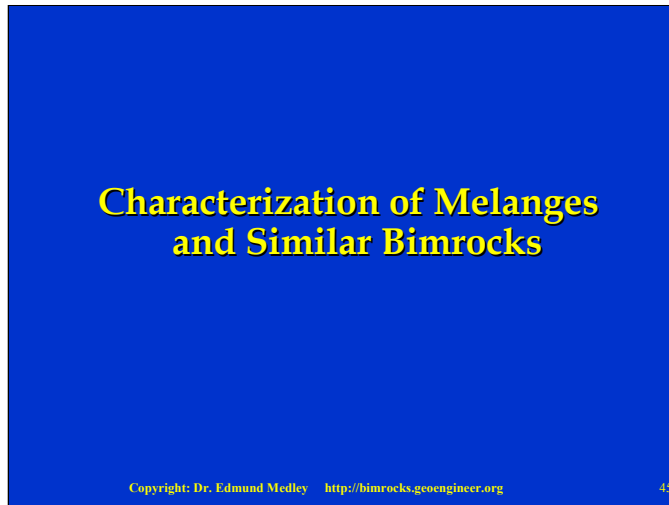
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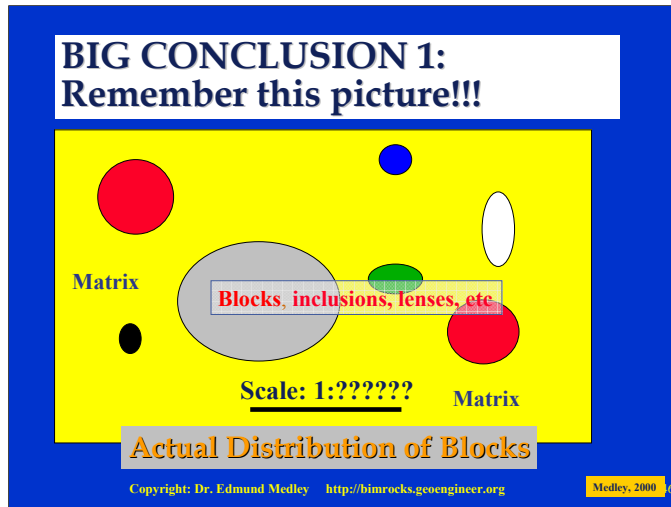
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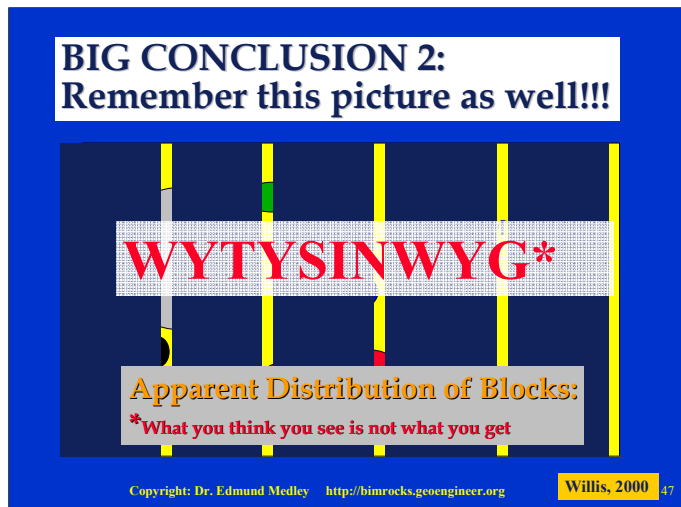
Sönmez, H., Gokceoglu, C., Tuncay, E., Medley, E.W. and Nefeslioglu, H.A., 2004, Relationship Between Volumetric Block Proportions and Overall UCS of a Volcanic Bimrock, Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling, v. 22 no. 5 (5/2004); pp 27-34



The next few slides show that, as chaotic as melanges and bimrocks are, much can still be done to characterize them in an orderly fashion using familiar geological procedures

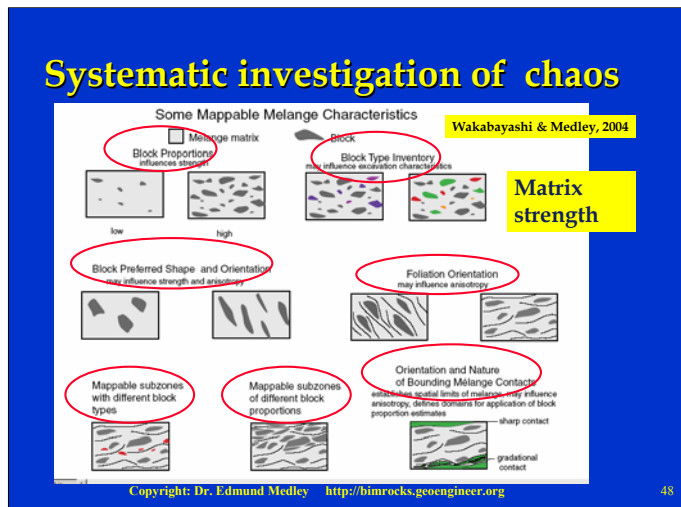


Again: the “real picture”, albeit in 2D...

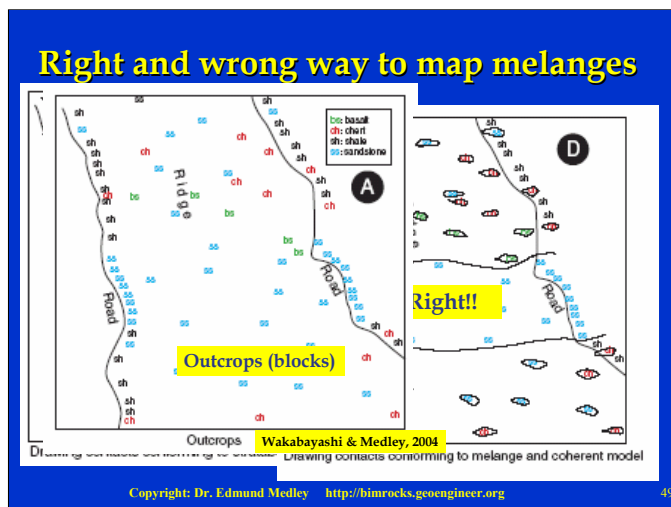


... and what we get to see: slices, patches, hints. The **WYTYSINWYG** is an echo of the historical acronym WYSIWYG (What You See Is What You Get) that was the attraction of Windows when it was introduced to a population of DOS users. If you don't understand what I mean then you are much younger than I am...

Time to Stretch!! Try this calming pose: put your hands in front of your face separated by a narrow vertical slit. Imagine that you can peer through the slit at the room you are in, and that you take several random "slit photographs". Now imagine that you email these slit images to a colleague as JPEGs and ask him/her to reconstruct the appearance of the room you were in. Hard, right? Impossible? Pretty well! But that is what we expect of ourselves when we explore melanges and other bimrocks with borings and attempt to characterize the 3D rockmass from the sparse slit photographs!



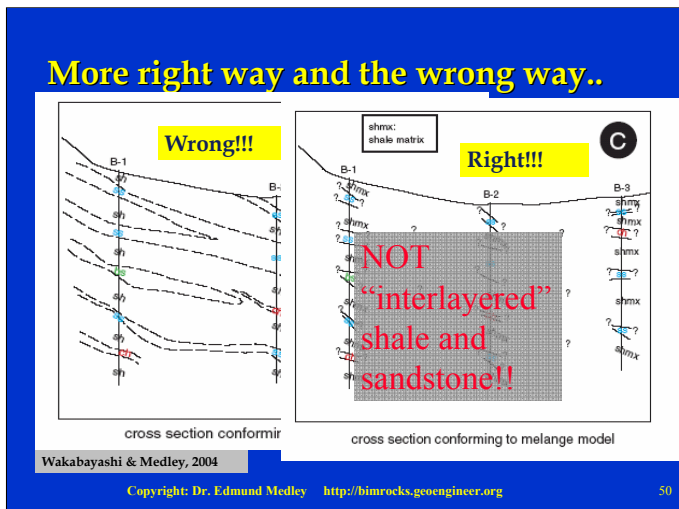
Melanges and other bimrocks can be mapped by geologists, using conventional approaches. This slide illustrates some of the characteristics that can be observed and recorded. (The source paper is available in the Resources web page at <http://bimrocks.geoengineer.org>)



This slide shows both the right way and wrong way to interpret geological observations of outcrops in a melange terrain (yes, I mean **terrain**, not *terrane*. The latter term has a specific tectono-stratigraphic meaning that may or may not be applicable).

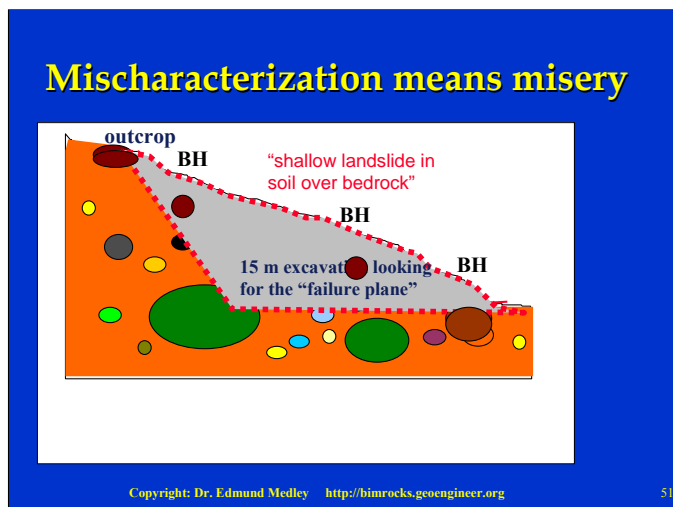
The outcrop map shows outcrops with diverse lithologies. In the days before melanges were fully understood (say from 1950's onward), melanges were mapped as stratiform layers, a bit like a "connect-the-dots" puzzle. To justify the layers, geologist had to interpret complex fault arrays to explain the improbable juxtaposition of rocks, such as barely metamorphosed limestones adjacent strongly metamorphosed exotic rocks such as blueschists.

The correct way to map the outcrops in a melange is to assume that the outcrops are isolated blocks within matrix. If there is sufficient evidence, then large blocks or coherent masses may be interpreted, such as the band of intact sandstone in the middle of the map (blue "ss")



Similarly, when working with borehole logs, resist the temptation to connect the contacts!.

Although the drill core may show sequences of (say) alternating sandstone and shale, it is **not correct** to assume that the sequences are “inter-beds” or “inter-layers”. Once the expression “inter-bedded shale and sandstone” is written on a boring log, there is a tendency to define layers in subsequent cross-section interpretations. And once the cross-section is produced in vibrant colors as a beautiful graphic, the picture becomes an appealing abstraction upon which engineering design will be built. But it takes little imagination to see that an excavation of tunnel constructed on the basis of the “wrong” stratiform geological model could be troublesome if the actual conditions are a bimrock.



This slide shows a graphical tale, based on a true story. It illustrates an all-too common problem, even in California where bimrocks abound.

A landslide was explored by drilling. The borings were terminated 5 feet (3m) into bedrock, which is a common practice for geotechnical exploration in California. An “outcrop” of “bedrock” was observed nearby. On the basis of the observed rock at the surface and in the borings, the engineer interpreted the landslide to be a shallow soil sliding on bedrock.

A remediation was recommended that involved excavation of the shallow slide. During construction, the earthwork contractor vainly sought the “failure plane”. Instead he encountered countless “failure planes” and unexpected “boulders” and kept on excavating looking for THE failure surface between the “soil” and the “bedrock”. There were very considerable cost overruns.

The problem could have been avoided. The USGS geological map showed that the rock in the area was a sheared Franciscan melange, and so it is conceivable that the problem would not have occurred if the geotechnical engineer had conceived of the possibility that he was working in a bimrock.

For further thoughts...

The Arrogance of Straight Lines

By Edmund W. Medley, Ph.D., P.E., C.E.G.



Figure 1. The red line is not straight. The red dots are not the same because all of them...

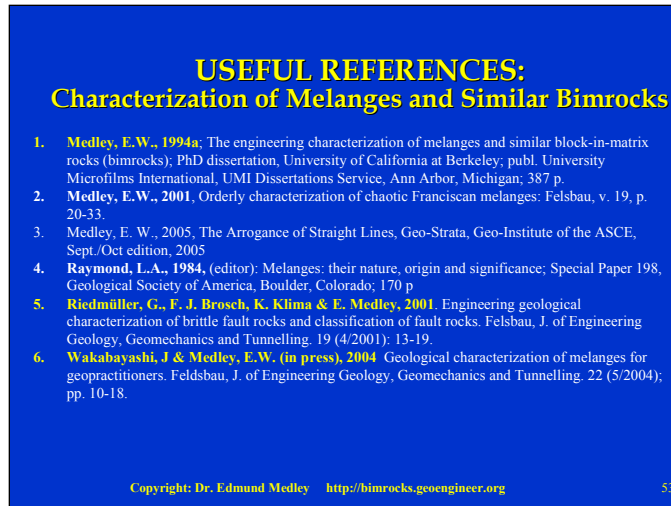
Geotechnical data are often considered from an...
 of finding correct data and recognizing them...
 to such like finding data to confirm data...
 to performing failure investigations, we cannot...
 to investigate the true nature of what happened...
 to investigate the true nature of what happened...
 to investigate the true nature of what happened...
 to investigate the true nature of what happened...

Straight Line Failure Analysis
 Relationships are sometimes described between data by...
 plotting and fitting curves to them. One can have a...
 more extensive data through all the data points or...
 Figure 1. Another way to represent the relationship...
 the data is to find a "best fit" curve. Conditions in...
 the field may require an additional data or value to be...
 In a failure investigation, often one needs to find...
 available data and then identify the conditions...
 that best represent the failure facts. Sometimes the...
 available, or if the data tends to be the same...
 the failure occurs in a certain, additional fact...
 the same case.
 But when an investigator has identified the...
 failure scenario, which is able to identify the...
 through other data sources. Figure 1. In the...
 then, it is not to "bring on conditions" and...
 the line

Geo-Strata Sept/Oct 2005

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I present some additional ideas on the tendency for geo-practitioners to “connect the dots” in this 2005 article in the ASCE Geo Institute news magazine “Geo-Strata” .



For highlighted references: see “Resources” page on <http://bimrocks.geoengineer.org>

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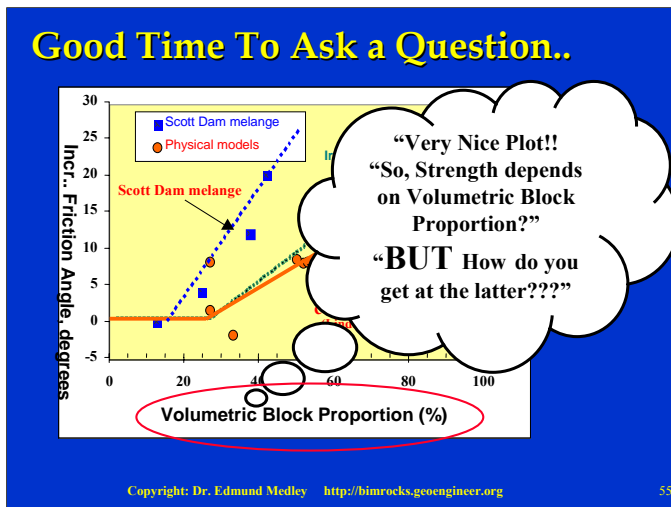


Estimation of Volumetric Block Proportions

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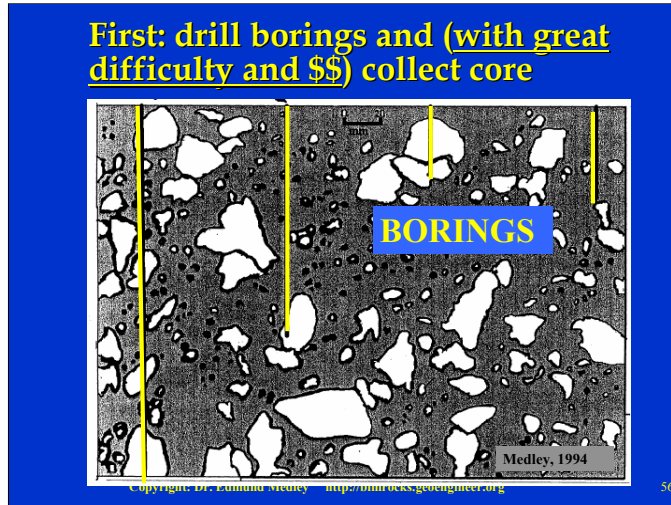
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The following slides give an idea of how to estimate this all-important parameter

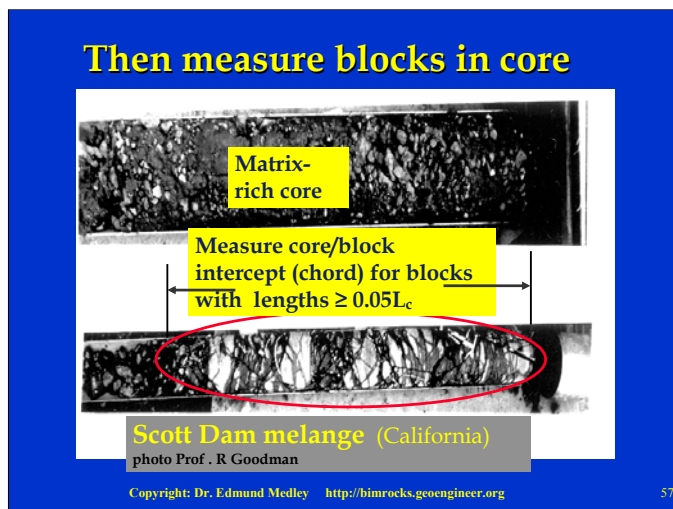


One of the most important aspects of the characterization of bimrocks is the estimate of volumetric block proportion. Recall the simple plots of strength vs. block proportion that I presented previously? It is apparent that there is a fundamental relationship between strength and volumetric block proportions, but for the relationships to be useful in practice we must somehow estimate the block proportion. That is easier said than done.

The means both be able to estimate volumetric block proportion AND identify the uncertainties in those estimates was my principal task during my PhD research.



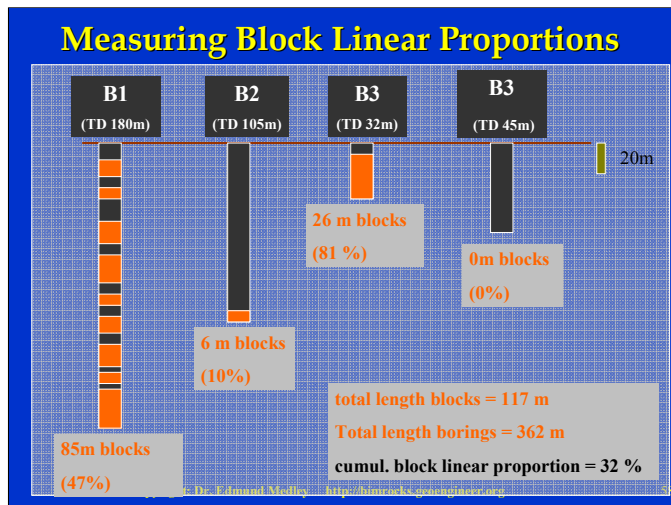
The graphic is a tracing of a photograph of a melange. But because of scale-independence one can just as well imagine that it is the cross-sectional view through a melange rock mass. Assume that rock mass is being explored by core drilling with borings of different lengths.



Once you have an idea of the characteristic engineering dimension (L_c) that is relevant (dam footing width, landslide height, tunnel diameter, etc.) the block/matrix threshold is established as $0.05 L_c$. Measure the lengths of the core/block intercepts (chord lengths) for blocks $\geq 0.05L_c$.

By the way: in melanges, one problem that shall become quickly apparent is how to discriminate the blocks of sandstone from surrounding shale matrix (which look like interbedded sandstone and shale in the core), from any blocks of relatively intact actual interbedded sandstone and shale! The way I identify sheared shale (besides the often characteristic scaly fabric, known as *argille scagliose* in Italy) is to look for very small blocks of sandstone in the shale.

Since blocks exist at all scales in melanges, sheared shale will contain very small fragments of sandstone and other rocks (which are not measured). But intact shale/sandstone sequences (turbidites), will not contain any sandstone blocks in the shale. So, to identify an intact block of turbidite, mark the depth at which the first bands of intact shale appear that lack small fragments of sandstone, and then mark the depth at which the sheared shale starts to appear which contains tiny fragments of sandstone. The intervening length of shale/sandstone is likely to be a block of relatively intact turbidite.



This graphic is based on the previous slide showing an imagined melange rock mass in cross section. The core in the four borings have been logged and the lengths of the blocks measured. Each boring has a certain linear proportion of blocks (total length of blocks divided by the length of the boring). The overall average linear block proportion in the explored rock mass is simply the total length of all the blocks divided by the total length of all the borings, which in this case is 32%.

So the important question now is: **“Is the Linear Block Proportion the same as the Volumetric Block Proportion”?**

**Estimation of volumetric
block proportions**

- Measure linear proportions from drill core
- Apply **stereological** principle:

linear proportion = volumetric proportion

**BE CAREFULL!!!! Don't believe
everything you hear/read!!**

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Well: the well-established statistical/mathematical field of **Stereology** has a fundamental rule that says that:

the point proportion=linear proportion=areal proportion=volumetric proportion.

Problem solved!! Hurrah!!

But not so fast.....

BIG Warning!!!!

Although stereology =>
volumetric % = linear %

**It is TRUE ONLY when you have sufficient
linear measurements!! (lots of \$\$\$
drilling!!)**

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Here is the reason to slow down: **the fundamental laws of stereology apply only when there is lots of data.** And the amount of data necessary in our case would mean lots of linear measurements which means lots of drilling. Which means we shall never get enough data because there is never enough time and money to perform the meager drilling that we want to perform on characterizations of even well-behaved geology.....

Kitchen and Garage Experiments

- Fabricated 4 physical melange models with known block size distributions, block proportions
- Generated 400 model borings

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So the problem boils down to: **“How wrong can we be if we substitute the linear block proportion we measure from chords for the volumetric block proportion needed to use Lindquist’s graphs”??**

The next few slides show an empirical approach I devised in order to answer the question. The experiments were performed over one weekend in the family garage when the family left me to entertain myself for a few days.



I fabricated 4 physical model melanges with known volumetric block proportions (about 13%, 32%, 42% and 55%) using a Franciscan type block size distribution, and generally vertically oriented blocks. The plan dimensions of the models were 100 mm by 150 mm (red box in graphic above) thus \sqrt{A} was 13 cm (blue bar). The characteristic engineering dimension was selected to be the \sqrt{A} of the plan area of the physical models

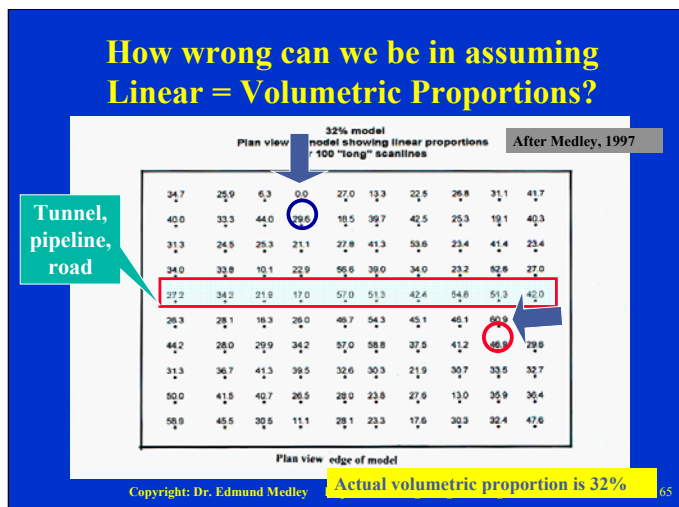
Using Play-Doh (in the UK: Plasticene), a children's plastic-based molding clay; potters clay and rice, I created a few large blocks and increasing numbers of smaller ones.. Blocks ranged in size between about less than $0.75\sqrt{A}$ (brown blocks) and $0.05\sqrt{A}$ (rice).



The blocks were mixed with Plaster of Paris and poured into a mold. The four models were cured for a day and then each model was sawn into 10 slices.



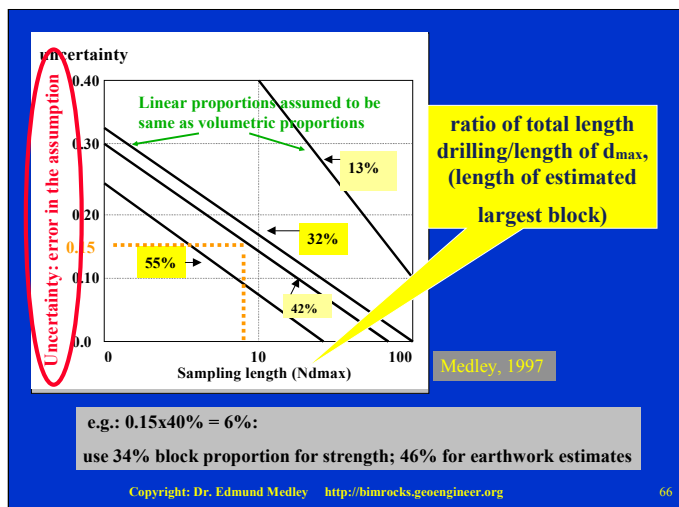
Each slice was photographed and 10 vertical “model borings” drawn on the photographs. Hence, each model yielded 100 borings. The lengths of the boring/block intersections were measured for chords $\geq 0.05L_c$, and the linear block proportions for each model boring calculated. So, each model melange was characterized by 100 linear block proportions.



The graphic in this slide shows the distribution of the 100 linear block proportions in the plan view for the 32% model. Observe that although the actual volumetric proportion was 32% the linear block proportions ranged between 0% and 61%. See also the variation in linear block proportions along an alignment in the middle of the model (such as for a tunnel or pipeline). The total linear block proportions for each model (based on all the data for all the borings) were approximately the same as the volumetric block proportions, which confirmed the fundamental law of stereology.

However, when exploring a real rockmass we would not have such a dense distribution of borings.

Imagine instead that we drilled any two random locations into a melange rockmass represented by the physical model above (say at the two blue arrows) and calculated two linear block proportions (29.6% and 46.9%). The overall average linear block proportion from the two borings is then 38.3%, somewhat close to the true volumetric block proportion of 32%. Now imagine that we redo the drilling program and take two other randomly located borings and calculate a new linear block proportion... Such realizations from the exhaustive" data set were performed hundreds of times using a Monte Carlo approach for model drilling programs with 2, 4, 6, 8, 10, 15 and 20 borings at a time. Statistical analyses were performed on the data.



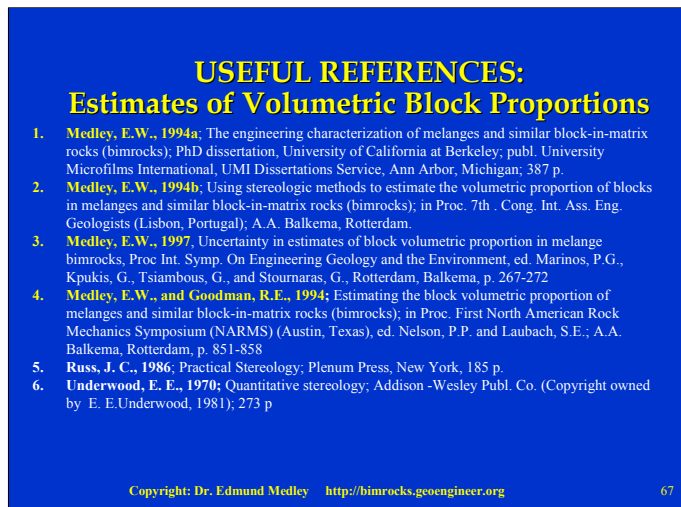
This plot is a simplified summary of the statistical analyses performed on the data obtained by the Monte Carlo exercises on the linear block proportions.

The “x” axis represents a measure of the linear sampling performed, expressed as a ratio of the total length of drilling to the length of the largest block (d_{max}) used in the models.

The “y” axis is simply called “uncertainty” but is actually the co-efficient of variation (standard deviation divided by the 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).

The plots (which are best fits to the data) show answers to the question: “How wrong is the assumption that the Linear Block Proportion is the same as the Volumetric Block Proportion?” In general, the more drilling performed, the lower the uncertainty and the error in the assumption. But also, the lower the actual block proportion, the higher the uncertainty or error. That is because with low block proportion, borings are less likely to hit blocks, and thus there is less intersection length data to begin with. With many blocks there will be more chords, for the same amount of drilling.

The orange dashed lines shows that for a certain amount of drilling, normalized by the length of the largest block (either equivalent to $0.75\sqrt{A}$, or else estimated in the field), and a measured Linear Block Proportion of 40% the uncertainty is about 0.15. In other words the assumption that the measured 40% Linear Block Proportions is the same as the Volumetric Block Proportion is $0.15 \times 40\%$, or 6% incorrect. Or: the actual Volumetric Block Proportion (within one standard deviation) is $40\% \pm 6\%$. For strength purposes, it would be prudent to take the lower estimate of 34%. For earthwork construction purposes, the higher estimate of 46% because construction claims may result on underestimates of the volume of hard, large blocks.



For highlighted references: see “Resources” page on <http://bimrocks.geoengineer.org>

Medley, E.W., 1994a; The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.

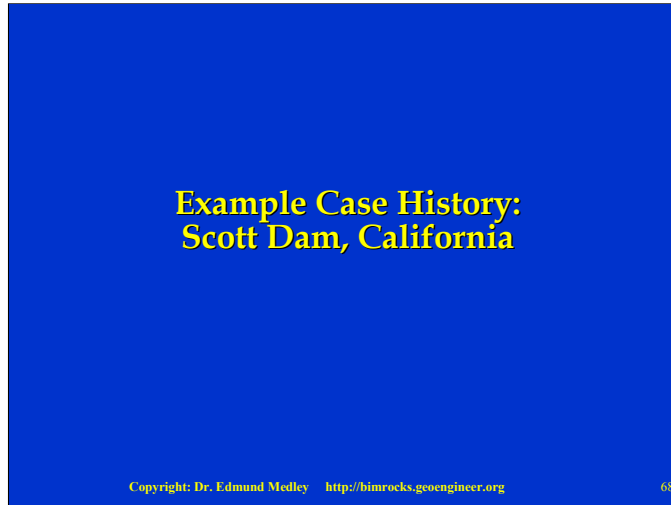
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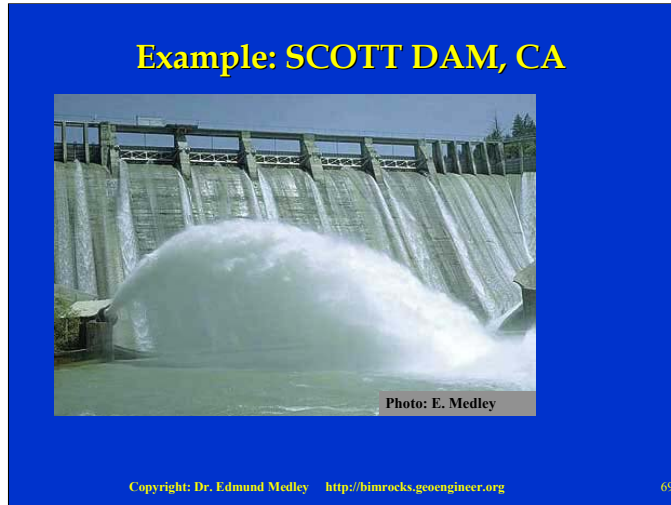
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Underwood, E. E., 1970; Quantitative stereology; Addison -Wesley Publ. Co. (Copyright owned by E. E. Underwood, 1981); 273 p



This case history shows some applications of the ideas presented thus far.....



The next few slides show an example of the use of the results presented in the last several slides.

Scott Dam impounds a reservoir in Northern California. It is owned by the Pacific Gas & Electric Company (PG&E). The dam was built in the 1920's. It is concrete, and about 50 m high.

Foundation of dam is melange

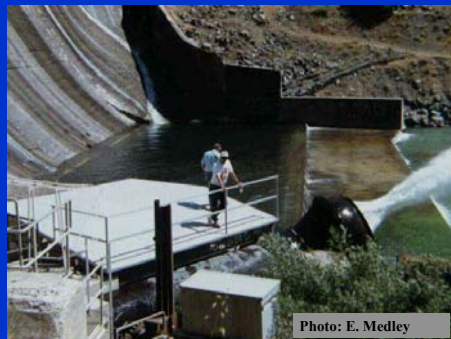


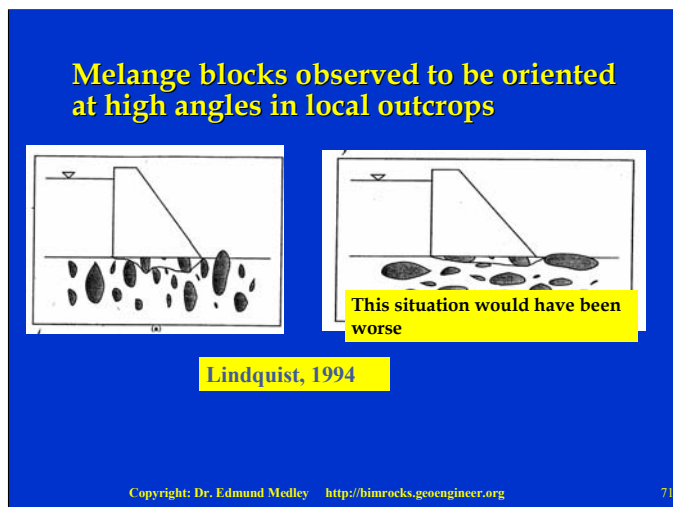
Photo: E. Medley

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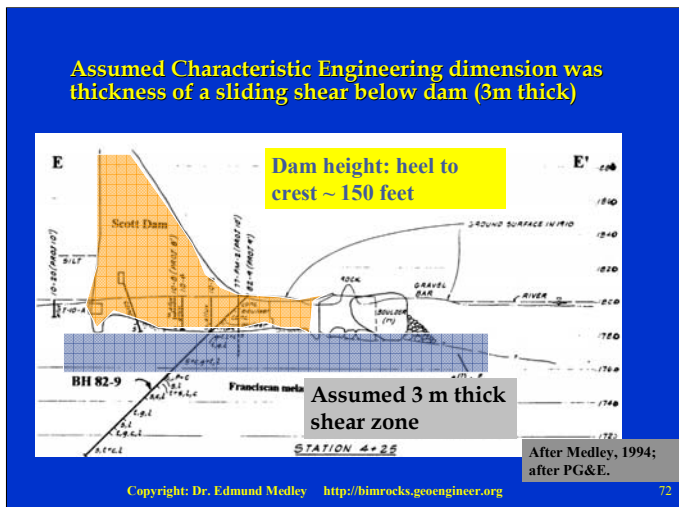
The dam is founded on Franciscan Complex melange, composed of sheared shale and blocks primarily of graywacke sandstone.

Several years ago, the dam was identified as being at risk during a future earthquake, partly because geotechnical analysis simply assumed that the dam foundation was entirely sheared shale. Remediation of the dam would have cost several million dollars. Professor Richard E Goodman consulted with PG&E on the problem. PG&E funded of the research performed by Dr. Eric Lindquist and myself.



The failure mode of most importance was considered to be sliding of the concrete dam along the surface so the melange. Since the blocks in the melange were locally observed to be approximately vertical, any seismically-induced shear would have to tortuously negotiate around the blocks. The shear surface would be much less irregular if the blocks were sub-parallel to the dams foundation.

The matter of the width of a failure zone in melange, and the nature of the “tortuosity” of failure surfaces is reviewed later in this presentation.



Since the problem investigated was related to a potential shear surface below the dam foundation, the characteristic engineering dimension that defined the scale of the problem was selected to be the assumed thickness of a potential shear surface: about 10 feet (3 m).

Estimating volumetric block proportion

- Since characteristic engineering dimension was 3m, block/matrix threshold selected at $0.05 \times (3\text{m}) = 0.15\text{m}$
- Drill core photographs and boring logs reviewed
- Measured all chords (core/block intercepts) $>0.10\text{m}$ and used them to calculate linear block proportion

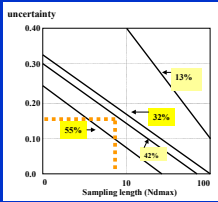
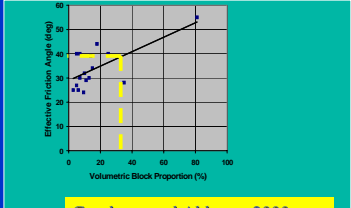
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The geotechnical properties of the assumed shear zone were required. Drill core photographs and boring logs were reviewed. Although a block/matrix threshold of 0.15 m was justified, (5% of the L_c of 3m), the actual blocks/matrix threshold used was 0.10 m, because I was still defining the concept of block/matrix threshold at the time I was performing the measurements.

Example: SCOTT DAM, CA

- Testing showed matrix $\phi = 25$ deg.
- Measured linear proportion = 40%
- Adjusted vol. block proportion = 32%
- **Rockmass $\phi = 39$ degrees**

Goodman and Ahlgren, 2000;
Medley, 2001

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Specimens of melange with various volumetric block proportions sampled from the Scott Dam foundation were collected and tested in triaxial compression. Although the overall linear block proportion was 40 % the volumetric block proportion was selected as 32%. As shown in the right graph, the use of this proportion resulted in a friction angle much higher than the originally assumed matrix-only friction angle of 25 degrees.

(It should be understood that the 32% volumetric block proportion was selected without using the Uncertainty graphic (left hand graphic) although there is good agreement between the 32% selected and the 34% estimated using the graph.)

The increase in friction angle due to the presence of blocks in the melange resulted in PG&E not having to remediate the dam foundation after all.

**USEFUL REFERENCES:
Scott Dam**

1. Goodman, R.E. and Ahlgren, C.S., 2000, Evaluating safety of concrete gravity dam on weak rock: Scott dam; *Journal of Geotechnical and Geoenvironmental Engineering*, v. 126, p. 429-442; with Discussion (by J. H. Hovland, E.W. Medley and R.L. Volpe; and Authors) in Vol 127, October 2000, p. 900-903.
2. Medley, E.W., 1994a; The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.

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For highlighted references: see "Resources" page on <http://bimrocks.geoengineer.org>

Goodman, R.E. and Ahlgren, C.S., 2000, Evaluating safety of concrete gravity dam on weak rock: Scott dam; *Journal of Geotechnical and Geoenvironmental Engineering*, v. 126, p. 429-442; with Discussion (by J. H. Hovland, E.W. Medley and R.L. Volpe; and Authors) in Vol 127, October 2000, p. 900-903.

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**Estimating 3D Block Size
distributions from 1D Borings**

Principal Conclusion: DON'T TRY!!

**1D chord length distributions are NOT the same
as 3D block size distributions**

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The next few slides show how difficult it is to estimate actual 3D block size distributions from 1D boring data.

Measurement of chords from Plaster of Paris models

- 10 scanlines per slice
- 100 borings per model
- "centerline" boring to model exploration for tunnel

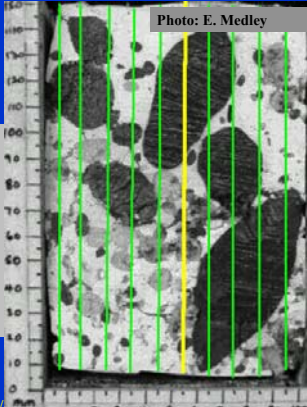
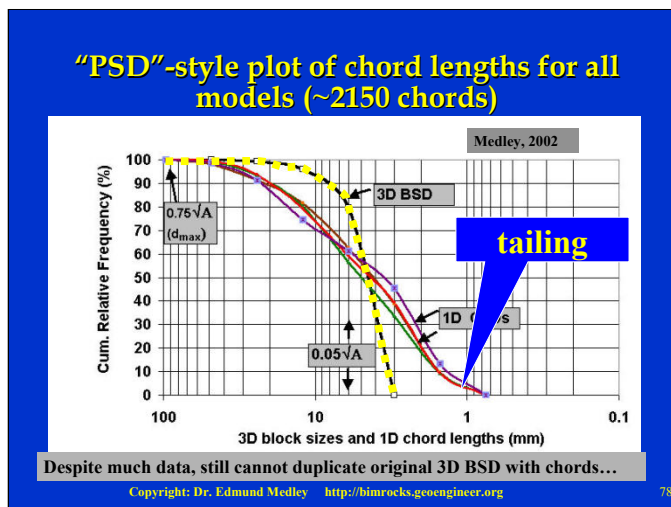


Photo: E. Medley

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Recall the earlier slides showing the physical model melanges fabricated from Play-Doh, clay, rice and Plaster and Paris? In the earlier slides, I showed you how the linear measurements from the model borings" led to an approach for understanding the uncertainty in estimates of volumetric block proportions. The same models were also used to investigate the problems associate with estimating 3D block size distributions from borings.

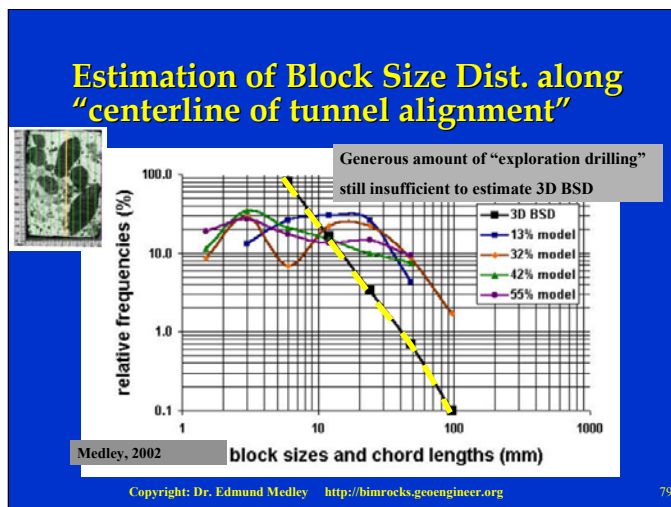
Recall that there were 4 models (13%, 32%, 42% and 55% volumetric proportions). 100 model borings were drawn on photographs of 10 slices cut from each model. The length of the chords of intersection between the blocks and the borings were measured. Additionally, for each slice the middle boring (yellow line) was considered to be a model boring along the centerline of a model tunnel.



The chord data are presented here in the style of a cumulative particle size distribution curve commonly found in soils engineering. The parent “true” 3D block size distribution for the blocks in the four models is shown as the dashed yellow line.

For the four models, the colored chord length distributions curves all show similar features: there is an overall stretching of the distribution curves. Chord lengths exist that are shorter than the shortest dimension of parent blocks, forming tailing segments to the curves.

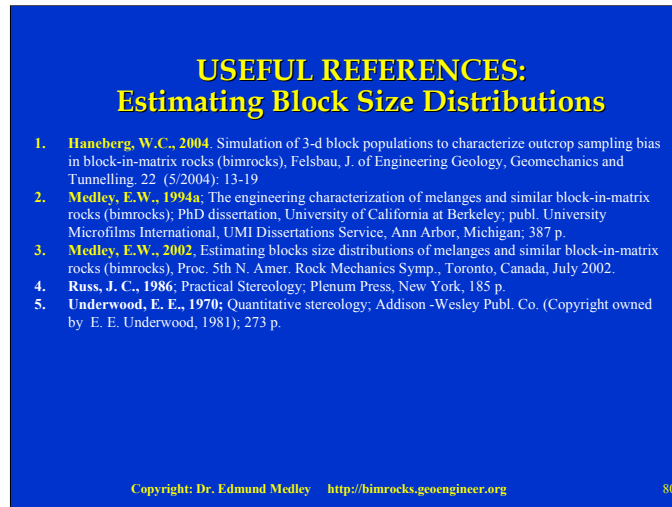
The proportion of larger blocks is under-represented. Indeed: there is little similarity between the chord length distributions and the parent 3D distributions. Using the latter as a substitute for the former would be erroneous, even in the case of considerable data, as was the case for the physical models, where the data from 400 borings is summarized by the plots.



In the case where just the centerline borings were measured, there is even more disparity between the parent 3D block size distributions (3D BSD) and the chord length distributions. (Be aware that these curves are for relative frequency not cumulative frequency). Notice also how the larger true blocks in the models are not predicted by the chords.

Clearly any characterization that depended on boring data could be in serious error.

By the way: the problems associated with reconstruction parent 3D size distribution curves from linear and 2D areal data has been studied for many decades by stereologists. There are some very complex mathematical approaches to the problem... A creative paper by Dr. Bill Haneberg is provided for reference.



For highlighted references: see “Resources” page on <http://bimrocks.geoengineer.org>

Haneberg, W.C., 2004. Simulation of 3-d block populations to characterize outcrop sampling bias in block-in-matrix rocks (bimrocks), Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling. 22 (5/2004): 13-19

Medley, E.W., 1994a; The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.

Medley, E.W., 2002, Estimating blocks size distributions of melanges and similar block-in-matrix rocks (bimrocks), Proc. 5th N. Amer. Rock Mechanics Symp., Toronto, Canada, July 2002.

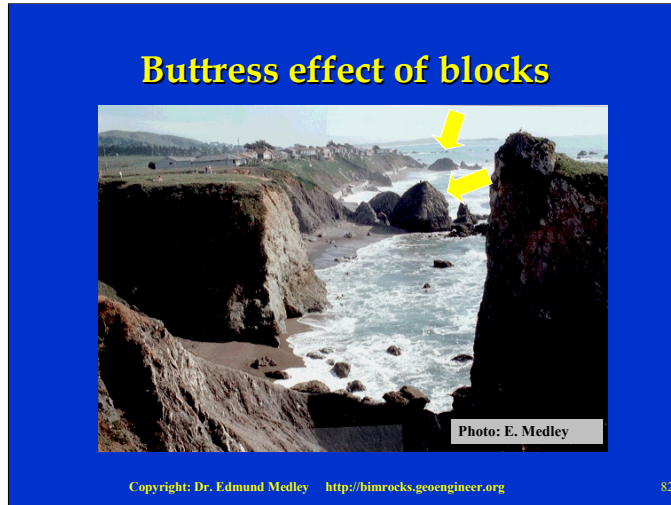
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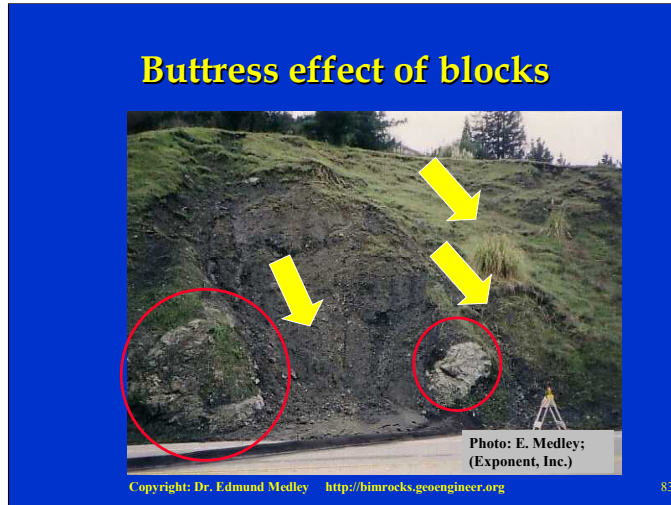
**a few words on SLOPE
STABILITY of bimrocks**

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This photograph shows a coastal cliff at the Sonoma County shore in northern California. The rock is Franciscan Complex melange, sheared shale matrix with blocks of graywacke sandstone, chert, greenstone and various exotic metamorphics. Note the remnant blocks stranded in the surf (yellow arrows). Strong blocks exhibit steep slopes. Observe also how the slopes form ridges behind the headland blocks. Between the large blocks the cliffs have receded, with evidence of landslides.



This photograph shows a highway slope in northern California. The rock is Franciscan Complex melange, sheared shale matrix with blocks of graywacke sandstone, chert and greenstone (metamorphosed basalt)

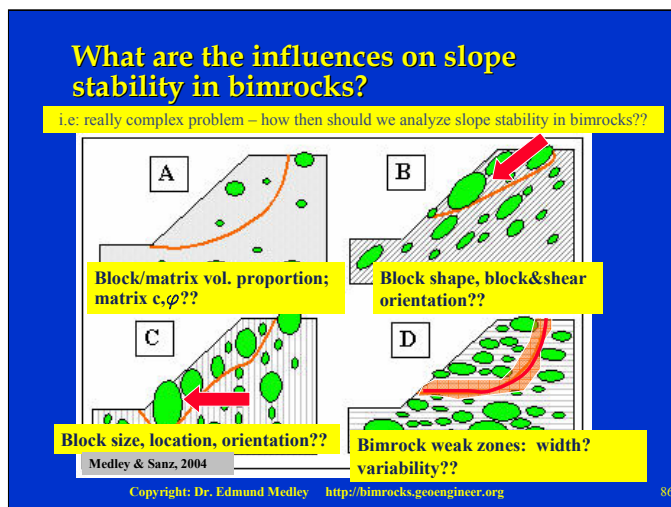
The slope pictured here contains landslides (yellow arrows). But the slopes are being held up by blocks at the base (red circles). What is the role of blocks in the stability of slopes underlain by bimrocks??



Recall that shears in melanges are observed to pass around blocks in tortuous fashion, as shown in this photograph of a Franciscan complex melange at Trinidad Beach, Humboldt County, northern California



The contact between blocks and matrix is often the weakest component of the mixture. This photo is of the Gwna Melange in Anglesey, North Wales.



There are several situations in which blocks influence the slope stability of bimrocks:

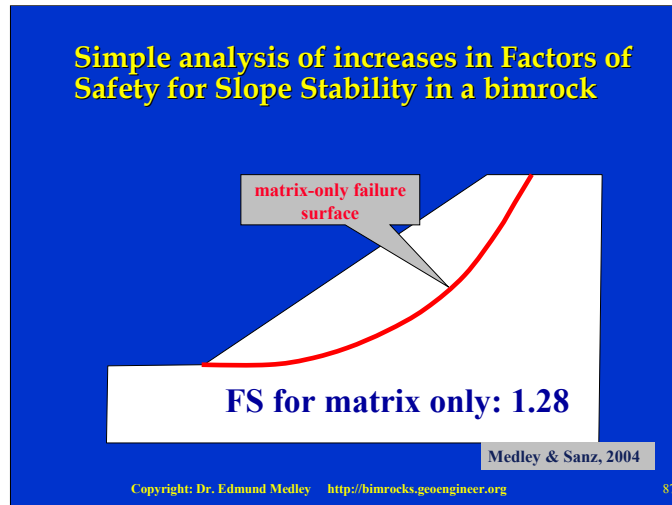
Situation A shows a hillslope in a low-block proportion bimrock that can be analyzed as a conventional soil.

Situation B shows a hillslope where there is a higher proportion of blocks, which cannot readily be conventionally analyzed as soil nor rock. Furthermore, typical of melanges and fault rocks, there is a fabric of sub-parallel blocks and shears, oriented out-of-slope, which decreases slope stability.

In **Situation C**, blocks are oriented at high angles to the slope, which increases stability due to the increased tortuosity of the failure surfaces forced around the blocks. Furthermore, the large blocks or block-rich regions at the toe of slopes tend to buttress slopes and add to slope stability.

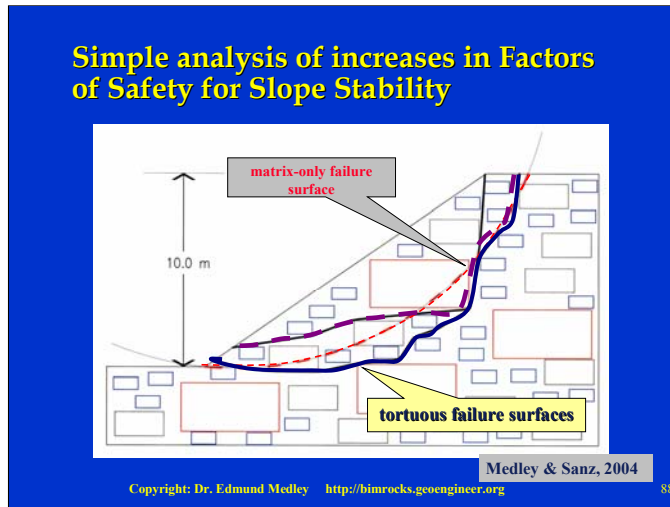
Situation D illustrates the common condition of variations in the block proportion within the rock mass. Failures can be expected through those regions where there is continuity within a low-proportion, weaker domain.

These simple geological situations clearly indicate that one cannot predict the location or geometry of potential failure surfaces within melanges and other bimrocks. Accordingly, rather than performing deterministic slope stability analyses with trial failure surfaces, it may be better to perform stochastic analyses with trial failure zones, or bands, with widths between 5% to 15% of the height of the landslide (Medley, 2004). (The basis for that recommendation is coming up in the next few slides).

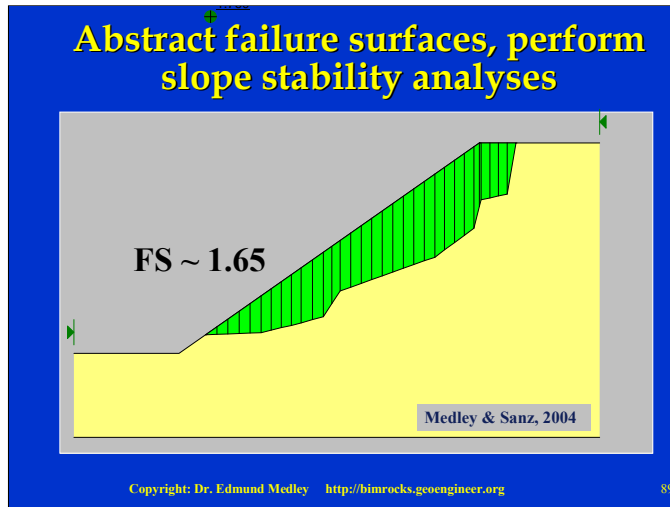


Using a simple model, Medley & Sanz (2004) explored the extent to which blocks increase the slope stability of bimrocks, relative to the stability of the slope in pure matrix. The strength parameters the matrix was

$c = 10 \text{ kPa}$ (200 pounds per square foot) and $\phi = 25$ degrees. The critical failure surface for a matrix-only slope had a Factor of Safety of 1.26.

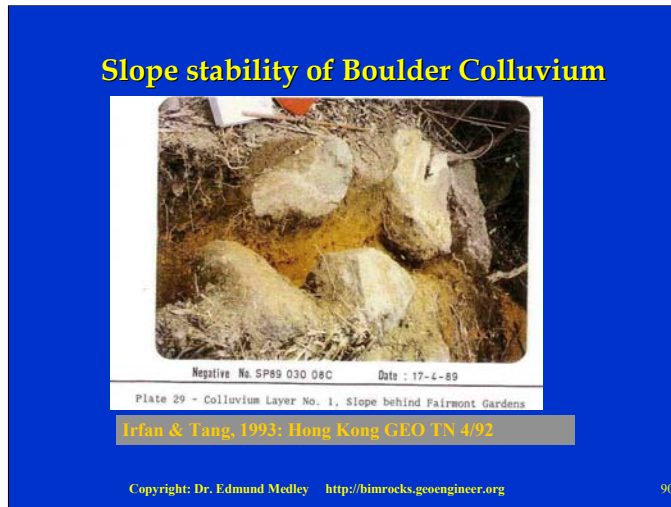


For a 10 m high, 35 degree slope (as illustrated) analyses were performed using random arrays of rectangular blocks with size distributions typical of the Franciscan, and various areal block proportions. The areal proportions were assumed to be same as the volumetric proportions. Some possible failure surfaces, which deviated only modestly from matrix-only failure trace, were traced around the blocks.

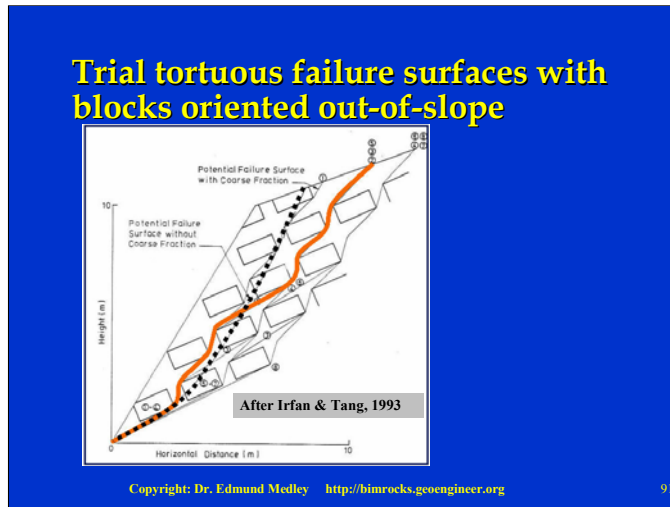


The profiles of the tortuous surfaces were exported into SlopeW™, (Geo-Slope International, Inc.) and the slope stability analyses performed to calculate the Factors of Safety.

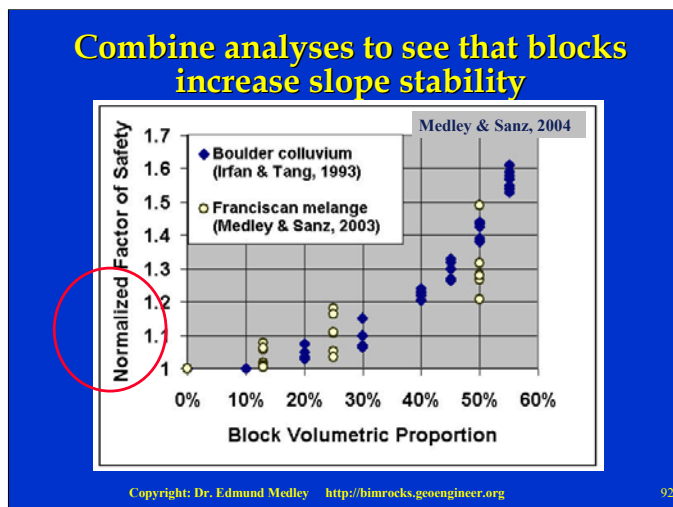
To generalize the findings, the Factors of Safety were normalized by dividing them by the Factor of Safety for the matrix-only case (FS=1.26). In the case illustrated above, the Factor of Safety of the slope has increased to 1.65 solely as the result of the tortuous failure surface.



Medley & Sanz (2004) incorporated findings from Irfan & Tang (1993), who performed stability analyses of 10m high, 60 degree slopes in boulder colluvium.



The model slopes analyzed by Irfan and Tang (1993) contained uniformly sized and uniformly separated blocks, layered out-of-slope. Block proportions were varied between 10% and 55%. The strength properties of the matrix were generally $c' = 5$ kPa and $\phi' = 35$ degrees. The sketch above shows the matrix-only failure surface and several tortuous surfaces negotiating around blocks.



Combining the results of stability analyses performed for melanges and boulder colluvium, it is apparent that there is a good relationship between the normalized Factor of Safety and the volumetric block proportions, despite the significant differences in the model geometries, orientation of blocks, geology of the modelled materials, and analytical methods used. (Not that the **normalized** Factors of Safety are individual Factors of Safety for bimrocks divided by the factor of Safety for matrix-only cases).

Although considerably more analyses should be performed to understand the statistical variations, it appears that up to about 25% to 30% block proportion blocks provide little geomechanical advantage. However, from this lower limit to greater than 55%, there is marked increase in slope stability, due to increases in the tortuosity of failure surfaces negotiating blocks.

This finding is remarkably similar to that of Lindquist (1994) and Lindquist & Goodman (1994) who determined that there was considerable increase in frictional strength for physical model melanges with volumetric block proportions between about 25% and 75% (as shown in previous slides).

Q: How do blocks add to slope stability?

A: Tortuosity of failure surfaces negotiating blocks (little to do with block strength)

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The HOW of blocks adding to the strength in slopes and to bimrock strength has to do with the tortuosity of failure surfaces forced to negotiate around blocks. Generally, as long as there is sufficient mechanical contrast to force shears and failure surfaces around blocks, the greater the volume of blocks, the greater the strength advantage.

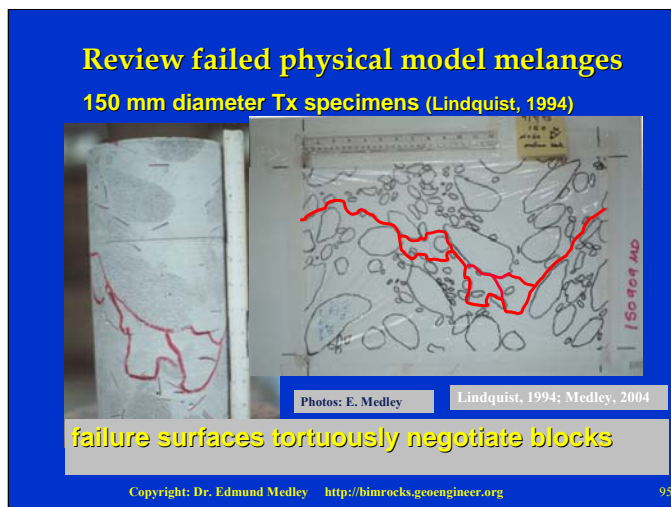
**BUT: We cannot even characterize
the actual block distribution in
bimrocks, so we can never predict
the actual trajectories of tortuous
failure surfaces in slopes!**

(as now shown....)

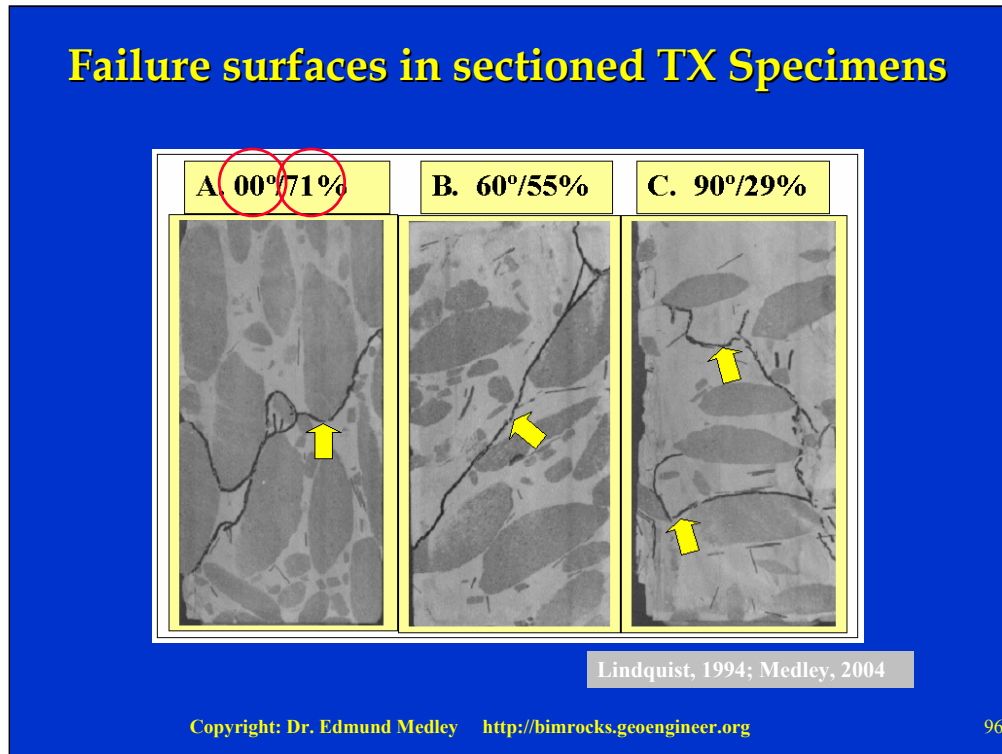
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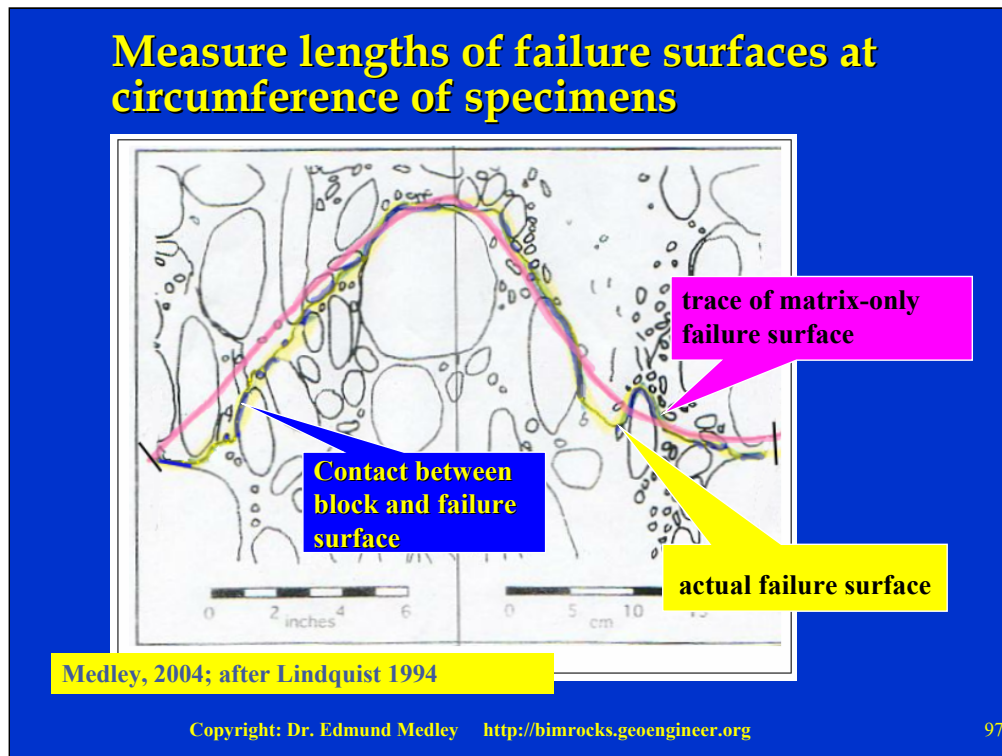
But: given the extreme heterogeneity of bimrocks, how can we perform slope stability analyses when we do not know the shape or location of failure surfaces negotiating around blocks, whose location, size, orientation, etc, we do not know either!??



Dr. Eric Lindquist tested over 100 specimens of physical model melanges in triaxial compression. An example failed specimen is shown (left photograph). The failure surface trace at the circumference of the specimen is shown in red. The specimen was wrapped in SaranWrap™ kitchen film (UK: cling film) and the outlines of the blocks and the failure surface traced (red lines on right photo). The film was mounted on cardboard and the image photocopied/scanned for analysis.



Three specimens sliced to show interior and failure surfaces. Specimen A has blocks oriented at 0 degrees to axis of loading (vertical) and 71% volumetric block proportion; Specimen B has blocks oriented at 60 degrees and had 55% blocks; and Specimen C has blocks oriented at 90 degrees and has 29 % blocks.



The SaranWrap™ film was mounted on cardboard and the image photocopied/scanned for analysis. Hence the image above is the “developed” view of the unrolled circumference of the specimen.

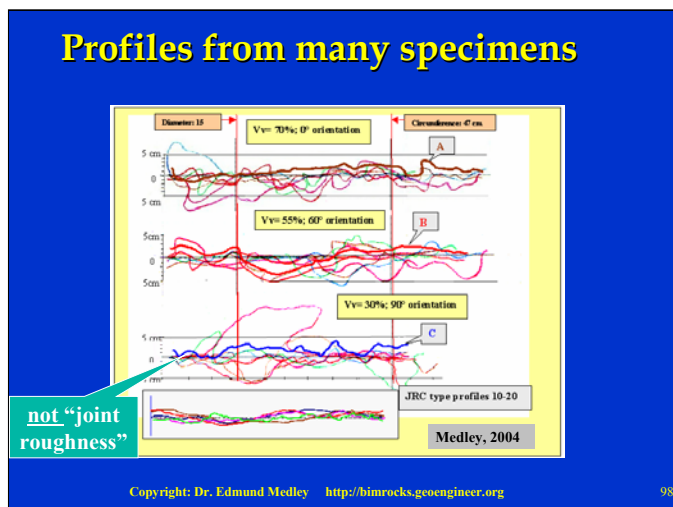
This specimen was one of about 70 that were analyzed (Medley, 2004).

The pink trace line is an approximation of the matrix-only failure surface, which was estimated on the basis of matrix-only triaxial failures; and was also reasonably assumed to pass relatively close to the actual failure surface.

The yellow trace is the actual failure surface as expressed at the circumference of the specimen.

The length of the estimated matrix-only failure trace and the actual failure trace was measured.

The blue lines are the segments of the failure surface tangent to blocks, and these were also measured.



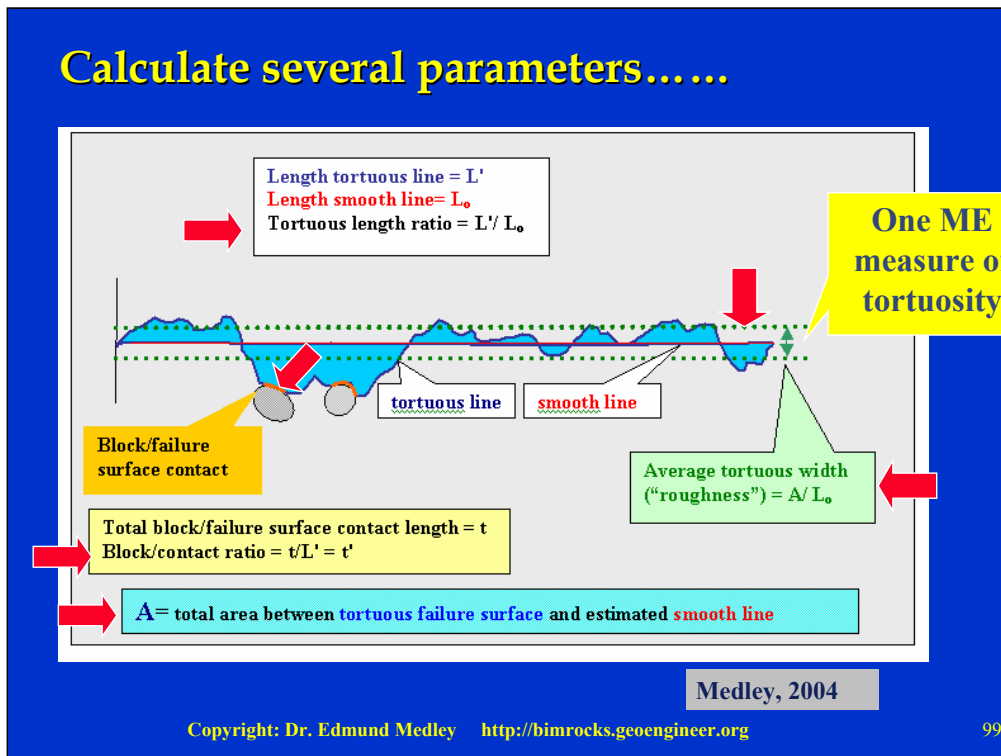
The graphic shows some of the traced failure trajectories.

For scale: the diameter of the specimens was 15 cm, and the circumferences 47 cm. There are three groups of plots, one each for volumetric proportions of 70% and 0 degrees orientation; the middle group for 55% volumetric proportion and 60 degrees block orientation; and the lower group for 30% volumetric proportion and 90 degrees orientation.

The various trajectories are for specimens tested at different confining stresses. The failure profiles for the three sliced specimens (A, B and C) shown in the previous slide are indicated. The horizontal "0" line is the reference line, with increasing distance from a start point along the matrix-only failure surface. The vertical axes either side of the "0" line indicate the distance that the failure trajectories depart from the "matrix-only" failure surface.

Observe that the trajectories are both unruly and unsystematic. There is no discernable correlation between the trajectories and volumetric block proportion and/or block orientation, which is surprising given that one would expect increased tortuosity with increases in both volumetric block proportion and block orientation.

Also observe that the trajectories cannot be thought of, or analyzed as, "joint roughness", as shown by comparison to the roughest of the trial joint profiles conventionally used to selected Barton's Joint Roughness Coefficient, which are shown to scale at the lower plot. The tortuous profiles are much rougher than the roughest type profiles.



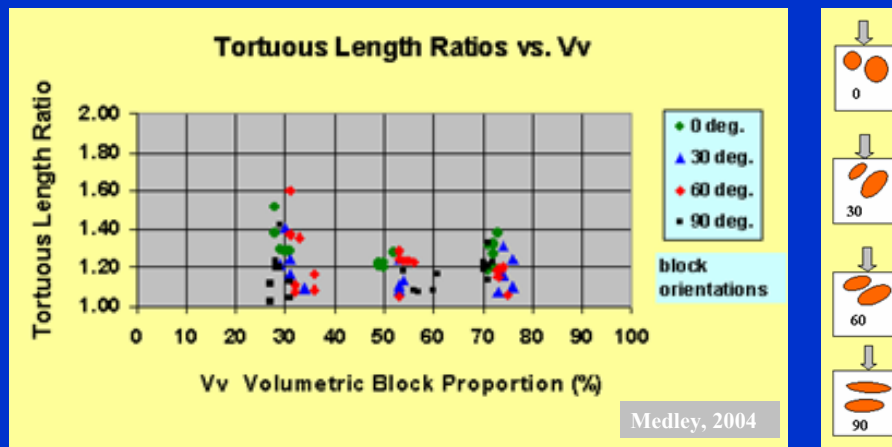
Several measures were gleaned from the profiles, an example of which is shown here.

There are definitions of “tortuosity” in anatomy and hydrogeology; the simplest measure is actually one used in mechanical engineering to characterize surface roughness of metals. For any given profile, the “average tortuous width” is calculated as the ratio of the area lying between the rough profile and a smooth line, divided by the length of the smooth line.

Another indicator of tortuosity is the ratio of the lengths of the tortuous line to the smooth line.

The total block/failure surface contact ratio was also measured, and for any tortuous profile, one can calculate the ratio of the total length of block/failure surface contacts to the length of the tortuous line. Intuitively: the more blocks there are, there will be more contacts between the failure surface and the blocks.

Lengthening of tortuous failure surfaces

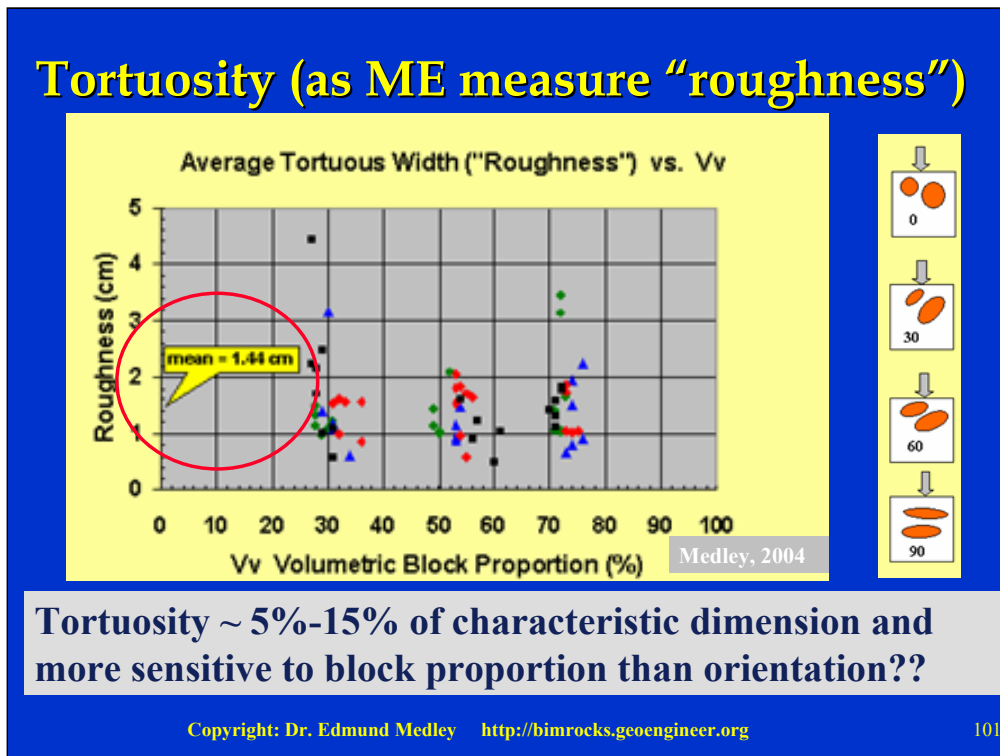


Lengthening apparently not much sensitive to block proportion nor block orientation

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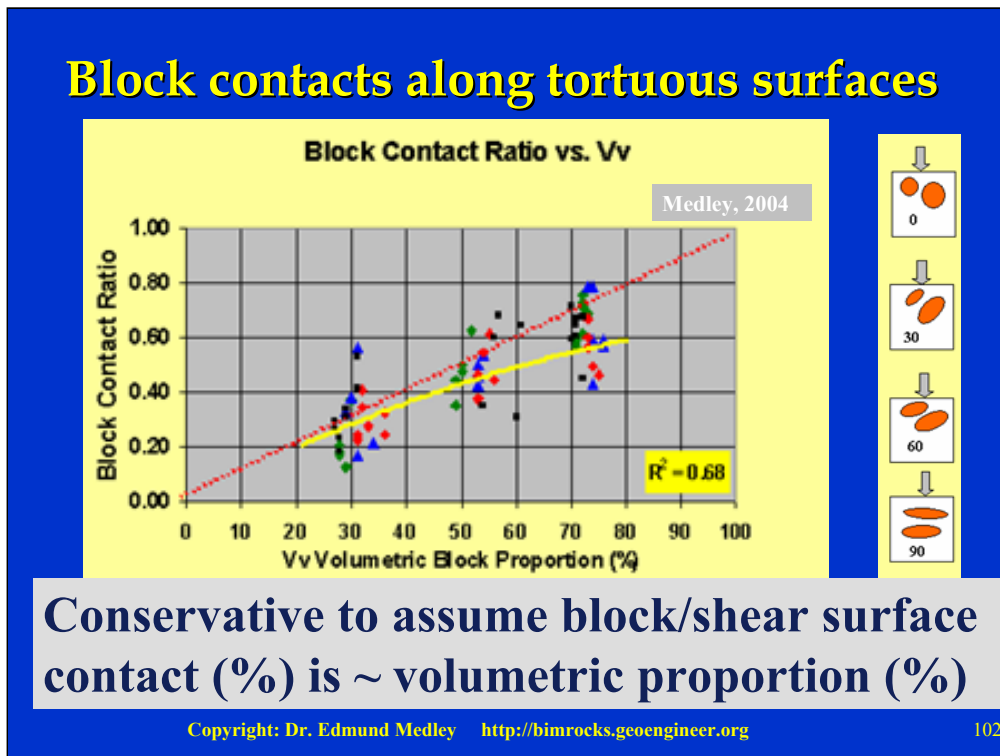
Plots of the tortuous length ratio does not show any clear correlation to volumetric block proportion, which is surprising.....



Neither is there any clear correlation between the tortuous width and volumetric block proportion....

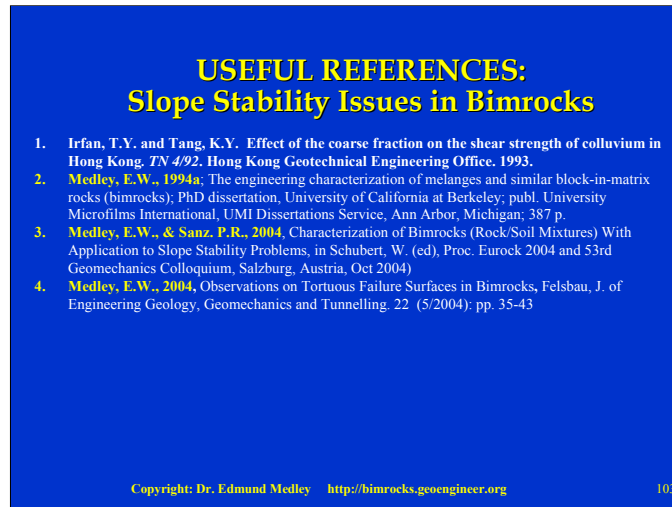
However, the mean "roughness" width for all the data is about 1.44 cm, which is about 10% of the characteristic engineering dimension (the diameter of the triaxial specimens) of 15 cm. The standard deviation of the data is about 0.7 cm. So it would be reasonable for a preliminary guideline, to estimate that the "width" of a "failure zone" containing tortuous surfaces is between about 0.7 and 2.1, or 5% to 15% of L_c , rounding the percentages.

Slope stability analyses could be performed with "trial failure zones", with a width of some 5% to 15% of L_c . However, there is much research yet to be performed to see if such an approach is feasible.



There is a reasonable correlation between block contact ratio and volumetric proportion.

It would be conservative to assume that the proportion of contacts between failure surfaces and blocks is thus about the same as the volumetric block proportion. Since the contacts are the weakest element in the bimrocks, this relationship thus confirms Lindquist's 1994 findings that cohesion decreases with increasing volumetric block proportion.



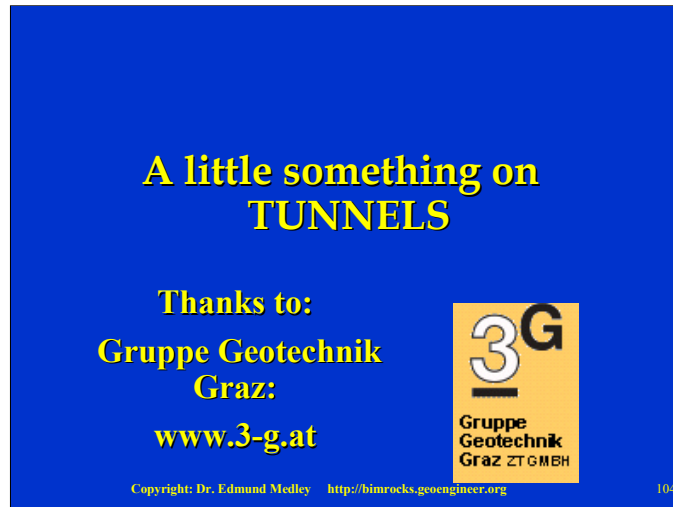
For highlighted references: see “Resources” page on <http://bimrocks.geoengineer.org>

Irfan, T.Y. and Tang, K.Y. Effect of the coarse fraction on the shear strength of colluvium in Hong Kong. *TN 4/92*. Hong Kong Geotechnical Engineering Office. 1993.

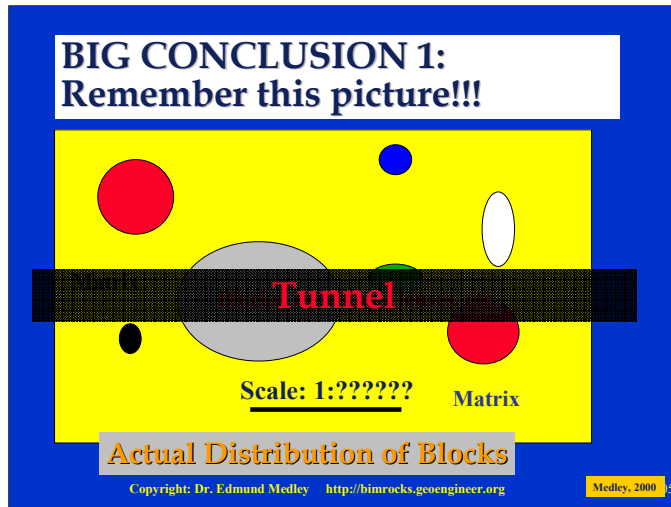
Medley, E.W., 1994a; The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.

Medley, E.W., & Sanz, P.R., 2004, Characterization of Bimrocks (Rock/Soil Mixtures) With Application to Slope Stability Problems, in Schubert, W. (ed), Proc. Eurock 2004 and 53rd Geomechanics Colloquium, Salzburg, Austria, Oct 2004)

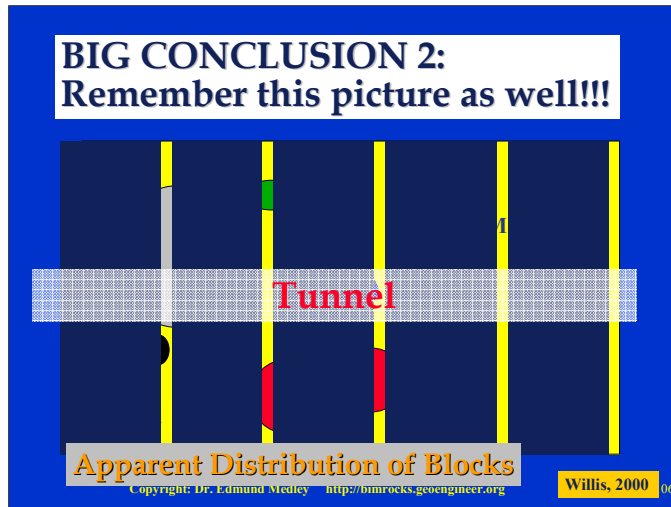
Medley, E.W., 2004, Observations on Tortuous Failure Surfaces in Bimrocks, Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling. 22 (5/2004): pp. 35-43



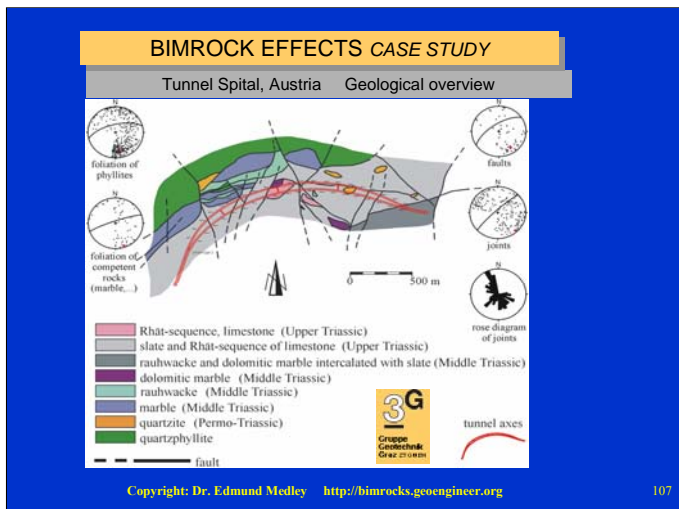
Here are a few words about tunnels. Colleagues at GGG in Graz, Austria, are the experts, though. . . .



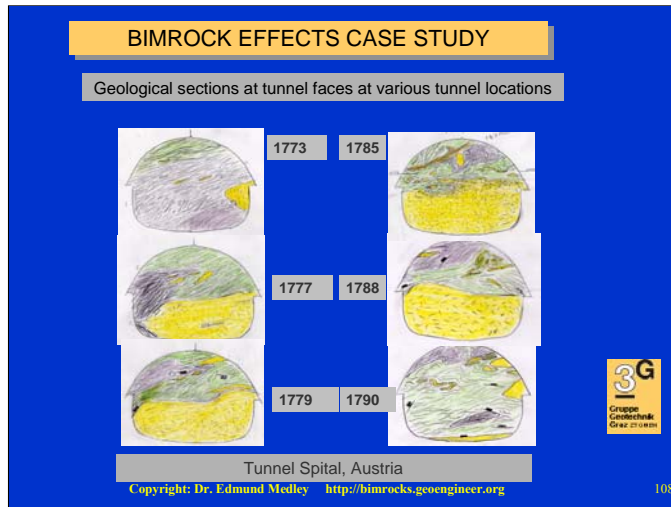
The real rock mass to be penetrated by a tunnel....



.. And what we have to work with: generally borings



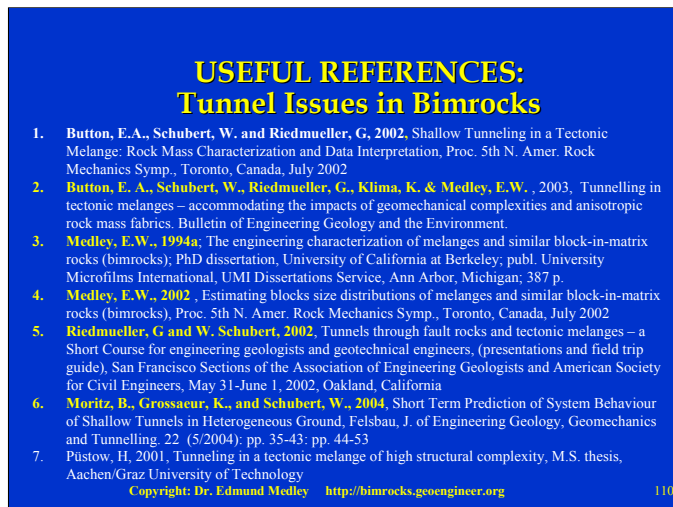
Here is an example of tunnels driven through the Austrian Alps in fault rocks



The geological conditions at the tunnel faces at various stations looked like those above. The stations are in meters. Note the rapidly changing mixed face conditions.

When tunneling through bimrocks....

Expect possible: “mixed face conditions”; complexity; abrupt groundwater flows at penetration of large blocks; squeezing ground at high-stressed matrix; variable geomechanical properties; contractor DSC claims; safety issues...



For highlighted references: see “Resources” page on <http://bimrocks.geoengineer.org>

Button, E.A., Schubert, W. and Riedmueller, G., 2002, Shallow Tunneling in a Tectonic Melange: Rock Mass Characterization and Data Interpretation, Proc. 5th N. Amer. Rock Mechanics Symp., Toronto, Canada, July 2002

Button, E. A., Schubert, W., Riedmueller, G., Klima, K. & Medley, E.W., 2003, Tunnelling in tectonic melanges – accommodating the impacts of geomechanical complexities and anisotropic rock mass fabrics. Bulletin of Engineering Geology and the Environment.

Medley, E.W., 1994a; The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks); PhD dissertation, University of California at Berkeley; publ. University Microfilms International, UMI Dissertations Service, Ann Arbor, Michigan; 387 p.

Medley, E.W., 2002, Estimating blocks size distributions of melanges and similar block-in-matrix rocks (bimrocks), Proc. 5th N. Amer. Rock Mechanics Symp., Toronto, Canada, July 2002


Riedmueller, G and W. Schubert, 2002, Tunnels through fault rocks and tectonic melanges – a Short Course for engineering geologists and geotechnical engineers, (presentations and field trip guide), San Francisco Sections of the Association of Engineering Geologists and American Society for Civil Engineers, May 31-June 1, 2002, Oakland, California

Moritz, B., Grossaeur, K., and Schubert, W., 2004, Short Term Prediction of System Behaviour of Shallow Tunnels in Heterogeneous Ground, Felsbau, J. of Engineering Geology, Geomechanics and Tunnelling. 22 (5/2004): pp. 35-43: pp. 44-53

Püstow, H, 2001, Tunneling in a tectonic melange of high structural complexity, M.S. thesis, Aachen/Graz University of Technology

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*TUNNELS THROUGH FAULT ROCKS
AND TECTONIC MELANGES:
A SHORT COURSE FOR ENGINEERING GEOLOGISTS
AND GEOTECHNICAL ENGINEERS*



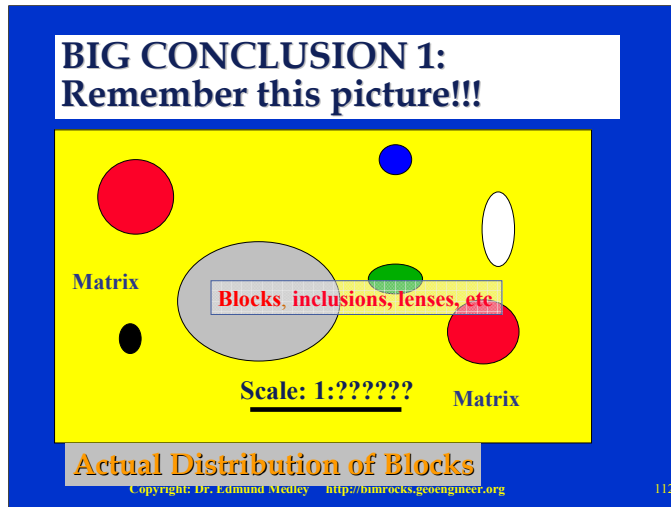
May 31 2002 and June 1 2002

Prof Wulf Schubert and Prof Gunter Riedmueller

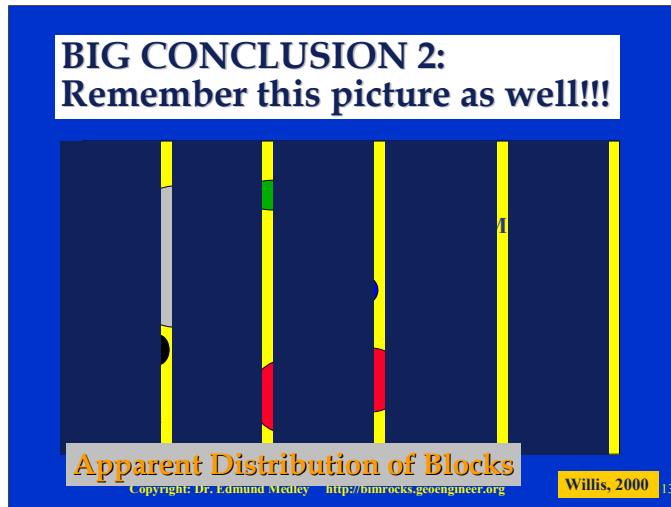
San Francisco Sections of the Association of
Engineering Geologists and American Society of
Civil Engineers

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This is an excellent resource to learn more about tunneling in bimrocks. See Resources page of <http://bimrocks.geoengineer.org> for some materials from this Short Course



To wrap up: Conclusion 1!



.. And Conclusion 2!

Other CONCLUSIONS

- Melange bimrocks and other bimrocks mixtures are chaotic but **can be characterized** in a disciplined fashion
- Strength and deformation properties of bimrocks **are determinable**
- Uncertainties in estimates **must** be considered

Conclusions continued:

- Bimrocks are **NOT**:
 - “soil with boulders”
 - “interlayered shale and sandstone”
 - “miscellaneous soils”
- Block volumes, sizes and lithologies are **\$important\$** to Contractors/Owners and some effort should be made to determine them
- Block sizes should be estimated **very** conservatively for construction

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LAST BUT NOT LEAST HARANGUE!!!:

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. Engineers and geologists should not shrug shoulders their shoulders at chaos and take the easy way by assuming the worst properties of the rock mass are representative; and should not disregard the construction difficulties faced by the excavation or tunneling contractor.

If nothing else, a study of bimrocks teaches one not to use the terms “inter-layered” (or “interbedded”) “shale and sandstone” indiscriminately when characterizing melange bimrocks. Such expressions can lead to false characterizations, incorrect design assumptions; problems during constructions, and possible construction claims and legal disputes.

