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Geopractitioner approaches to working with antisocial mélanges

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ABSTRACT

Although mélanges are exciting, puzzling, and controversial to geologists, it is geopractitioners and contractors who must work with them to engineer the constructed works of Society. Geopractitioners include geotechnical engineers, geological engineers, engineering geologists, and rock engineers. Mélanges are the most intractable *bimrocks* (block-in-matrix rocks), complex geological mixtures composed of hard blocks of rocks surrounded by weaker matrix, and are famously exemplified by those within the Franciscan Complex of Northern California. Bimrocks also include olistostromes, weathered rocks, fault rocks, and lahars. The conventional characterization, design, and construction procedures used by geopractitioners for well-behaved stratified rocks and soils are not well suited to mélanges. The considerable engineering and construction difficulties related to mélanges burden Society to the extent that they can be considered "antisocial." Case histories exemplify a recommended systematic procedure for characterization, design, and construction with mélanges. Geopractitioner approaches to characterizing California's chaotic Franciscan mélanges are applicable to geologists and geopractitioners working in fault zones, weathered rocks, lahars, and other bimrocks, and suggestions are offered for collaborative research between geologists and geopractitioners.

INTRODUCTION

Mélanges have been of exciting and controversial concern to geologists since Greenly (1919) first identified "autoclastic mélange."[1] There are thousands of publications on various aspects of mélanges; countless more contributions have been published on other geologically complex rock mixtures of competent blocks of rock embedded within weaker matrix rocks, such as fault rocks, lahars, tillites, and weathered rocks.

Whereas geological complexity may be delightful for geologists, it can result in despair for geopractitioners. Geopractitioners specialize in the engineering of earth materials and include geotechnical engineers, geological engineers, engineering geologists, and rock engineers. Geopractitioners are professionals who apply

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[1]I believe that it is unnecessary and affected to use an acute "é" in *mélange*. However, I have deferred to the publisher's preference throughout this chapter, on the condition that we shall share café one day.—*EWM*

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scientific and mathematical principles to the efficient, economical, and safe design, construction and operation of the civil engineering works essential to Society's built environment: building foundations, port facilities, tunnels, bridges, buried utilities, dams, etc.

Geotechnical engineers are civil engineers specializing in soil mechanics but who may have little knowledge of rock mechanics or geological principles (Turner, 2005; Medley, 2009). Geological engineers are trained as engineers with broad training in geology, groundwater, soil mechanics, and rock mechanics. Engineering geologists are applied geologists with some training in the mechanical behaviors of soils, rock, and water but less familiarity with engineering design principles–practices and construction procedures. Rock engineers are often geological engineers or mining engineers with specialized training in rock mechanics.

MÉLANGES AND BIMROCKS

Mélange bodies are found in more than 60 countries, generally within current and ancient mountain systems (Medley, 1994a). Mélange bodies are famously abundant in the Franciscan Complex (the Franciscan), which covers about one-third of Northern California. Many geologists have described various aspects of Franciscan mélanges, such as Wakabayashi (2008), Berkeland et al. (1972), Fox (1983), Cloos (1990), Blake and Jones (1974), Raymond (1984), Cowan (1985), and Hsü (1985). Franciscan mélanges provide a superb field laboratory for geologists studying convergent margin tectonics: Useful field guides have been prepared by Wahrhaftig (1984), Blake and Harwood (1989), and Wakabayashi (1999). The mélanges of the Franciscan are similar to mélanges elsewhere in the world in appearance, properties, and the problems they present globally to geopractitioners.

There are surprisingly scant treatments written about mélanges from the perspective of geopractitioners, despite the myriad of geological publications. Some early papers described engineering experience with Italian olistostromes and argille scagliose (Associazone Geotechnica Italiana, 1977; Aversa et al., 1993; D'Elia et al., 1986). More recent research has been performed by the senior author, and a few others, including Lindquist (1994a), Lindquist and Goodman, 1994), Goodman and Ahlgren (2000), Riedmüller et al. (2001), Sönmez et al. (2004), and Roadifer et al. (2009).

Raymond (1984) classified mélanges, as "block-in-matrix rocks," a term that joins the several aliases for mélanges such as: friction carpets, wildflysch, broken formation, argille scagliose, olistostromes, mega-breccias, sedimentary chaos, varicolored clays, etc., and is one of many geological terms for comminuted, mixed, fragmented, and chaotic rocks as listed by Laznicka (1988) and the *Glossary of Geology* (Neuendorf et al., 2005). This ample geological language describing various complex geological mixtures is of little significance to engineers, because their interest is not generally on geologic origin but on the mechanical properties of geological materials and their relationships to engineering design and construction. To focus engineers' attention on the fundamental engineering properties of complex geological mixtures for the purposes of design and construction, Medley (1994a) coined the neutral word *bimrock* from Raymond's (1984) term *block-in-matrix rock*. Formally, 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 geometry and proportion of the blocks influence the rock mass properties at the scales of engineering interest, which range between centimeters for laboratory test specimens through tens of kilometers for tunnel lengths.

Bimrocks include complex geological mixtures such as olistostromes, weathered rocks, fault rocks, and mélanges. Weathered rocks can include mixtures of decomposed soil surrounding fresher core-stones (Fig. 1). Fault rocks, composed of blocks within gouge and sheared rock (Fig. 2), exist at many scales, with blocks ranging between several tens to hundreds of meters in size to millimeter-sized fragments within gouge (Riedmüller et al., 2001, 2004). Mélanges, the most intractable of bimrocks, contain competent blocks of varied lithologies, commonly embedded in sheared matrices of weaker rock (Fig. 3).

Regardless of geological nomenclature and formative processes, simplistically, bimrocks have a similar fabric of relatively hard blocks of rock surrounded by weaker matrix rocks. Yet, despite simplifications, characterization, design, and construction within bimrocks is still challenging because of the considerable spatial, lithological, and mechanical variability, and because geopractitioners often mischaracterize them.

The conventional and simplistic expectation in geopractice is that soil and rock masses are orderly and stratified to the extent that the words *layers, strata,* and *formations* are frequently used in geopractice. Stratified conditions permit geological, spatial, and mechanical interpolations between relatively scant borings, outcrop observations, and test results. Economic and efficient design and construction can usually follow, to the benefit of designers, contractors, owners, and Society at large. Geopractitioners often

Figure 1. A block-in-matrix rock (bimrock) in the Sierra Nevada of California. Decomposed granite contains hard blocks (core-stones) surrounded by a matrix of dense sandy soil (grus). Photo: E. Medley.

also use the expressions "well-behaved" and "nicely behaved" for spatially and mechanically uniform stratified conditions, although even "well-behaved" rock masses have discontinuities (joints, fractures, shears, etc.) that complicate simple characterizations.

Accordingly, complex geological mixtures of weak matrix and strong blocks can be considered "badly behaved," and the worst offenders, mélanges, are so much trouble to geopractitioners and Society that it is irresistible to suggest that "badly behaved" mélanges are "antisocial," particularly since "deranged" mélanges cost Society considerably more effort, money, and time than well-behaved stratified rocks.

GEOPRACTICE WITH MÉLANGES AND SIMILAR BIMROCKS

In general, geopractitioners work with mélanges, rather than try to understand how they came to be. "Work" is used to describe characterization, design, and construction, although in this chapter we mostly address characterization. Geopractitioners strive to solve engineering problems economically, efficiently, and safely, so the geopractice approaches we describe may seem coarse to geologists interested primarily in understanding the scientific details of mélanges and their formation.

Some geopractitioners are not aware of the existence of complex geological mixtures of weak matrix and strong blocks. Others regard mélanges as soil-rock mixtures. Geotechnical engineers, with their soils bias, often analyze bimrocks as soil, or assume that the geomechanical properties of the weakest materials in mélanges adequately represent the mixed rock mass, and design on that basis. Some geotechnical engineers and rock engineers may focus on the rock content, and consider the mixture to be stable material. Hence, the words of Prof. Harry Bolton Seed, a principal authority for geopractitioners, are thus appropriate: "The general thrust behind engineering problem solving is to simplify the problem enough to make it solvable. However, we must check to see if we have oversimplified the problem so much that we get other problems instead of the solution we desire" (Rogers, 2008). So, in making the assumptions described above, geopractitioners invite future problems during construction, because extremely weak shear zones and complex stress conditions may exist that are hidden until the ground is exposed during construction.

Civil engineering works require characterization, design, and construction. Geological and geotechnical characterization involves exploration of the ground surface and subsurface by direct and indirect means, sampling and testing of its constituent parts, and assigning to the ground mass mechanical properties that are representative of the material for the purposes of the design of a particular project. The chaotic nature of mélanges has more than usual constraining impact on the design and construction of tunnels, dams, excavations and other civil engineering works. Discussion of the general procedures for the characterization of subsurface conditions is beyond the scope of this paper, but many resources are available (e.g., Hunt, 2005). Specific guidance to geopractice characterization of mélanges is provided in the following section as well as by Medley (2001) and Wakabayashi and Medley (2004). Successful characterizations of mélanges depend on geopractitioner skills at interpreting scant ground clues and anticipating the complexity of the rock mass.

Depending on the scope of the work, different aspects of the behavior of the rock mass conditions will be critical, and the characterization may need to be focused on those aspects more than on others. Hence a geopractitioner's exploration of mélanges is often an economic compromise. Too few borings or scant mapping results in a cheap but inadequate characterization. On the other hand, a comprehensive and expensive program may generate ample observations but still may not provide enough data to accurately model the mélange.

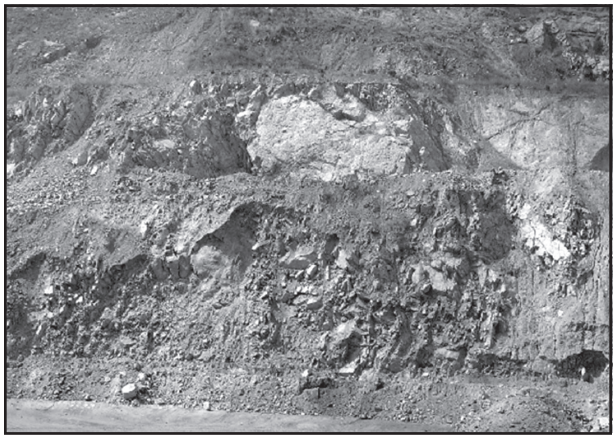

Figure 2. Wall of a quarry located within a major fault zone, California. Sheared rock surrounds hard blocks of relatively intact rock. Blocks range between centimeters and tens of meters in size. Photo: E. Medley–Geosyntec Consultants.

Figure 3. Franciscan Complex mélange, Northern California. Blocks buttress base of slope between landslides in sheared shale matrix. Photo: E. Medley–Exponent, Inc.

Characterizations are also based on laboratory tests of specimens that are inevitably disturbed to some extent by drilling, transportation, and specimen preparation. If characterization is performed correctly, potential construction issues will be recognized early in the project. But the geological-geomechanical model is often only a sketch of the actual geological conditions, and geopractitioners must accommodate uncertainty about the likely behavior of ground masses by qualifying their characterizations and adding generous margins of safety to their estimates of the mechanical properties of the soil or rock masses. The geopractitioner also has a duty to warn the client and the contractor about the uncertainties involved in the characterization and design and to recommend methods to deal with problems anticipated during construction.

Design and construction follow characterization, although they proceed together with characterization on large design-build projects. Geopractice design is the commissioned (i.e., compensated) systematic conception, invention, and specification of the appropriate means (geometry, loads, etc.) required for acceptable performance of civil infrastructure as it relates to the geologic environment. In practice, designs are subject to the constraints of ground conditions, costs, time, and labor-equipment resources.

Construction is performed by contractors using the plans and specifications prepared by the design engineer. Geopractitioners may work with, and for, contractors, although most often they work for owners, who pay for the work. Flaws in the characterization and design will become evident during construction and may cause ground failures, schedule delays, and contractor claims for additional compensation. Table 1 summarizes some of the construction issues, the design and analyses considerations, and the characterization needs for excavations, slopes, foundations, dams, and underground facilities, some of which are addressed in more detail below.

GEOPRACTICE METHODS FOR CHARACTERIZATION OF MÉLANGES

A major geopractitioner concern is the evaluation of the strength and deformation properties of soil and rock masses. For mélanges, conventional engineering approaches using simple stratigraphic-type characterizations are of little value. Instead, there should be a focus on volumetric block proportions; block and matrix lithologies; strength and discontinuity fabrics; block sizes, shapes, and orientations; and groundwater regimes (Wakabayashi and Medley, 2004).

Characterization typically includes review of aerial photographs and available geological information, geological mapping, drilling and coring, and laboratory testing. Ideally, aerial photos can be used with image processing techniques to identify blocks within mélanges, as tonal contrasts may discriminate large blocks from matrix (Medley, 1994a). More typically, information about the blocks is collected by mapping and drilling. The relative strengths of blocks and matrix of blocks can be evaluated using a geologic hammer and reference to engineering geology protocols such as that of the Geological Society Engineering Geology Working Party (1995), a Schmidt hammer, or a Point Load Test apparatus.

The geometry of blocks and fabric of matrix around the blocks must be evaluated because of possible shears and ellipsoidal or prolate-shaped blocks adversely oriented into proposed excavation slopes or tunnel walls. Observations about large blocks buttressing slopes (such as is evident in Fig. 3), and existing failed rock masses can be used to back-calculate the overall strength of mélange (Kim et al., 2004).

It can be difficult to recover good quality core in bimrocks during drilling exploration because of the abrupt variations between blocks and matrix, varying block lithologies, extensive shearing, and the highly fractured nature of small blocks (Fig. 4). Recovery of drilled core tends to be much better in blocks than in matrix because the blocks survive the drilling process, whereas the weak matrix generally does not (Riedmüller et al., 2001). Good core recovery has been reported by using triple-tube core barrels (Roadifer et al., 2009), and the Integral Method (Rocha, 1971). Downhole optical and geophysical techniques (such as borehole televiewers) provide rock mass information of the walls of the drilled holes, and are particularly useful when core recovery is poor. The lengths of blocks in cores, core photographs, or televiewer records should be measured to estimate the linear proportion of blocks versus matrix, and to approximately indicate the range of possible block sizes. Because the matrix of mélanges is prone to slake quickly, it is prudent to promptly protect selected specimens in wax or else protect them within shrink-wrapped plastic film (Waeber, 2008).

It would seem that geophysical methods could be useful in estimating the presence and geometry of blocks in bimrocks. However, although successful in discriminating density contrasts, geophysical methods in mélanges are hampered by the myriad of smaller blocks that mask the geophysical response of the larger target blocks.

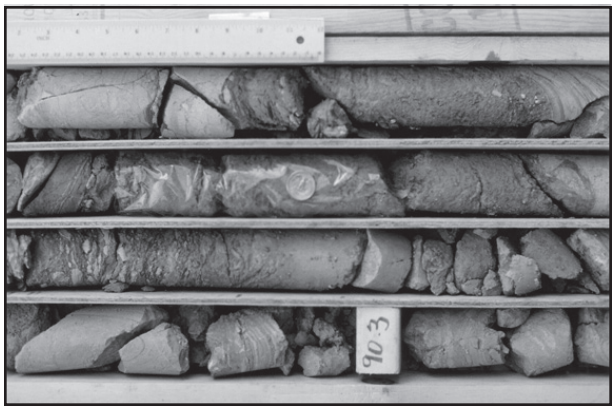

Figure 4. Typical Franciscan mélange recovered in drilled core. Blocks (light gray) interspersed by weak, sheared matrix. Core from exploration boring BH 103, for Richmond Transport Tunnel, San Francisco, California. Photo: E. Medley.

TABLE 1. GEOPRACTICE CONSIDERATIONS WHEN WORKING WITH MÉLANGES AND OTHER BIMROCKS

Characterization	Design/analysis	Construction
Common to all civil engineering works		
Identify unusual lithologies	Decide soil engineering, rock engineering, or bimrock approaches on basis of volumetric block proportions	Anticipate possible considerable differences between site conditions as characterized and conditions encountered in construction
Drill rock core using triple tube samplers; shrink wrap core	Evaluate potential destabilizing effects of large blocks, block and matrix discontinuity fabrics, shears, block orientations, and shapes	Review equipment limitations and handling of oversize blocks, fragmentation, rippability, and excavatability of very hard blocks
Measure block linear proportions from core and mapping scan lines	Evaluate variable groundwater conditions in blocks and matrix	Plan for possible unexpected large pressurized groundwater flows when blocks are penetrated
Beware of optimistic cross sections	Predict long-term performance of rock mass	
Perform triaxial strength testing at differing block proportions	Evaluate how block proportions, size distributions, lithology, and individual block and matrix strengths affect construction method and performance	
Slopes, excavations, and dams		
Perform direct shear tests on discontinuities and/or matrix	Assess destabilizing effect of stress and groundwater concentrations	Monitor short-term stability of excavated rock with abruptly variable shear fabric
Map critical failure surfaces	Analyze stabilizing/destabilizing effects of block orientations	Consider leaving large blocks to protrude at grade or incorporate block stick-ups into the work
	Anticipate through-going shears in matrix and/or blocks	Monitor potential for block fallouts
Tunnels, pipelines, and underground spaces		
Anticipate that observed ground conditions may provide little basis for accurate subsurface profiles and geological characterization along tunnel alignments	Analyze stress and groundwater effects of encountering unexpected large blocks	Select equipment and construction procedures flexible enough to accommodate possible extreme mixed-face conditions
	Analyze effect of short stand-up times, squeezing ground in weak matrix	Develop procedures for penetrating large, extremely hard blocks, and handling many intact, small blocks
	Develop detailed geotechnical observation method protocol	Perform detailed face mapping and real-time analysis of ground deformation data

A common error made by geopractitioners is to map outcrops and draw cross sections (Fig. 5) of mélanges as continuous strata because of the interlayered appearance of blocks and matrix in drill core (Fig. 4). Boring logs in mélanges may include misleading expressions such as "interbedded shales and sandstones," which implies stratal continuity that does not exist. But blocks may include coherent turbidite or sandstone-shale sequences; for such cases, block boundaries can be discriminated because the shale layers in intact sandstone-siltstone-shales will not contain tiny blocks, whereas sheared matrix will. The upper and lower limits of fragment-free sections of shale-siltstone are the boundaries of intact blocks of actual interlayered rocks.

Relatively undisturbed samples can be tested in a geotechnical laboratory to evaluate the density and moisture content of the rock, and depending on the scale of interest, multistage triaxial tests (Bro, 1996, 1997). Ideally, consolidated undrained tests with pore pressure measurements will measure the strength of specimens with various volumetric block proportions (Lindquist, 1994a) as a necessary step in estimating the overall strength of the rock mass as explained further below. Unconfined compression tests are not recommended for mélanges where significant shears exist prior to testing, as these may prejudice the test results. Direct shear testing may be performed to measure the strength of selected discontinuities in blocks or, if the specimen is robust, in matrix.

SIGNIFICANCE OF BLOCK SIZES IN MÉLANGES

Geological terms for rock fragments that suggest size, such as *boulders,* are generally taken to be larger than about 0.3 m in size, with no apparent upper size limit. Such terms should not be used to describe the rock inclusions in mélanges: The neutral word *block* is preferred. However, it is misleading to refer to block "sizes" or block "diameters" on the basis of drill-core- or outcrop-observed dimensions, because, as a matter of geometrical probability (Fig. 6), block measurements from field mapping or drilling are chords that are almost always shorter than the true "diameter" of a block. (A chord is a line with end points on a curve.) In one dimension, d_{mod} (the *m*aximum *o*bserved *d*imension—Fig. 6) is the chord length formed by the intersection of blocks with sampling lines traversing outcrops (scan lines of Priest, 1993), or linear drill core (Figs. 6 and 7).

Franciscan mélanges are self-similar, or scale-independent, having the same general appearances regardless of scale, with a few large blocks and an increasing number of smaller blocks (Cowan, 1985; Medley, 1994a; Medley and Lindquist, 1995). Scale independence has also been observed at a large exposure of an Italian olistostrome (Coli et al., 2008). Figure 8 and its inset are photographs taken at different scales of the same outcrop of Franciscan mélange. Small blocks at one scale of interest (detailed photo in Fig. 8) are part of the matrix at the smaller

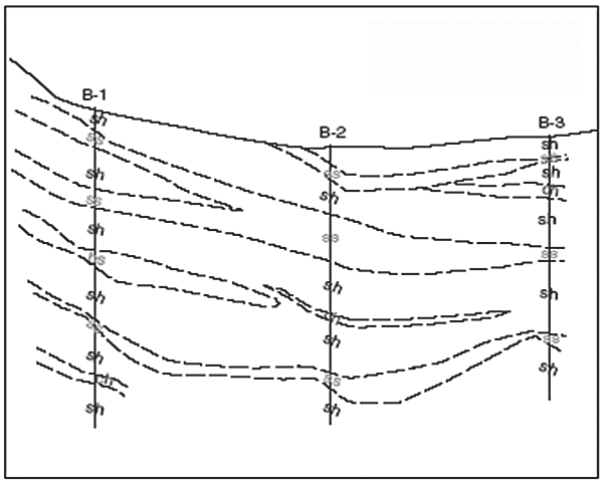

Figure 5. Bimrocks generally cannot be accurately depicted on cross sections. Borehole contacts should be shown with question marks and not connected by lines interpreted to be stratal boundaries, here drawn between borings. After Wakabayashi and Medley (2004).

scale of the main photo in Figure 8. Many other geological mixtures and comminuted rocks, such as fault gouges (Sammis and Biegel, 1989) and fractured rock masses (Nagahama, 1993), also exhibit self-similar block size distributions.

Using geological maps and photographs of outcrop exposures of Franciscan mélanges at many scales, Medley (1994a) measured almost 2000 d_{mod} lengths. The resulting block size distributions were poorly sorted (in soil mechanics terminology, well graded) or fractal (i.e., conforming to negative power laws), with a few large blocks and increasing numbers of smaller blocks, as shown in Figure 9. Log-histograms, as developed by Bagnold and Barndorff-Nielsen (1980), are useful in presenting the measurements because the histogram size classes embrace several orders of magnitude.

In the Franciscan mélanges measured, the range in block sizes exceeds seven orders of magnitude between sand (millimeters) and mountains (tens of kilometers), as illustrated in Figure 10. Despite the considerable difference in scales, the mélanges measured from outcrops and maps shown in Figure 10 indicate individual scale-independent block-size distributions with similar appearances. Consequently, blocks will always be found in Franciscan mélanges regardless of the scale of observation.

DISCRIMINATING BLOCKS FROM MATRIX

A sufficient volumetric proportion of blocks in mélanges provides mechanical advantages to a mélange. Since there is a very large range in block sizes in mélanges, the geotechnically significant blocks must be discriminated from matrix. Because of scale independence, any reasonable dimension can be used to scale a mélange rock mass for the problem at hand to bound the range of significant block sizes. Medley (1994a) called such a descriptive length the characteristic engineering dimension (ced), L_c (the ced of Medley, 1994a), or simply, the characteristic dimension. A characteristic dimension is analogous to showing a measuring tape, coin, hand, or spouse in a photograph, without which reference the observer cannot appreciate the scale of the image. The characteristic dimension changes as scales of interest change. L_c may variously be (1) an indicator of the scale of a site, such as $\sqrt{A}$, where A is the area of the site; (2) the size of the largest mapped or estimated largest block (d_{max}) at the site; (3) the thickness of a failure zone beneath a landslide; (4) a tunnel

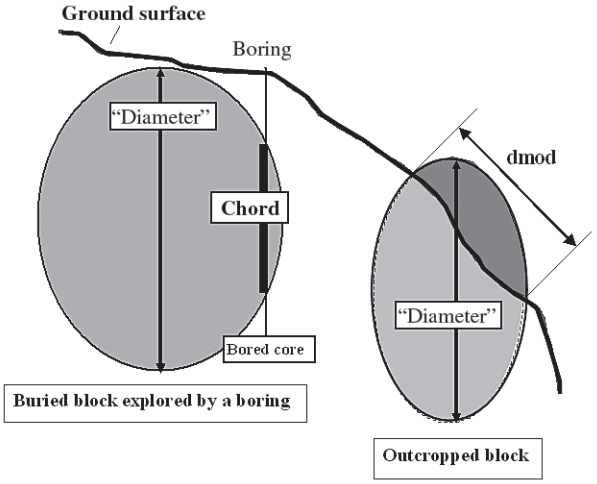

Figure 6. In two dimensions, such as at an outcrop, a block has an apparent block size of d_{mod}, the *m*aximum *o*bserved *d*imension. In one dimension, such as in a drilled boring, the block size is apparently indicated by the chord, the length of interception between the boring and a block. However, only rarely will a d_{mod} or a chord be equivalent to the actual "diameter" or maximum dimension of a block. After Medley (2002).

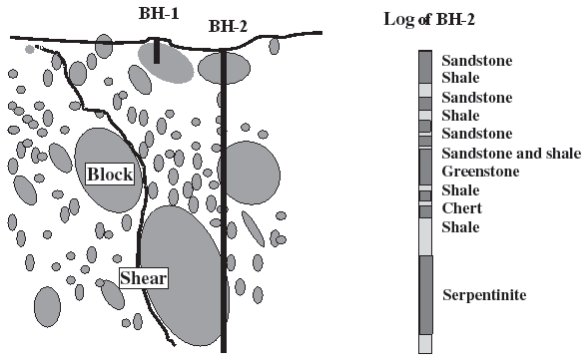

Figure 7. Block-core intersections (chords) rarely indicate true block sizes, or shapes, orientations, and distributions of blocks. Note that shears in the matrix negotiate tortuously around blocks. Sandstone-shale sequence in core is *not* "interbedded shale and sandstone." Improbable juxtaposition of rocks (e.g., greenstone and shale) strongly suggest mélange. After Medley (2002).

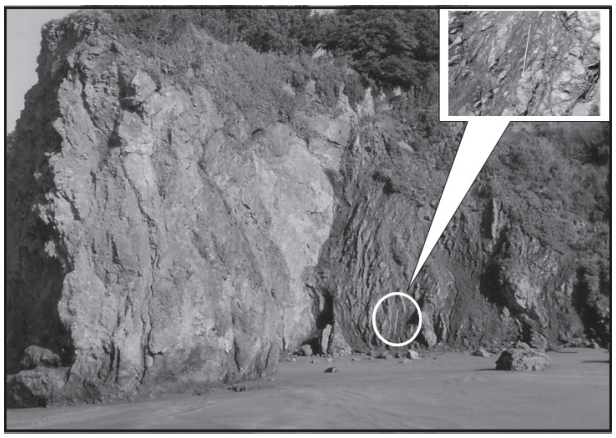

Figure 8. Franciscan Complex mélange, Northern California. Note shearing in shale matrix adjacent to the large headland block, in which smaller blocks are oriented subparallel to shearing. Block sizes range between tens of meters and meters. Detail showing matrix in the circled area also has block-in-matrix fabric at the scale of the 3.1-m-long bar. Photo: E. Medley.

diameter; (5) a foundation width or length; or (6) the dimension of a laboratory specimen.

Scale independence also means that a laboratory scale specimen of mélange is more closely a "model" of the parent rock mass at site scale than is typically encountered in conventional rock engineering. This concept was used by Lindquist (1994) in his pioneering investigation into the strength and deformation properties of mélanges by fabricated physical model mélanges of different volumetric proportions and testing them under multistage triaxial loading to failure.

Medley (1994a) and Medley and Lindquist (1995) showed that the largest geotechnically significant block (d_{max}) within any given volume of Franciscan mélange is ~0.75L_c (Fig. 10). Blocks greater than 0.75Lc result in such a diminished proportion of matrix in a local volume of rock mass that the volume can be considered to be massive, unmixed rock composed mostly of the block. Furthermore, for any given volume of Franciscan mélange, blocks <0.05L_c in size (Fig. 10) constitute greater than 95% of the total number of blocks but contribute <1% to the total volume of mélange and have a negligible effect on the mechanical behavior of the mélange (Medley, 1994a). For these reasons, the threshold size between blocks and matrix at any scale is taken to be 0.05L_c.

In practice, the most conservative block-matrix threshold that can be justified should be selected and used to measure the blocks between these limits. Blocks smaller than 0.05 L_c at one scale (e.g., 1:1000) must be assigned to matrix at a smaller scale (say, 1:10,000), although they may still be of substantial size. If the scale of interest becomes larger, blocks previously demoted into matrix are then promoted to geotechnically significant blocks and must be included in the characterization. Also, large blocks at one scale of interest (e.g., 1:10,000) are not geotechnically significant at a larger scale (e.g., 1:1000) because they are then massive, unmixed blocky rock masses that can be characterized according to conventional rock engineering practice.

MECHANICAL PROPERTIES OF MÉLANGES

The matrix of Franciscan mélanges is most commonly composed of sheared shale, argillite, siltstone, serpentinite, or sandstone, commonly weakened to the consistency of soil. Intact portions of these lithologies may be competent enough to be blocks. Very weak matrix and the most intense shearing within mélanges may be found in block-poor zones adjacent to blocks exceeding tens of meters in largest dimensions. Indeed, Savina (1982) measured up to 800 shears per meter in a Franciscan mélange. Because of highly sheared matrix, landslides are common in block-poor Franciscan mélanges (Medley and Sanz, 2004), although large blocks appear to add buttress support (Fig. 3).

The weakest elements in mélanges are commonly the contacts between blocks and matrix (Fig. 11). In some bimrocks, such as welded tuffs, the contacts may be strong (Sönmez et al., 2004). In outcrops and core, contacts may be marked by a lustrous surface on the blocks and a wafer of sheared material that weathers to a slick film of clay. Matrix shears generally pass around blocks via the block-matrix contacts (Figs. 7 and 11) with

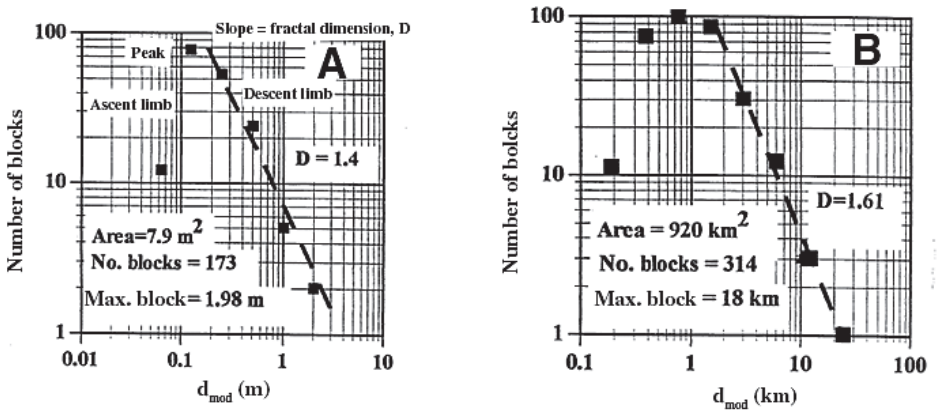

Figure 9. Left plot is a log-histogram of d_{mod}s measured from the outcrop of Franciscan mélange shown in Figure 8. The right plot is a log histogram of d_{mod}s of blocks measured from a map of Franciscan Complex in Marin County, California (Ellen and Wentworth, 1995). The slopes of the log-log plots are the fractal dimension D. The shapes of the two plots are similar despite the extreme difference in scales. After Medley (1994a).

the most intense shearing commonly present adjacent to the largest blocks. Blocks within the shears are commonly entrained within and oriented subparallel to shears (Fig. 8). Because shears have a tortuous path through the rock mass, the overall orientation of entrained blocks can also abruptly change from place to place within the rock mass.

Relatively modest block-matrix mechanical contrast is necessary for a block-in-matrix rock mass to be considered a bimrock. For physical models of mélange, Lindquist (1994) selected a criterion based on the ratio between block stiffness (E, Young's modulus) and matrix stiffness to generate triaxially induced shears along block-matrix contacts:

$$(E_{block}/E_{matrix})\sim 2.0.$$

Sufficient contrast between block and matrix to deflect failure surfaces can be evaluated by a friction angle ratio suggested by Medley (1994a) based on work by Lindquist (1994a), Lindquist and Goodman (1994), and Volpe et al. (1991):

$$(\tan\phi_{weakest\ block})/(\tan\phi_{matrix})>1.5–2.0.$$

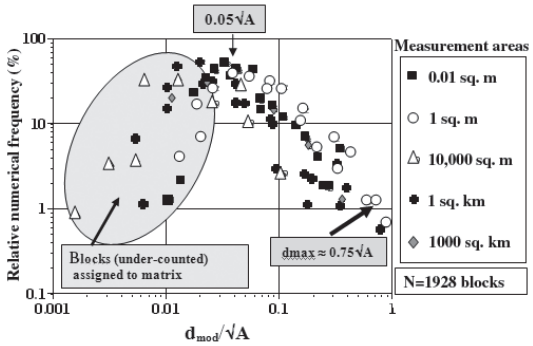

Figure 10. Normalized block-size distribution curves for 1928 blocks measured from outcrops and geological maps of several Franciscan mélanges ranging over seven orders of magnitude in scale. The sizes of blocks are indicated by d_{mod}, the maximum observed dimension of the blocks in the outcrops and maps. The block sizes are divided by the square root of the area ($\sqrt{A}$) containing the measured blocks to yield dimensionless $d_{mod}/\sqrt{A}$. The dimensionless relative frequency for each plot is the number of blocks in any size class divided by the total number of blocks measured for the various data sources. The clustered normalized plots are similar in shape, indicating that the block size distributions are scale independent. The plots peak at ~$0.05d_{mod}/\sqrt{A}$, which is the block-matrix threshold size at any scale. Blocks smaller than $0.05d_{mod}/\sqrt{A}$ are assigned to the matrix; they tend to be too small to measure and are undercounted. The largest indicated block size is approximately equivalent to $\sqrt{A}$ (at $d_{mod}/\sqrt{A} = 1$), but 99% of the blocks are smaller than ~$0.75\sqrt{A}$, which is defined as the maximum block size (or d_{max}) at any scale. After Medley (1994).

However, rock strength is a function of both friction angle and cohesion, and the block-matrix contrast will also be influenced by both strength components. Accordingly, as recommended by Prof. Harun Sönmez (2009, personal commun.) the unconfined compressive strengths (UCS) of blocks and matrix could be used to define a strength-based block-matrix contrast criterion: assuming that reliable UCS tests can be performed on weak matrix,

$$UCS_{block}/UCS_{matrix} >1.5.$$

For strength ratios or stiffness ratios less than the lower bounds described above, there will be an increased tendency for shears and failure surfaces to pass through blocks rather than around them.

The overall strength of a mélange is directly related to the volumetric proportions of the blocks and is largely independent of the strength of the blocks (Lindquist, 1994a). The dependence on volumetric proportion to overall strength is an apparent fundamental property of bimrocks, as indicated by Savely (1990) for the boulder-rich Gila Conglomerate in Arizona; and by Irfan and Tang (1993) for boulder-rich colluvium in Hong Kong. A sufficient block volumetric proportion and range of block sizes can contribute to strength, because failure surfaces are forced tortuously to negotiate around blocks, thus increasing passive resistance to shear failures (Lindquist, 1994a; Medley, 2004; Sönmez, et al., 2006a, 2006b). Where blocks are uniformly sized, failure surfaces tend to have smoother, undulating profiles (figure 4.4 of Medley, 1994a; Medley, 2004), and hence the mixed rock mass has less shear resistance, and a lower overall strength. But there is a dependence on the normal stresses to which the mélange rock mass is subjected: At sufficiently high normal stresses, failure surfaces will penetrate blocks regardless of the mechanical contrast between matrix and blocks. Inherent defects in the blocks will aggravate the effect.

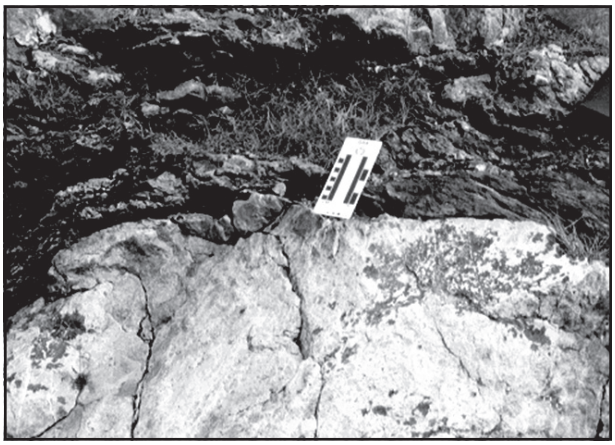

Figure 11. The weakest element in a bimrock is commonly the block-matrix contact. Gwna mélange, Anglesey, Wales. Photo: E. Medley.

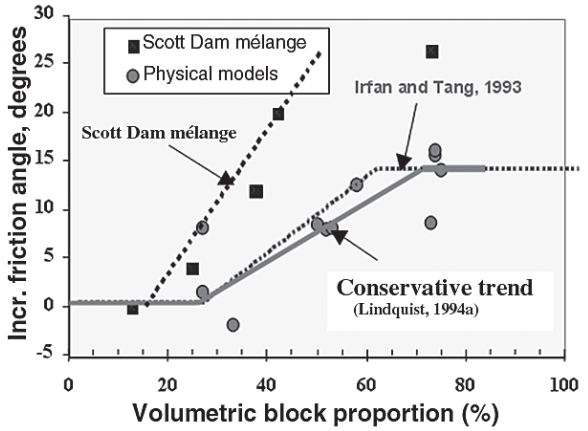

Figure 12. This plot shows that strength of bimrocks increases with volumetric block proportion. The increase is added to the strength of the matrix. After Medley (2001), from data of Lindquist (1994a) and Irfan and Tang (1993).

As shown in Figure 12, Lindquist (1994a) conservatively established that <~25% volumetric block proportion the frictional strength and deformation properties of a physical model mélange was that of the matrix, a conclusion supported by the research of Irfan and Tang (1993). However, Goodman and Ahlgren (2000) and Roadifer et al. (2009) identified increases to overall mélange strength at volumetric block proportions <~25%.

Lindquist (1994a) also showed that between ~25% and 75%, the friction angle and modulus of deformation of a physical model mélange proportionally increased, depending on the relative orientation of blocks to applied stresses; and cohesion generally decreased because of increasing weak block-matrix contacts. Cohesion has also been noted to increase with increasing volumetric block proportions in mélanges (Goodman and Ahlgren, 2000; Roadifer et al., 2009) and volcanic agglomerates (Sönmez et al., 2006b), possibly owing to block-matrix contact strengths being greater than matrix strengths for the materials evaluated.

Beyond ~75% block proportion, Lindquist (1994a) showed there was no further increase in bimrock strength, as blocks tended to be in contact, and the rock mass approached the condition of being a jointed rock mass with infilled joints.

Franciscan complex mélanges have been assigned strength parameters varying between a block-poor mélange in a landslide: c′ (effective cohesion) of 9.6 kPa to 14.8 kPa (100–200 pounds per square foot [psf]), and ϕ′ (effective friction angle) of 25°–35° (Kim et al., 2004); for a block-rich mélange below Scott Dam: c′ of 76 kPa (1590 psf), and ϕ′ of 39° (Goodman and Ahlgren, 2000); and for mélange below Calaveras Dam: c′ of 6.9 kPa to 39.9 kPa (1000–5740 psf), and ϕ′ of 25°–45° (Roadifer et al., 2009). Sheared matrix in Franciscan mélange can be extremely weak, with low to zero cohesion and effective friction angles of <10°.

Based on the findings summarized above, it is apparent that if geopractitioners follow soil mechanics convention and assume that the mechanical behavior is adequately represented by solely the properties of the weak matrix materials, any mechanical advantage afforded by blocks will be discounted, hence penalizing the rock mass strength. Furthermore, ignoring blocks during characterization increases the risk that they will be neglected during design, only to be rediscovered later by the earthwork or tunneling contractor, with expensive consequences. Because evaluation of the strength of mélanges is not straightforward, the procedural steps of Table 2 may be helpful.

ESTIMATING VOLUMETRIC BLOCK PROPORTIONS

The direct and relatively simple relationship between strength and volumetric block proportions for mélanges and other bimrocks is appealing to geopractitioners. Nevertheless, to

TABLE 2. FLOWCHART OF STEPS TO CHARACTERIZE MÉLANGE STRENGTH

Step 1: Check block-matrix strength contrast using estimates of weakest block and matrix mechanical parameters and following criteria: $\tan\phi_{block}/\tan\phi_{matrix} \geq 1.5–2.0$ $E_{block}/E_{matrix} \geq 2.0$ $UCS_{block}/UCS_{matrix} \geq 1.5$
Step 2: Select characteristic dimension L_c at scale of engineering interest; e.g.: height of landslide, width of tunnel face; length of foundation, diameter of laboratory specimen, etc.
Step 3: Calculate block size thresholds: $d_{min}=0.05*L_c$ (block-matrix threshold) $d_{max}=0.75*L_c$ (block–blocky rock mass threshold)
Step 4: Drill and core exploration length of (preferably) $\geq 10*d_{max}$
Step 5: Measure total linear block proportion L_L
Step 6: Assume L_L is equivalent to volumetric block proportion V_v and estimate uncertainty range in estimate of V_v (use Fig. 14)
Step 7: Establish conservative design values of volumetric block proportion, using lower bound for strength and upper bound for earthwork construction
Step 8: Measure lab strengths of specimens with different V_v proportions and construct a plot of specimen strength vs. V_v (such as Fig. 12 or Fig. 18)
Step 9: On plot of specimen strength vs. V_v identify critical volumetric block proportions and following three regions: Lower bound strength controls if V_v <15%–25%, use soils or rock engineering analyses Variable strength controls if 15%–25%<V_v<65%–75%, use strength from plot and rock engineering analyses Upper bound strength controls if V_v >65%–75%, use rock engineering analyses

evaluate the mechanical properties of a bimrock the volumetric block proportion must be estimated, which may not be a simple matter. The volume of blocks in laboratory specimens can be measured by disaggregation, or estimated from specimen densities, if the individual densities of block and matrix materials are known (Lindquist, 1994a).

Although the laboratory method does not work at site scales, stereological techniques do. Stereology relates point, linear, and planar observations to volumetric properties and is based on the original work of the mineralogist Rosiwal (1898), who evaluated the mineral content of rock specimens using microscope traverses of thin section slides. A fundamental principle of stereology is that, given enough sampling, linear block proportions and areal block proportions are equivalent to volumetric block proportions (Ross, 1986; Underwood, 1970; Weibel, 1980; Medley, 1994a). Linear block proportions are the ratios of the total lengths of blocks intersected by sample lines to the total length of the sample lines, and depending on the scale of interest, these can be estimated from scan-line measurements at outcrops, measured from drilled cores (Medley, 1994a, 1994b), or from laboratory specimens (Medley, 1994a, 1994b). The areal block proportions can also be measured from outcrops, geological maps, or air photos, using image analysis (Medley, 1994a, 1994b; Coli et al., 2008).

As indicated in Table 2, a characteristic dimension (L_c) is selected that describes the scale of the problem at hand (Medley, 1994a, 2004), and the block-matrix threshold selected as $0.05L_c$. During mapping, the d_{mod} of the blocks are measured. When logging core, all block-core intersections (chords) greater than $0.05L_c$ are measured. But in practice, block lengths greater than ~5 cm long could be measured, even if the block-matrix threshold is larger, as this information will be useful for work performed at laboratory scale, where $0.05L_c$ is 5% of typical 100-mm-diameter core specimens.

Blocks in mélanges are not uniformly sized or distributed, so the volumetric block proportion cannot be accurately determined from a few borings. Also the assumption that measured areal or linear block proportions are equivalent to the required volumetric block proportions is only valid if the sampling size is large. However, if the total length of drilling or other liner sampling of at least $10d_{max}$ is performed, the linear block proportion reasonably approaches the volumetric block proportion (Medley, 1994a, 1997). But in geopractice exploration, the desirable optimum total length of exploration drilling is frequently not performed because of the expense of drilling, which in mélanges can be higher owing to the troublesome effort required to secure good quality cores from mechanically variable rock.

Medley (1997) investigated the potential error in estimates of volumetric block proportion based on the assumption that they are the same as the measured linear block proportions. Four physical models of mélange were fabricated with known block size distributions and volumetric block proportions. The models were explored with hundreds of model boreholes. The extreme variability in linear proportions, even for adjacent borings, is indicated by Figure 13. Based on thousands of randomized realizations of the model boring data, Medley (1997, 2002) concluded that potentially serious errors result if volumetric block proportions, total block volumes, and block size distributions are assumed, without qualification, to be equivalent to the linear block proportions measured from few borings or outcrops.

Medley's (1997) experiments showed that measured linear block proportions have to be adjusted by an uncertainty factor (actually, the coefficient of variation) to yield an appropriate estimate of the volumetric block proportion (Fig. 14). Uncertainty depends on both the total length of the linear measurements, such as from drilled core, and the linear block proportion itself. In Figure 14 the total length of drilled core is shown as Nd_{max}, or multiples of the size of the largest expected block, d_{max}, which can be estimated from field exposures or else assumed to be 0.75Lc at site scale.

The volumetric block proportion is within a range between the adjusted lower and upper volumetric block proportions. It is prudent and conservative to apply the uncertainty adjustment downward for the calculated estimates of volumetric block proportions for the purpose of assigning strength parameters for a bimrock. On the other hand, for the purpose of assessments of excavation rippability and construction preparedness in tunneling or earthwork construction, it is prudent and conservative to adjust upward the calculated estimates of volumetric block proportions.

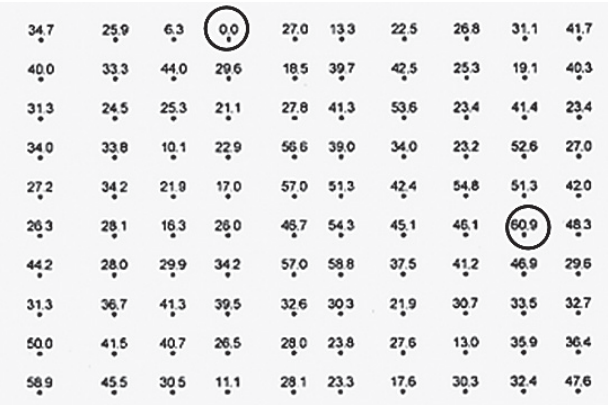

Figure 13. Plan view of an array of 100 linear block proportions ranging between 0% and 61%, measured for a physical model bimrock with an actual volumetric block proportion of 32%. This data representation clearly shows the spatial variability, the extremes being indicated by the circled values. Coincidentally, the average of the extreme values of liner block proportions (30.5%) closely matches the actual volumetric block proportion of 32%. However, other random pairings of data will generally not yield average linear proportions that match the actual volumetric block proportion. Likewise, in geopractice explorations of mélange, it is unlikely that two borings will yield average linear block proportions that match the actual volumetric block proportion of an explored rock mass. After Medley (1997).

ESTIMATING BLOCK SIZE DISTRIBUTIONS

Given the economic ramifications for construction planning, it is of great value to geopractitioners to be able to reasonably estimate the volumes and block size distributions of bimrocks to be excavated or tunneled (Attewell, 1997). Hard blocks in mélanges that are larger than ~0.6 cm in diameter are too large to pass through the apertures of earthmoving scrapers, which are like the gaps in cheese parers and potato peelers. Blocks >~2 m cannot be easily removed by conventional bulldozers. Because blasting is often not permitted during earthwork in urban areas, excavation of large blocks must be performed by fragmenting them with hydraulic rock hammers, resulting in noise, dust, and expensive delays to earthwork grading schedules, although non-explosive chemical demolition agents are available.

As the primary means of obtaining subsurface data is by drilling, it is logical to attempt to estimate block size distributions from chord length distributions. The degree to which 1-D (one dimension) chord length distributions match actual 3-D block size distributions is dependent on the orientation of blocks relative to the boring directions, volumetric block proportion, and total length of drilling. Because observed chord lengths are almost invariably smaller than the actual block diameters (Fig. 15) the frequency of larger block sizes tends to be underestimated, and the frequency of smaller sizes overestimated. Indeed, larger blocks are mischaracterized as smaller blocks to the degree that small block sizes are indicated that may not even be part of the actual 3-D block size distribution (Fig. 15). Estimates of 3-D block size distributions from measurements of 2-D outcrop areas also yield widely erroneous estimates (Haneberg, 2004).

It is thus unlikely that drilling and coring into a mélange rock mass will yield actual 3-D block size distributions, so estimating 3-D block size distributions should be attempted with great caution, or better yet, not at all. The practical consequence of underestimating block sizes from exploration drilling is that unpleasant and costly surprises may occur during excavation and tunneling of bimrocks.

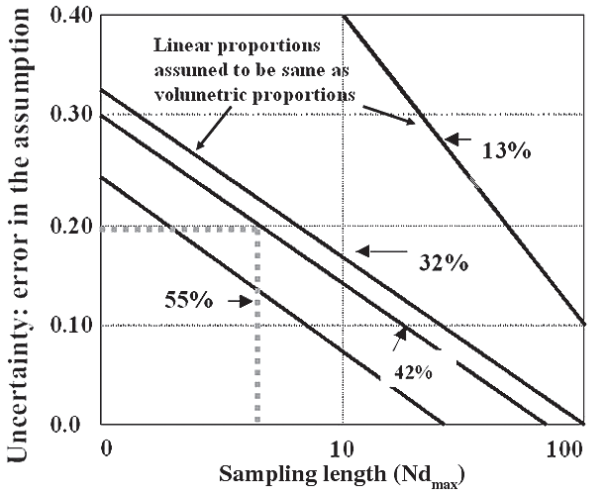

Figure 14. This plot provides the uncertainty in assuming that measured linear block proportions (13% to 55%) are assumed to represent volumetric block proportion. Uncertainty (coefficient of variation) in estimates of volumetric block proportions are a function of the total length of linear measurement, expressed as multiples (N) of the length of the largest block (d_{max}). The dashed line shows an example for Scott Dam, California, where the total length of drilling performed was equivalent to ~5 times the size of the largest block; i.e., Nd_{max} was ~5. Based on the drilling, the linear block proportion was ~40%. When assumed to represent the actual volumetric block proportion, there was an uncertainty of 0.2. Hence the adjusted volumetric block proportion was 40% – (0.2*40%), or 32%. After Medley (1997).

CONSTRUCTION IN MÉLANGES

The size and volumetric proportion of hard blocks, and their individual lithology, strength, and discontinuity fabrics, are critical considerations in the selection of the appropriate method of excavation and the equipment required to safely perform the excavation of weaker matrix material and stronger, commonly very large blocks. Large blocks (greater than tens of meters in size) indicate the possibility of generally weaker sheared matrix adjacent to the block and potentially dangerous ground conditions.

Stress distributions in mélanges influence the construction behavior and long-term performance of dam and structure foundations, slopes (Medley and Sanz, 2004), and underground excavations (Button et al., 2003; Moritz et al., 2004; Riedmüller and Schubert, 2002). Stress states depend on the in situ stress and lithologies; size distributions, orientations, and shapes of blocks;

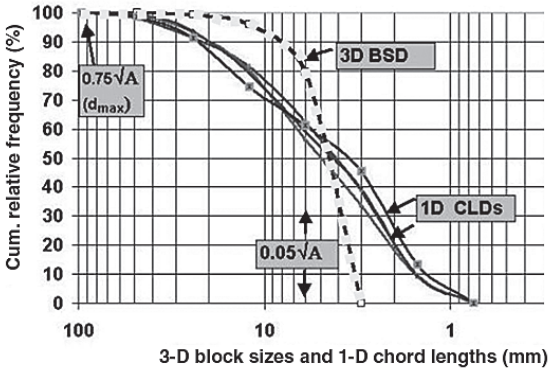

Figure 15. Comparison of true 3-D block size distribution (3D BSD) used in the fabrication of each of four physical model bimrocks. The 1-D chord length distributions (CLDs) were generated from measuring all chord lengths in 100 model borings generated for each model. Despite the 400 borings, the 1-D distributions do not mimic the actual 3-D distribution. Instead, small blocks are indicated that were not incorporated into the actual models, and the proportions of larger block sizes are underestimated. After Medley (2002).

orientations of matrix shears and groundwater; and the geometry and type of construction. High stresses may be transferred into the sheared matrix surrounding unexpected large blocks as tunnels or excavations under construction approach the blocks. Such rearranged ground stresses, in combination with high in situ tectonic stresses, and/or from topographic effects, may yield problematic to disastrous "squeezing ground" conditions during tunnel excavation (Hoek, 2001; Button et al., 2003).

A site evaluation must consider the general hydrogeologic setting and the potential for variable water flow or artesian pressures during and after construction, as groundwater has an important impact on the stress conditions as well as the mechanical properties. Haneberg (1995) demonstrated that in heterogeneous colluvium, variations in the permeability of matrix and blocks perturb fluid flow and influence local factors of safety in mélanges and fault rocks. Unexpected inflows of groundwater may also discharge from large fractured blocks, or stress imbalances may arise from pore water pressure variations around large blocks.

In mélanges, the permeabilities may also differ by orders of magnitude over short distances, because intact blocks, fractured blocks, intact matrix, and sheared matrix may have widely varied individual permeabilities. The impact of abrupt changes in permeability, as well as the potential for preferential flow, needs to be considered in the design and may impact construction. The installation of piezometers prior to construction will help evaluate the local hydrogeologic regime. However, the common construction practice of using drilled sub-horizontal drains to lower water levels in mélange rock masses at landslides is only erratically successful. Relatively impermeable matrix drains slowly. Fractured and relatively permeable blocks penetrated by drains may gush water for a while, providing an illusion of success, but discharge often diminishes with time as the blocks empty.

GEOTECHNICAL OBSERVATIONAL METHOD

The confirmation of design assumptions during construction is important, but based on the generally limited investigations and characterizations of mélanges normally performed, the geopractitioner may be unable to predict the performance of the work during construction. Hence adherence to the geotechnical observational method (Peck, 1969) is essential. This method requires that all possible modes of failure are anticipated and observations and measurements in the field are used to identify critical, potentially unforeseen, conditions. Different rock mass strengths may be assigned for the different failure modes. For example, in an excavation, there may be potential for large-scale slope failures through the bimrock; or else the detachment of a critically oriented block along adversely oriented matrix shears could cause significant damage. Estimates are then made of the likely progression of ground movements as the various failure mechanisms develop, as ground failures are rarely instantaneous. Once failure modes and scenarios are conceived, action criteria based on critical thresholds of ground movement are established, rock mass and groundwater monitoring programs developed, and consequent remediation procedures prepared. During construction, ground deformations are monitored and ideally analyzed in real time (Moritz et al., 2004). If ground movements approach action thresholds, the construction remediation procedures are implemented to deter the failures.

CASE HISTORIES

The following four case histories are summaries of experience in geoengineering practice that illustrate many of the points made in this chapter.

Case History 1: Mischaracterization of a Landslide

As described by Medley and Sanz (2004), there are many factors that should be considered when characterizing and analyzing the slope stability of mélanges and other bimrocks. However, the most fundamental consideration is the recognition that a rock mass is a bimrock. The consequences of nonrecognition can be expensive, as described here.

Hillside repairs were proposed to mitigate landslides that intermittently disrupted a main road in California. Based on borings terminated ~2 m into apparent sandstone bedrock, the investigating geopractitioner concluded that each of the landslides was composed of a shallow layer of clay and boulder colluvium sliding on the surface of underlying sandstone bedrock (Fig. 16). He recommended that the most economical repair would be removal of the failed soil down to the solid bedrock and re-grading of the failed slopes. The successful contractor bid for the designed repairs of the several landslides for a fixed price of more than a million dollars.

During construction of the first landslide repair, the earthwork contractor encountered pervasively sheared shale containing abundant rock blocks up to several meters in size, which required considerable effort to remove, as blasting was not permitted. Neither solid bedrock, nor even a definite landslide "failure surface" between the landslide and the bedrock was observed; instead there were countless shear surfaces. In an attempt to find continuous bedrock, the excavation was deepened to several tens of meters below the design depth of a few meters. The project was halted when the repair for this first landslide repair had cost almost all the total contract amount set aside for repair of all the landslides.

The landslide was actually a deep-seated earth flow in pervasively sheared mélange rather than a shallow soil mass sliding on top of apparent bedrock, as interpreted from exploration drilling. The interpreted bedrock was the graphical artifact of connecting straight lines between the soil-rock contacts intersected by the borings (Figs. 5 and 16). Although the geological chaos was a surprise to the geotechnical engineer, it should not have been, as publically available geological maps showed the locale of the landslide to be within Franciscan mélange, with large blocks protruding prominently from the hillside around the site.

Case History 2: Estimate of Volumetric Block Proportion in an Excavation

The Lone Tree Slide was a major landslide in Franciscan mélange that blocked California State Highway 1 near San Francisco (Van Velsor and Walkinshaw, 1993). To stabilize the slope, 950,000 m^3 of intact and failed mélange were excavated to an average depth of 37 m. The drilled exploration of the landslide intersected a maximum block chord length of ~8 m. Based on the percentage length of drilled chords through blocks, the project geopractitioners estimated that 5% of the total volume to be excavated would be blocks large enough to be troublesome to excavate and thus eligible for extra compensation as rock. However, the sizes and proportion of the hard, large blocks encountered during excavation were far greater than had been anticipated during design and caused delays and unanticipated expense (Van Velsor and Walkinshaw, 1993).

To develop approaches useful for future construction projects, Medley (1994a, 1994b) logged the drilled core and mapped the slopes of the excavation at Lone Tree Slide. The characteristic engineering dimension (L_c) for the landslide was assumed to be the average thickness of the original slide, some 30 m. The block-matrix threshold was selected as 1.5 m ($0.05L_c$). Several large blocks protruded from the undisturbed hillside adjacent to the landslide the exposed parts of which suggested that the intact blocks were at least 30 m or more in size (Medley, 1994a). Accordingly, the size of the largest block (d_{max}) was assumed to be ~30 m.

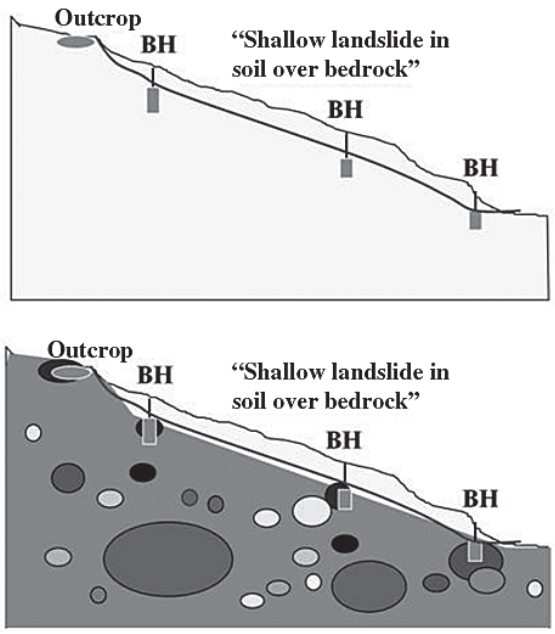

Figure 16. The upper sketch shows a geopractitioner's landslide characterization based on shallow borings and an observed outcrop: a shallow soil landslide sliding on an assumed underlying continuous bedrock surface. The lower sketch shows the actual bedrock conditions in which the four borings intersected discrete blocks in a mélange composed of sheared shale matrix and blocks of various dimensions and lithologies. After Medley (2001). BH—borehole.

About 375 m of drilled core from the landslide exploration was reviewed. Block/core chords were measured between 1.0 m and up to 7.9 m in length. The linear block proportion for all the mélange explored was ~10%, which was the weighted average of block-poor mélange within the landslide (about zero percent) and block-rich mélange beneath the slide (28%). The 375 m total length of drilling was equivalent in length to $12.5d_{max}$ (where d_{max} was 30 m). Figure 14 indicates the uncertainty to be at least 0.40 for a measured linear block proportion of 10%, total drilling of 375 m equivalent to 12.5 times the length of the estimated d_{max} of 30 m (i.e., Nd_{max} of 12.5), and the assumption that the measured linear block proportion of 10% was equivalent to a volumetric block proportion of 10%. Hence the estimated range of volumetric block proportions ranged between 6% and 14% (10% ± 0.4 times 10%). In a similar situation, for excavation purposes a conservative geopractitioner should adopt the higher bound (in this case, 14%). For an estimate of volumetric block proportion for evaluating the overall rock mass strength, the 6% lower bound was too low to improve the geomechanical properties of the rock mass.

Nevertheless, if it had been available at the time, the higher bound estimate of block proportion would have been useful for construction cost purposes. According to the contractor, after the excavation work was completed, the volumetric proportion of excavated blocks was estimated to be between 6% and 11%, which was greater than the original design estimate of 5% but closer to the conservative post-project estimate of 14%. If the estimation had been performed prior to excavation instead of afterward, a suggested range of between 5% and 15% would have been reasonable for estimating the volumetric block proportion as the basis for pre-construction cost estimates to excavate and remove blocks.

Case History 3: Estimate of the Strength of a Mélange Underlying a Dam

This case history outlines the approach adopted to characterize the bedrock underlying Scott Dam, which impounds the Eel River at Lake Pillsbury, 160 km north of San Francisco. Built in the 1920s, the dam is a masonry gravity structure ~40 m high. The dam is underlain by a Franciscan mélange (Goodman and Ahlgren, 2000; Hovland et al., 2000).

In the 1970s conventional geotechnical analysis indicated that if the strength of the mélange under the dam was the same as the strength of the weak, sheared shale matrix (the then-conventional assumption), the foundation rock would be too weak to resist lateral sliding and the dam would fail by sliding mode along the base contact with mélange. But the dam was still intact more than 50 years after it was built, so the mélange bedrock was clearly stronger, possibly due to the presence of blocks

in the sheared shale, as suggested by Volpe et al. (1991). A re-characterization of the Franciscan mélange and a reevaluation of the foundation strength was commissioned by the dam owner, an investigation which funded the Ph.D. research of Medley (1994a) and Lindquist (1994a).

Characterization required selection of the block-matrix threshold, which in turn required selection of L_c, the characteristic dimension scaling the problem at hand. In general, flexibility is inherent in the selection of L_c for dam foundations. The dam width, dam height, square root of the area ($\sqrt{A}$) of the dam footprint, or thickness of a critical failure zone could all have been used for L_c. But the likely critical mode of failure was considered to be basal sliding at the contact between Scott Dam and the Franciscan mélange foundation rock. Accordingly, L_c was selected as a postulated 3 m thickness of a basal failure shear zone within the mélange rock at the base of the dam.

As described above, geotechnically significant blocks that influence bimrock strength range between ~$0.05L_c$ at the block-matrix threshold, and 0.75 L_c, for the largest block, d_{max}. For the Scott Dam project, the block-matrix threshold was selected as 0.15 m, or 5% of the postulated 3-m-thick basal shear zone. This criterion was used to discriminate blocks from matrix when reviewing drill core and drill logs. Measurement of block chord lengths in drill logs and photographs (Fig. 17) of Scott Dam core in the assumed critical potential failure zone indicated that the linear block proportion was ~40% for the postulated critical 3-m-thick shear band of failed mélange below the dam.

The total length of exploration core required to yield a reasonably accurate estimate of a volumetric block proportion from drilling should be at least 10 times the size of the expected largest block d_{max}, or $10d_{max}$. At Scott Dam, based on field observations and drilling, the size of the largest block was estimated to be between 30 and 43 m (Medley, 1997), so greater than 300 to 430 m of drilling would have been preferable. In actuality, only ~150 m of core (representing at least $5d_{max}$) was recovered from the several extensive exploration campaigns performed since the 1970s.

Because there were insufficient data, the estimated volumetric block proportion had to be adjusted for uncertainty. As shown in Figure 14, using the procedure described by Medley (1997) the estimated linear block proportion was 40%, the uncertainty was 0.2, and the adjusted estimate was 32% to 48% (40% ± 0.2 times 40%). For purposes of strength estimates, it is prudent to use the lower bound, so a conservatively adjusted volumetric block proportion of 32% was selected for the volumetric block proportion of the Franciscan mélange below the dam. The estimate was subsequently lowered to 31% on the basis of additional exploration drilling (Goodman and Ahlgren, 2000).

Because of scale independence, mélange and other bimrocks at the scale of laboratory specimens are closer to being scale models of the parent rock masses than is generally true in geotechnical engineering. Laboratory specimens of Franciscan mélange from the dam foundation (Goodman and Ahlgren, 2000) were tested using multistage triaxial compression tests such as those described by Lindquist (1994), Lindquist and Goodman (1994), Bro (1996, 1997), and Goodman and Ahlgren (2000). Given that the diameter of the laboratory specimens was the characteristic engineering dimension L_c, blocks in the specimens were those intact inclusions that had maximum dimensions between ~5% and 75% of the specimen diameter. The volumetric block proportions of each specimen were measured after specimen disaggregation and wash-sieving to retrieve the blocks.

Strength testing of Scott Dam laboratory specimens with different block proportions yielded a plot of effective friction angle as a function of volumetric block proportion (Fig. 18). The overall strength of the foundation rock mass was evaluated using

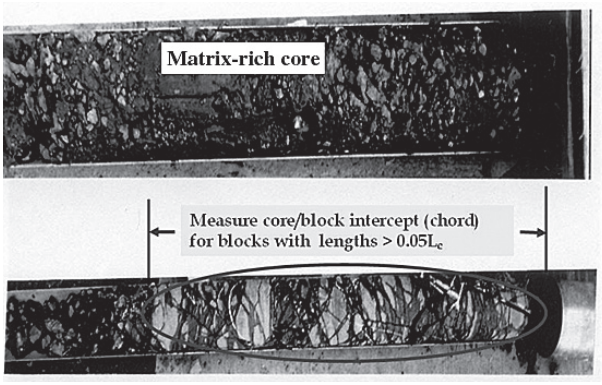

Figure 17. Typical core from an exploration boring at Scott Dam, California, showing matrix of sheared shale containing blocks that were smaller than 0.05 L_c (0.15 m) and assigned to the matrix, and a measurable block. Photo: Richard E. Goodman.

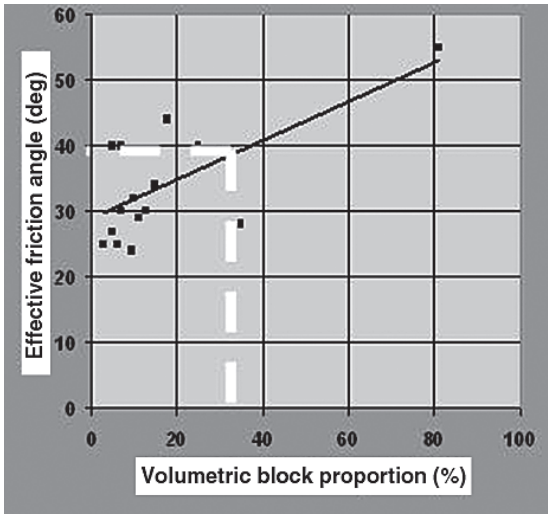

Figure 18. Plot of effective angle of friction (ϕ') as a function of volumetric block proportion, generated from laboratory testing of Franciscan mélange specimens obtained from core drilling at Scott Dam, Northern California. From Medley (2001), after Goodman and Ahlgren (2000).

the adjusted estimate of rock mass volumetric block proportion and the laboratory plot of effective friction angle as a function of volumetric block proportion. For the mélange beneath Scott Dam, the friction angle was estimated to be 39° for the overall 31% volumetric block proportion (Fig. 18).

Additional geotechnical engineering analyses confirmed that the strength of the mélange bimrock at the dam foundation was considerably greater than the strength of the matrix alone. On the basis of the geotechnical characterization and analysis of the mélange, both the California Division of Safety of Dams and the Federal Energy Regulatory Commission agreed that Scott Dam was safe and did not require any of the initially proposed structural reinforcement (Goodman and Ahlgren, 2000; Hovland et al., 2000). Essentially the same procedure described here for Scott Dam was used for the evaluation of the shear strength of Franciscan mélange below Calaveras Dam (Roadifer et al., 2009).

Case History 4: Evaluation of Permeability of a Mélange

In February 2000 a high excavated slope failed at a long-established residential area of Millbrae, California (Snell and Medley, 2008). The slide was largely within Franciscan Complex mélange. Litigation proceedings followed shortly afterward, during which several allegations were made, one being that the San Andreas Lake water-supply reservoir, some 1500 ft from the landslide, had leaked groundwater through the intervening low broad ridge and caused the landslide.

Geological and geotechnical investigations revealed Franciscan mélange within the ridge, consisting of a chaotic mixture of clayey, highly sheared matrix with blocks composed of sandstone, shale, greenstone, and other lithologies. Hydrogeological observations and analyses concluded that the permeability of the mélange ranged between 2.1×10^{-8} and 1.4×10^{-7} cm/s. Detailed hydrogeological analyses showed that the alleged contribution to the landslide of groundwater leaking from the reservoir through the ridge was invalid. Following additional investigations and analyses, it was apparent that other factors had contributed to the landslide. These included long-term degradation of the mélange exposed in the excavated slope, which was aggravated by lack of slope maintenance and the effects of poorly controlled surface drainage.

CONCLUSIONS

Mélanges, fault rocks, weathered rocks, and similar bimrocks are common and problematic for geopractitioners (geotechnical engineers, geological engineers, engineering geologists, and rock engineers) working in geologically complex areas of the world. Hence it is vital that geopractitioners have at least a conceptual understanding of the existence of bimrocks and are able to recognize them, even if they are unfamiliar with the processes of formation and other geological details.

Despite their heterogeneity, mélanges and other bimrocks can be characterized for the purpose of geoengineering design and construction, even where there is great uncertainty in the characterization, or where the volumetric proportion of blocks is too small to provide geomechanical benefit. Simple procedures are available to characterize and analyze mélanges, and implementation of these procedures may reduce expensive surprises by focusing the geopractitioners', owners', and contractors' attentions on the difficulties that may be encountered during design and construction. Accordingly, Society will be better served if geopractitioners working with mélanges learn to expect the unexpected.

We have written this chapter to increase awareness by geologists of the practical problems faced by engineers working (often heroically) with geologically exciting but chaotic mélanges and other troublesome bimrocks. Geologists have much understanding, which, if shared without unnecessary geological jargon, could assist engineers in recognizing mélanges and other geologically complex rocks with a view to improving the simple approaches described here for their characterization, design, and construction. The writers hope that geologists and geopractitioners are more cautious the next time they use the expressions *interbedded* or *soil with boulders* in boring logs or reports, and that they persuade engineers to critically review the cross sections they develop from their field observations of sites in mélanges. Overall, we believe that better geologist-geopractitioner collaboration will reduce the expensive surprises that so often occur in the design and construction of Society's constructed works.

SUGGESTED RESEARCH

We suggest the following avenues of cooperative research between geologists and geopractitioners:

- Understand better the effects of block-matrix contrast strength on the overall mechanical behavior of bimrocks.
- Develop virtual bimrocks using numerical modeling methods to simulate under-controlled conditions of bimrock masses, and investigate geomechanical behaviors of model bimrocks with variations in block-matrix and strength-stiffness contrasts, block shapes and sizes, block size distribution, and spacing. Pan et al. (2008) have made a start on such research.
- Survey how various geological disciplines characterize the complexity of the range of geological mixtures, such as ore bodies within waste rock, fault rocks, and discontinuous contaminated soil and groundwater within pristine geology.
- Develop statistical, geostatistical, and stereological approaches to understanding and predicting the uncertainties of our estimates of rock block volumes, sizes, shapes, orientations, etc., based on the limited drilling and mapping exploration tools available to geologists and geopractitioners.
- 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 et al. (2008) and Roadifer et al. (2009) in Franciscan mélanges.

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REFERENCES CITED

Associazone Geotechnica Italiana (AGI), 1977, Proceedings of the International Symposium on the Geotechnics of Structurally Complex Formations: Capri, Italy, Associazone Geotechnica Italiana.

Attewell, P.B., 1997, Tunnelling and site investigation: Proceedings of the International Conference on Geotechnical Engineering of Hard Soils–Soft Rocks: Rotterdam, A.A. Balkema, v. 3, p. 1767–1790.

Aversa, S., Evangelista, A., Leroueil, S., and Picarelli, L., 1993, Some aspects of the mechanical behaviour of "structured" soils and soft rocks: Proceedings of the International Symposium on Geotechnical Engineering of Hard Soils–Soft Rocks: Rotterdam, A.A. Balkema, v. 1, p. 359–366.

Bagnold, R.A., and Barndorff-Nielsen, O., 1980, The pattern of natural size distribution: Sedimentology, v. 27, p. 199–207, doi:10.1111/j.1365-3091.1980.tb01170.x.

Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., and O'Day, M., 1972, What is Franciscan?: American Association of Petroleum Geologists Bulletin, v. 56, p. 2295–2302.

Blake, M.C., and Harwood, D.S., 1989, Tectonic Evolution of Northern California, Field Trip Guidebook for Trip 108: Washington, D.C., American Geophysical Union.

Blake, M.C., and Jones, D.L., 1974, Origin of Franciscan melanges in northern California, *in* Dott, R.H., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Tulsa, Society of Economic Paleontologists and Mineralogists, p. 345–357.

Bro, A., 1996, A weak rock triaxial cell; Technical Note: International Journal of Rock Mechanics and Mining Sciences, v. 33, p. 71–74, doi:10.1016/0148-9062(95)00047-X.

Bro, A., 1997, Analysis of multi-stage triaxial test results for a strain-hardening rock: International Journal of Rock Mechanics and Mining Sciences, v. 34, p. 143–145, doi:10.1016/S1365-1609(97)80040-8.

Button, E.A., Schubert, W., Riedmueller, G., Klima, K., and Medley, E.W., 2003, Tunnelling in tectonic mélanges—Accommodating the impacts of geomechanical complexities and anisotropic rock mass fabrics: International Bulletin of Engineering Geology and the Environment.

Cloos, M., 1990, Evolution of the geological interpretation of the Franciscan Complex in the San Francisco Bay region: A comparison of cross-sections, *in* Bilodeau, B.J., and Davis, S.O., eds., Geologic Guidebook to the Point Reyes Area, Northern California: Bakersfield, California, American Association of Petroleum Geologists, Pacific Section, p. xxiii–xxxi.

Coli, N., Berry, P., Boldini, D., and Castellucci, P., 2008, Analysis of the Block Size Distribution in the Shale-Limestone Chaotic Complex (Tuscany, Italy): San Francisco, Proceedings, Symposium of American Rock Mechanics Association, June 27–July 3, 2008, 7 p.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic melanges in the Western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451–462, doi:10.1130/0016-7606(1985)96<451:SSIMAC>2.0.CO;2.

D'Elia, B., Distefano, D., Esu, F., and Federico, G., 1986, Slope movements in structurally complex formations, *in* Tan Tjong Kie, Li Chengxiang, and Yang Lin, eds., Proceedings of the International Symposium on Engineering in Complex Rock Formations (Beijing, China), p. 430–436.

Ellen, S.D., and Wentworth, C.M., 1995, Hillside Materials and Slopes of the San Francisco Bay Region, California: U.S. Geological Survey Professional Paper 1357, 215 p.

Fox, K.F., 1983, Melanges and Their Bearing on Late Mesozoic and Tertiary Subduction and Inter-Plate Translation at the West Edge of the North American Plate: U.S. Geological Survey Professional Paper 1198, 40 p.

Geological Society Engineering Geology Working Party, 1995, The description and classification of weathered rocks for engineering purposes: Quarterly Journal of Engineering Geology, v. 28, p. 207–242, doi:10.1144/GSL.QJEGH.1995.028.P3.02.

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

Greenly, E., 1919, The Geology of Anglesey: London, Geological Society of Great Britain Memoir, v. 1, 980 p.

Haneberg, W.C., 1995, Groundwater flow and the stability of heterogeneous infinite slopes underlain by impervious substrata, *in* Haneberg, W.C., and Anderson, S.A., eds., Clay and Shale Slope Instability: Geological Society of America Reviews in Engineering Geology 10, p. 63–78.

Haneberg, W.C., 2004, Simulation of 3D block populations to characterize outcrop sampling bias in bimrocks: Felsbau Rock and Soil Engineering Journal for Engineering Geology, Geomechanics and Tunneling, v. 22, p. 19–26.

Hoek, E., 2001, Terzaghi lecture: Big tunnels in bad rock: Journal of Geotechnical and Geoenvironmental Engineering, v. 127, p. 726–740, doi:10.1061/(ASCE)1090-0241(2001)127:9(726).

Hovland, J.H., Medley, E.W., Volpe, R.L., Goodman, R.E., and Ahlgren, A.S., 2000, Discussion—Evaluating the safety of a concrete gravity dam in weak rock—Scott Dam: Journal of Geotechnical and Geoenvironmental Engineering, v. 127, p. 900–903.

Hsü, K.J., 1985, A basement of melanges: A personal account of the circumstances leading to the breakthrough in Franciscan research, *in* Drake, E.T., and Jordan, W.M., eds., Geologists and Ideas: A History of North American Geology: Boulder, Colorado, Geological Society of America, Centennial Special Volume, v. 1, p. 47–64.

Hunt, R.E., 2005, Geotechnical Engineering Investigation Handbook (2nd ed.): Boca Raton, Florida, Taylor and Francis Group, 1066 p.

Irfan, T.Y., and Tang, K.Y., 1993, Effect of the coarse fraction on the shear strength of colluvium in Hong Kong: Hong Kong Geotechnical Engineering Office, TN 4/92, 128 p.

Kim, C., Snell, C., and Medley, E., 2004, Shear Strength of Franciscan Complex Melange as Calculated from Back-Analysis of a Landslide: Proceedings of the 5th International Conference on Case Histories in Geotechnical Engineering, New York, April 2004, 8 p.; available at http://bimrocks.geoengineer.org/files/Kimetal2004.pdf (accessed 20 June 2011).

Laznicka, P., 1988, Breccias and Coarse Fragmentites—Petrology, Environments, Associations, Ores: Amsterdam, Elsevier, Developments in Economic Geology, v. 25, 832 p.

Lindquist, E.S., 1994, The strength and deformation properties of mélange [Ph.D. thesis]: Berkeley, Department of Civil Engineering, University of California, 262 p.

Lindquist, E.S., and Goodman, R.E., 1994, The strength and deformation properties of a physical model mélange, *in* Nelson, P.P., and Laubach, S.E., eds., Proceedings of North American Rock Mechanics Conference (NARMS), 1st, Austin, Texas: Rotterdam, A.A. Balkema, p. 843–850.

Medley, E.W., 1994a, The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks) [Ph.D. thesis]: Berkeley, Department of Civil Engineering, University of California, 387 p.

Medley, E.W., 1994b, Using stereologic methods to estimate the block volumetric proportion in melanges and similar block-in-matrix rocks (bimrocks): Proceedings of the Congress of the International Association of Engineering Geologists, 7th, Lisbon, Portugal: Rotterdam, A.A. Balkema, p. 1031–1040.

Medley, E.W., 1997, Uncertainty in estimates of block volumetric proportion in melange bimrocks: Proceedings of the International Symposium of the International Association of Engineering Geologists, Athens, Greece, June 23–27: Rotterdam, A.A. Balkema, p. 267–272.

Medley, E.W., 2001, Characterization of Franciscan melanges and other heterogeneous rock/soil mixtures, *in* Ferriz, H., and Anderson, R., eds., Engineering Geology Practice in Northern California: Association of

Engineering Geologists Special Publication 12, and California Geological Survey Bulletin 210, p. 107–122.
Medley, E.W., 2002, Estimating block size distributions of melanges and similar block-in-matrix rocks (bimrocks): Proceedings of the North American Rock Mechanics Symposium, 5th, Toronto, Canada: University of Toronto, p. 599–606.
Medley, E.W., 2004, Observations on tortuous failure surfaces: Felsbau, Rock and Soil Engineering: Journal for Engineering Geology, Geomechanics and Tunneling, v. 22, p. 35–43.
Medley, E.W., 2005, The arrogance of straight lines: GeoStrata Magazine of the Geo-Institute of American Society of Civil Engineers, v. 5, p. 28–32.
Medley, E.W., 2009, Commentary: Engineering geology—A vital phase of geoengineering: Geo-Strata Magazine of the Geo-Institute of the American Society of Civil Engineers, Reston, Virginia, American Society of Civil Engineers, v. 10, no. 2, p. 10–12.
Medley, E.W., and Lindquist, E.S., 1995, The engineering significance of the scale-independence of some Franciscan melanges in California, USA, *in* Daemen, J.K., and Schultz, R.A, eds., Proceedings of the U.S. Rock Mechanics Symposium, 35th: Rotterdam, A.A. Balkema, p. 907–914.
Medley, E.W., and Sanz, P.R., 2004, Characterization of bimrocks (rock/soil mixtures) with application to slope stability problems: Proceedings of Eurock 2004 and Geomechanics Colloquium, 53rd, Salzburg, Austria, October 2004.
Moritz, B., Grossaeur, K., and Schubert, W., 2004, Short term prediction of system behaviour of shallow tunnels in heterogeneous ground: Felsbau, Journal of Engineering Geology, Geomechanics and Tunnelling, v. 22, p. 44–53.
Nagahama, H., 1993, Technical note: Fractal fragment size distribution for brittle rocks: International Journal of Rock Mechanics and Geomechanics Abstracts, v. 30, p. 173–175, doi:10.1016/0148-9062(93)90710-U.
Neuendorf, K.K.E., Mehl, J.P., Jr., and Jackson, J.A., 2005, Glossary of Geology (5th ed.): Alexandria, Virginia, American Geological Institute, 800 p.
Pan, Y.W., Hsieh, M.H., and Liao, J.J., 2008, Mechanical properties of virtual block-in-matrix colluvium: Proceedings of the Symposium of American Rock Mechanics Association, San Francisco, California, June 27–July 3, 2008.
Peck, R.B., 1969, Advantages and limitations of the observational method in applied soil mechanics, Ninth Rankine Lecture: Geotechnique, v. 19, p. 171–187, doi:10.1680/geot.1969.19.2.171.
Priest, S.D., 1993, Discontinuity Analysis for Rock Engineering: New York, Chapman and Hall, 473 p.
Raymond, L.A., 1984, Classification of mélanges, *in* Raymond, L.A., ed., Melanges: Their Nature, Origin, and Significance: Geological Society of America Special Paper 228, p. 7–20.
Riedmüller, G., and Schubert, W., 2002, Tunnels through fault rocks and tectonic mélanges—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.
Riedmüller, G., Brosch, F.J., Klima, K., and Medley, E.W., 2001, Engineering geological characterization of brittle faults and classification of fault rocks: Felsbau, Rock and Soil Engineering: Journal for Engineering Geology: Geomechanics and Tunneling, v. 19, p. 13–18.
Riedmüller, G., Brosch, F.J., Klima, K., and Medley, E.W., 2004, Engineering Geological Classification of Fault Rocks: Poster at Eurock 2004 and Geomechanics Colloquium, 53rd, Salzburg, Austria, October 2004.
Roadifer, J.W., Forrest, M.P., and Lindquist, E.S., 2009, Evaluation of Shear Strength of Mélange Foundation at Calaveras Dam: Proceedings of U.S. Society for Dams, Annual Meeting and Conference, 29th, on "Managing Our Water Retention Systems," April 20–24, Nashville, Tennessee, p. 507–521; available at http://ussdams.com/proceedings/2009Proc/507-522.pdf (accessed 20 June 2011).
Rocha, M., 1971, A method of integral sampling of rock masses: Rock Mechanics, v. 3, p. 1–12, doi:10.1007/BF01243548.
Rogers, D., 2008, Memorable Quotes from Some of Prof. H. Bolton Seed's Lectures at U.C. Berkeley 1976–82: http://web.mst.edu/~rogersda/mentors/Harry%20Seed%20Quotes.pdf.
Rosiwal, A., 1898, Über Geometrische Gesteinsanlysen: Verhandl, Der K-K geologische Reichanstalt, v. 5/6, 143 p.
Ross, J.C., 1986, Effective Stereology: New York, Plenum Press, 185 p.
Sammis, C.G., and Biegel, R.L., 1989, Fractals, fault gouge and friction: Journal of Pure and Applied Geophysics, v. 131, p. 255–271, doi:10.1007/BF00874490.
Savely, J.P., 1990, Comparison of shear strength of conglomerates using a Caterpillar D9 ripper and comparison with alternative methods: International Journal of Mining and Geological Engineering, v. 8, p. 203–225, doi:10.1007/BF01554042.
Savina, M.E., 1982, Studies in bedrock lithology and the nature of down slope movement [Ph.D. thesis]: Berkeley, University of California, Department of Geological Sciences, 298 p.
Snell, C.B., and Medley, E., 2008, Evaluation of simple claims for a landslide in complex melange: Program with Abstracts, Annual Meeting of the Association of Environmental and Engineering Geologists, New Orleans, Louisiana, September, *in* AEG News, Magazine of the Association of Environmental and Engineering Geologists, July 2008, p. 84.
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, Journal of Engineering Geology: Geomechanics and Tunnelling, v. 22, p. 27–34.
Sönmez, H.A., Gokceoglu, C., Medley, E.W., Tuncay, E., and Nefeslioglu, H.A., 2006a, Estimating the uniaxial compressive strength of a volcanic bimrock: International Journal of Rock Mechanics and Mining Sciences, v. 43, p. 554–561, doi:10.1016/j.ijrmms.2005.09.014.
Sönmez, H., Altinsoy, H., Gokceoglu, C., and Medley, E.W., 2006b, Considerations in developing an empirical strength criterion for bimrocks: Proceedings of the Asian Rock Mechanics Symposium, 4th, November 6–10, 2006, Singapore; available at http://bimrocks.geoengineer.org/files/Sonmez-et-al-2006.pdf (accessed 20 June 2011).
Spreng, S.P., McRae, M.T., Nolting, R.M., and Desai, H., 2008, Tunnel design and construction in a Franciscan mélange: Proceedings, Symposium of American Rock Mechanics Association, San Francisco, June 27–July 3, 2008, 9 p.
Turner, A.K., 2005, Geological Engineering, *in* Selley, R., Cocks, R., and Plimer, I., eds., Encyclopedia of Geology, Vol. 3: New York, Academic Press, p. 35–42.
Underwood, E.E., 1970, Quantitative Stereology: Reading, Massachusetts, Addison Wesley, 272 p.
Van Velsor, J.E., and Walkinshaw, J.L., 1993, Accelerated movement of a large coastal landslide following the October 17, 1989, Loma Prieta earthquake in California: Annual Meeting of the Transportation Research Board, January 1992, Washington, D.C., p. 63–71.
Volpe, R.L., Ahlgren, C.S., and Goodman, R.E., 1991, Selection of engineering properties for geologically variable foundations, *in* Question 66: Proceedings of the International Congress on Large Dams, 17th, Vienna: Paris, International Commission on Large Dams, p. 1087–1101.
Waeber, J.C., 2008, Incorporating depth-varying geological strength index values to the characterization of weak rock masses in northern California: Program with Abstracts, Annual Meeting of the Association of Environmental and Engineering Geologists, New Orleans, Louisiana, September 2008, *in* AEG News, Magazine of the Association of Environmental and Engineering Geologists, July 2008.
Wahrhaftig, C., 1984, Streetcar to Subduction: Washington, D.C., American Geophysical Union, 76 p.
Wakabayashi, J., 1999, The Franciscan complex, San Francisco Bay Area: A record of subduction complex processes, *in* Wagner, D.L., and Graham, S.A., eds., Geologic Field Trips in Northern California, Centennial Meeting of the Cordilleran Section of the Geological Society of America: Sacramento, California Division of Mines and Geology Special Publication 119, p. 1–21.
Wakabayashi, J., 2008, Franciscan Complex, California: Problems in recognition of melanges, and the gap between research knowledge and professional practice: Proceedings, Conference of American Rock Mechanics Association, San Francisco, June 27–July 3, 2008, 13 p.
Wakabayashi, J., and Medley, E.W., 2004, Geological characterization of melanges for geopractitioners: Felsbau, Journal of Engineering Geology: Geomechanics and Tunnelling, v. 22, p. 10–18.
Weibel, E.R., 1980, Stereological Methods, Volume 2: Theoretical Foundations: New York, Academic Press, 340 p.

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