Engineering the Geological Chaos of Franciscan and Other Bimrocks

Dr. Edmund E Medley, PE, CEG, F.ASCE

Geosyntec Consultants, Oakland, CA

emedley@geosyntec.com emedley@bimrocks.com

http://bimrocks.geoengineer.org

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E.W. Medley
Geosyntec Consultants, Oakland, California, USA

ABSTRACT: The geologically neutral term *bimrocks* (block-in-matrix rocks) includes melanges, fault rocks, lahars, weathered rocks and other geologically complex mixtures of strong rock blocks embedded within weaker matrix rocks. Bimrocks have mechanical contrast between blocks and matrix, and the geometry and proportion of blocks influence the rock mass properties. The most intractable bimrocks are melanges, exemplified by those of the Franciscan Complex (the Franciscan) of Northern California. The rich geological literature on geologically complex mixtures provides little guidance to practitioners, despite the considerable tunneling, excavation and landslide remediation projects in chaotic rocks worldwide. To effectively engineer with bimrocks, geological chaos must first be recognized and then disciplined characterization performed. The strength of melange bimrocks is simply related to the volumetric proportion of blocks, the evaluation of which must accommodate uncertainties. Although progress is being made in the engineering of geological chaos, much research must yet be performed – some suggestions are offered.

1. INTRODUCTION

Geological materials are generally neatly classified as either Soil or Rock. But engineers and geologists worldwide commonly encounter geologically complex mixtures of strong blocks of rock embedded in soil-like matrices. Nevertheless, many practitioners do not recognize geologically complex “soil/rock” mixtures, let alone adequately characterize them.

The chaotic mixtures are created by several modes of genesis and are known by a myriad of geological names (melanges, olistostromes, cataclasites, fault rocks, breccias, lahar deposits, diamictites, etc.) which have firm and important connotations for geologists, but are confusing to most engineers. The vast geological nomenclature masks the similar physical and mechanical traits of complex mixtures. Therein lies the advantage of treating geologically complex mixtures as bimrocks (block-in-matrix rocks), an engineering material that can be systematically characterized for engineering purposes.

This paper presents a broad overview on some fundamental observations on bimrocks, highlights the most significant problems encountered when characterizing them, and offers suggestions for future bimrock research.

2. FRANCISCAN MELANGES

This paper is appropriately published in the Proceedings of the 2008 American Rock Mechanics Association conference hosted in San Francisco, California. San Francisco, with its many picturesque hills - actually large resistant blocks surrounded by weaker sheared rock - is the geological type locality of the Franciscan Complex (“the Franciscan”), a regional scale jumble that covers a large proportion of Northern California. The Franciscan is world-famous amongst geologists who make pilgrimages to San Francisco and Northern California to investigate its complexity (Figure 1). Understanding of the Franciscan has evolved over nearly 150 years [1] during which time it has been variously known as the Franciscan Series, Franciscan Formation, Franciscan Assemblage, and currently, the Franciscan Complex [2, 3]. The name "Franciscan Complex" is geologically objectionable [4] but semantically appealing: the rocks, the structures, the history and the geological arguments are complicated. Although many engineers and geologists still use the incorrect and dated “Franciscan Formation” it is common and acceptable to refer to the Franciscan Complex as “the Franciscan” as a way to avoid the uncertainty of which name to use.

The Franciscan has been identified in Baja California, the Catalina Islands, central California north of the Coast

Ranges, and continuously from San Francisco north into Oregon. It covers about a third of northern California in three roughly parallel belts, defined on the basis of their lithology and tectonic separation. The belts show increasing age and degree of metamorphism from west to east, indicating deepening immersion in a subduction zone [5].

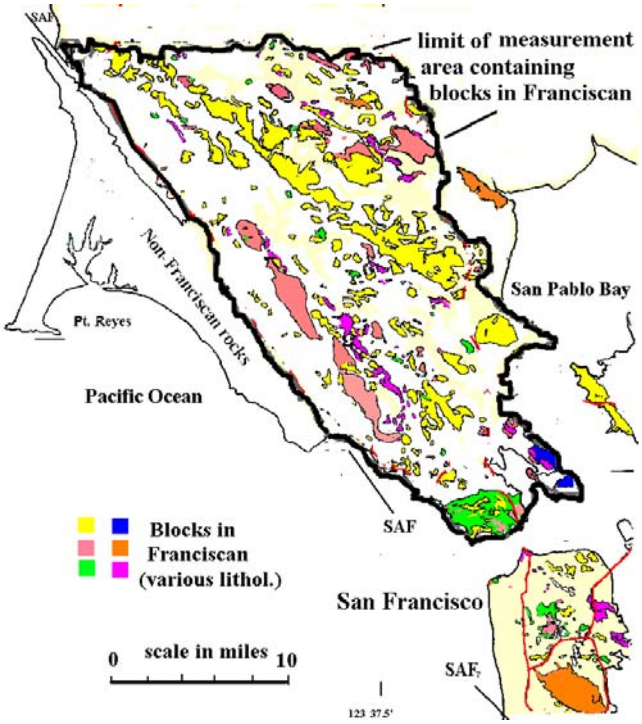


Figure 1. The Franciscan in Marin County, north of San Francisco (after [2,6]).

Figure 2. Franciscan Complex melange, Caspar Headlands, Mendocino County. Note shearing in “matrix” adjacent to large block with matrix blocks sub-parallel to shearing. Block sizes range between tens of meters and fractions of meters. Detail shows “matrix” at circle, with block-in-matrix fabric.

The Franciscan is famous for its melanges (French: *mélange* or “mixture”) as evident in hundreds of references [6]. After the 1950’s geologists recognized the chaos of melanges within the Franciscan that are characteristic of subduction and convergent margin tectonics around the world. Melanges are heterogeneous, complex geological mixtures of competent blocks of varied lithologies, embedded in sheared matrices of weaker rock (Figure 2). Melanges (and related olistostromes) are found in over 60 countries and are associated with mountainous areas at plate convergences [6]. The melanges of the Franciscan are similar to melanges elsewhere in the world in appearance, properties and the problems they present engineers.

Figure 3. Blocks in melange protrude from hillside along proposed right-of-way, Egnatia Highway, Greece. (Photo: late Professor Gunter Riedmueller/GGG, Austria).

Most blocks in Franciscan melanges are of greywacke sandstone, with lesser proportions of volcanic, chert, serpentinite, limestone and exotic metamorphic blocks [6]. Large blocks in melanges (and many fault rocks) tend to be ellipsoidal to irregular in shape. Blocks are relatively erosion-resistant and often protrude above the ground surface in Franciscan melange landscapes, a characteristic of melanges evident worldwide (Figure 3). The matrix of Franciscan melanges is composed of shale, argillite, siltstone, serpentinite or sandstone, often pervasively sheared to the consistency of soil. Landslides are common in block-poor Franciscan melanges [6] but large blocks appear to add buttress support (Figure 4).

Figure 4. Blocks in Franciscan melange buttress slope between landslides in sheared shale. (E. Medley/Exponent)

Figure 5. Franciscan melange, Sonoma County, California. Blocks form erosion-resistant headlands and buttress slopes.

Blocks and matrix are best seen at excavations Figure 3) and cliffs where blocks are prominent headlands ((Figure 2 and Figure 5). Although blocks often protrude conspicuously from hillsides their presence generally must be inferred by subtle topographic or vegetation contrasts. The early summer browning of grass in melange landscapes in northern California occurs first above blocks because the generally sandier soils dry faster than the clayey soils above matrix. The result is a mottling that is characteristic in melange terrains (Figure 6) and which is well exhibited in air photos taken in Spring and early Summer.

Figure 6. Franciscan melange in Marin County, Northern California. Occasional blocks protrude from the hillside or form bumps in the topography. During Spring, brown patches indicate drying grass on coarser soils formed above blocks; green areas indicate underlying clayey soils above matrix rock.

3. BIMROCKS

Thousands of papers, books and abstracts have been written on various aspects of melanges and their aliases (*friction carpets, wildflysch, broken formation, mega-breccias, sedimentary chaos, block-in-matrix rocks and varicolored clays*, being a few) with countless other treatments on other geologically complex mixtures of hard blocks surrounded by weaker matrix, such as fault rocks, lahars, tillites, and weathered rocks [6].

The term “block-in-matrix rocks” was originally coined by Professor Loren Raymond [7] for the fabric of melanges and olistostromes, geological names which have firm and important connotations for geologists but are largely meaningless to most engineers. Despite the wealth of geological literature, there are still very few engineering papers addressing those aspects of complex geological mixtures most important to engineers: characterization and geomechanical properties.

Figure 7. Decomposed granite located in the Sierra Nevada mountains of Northern California. Hard blocks (corestones) surrounded by matrix of “gruss” (granite decomposed to dense sandy soil).

To focus on the common fundamental engineering problems related to the characterization of complex geological mixtures, Medley [6] coined the geologically neutral word “bimrocks” from Raymond’s [7] “block-in-matrix rocks”. A bimrock is: *"a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture*”. The expression “geotechnically significant blocks” means that there is mechanical contrast between blocks and matrix, and the volume and size of the blocks influence the rock mass properties at the scales of engineering interest.

Despite different formative processes, globally common bimrocks have a similar fabric of relatively hard blocks of rock surrounded by weaker matrix rocks. Bimrocks are found in most parts of the world, particularly in mountainous areas with old or current tectonic legacies, and include weathered rocks, mixtures of decomposed soil surrounding fresher corestones (Figure 7). The most intractable bimrocks are melanges and fault rocks (Figure 8), which exist at many scales, having blocks ranging from thousands to tens of meters in size through millimeter-sized fragments within gouge ([8,9]. Besides hosting melanges, Northern California has a rich distribution of fault rocks and weathered rocks.

Figure 8. Rock exposed in slope excavated within San Andreas fault zone, Northern California. Sheared rock surrounds hard blocks of relatively intact rock. Blocks range between centimeters to tens of meters in size. (Photo: E. Medley/Geosyntec Consultants).

4. CHARACTERIZATION OF BIMROCKS

Bimrocks may have considerable spatial, lithological, and mechanical variability, and characterization, design and construction in bimrocks are daunting tasks. So, when characterizing bimrocks, many engineers wrongly assume that adoption of the geomechanical properties of either the soil or the rock should suffice. Consequently, failures during construction, construction claims and litigation result from poor characterization of bimrocks.

The complexity of bimrocks can be lessened if an orderly approach is adopted [10]. Disciplined implementation of even simple characterization procedures may reduce expensive surprises by focusing the practitioner's attention on the difficulties that may be encountered during design and construction of excavations, foundations, earthwork, and tunnels. Bimrocks should be purposefully characterized for design and construction even where there is great uncertainty in the characterization, or when the volumetric proportion of blocks is too little to provide geomechanical benefit [10, 11, 12].

The most important requirement for correct characterization is for the investigator to recognize bimrocks and not approach them as stratigraphically orderly ("layer-cake") rocks [10, 11]. Additional important engineering aspects of a characterization include: block volumetric proportions, block size distributions, overall block orientations, matrix and block discontinuity fabrics, matrix strengths, and matrix/block contact strengths. Of lesser importance are block lithologies, matrix lithologies and individual block shapes.

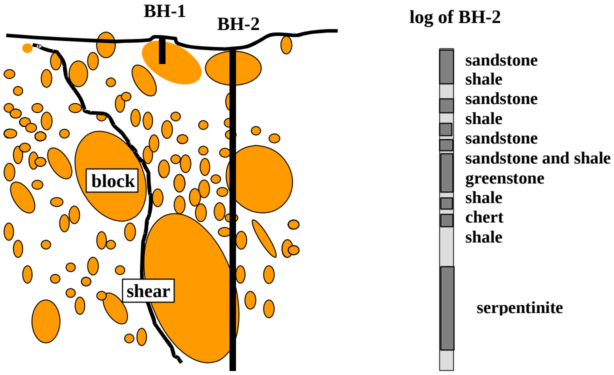


Figure 9. Block/core intersections (chords) do not generally indicate true block sizes. Sandstone/shale sequence in core is not "interbedded/interlayered shale and sandstone"!! Improbable juxtaposition of rocks (e.g.: greenstone and shale) suggest melange. Note that shears in the matrix negotiate tortuously around blocks.

A mental picture (Figure 9) of the spatial and lithologic variety of block/matrix mixtures will reduce errors in geological interpretations when characterizing bimrocks: we see only the intersections of block and matrix in core, not the 3-D array of blocks separated by matrix. Despite the apparent interlayered appearance of drill core recovered from bimrocks, it is preferable not to log borings in bimrocks with expressions such as "interbedded/interlayered shales and sandstones" since this term implies stratigraphic continuity. Once the words "interlayered" or "interbedded" are used in boring logs, there is a tendency to imagine continuous "layer-cake" stratigraphic contacts between borings [10], such as shown in Figure 10.

The fundamental error of drawing straight lines and layers in cross-sections is the basis for extraordinary and expensive mistakes in design and construction when working in bimrocks.

As outlined by Wakabayashi and Medley [10] accurate descriptions of bimrocks are critical, otherwise misinterpretation of the geologic data by non-geologists may result causing unexpected costs and construction disputes. For fault rocks, terms such as "melange" may be geologically correct and impart the correct sense of chaos but basic descriptions such as "elongate masses of sandstone and siltstone in a sheared shale matrix" are more appropriate.

Logging the material encountered in the borings as "soil above bedrock" increases the probability that the blocks will be interpreted as continuous bedrock. Bimrocks should not be described as "miscellaneous soils" or "soil with boulders". The latter term may mean different things to the geologist who encounters blocks during exploration, and the contractor who has to construct through or around them.

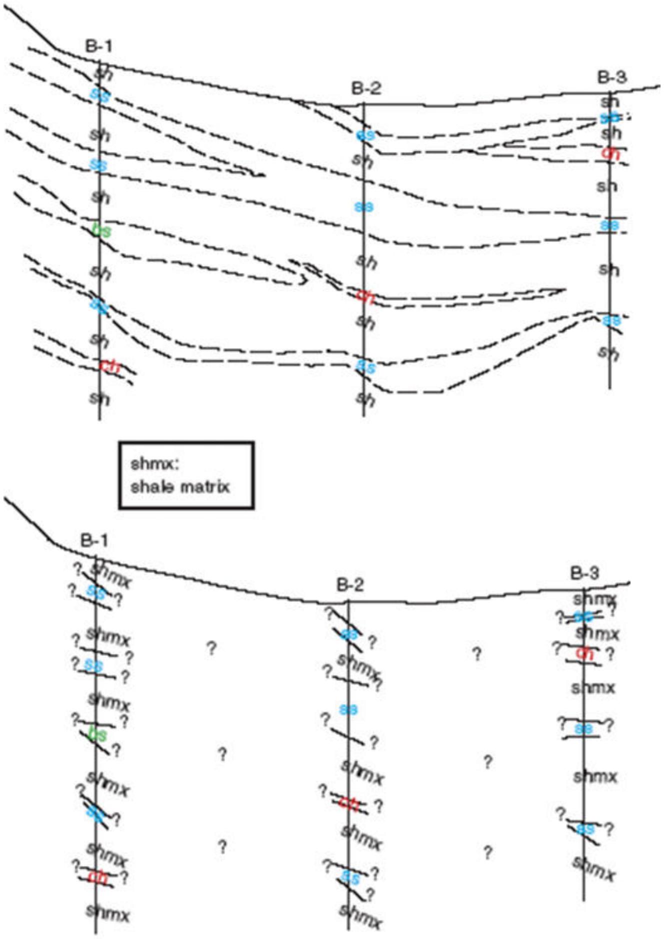


Figure 10. Bimrocks generally cannot be accurately characterized on cross-sections. Borehole contacts should not connected between borings (Top) but shown as short lines with question marks (Bottom) (After [10]).

A mischaracterization of Franciscan melange provides a lesson. Hillside repairs were proposed to mitigate a landslide in the Franciscan. During the geotechnical investigation the exploration borings were terminated about 2m into “sandstone bedrock.” It was concluded that the landslide was shallow, being composed of clay and boulder colluvium sliding on the contact with the underlying sandstone bedrock (Figure 11). The geotechnical engineer recommended that the failed soil be removed and the slope re-graded. A repair was designed to remove the shallow landslide. The successful contractor bid was for several hundred thousand dollars. However, during construction, the contractor encountered pervasively sheared shale containing abundant rock blocks to several meters in size, which required considerable effort to remove since blasting was not permitted. The contractor failed to find solid “bedrock”, or even a definite landslide “failure surface” given the pervasive shearing. The excavation was deepened below the design depth of a few meters to tens of meters. The repair finally cost more than a million dollars.

The landslide was actually a deep-seated slope failure in pervasively sheared melange, rather than the shallow soil mass sliding on top of “bedrock” interpreted from exploration drilling. “Bedrock” was the result of the engineer connecting straight lines between his interpreted “soil/rock” contacts as intersected by the borings (Figure 11). This error is commonly made by many engineers and some geologists. Although the geological chaos was a surprise to the geotechnical engineer, publically available geological maps actually showed the locale of the landslide to be within Franciscan melange, and large blocks protruded from hillsides around the site, as is typical in Franciscan melanges.

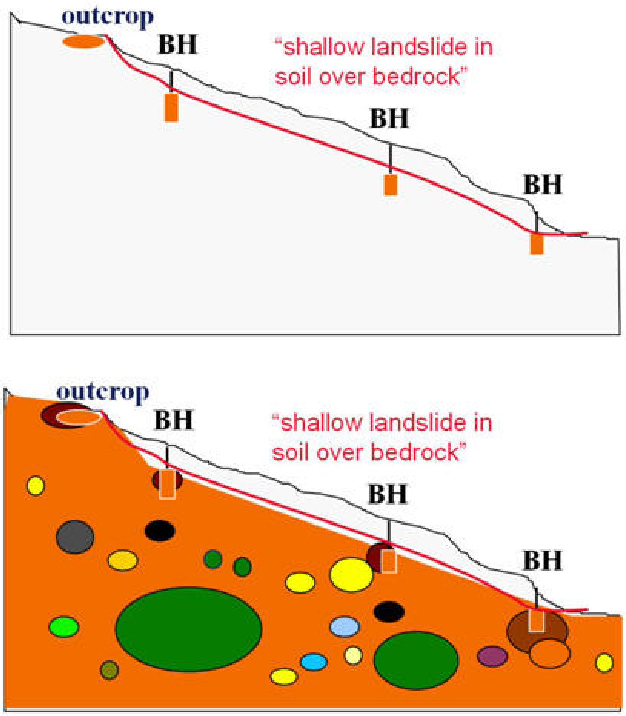


Figure 11: Upper sketch shows interpretation of geology based intersections by borings of an assumed continuous and homogeneous sandstone bedrock surface. Lower sketch shows more realistic bedrock conditions in which borings intersect discrete blocks in a bimrock containing blocks of various dimensions and lithologies within a matrix.

5. WHAT IS BLOCK, WHAT IS MATRIX?

When mapped, the largest observed dimension of exposed blocks can be recorded. When drilled, the observed block dimensions are indicated by chords, the lengths of the intersections between blocks and the drilled core. The word “size” or “diameter” should not be used when describing the dimensions of blocks, unless those are known because, as evident from geometrical probability, the observed dimensions of blocks generally will almost always be less than the maximum block dimension (Figure 9). For the same reasons, it is virtually impossible to recover actual 3-D block size distributions from observed 1-D chords from drilling or mapped maximum observed dimensions [13].

Figure 12. Weakest element in a bimrock is generally the block/matrix contact. Gwna Melange, Anglesey, N. Wales.

Block sizes in Franciscan melanges (which are typical of melanges worldwide) can exceed seven orders of magnitude, ranging between millimeters and tens of kilometers [6, 14]. Figure 2 and its insert are photographs taken at different scales of the same outcrop of Franciscan melange. Small blocks at one scale of interest in the detail photo in Figure 2, are part of the matrix at the larger scale photo of Figure 2. Blocks assigned to matrix do not contribute to the mechanical behavior of the bimrock, and relative to the definition of bimrocks, they are not "geotechnically significant" at that scale, although they may be at larger scales.

Since blocks exist at many scales of engineering interest in bimrocks: <u>what is block and what is matrix</u>? The answer: it depends on the scale of engineering interest. Because of the scale independence of block sizes [6, 14] a "*characteristic engineering dimension*, L_c" must be defined [6] which is analogous to the scale bar in the insert photograph of Figure 2. The characteristic engineering dimension changes as scales of interest change at a project. L_c may variously be: 1) an indicator of the size of the entire site, such as the square root of A ($\sqrt{A}$) where A is the area of the site; 2) the size of the largest block (d_{max}) at the site; 3) the thickness of a failure zone beneath a landslide; 4) the height of a slope or excavation; 5) a tunnel diameter; 6) a footing width or; 7) the dimension of a laboratory specimen; and so on.

The smallest geotechnically significant block within a volume of bimrock is about 0.05 L_c, which is the threshold size between blocks and matrix at the chosen scale [6]. For any given volume of bimrock, blocks smaller than 0.05 L_c constitute greater than 95 percent of the total number but contribute less than 1 percent to the total volume of bimrock and thus have negligible effect on the bimrock strength [6]. The largest block (d_{max}) is approximately 0.75 L_c [6].

6. BIMROCK STRENGTH

Geoengineers often neglect the contributions of blocks to overall bimrock strength, choosing instead to design on the basis of the strength of the weak matrix. However, this practice may be too conservative for many bimrocks and often results in ignoring the presence of blocks altogether, to the detriment of accurate characterizations.

The weakest elements in bimrocks are the contacts between blocks and matrix (Figure 12). In melanges, matrix shears generally pass around blocks with intense shearing adjacent to the larger blocks (Figure 2). Only modest mechanical contrast between competent blocks and weaker matrix is required to force failure surfaces to negotiate tortuously around blocks at the block/matrix contacts [6, 15, 16, 17, 18] (Figure 9 and Figure 13).

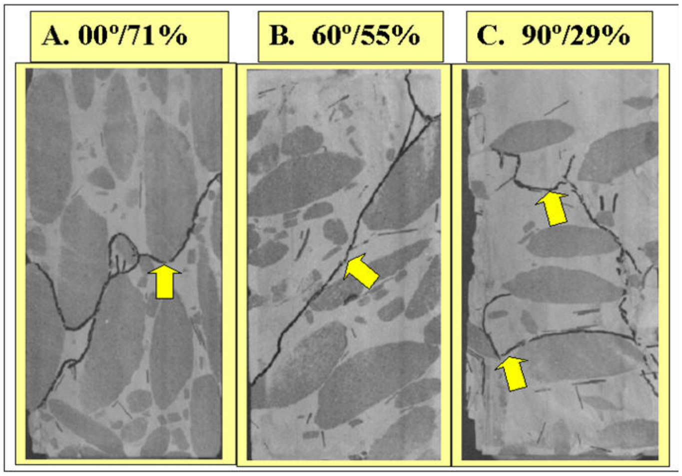


Figure 13. Sections through three failed triaxial compression specimens of physical model melanges, showing that failure surfaces negotiate around blocks. Specimens have blocks oriented at 0, 60 and 90 degrees to vertical and volumetric block proportions of 71%, 55% and 29%. After [20, 29].

The overall strength of a bimrock is <u>independent of the strength of the blocks</u>. Blocks greater than the block/matrix threshold contribute to strength- as long as there is sufficient mechanical contrast, blocks with a range of sizes adds strength to a bimrock by forcing tortuous failure surfaces to tortuously negotiate around them [15, 16, 19 ,20, 21, 22, 29].

As block proportions increase, stiffness increases and deformation decreases depending on the relative orientation of blocks to applied stresses [20, 21]. As shown in Figure 14, Lindquist [20] conservatively established that below about 25 percent volumetric block proportion the strength and deformation properties of a bimrock is that of the matrix; between about 25 percent and 75 percent, the friction angle and modulus of deformation of the bimrock mass proportionally increase (and cohesion decreases); and, beyond 75 percent block proportion, the blocks tend to touch and there is no further increase in bimrock strength. Goodman and Ahlgren [22] identified contributions to overall bimrocks strength at volumetric block proportions much lower than 25 percent.

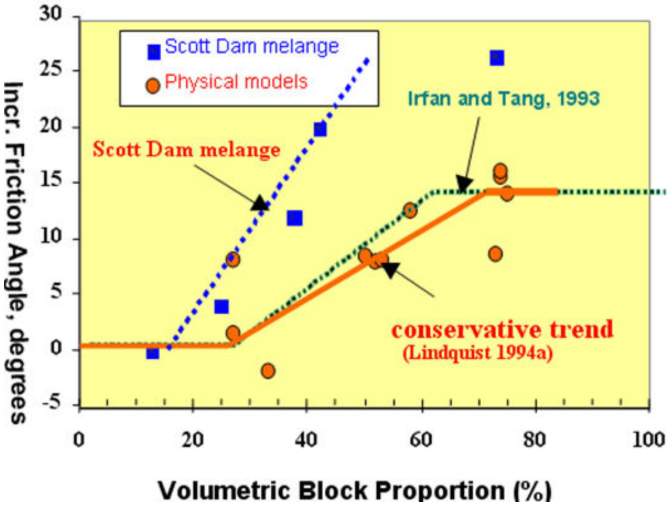


Figure 14. Strength of bimrocks increases with volumetric block proportion. The increase is added to the strength of the matrix. After [19,20].

Stress distributions in bimrocks depend on the lithologies, size distributions, orientations and shapes of blocks, and the orientations of matrix shears; all of which influence slope stability [23] and underground excavations [24, 25, 26].

7. ESTIMATION OF VOLUMETRIC BLOCK PROPORTIONS

To evaluate the mechanical properties of bimrocks, the volumetric block proportion must be estimated. The volumetric block proportion of a bimrock can be approximated by measuring linear block proportions of drilled cores (Figure 15). A linear block proportion is the ratio of the total lengths of blocks intersected to the total length of sample lines (Figure 16). According to stereological principles given enough sampling (drilled core), such linear block proportions are equivalent to volumetric block proportions [6, 27]. Estimates of areal block proportions can also be derived from outcrops by geological mapping, air photos, or by using image analysis [6]. The estimates of volumetric block proportions derived from areal block proportions are also subject to great uncertainty [6, 28].

Potentially expensive errors will result if volumetric block proportions, bimrocks strengths, and total block volumes are estimated from a few borings (or outcrops), as indicated by the typically extreme variability indicated by Figure 16. The stereological assumption that the linear block proportion is equivalent to volumetric block proportion [6,27,29] is valid only for considerably more drilled core investigation than is normally performed in geotechnical engineering. It is vital to understand that the actual volumetric block proportion is likely to be significantly different from a measured overall linear block proportion and adjustments should be made for the uncertainties [29].

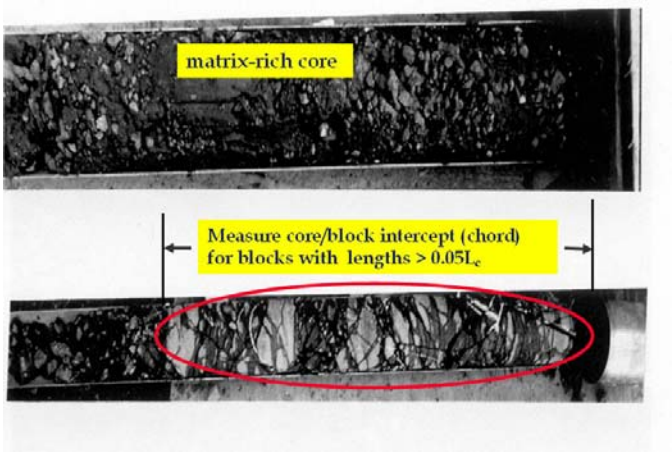


Figure 15: Franciscan melange recovered in core from an exploration boring near Scott Dam, Eel River, Northern California. A typical measurable block longer than 0.15m ($0.05L_c$) and matrix of sheared shale with smaller blocks assigned to matrix. (Photo: Professor Richard E. Goodman).

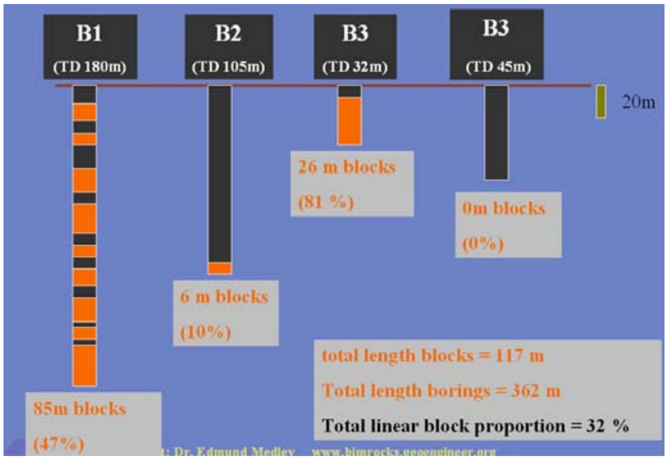
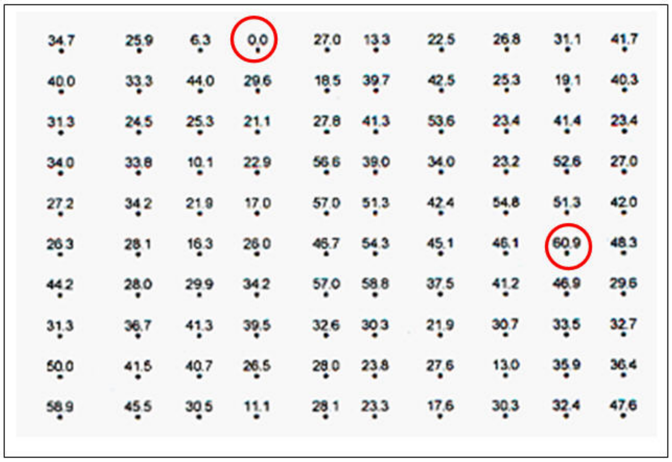


Figure 16: Block intersections (shown in orange) for adjacent borings - 20m scale bar shown. TD is total depth of an individual boring. Individual linear block proportions for boreholes B1 to B4 range between 0% and 47%. Overall cumulative linear block proportion is 32%.



34.7	25.9	6.3	0.0	27.0	13.3	22.5	26.8	31.1	41.7
40.0	33.3	44.0	29.6	18.5	39.7	42.5	25.3	19.1	40.3
31.3	24.5	25.3	21.1	27.8	41.3	53.6	23.4	41.4	23.4
34.0	33.8	10.1	22.9	56.6	39.0	34.0	23.2	52.6	27.0
27.2	34.2	21.9	17.0	57.0	51.3	42.4	54.8	51.3	42.0
26.3	28.1	16.3	26.0	46.7	54.3	45.1	46.1	60.9	48.3
44.2	28.0	29.9	34.2	57.0	58.8	37.5	41.2	46.9	29.6
31.3	36.7	41.3	39.5	32.6	30.3	21.9	30.7	33.5	32.7
50.0	41.5	40.7	26.5	28.0	23.8	27.6	13.0	35.9	36.4
58.9	45.5	30.5	11.1	28.1	23.3	17.6	30.3	32.4	47.6

Figure 17: Plan view of an array of measured linear block proportions ranging between 0% and 61% (circled) for a physical model bimrock with actual volumetric block proportion of 32%. (After [29]).

8. SUGGESTIONS FOR FURTHER RESEARCH

Future interdisciplinary research is suggested to further develop growing geoengineering interest in bimrocks:

- Develop virtual bimrocks using numerical methods to simulate, under controlled conditions, model bimrock masses, investigate geomechanical behaviors and advance approaches to characterization by drilling and mapping. A promising start is presented by Pan et al. in a companion paper in these Proceedings [30].
- Survey the means by which other scientific and engineering disciplines characterize complexity of geological mixtures such as ore bodies within waste rock, discontinuous groundwater bodies and contamination lenses.
- Develop statistical means of understanding and predicting the uncertainties of our estimates of rock block volumes, sizes, orientations and so on based on the limited exploration tools available to the geo-practitioner (generally drilling and mapping). Geostatistics is certain to be one of the tools that can be used. An understanding of stereology and geometrical probability is also essential in such work, since predictions of 3D properties have to be made based on 1D and 2D observations. The stereological contributions of medical researchers (who characterize complex 3D biological features from limited data) shall thus be useful.
- Understand better the complex hydrogeological interactions within stressed rock soil mixtures by learning from structural geology and geomechanics.
- Develop a database of characterization/design and construction experience in bimrocks, such as the recent tunneling experience of Spreng at el in the Franciscan [31].

9. CONCLUSIONS

Bimrocks are commonly encountered by geotechnical engineers in the Franciscan of Northern California and many other parts of the world. Conceptual understanding of the nature of bimrocks aids accurate characterizations, and procedures to characterize and analyze bimrocks are available, but much more research and practitioner experience should be published. Regardless of where they are practicing, the problems of characterization of bimrocks are reduced if engineers initially recognize they are working in geological chaos and not stratigraphic order.

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*Note: References shown with * are available at http://bimrocks.geoengineer.org/resources.html*

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