Geopractitioner Approaches to Working with Antisocial Melanges

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ABSTRACT

Although melanges 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. Melanges 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 melanges. The considerable engineering and construction difficulties related to melanges burden Society to the extent that they can be considered “antisocial”. Case histories exemplify a recommended systematic procedure for characterization, design and construction with melanges. Geopractitioner

approaches to characterizing California's chaotic Franciscan melanges 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

Melanges have been of exciting and controversial concern to geologists since Greenly (1919) first identified "autoclastic mélange" (French, *mélange* or "mixture" - the acutely accented "é" is unnecessary.) There are thousands of publications on various aspects of melanges; 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 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, soils 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.

MELANGES AND BIMROCKS

Melange bodies are located in more than 60 countries, generally within current and ancient mountain systems (Medley, 1994). Melange 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 melanges, such as Berkeland et al. (1972), Fox (1983), Cloos (1990), Blake and Jones (1974), Raymond (1984), Cowan (1985), and Hsü (1985). Franciscan melanges 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 melanges of the Franciscan are similar to melanges elsewhere in the world in appearance, properties and the problems they present globally to geopractitioners.

There are surprisingly scant treatments written about melanges from the perspective of geopractitioners, despite the myriad of geological publications. Some early papers described engineering experience with Italian olistostromes and argille scagliose (AGI, 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 melanges, as “block-in-matrix rocks”, a term which joins the several aliases for melanges 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 the 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 melanges. Weathered rocks can include mixtures of decomposed soil surrounding fresher corestones (Figure 1). Fault rocks, composed of blocks within gouge and sheared rock (Figure 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). Melanges, the most intractable of bimrocks, contain competent blocks of varied lithologies, often embedded in sheared matrices of weaker rock (Figure 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 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 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.) which complicate simple characterizations.

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

GEOPRACTICE WITH MELANGES AND SIMILAR BIMROCKS

In general, geopractitioners work with melanges, rather than try to understand how they came to be. “Work” is used to describe characterization, design and construction; although in this paper 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 melanges and their formation. .

Some geopractitioners are not aware of the existence of complex geological mixtures of weak matrix and strong blocks. Others regard melanges 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 melanges adequately represent the mixed rock mass, and design on that basis. Some geotechnical engineers and rock engineers may focus on the 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, since 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 which are representative of the material for the purposes of the design of a particular project. The chaotic nature of melanges 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 in melanges is provided in the following section as well as by Medley (2001) and Wakabayashi and Medley (2004). Successful characterizations of melanges 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 others. Hence a geopractitioner’s exploration of melangesis 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 melange.

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 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 works. Flaws in the characterization and design will become evident during construction which 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 MELANGES

A major geopractitioner concern is the evaluation of the strength and deformation properties of soil and rock masses. For melanges, 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 melanges, since 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 (1993); 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 evident in Figure 3), and existing failed rock masses can be used to back-calculate the overall strength of melange (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 (Figure 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 vs. matrix, and to very roughly indicate the range of possible block sizes. Since the matrix of melanges 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 melanges are hampered by the myriad of smaller blocks which mask the geophysical response of the larger target blocks.

A common error made by geopractitioners is to map outcrops and draw cross-sections (Figure 5) of melanges as continuous strata because of the interlayered appearance of blocks and matrix in drill core (Figure 4, Figure 7). Boring logs in melanges 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; 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, multi-stage triaxial tests (Bro 1996, 1997), ideally: consolidated undrained 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 melanges where significant shears exist prior to testing, since 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 MELANGES

There are geological terms for rock fragments which suggest size, such as “boulders”, which are generally taken to be larger than about a 0.3 m in size, with no apparent upper size limit. Such terms should not be used to describe the rock inclusions in melanges: 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, (Figure 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 maximum observed dimension – Figure 6) is the chord length formed by the intersection of blocks with sampling lines traversing outcrops (scanlines of Priest, 1993), or linear drill core (Figure 6 and Figure 7).

Franciscan melanges 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 been also observed at a large exposure of an Italian olistostrome (Coli, 2008). Figure 8 and its insert are photographs taken at different scales of the same outcrop of Franciscan melange. Small blocks at one scale of interest (detail photo in Figure 8) are part of the matrix at the smaller 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 outcrops exposures of Franciscan melanges 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-Nielson (1980), are useful in presenting the measurements because the histogram size classes embrace several orders of magnitude.

In the Franciscan melanges 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 melanges 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 melanges regardless of the scale of observation.

DISCRIMINATING BLOCKS FROM MATRIX

A sufficient volumetric proportion of blocks in melanges provides mechanical advantages to a melange. Since there is a very large range in block sizes in melanges, the geotechnically significant blocks must be discriminated from matrix. Because of scale independence, any reasonable dimension can be used to scale a melange 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, 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 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 melange 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 melanges by fabricated physical model melanges of different volumetric proportions and testing them under multi-stage 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 melange is about $0.75L_c$ (Figure 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 melange, blocks less than $0.05L_c$ in size (Figure 10) constitute greater than 95 percent of the total number of blocks, but contribute less than 1 percent to the total volume of melange and have negligible effect on the mechanical behavior of the melange (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. 1:1,000) 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. 1:1,000) because they are then massive, unmixed blocky rock masses that can be characterized according to conventional rock engineering practice.

MECHANICAL PROPERTIES OF MELANGES

The matrix of Franciscan melanges is most commonly composed of sheared shale, argillite, siltstone, serpentinite or sandstone, often 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 melanges 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 melange. Because of highly sheared matrix, landslides are common in block-poor Franciscan melanges (Medley and Sanz, 2004), although large blocks appear to add buttress support (Figure 3).

The weakest elements in melanges are often the contacts between blocks and matrix (Figure 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 (Figure 7 and Figure 11) with the most intense shearing often present adjacent to the largest blocks. Blocks within the shears are often entrained within, and oriented sub-parallel, to shears (Figure 8). Since shears have a tortuous path through the rocks mass, the overall orientation of entrained blocks can also abruptly change from place to place within the rockmass.

Relatively modest block/matrix mechanical contrast is necessary for a block-in-matrix rock mass to be considered a bimrock. For physical models of melange, 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 a friction angle ratio suggested by Medley (1994a) based on work by Lindquist (1994a) Lindquist and Goodman (1994) and Volpe and others (1991):

$$(\tan\phi_{weakest\ block})/(\tan\phi_{matrix}) > 1.5 \text{ to } 2.0$$

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 (pers. comm., 2009) 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 melange 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 bimrock as indicated by Savely (1990) for 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 and contribute to strength because failure surfaces are forced tortuously negotiate around blocks, thus increasing passive resistance to shear failures (Lindquist, 1994a; Medley, 2004; Sönmez, et al, 2006a, 2006b). When blocks are uniformly sized, failure surfaces tend to have smoother, undulating profiles (Fig. 4.4 of Medley, 1994a; Medley, 2004), and hence the mixed rock mass has less shear resistance, and lower overall strength. But there is a dependence on the normal stresses to which the melange 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.

As shown in Figure 12, Lindquist (1994a) conservatively established that below about 25 percent volumetric block proportion the frictional strength and deformation properties of a physical model melange wasthat 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 melange strength at volumetric block proportions lower than 25 percent.

Lindquist (1994a) also showed that between about 25 percent and 75 percent, the friction angle and modulus of deformation of a physical model melange 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 melanges (Goodman and Ahlgren, 2000; Roadifer et al, 2009) and volcanic agglomerates (Sönmez et al, 2006b) possibly due to block/matrix contacts strengths being greater than matrix strengths for the materials evaluated.

Beyond about 75 percent 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 in-filled joints.

Franciscan complex melanges have been assigned strength parameters varying between: block-poor melange 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 degrees (Kim et al, 2004); for block-rich melange below Scott Dam: c' of 76 kPa (1590 psf) and ϕ'of 39 degrees (Goodman and Ahlgren, 2000); and for melange below Calaveras Dam: c' of 6.9 kPa to 39.9 kPa (1000 to 5740 psf); and ϕ' of 25 to 45 degrees (Roadifer et al, 2009). Sheared matrix in Franciscan melange can be extremely weak, with low to zero cohesion and effective friction angles of less than 10 degrees.

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 melanges 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 melanges and other bimrocks is appealing to geopractitioners. Nevertheless, to 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 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 the 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 can be estimated from scanline 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 about 5 cm long could be measured, even if the block/matrix threshold is larger, since 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 melanges are not uniformly sized or distributed, so the volumetric block proportion cannot be accurately determined from a few borings. Also. tThe 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; Medley, 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 melanges can be higher due to the troublesome effort required to secure good quality cores the 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 melange 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 (Figure 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.

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 melanges that are larger than approximately 0.6 cm in diameter are too large to pass through the apertures of earthmoving scrapers, which are like the gaps in a cheese parers and potato peelers). Blocks larger than about 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.

Since 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. Since observed chord lengths are almost invariably smaller than the actual block diameters (Figure 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 (Figure 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 melange 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.

CONSTRUCTION IN MELANGES

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, often 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 distribution sin melanges 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; Riedmueller and Schubert, 2002). Stress states depend on the in-situ stress, lithologies; size distributions, orientations, and shapes of blocks; orientations of matrix shears, 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 since 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 perturbs fluid flow and influences local factors of safety in melanges 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 melanges, the permeabilities may also differ by orders of magnitude over short distances since 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 melange 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 melanges normally performed, the geopractitioner may be unable predict the performance of the work during construction. Hence adherence to the Geotechnical Observational Method (Peck, 1969) is essential. The Geotechnical Observational Method requires that all possible modes of failure are anticipated and observations/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, since ground failures are rarely instantaneous. Once failure modes and scenarios are conceived, action criteria based on critical thresholds of ground movement tare 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 of geoengineering practice which illustrate many of the points made in this paper.

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 melanges and other bimrocks. However, the most fundamental consideration is the recognition that a rock mass is a bimrock. The consequences of non-recognitions 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 about 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

(Figure 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 landslide for a fixed price of over 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 since 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 the 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 melange, rather than a shallow soil mass sliding on top of the 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 (Figure 5 and Figure 16). Although the geological chaos was a surprise to the geotechnical engineer, it should not have been since publically available geological maps showed the locale of the landslide to be within Franciscan melange and large blocks protruded 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 melange that blocked California State Highway 1 near San Francisco (Van Velsor and Walkinshaw, 1993). To stabilize the slope, 950,000 cubic meters of intact and failed melange were excavated to an average depth of 37 m. The drilled exploration of the landslide intersected a maximum block chord length of about 8 m. Based on the percentage length of drilled chords through blocks, the project geopractitioners estimated that 5 percent 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 the landslide, the exposed parts of which suggested that the intact blocks were at least 30m or more in size (Medley, 1994a). Accordingly, the size of the largest block (d_{max}) was assumed to be about 30 m.

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 melange explored was about 10 percent, which was the weighted average of block-poor melange within the landslide (about zero percent) and block-rich melange beneath the slide (28 percent). 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 percent, total drilling of 375 m equivalent to 12.5 times the length of the estimated d_{max} of 30m (i.e., Nd_{max} of 12.5); and the assumption that the measured linear block proportion of 10 percent was equivalent to a volumetric block proportion of 10 percent. Hence, the estimated range of volumetric block proportions ranged between 6 percent and 14 percent (10 percent +/- 0.4 times 10 percent). In a similar situation, for excavation purposes a conservative geopractitioner should adopt the higher bound (in this case, 14 percent). For an estimate of volumetric block proportion for evaluating the overall rock mass strength, the 6 percent lower bound, was too low to improve the geomechanical properties of the rock mass.

Nevertheless, if 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 percent and 11 percent, which was greater than the original design estimate of 5 percent, but closer to the conservative post-project estimate of 14 percent. If the estimation had been performed prior to excavation instead of afterward, a suggested range of between 5% and 15% would have been reasonable to estimate 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 Melange 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 1920’s, the dam is a masonry gravity structure about 40 m high. The dam is underlain by a Franciscan melange.

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In the 1970’s conventional geotechnical analysis indicated that, if the strength of the melange 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 melange. But the dam was still intact more than 50 years after it was built, so the melange bedrock was clearly stronger, possibly due to the presence of the blocks in the sheared shale, as suggested by Volpe et al. (1991). A re-characterization of the Franciscan melange and re-evaluation 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 (√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 melange foundation rock. Accordingly, L_c was selected as a postulated 3 m thickness of a basal failure shear zone within the melange rock at the base of the dam.

As described above, geotechnically significant blocks that influence bimrock strength range between about $0.05L_c$ 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 0.15m, or 5 percent 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 (Figure 17) of Scott Dam core in the assumed critical potential failure zone indicated that the linear block proportion was about 40 percent for the postulated critical 3 m thick shear band of failed melange below the dam.

The total length of exploration core required to yield a reasonably accurate estimate of 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 m and 43 m (Medley, 1997), so greater than 300 m to 430 m of drilling would have been preferable. In actuality, only about 150 m of core (representing at least $5d_{max}$) was recovered from the several extensive exploration campaigns performed since the 1970's.

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): for the estimated linear block proportion of 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 percent was selected for the volumetric block proportion of the Franciscan melange below the dam. The estimate was subsequently lowered to 31 percent on the basis of additional exploration drilling (Goodman and Algren, 2000).

Because of scale independence, melange 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 melange from the dam foundation (Goodman and Ahlgren (2000) were tested using multi-stage 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 about 5 percent and 75 percent 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 (Figure 18). The overall strength of the foundation rock mass was evaluated using 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 melange beneath Scott Dam, the friction angle was estimated to be 39 degrees for the overall 31 percent volumetric block proportion (Figure 18).

Additional geotechnical engineering analyses confirmed that the strength of the melange 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 melange, 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). Essentially the same procedure described here for Scott Dam was used for the evaluation of the shear strength of Franciscan melange below Calaveras Dam (Roadifer et al, 2009).

Case History 4: Evaluation of Permeability of a Melange

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 melange. Litigation proceedings followed shortly afterward during which several allegations were made, one being that the San Andreas Lake water-supply reservoir, located some 1500 feet from the landslide, had leaked groundwater through the intervening low broad ridge and caused the landslide.

Geological and geotechnical investigations revealed Franciscan melange 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 melange ranged between 2.1×10^{-8} to 1.4×10^{-7} cm/s. Detailed hydrogeological analyses showed 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 melange exposed in the excavated slope, aggravated by lack of slope maintenance and the effects of poorly controlled surface drainage.

CONCLUSIONS

Melanges, 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, melanges and other bimrocks can be characterized for the purpose of geoengineering design and construction, even where there is great uncertainty in the characterization, or when the volumetric proportion of blocks is too little to provide geomechanical benefit. Simple procedures are available to characterize and analyze melanges 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 melanges learn to expect the unexpected.

We have written this paper to increase awareness by geologists of the practical problems faced by engineers working (often heroically) with geologically exciting but chaotic melanges and other troublesome bimrocks. Geologists have much understanding that, if shared without unnecessary geological jargon, could assist engineers in recognizing melanges 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 persuade engineers and they critically review the cross-sections they develop from their field observations of sites located in melanges. 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 bimrock masses, and investigate geomechanical behaviors of model bimrocks with variations in block/matrix strength/stiffness contrasts, block shapes and sizes, block size distributions and spacing.
- 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 (2009) in Franciscan melanges.

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

Characterization	**Design/analysis**	**Construction**
Common to All Civil Engineering Works		
Identify unusual lithologies Drill rock core using triple tube samplers; shrink wrap core Measure block linear proportions from core and mapping scanlines Beware of optimistic cross-sections Perform triaxial strength testing at differing block proportions	Decide soil engineering, rock engineering or bimrock approaches on basis of volumetric block proportions Evaluate potential destabilizing effects of large blocks, block and matrix discontinuity fabrics, shears, block orientations and shapes Evaluate variable groundwater conditions in blocks and matrix Predict long term performance of rock mass Evaluate how block proportions, size distributions, lithology and individual block and matrix strengths affect construction method and performance	Anticipate possible considerable differences between site conditions as characterized and conditions encountered in construction Review equipment limitations and handling of oversize blocks, fragmentation, rippability and excavatability of very hard blocks Plan for possible unexpected large pressurized groundwater flows when blocks are penetrated
Slopes, Excavations and Dams		
Perform direct shear tests on discontinuities and/or matrix Map critical failure surfaces	Assess destabilizing effect of stress and groundwater concentrations Analyze stabilizing/destabilizing effects of block orientations Anticipate through-going shears in matrix and/or blocks	Monitor short-term stability of excavated rock with abruptly variable shear fabric Consider leaving large blocks to protrude at grade or incorporate block stick-ups into the Work Monitor potential for block fall-outs
Tunnels , Pipelines and Underground Spaces		
Anticipate that 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 Analyze effect of short stand up times, squeezing ground in weak matrix Develop detailed Geotechnical Observation Method protocol	Select equipment and construction procedures flexible enough to accommodate possible extreme mixed-face conditions Develop procedure for penetrating large, extremely hard, blocks and handling many intact, small blocks Perform detailed face mapping and real-time analysis of ground deformation data

TABLE 2. FLOWCHART OF STEPS TO CHARACTERIZE MELANGE STRENGTH

Step 1: Check block/matrix strength contrast using estimates of weakest block and matrix mechanical parameters and following criteria:

$\mathrm{Tan}\phi_{block}/\tan\phi_{matrix} \geq 1.5\text{-}2.0$

$E_{block}/E_{matrix} \geq 2.0$

$UCS_{block}/UCS_{matrix} \geq 1.5$.

Step 2**:** Select characteristic dimension L_c at scale of engineering interest; eg: 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 Figure 12, or Figure 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

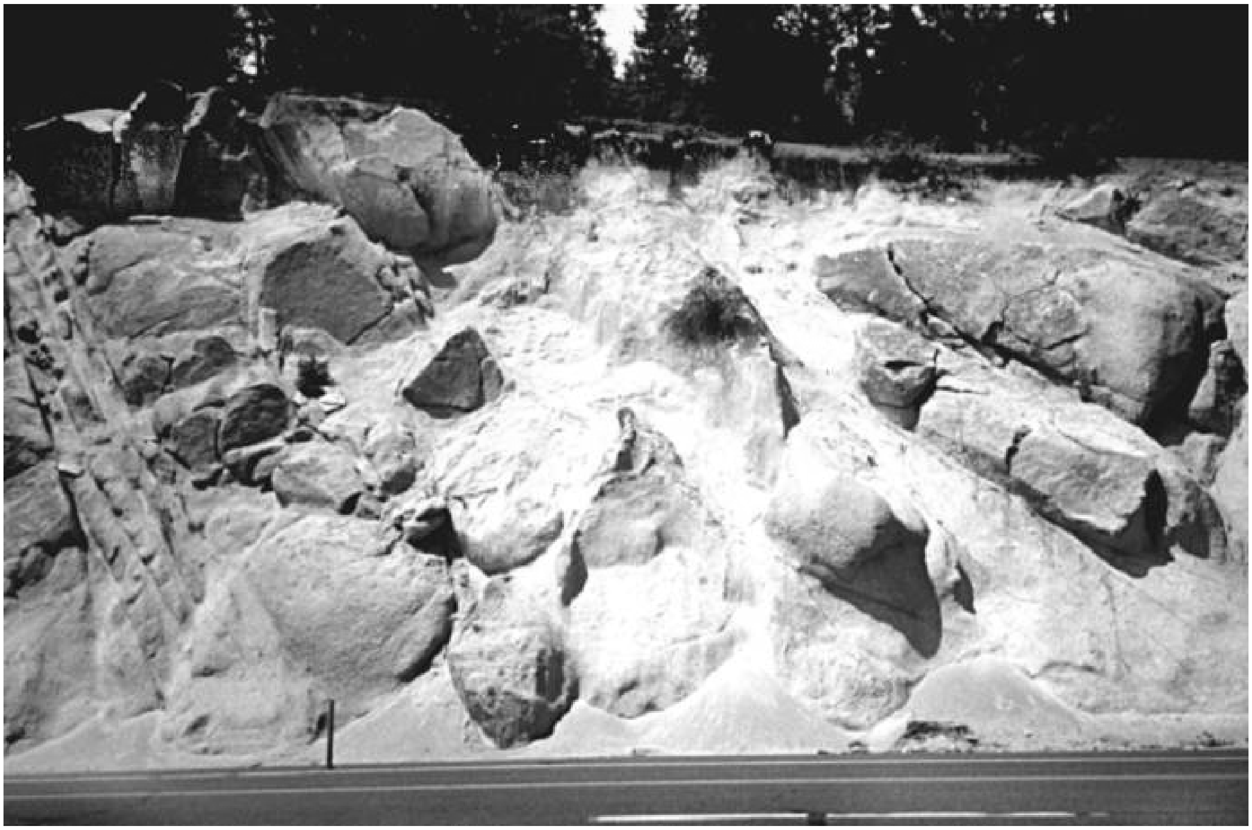

Figure 1. A bimrock located in the Sierra Nevada of California. Decomposed granite contains hard blocks (corestones) surrounded by a matrix of dense sandy soil (gruss). Photo: E. Medley.

Figure 2. Wall of a quarry located within 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 melange, Northern California. Blocks buttress base of slope between landslides in sheared shale matrix. Photo: E, Medley/Exponent, Inc.

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Figure 4. Typical Franciscan melange 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.

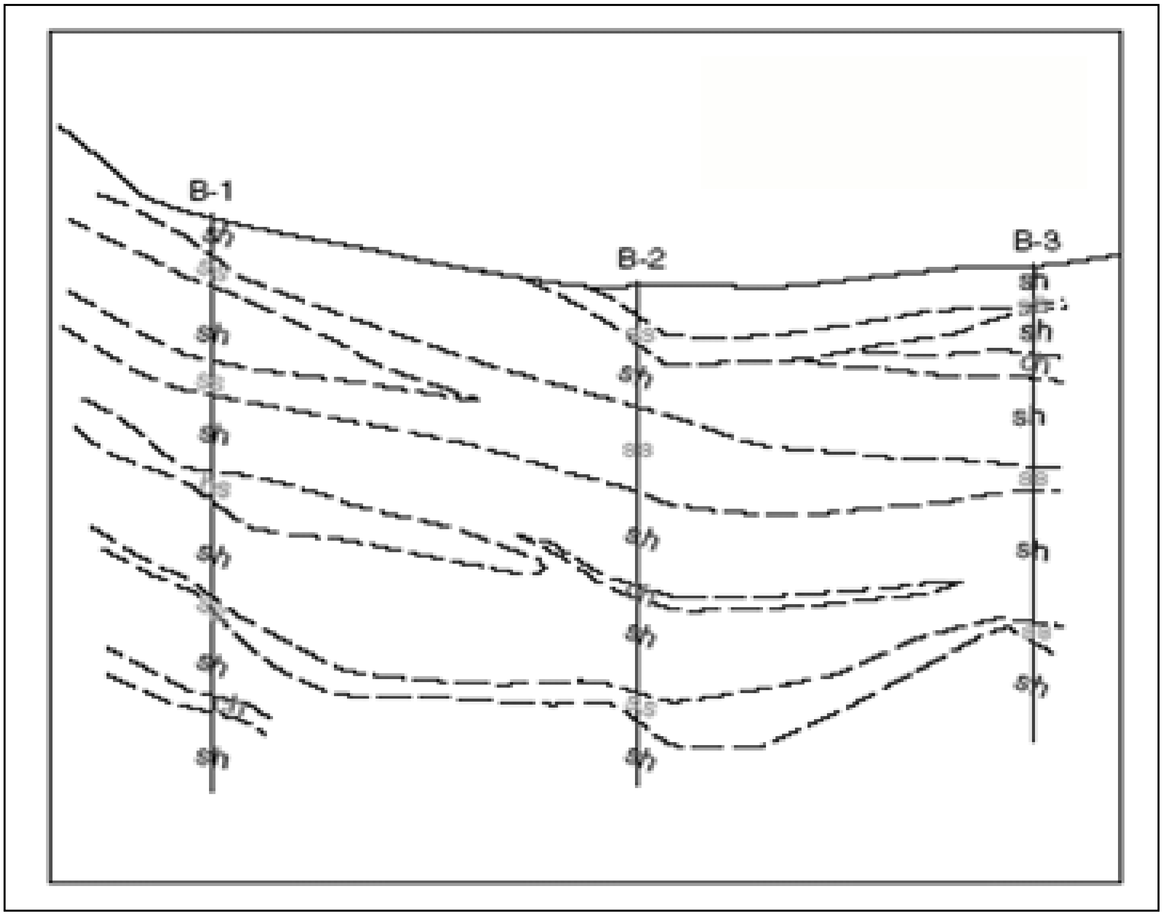


Figure 5. Bimrocks generally cannot be accurately depicted on cross-sections. Borehole contacts should be shown with question marks and not connected by lines interpreted to be strata boundaries, here drawn between borings. After Wakabayashi and Medley (2004).

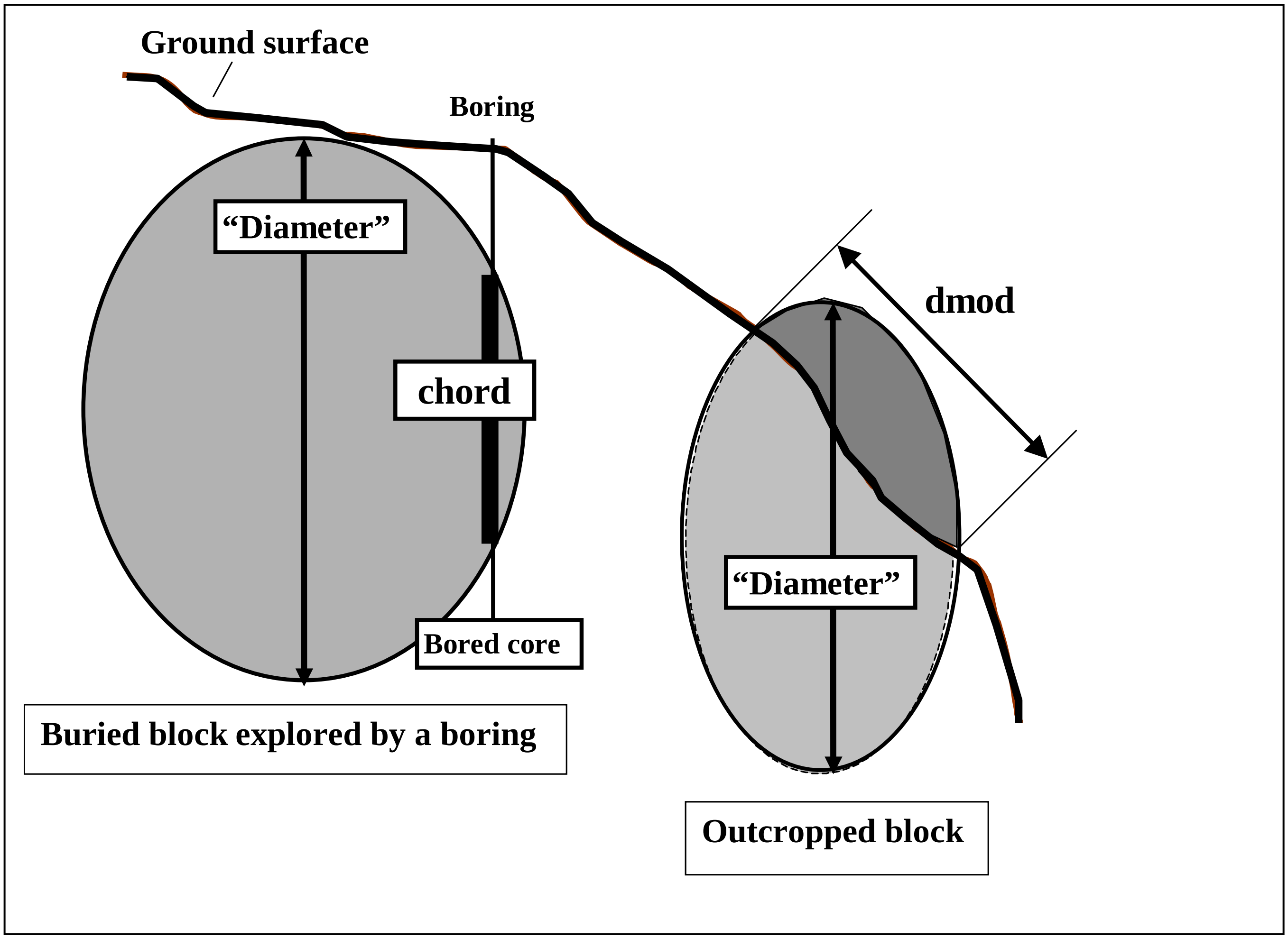


Figure 6. In two dimensions, such as at an outcrop, a block has an apparent block size of d_{mod}, the maximum observed dimension. In one dimension, such as in a drilled boring, the block size is apparently indicated by the chord, the length of interception between the boring and a block. However, only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

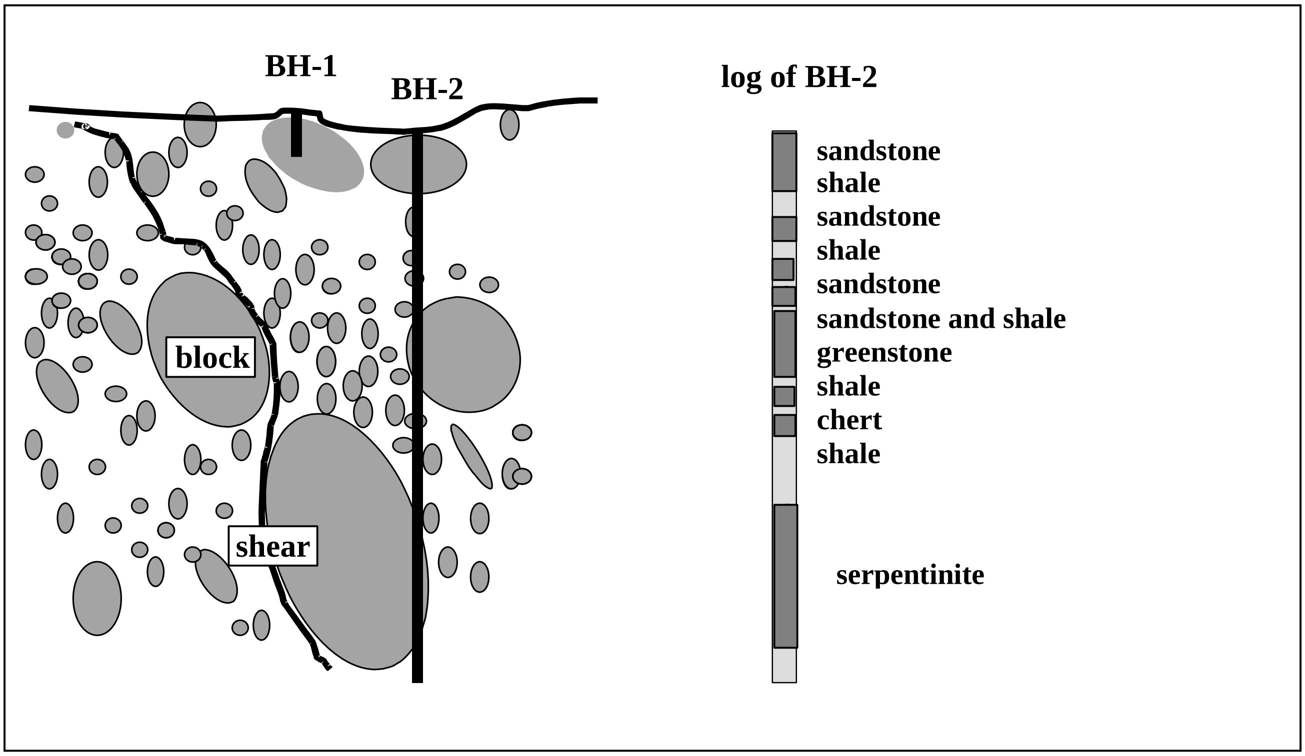


Figure 7. Block/core intersections (chords) rarely indicate true block sizes, nor shapes, orientations and distributions of blocks. Note that shears in the matrix negotiate tortuously around blocks. Sandstone/shale sequence in core is <u>not</u> “interbedded shale and sandstone”. Improbable juxtaposition of rocks (e.g.: greenstone and shale) strongly suggest melange. After Medley (2002).

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

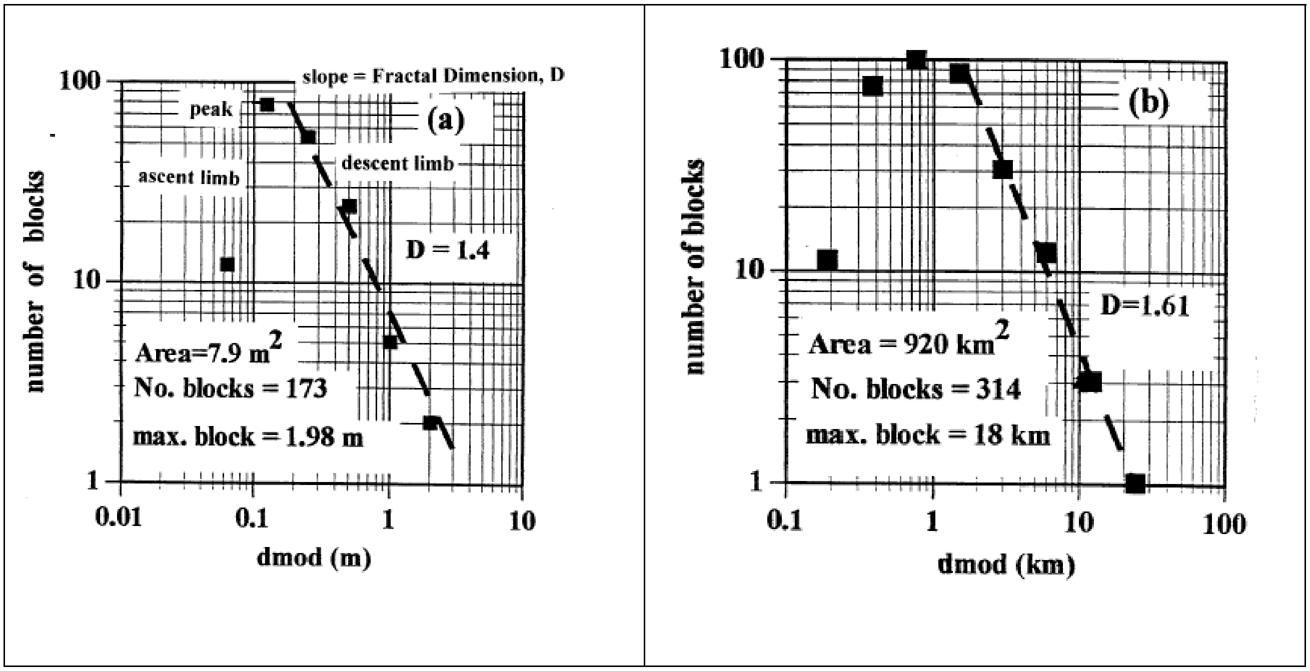
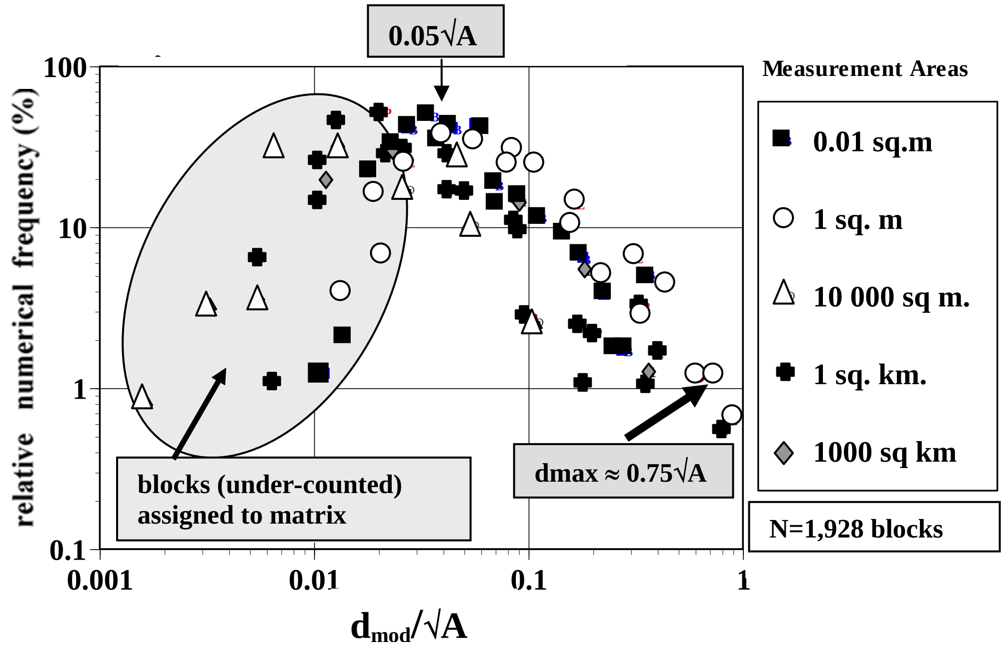


Figure 9. Left plot is a log-histogram of d_{mod}s measured from the outcrop of Franciscan melange shown in Figure 8. The right plot is a log histogram of d_{mod}s of blocks measured from a map of Franciscan Complex in the County of Marin, California. The slopes of the log-log plots are the fractal dimension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



Compilation of Log-histograms for block sizes in Franciscan melange

Figure 10. Normalized block size distribution curves for 1, 928 blocks measured from outcrops and geological maps of several Franciscan melanges 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 (√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 about $0.05d_{mod}/\sqrt{A}$, 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 percent of the blocks are smaller than about $0.75\sqrt{A}$, which is defined as the maximum block size (or d_{max}) at any scale. After Medley, 1994.

Figure 11. The weakest element in a bimrock is often the block/matrix contact. Gwna Melange, Anglesey, Wales. Photo: E. Medley.

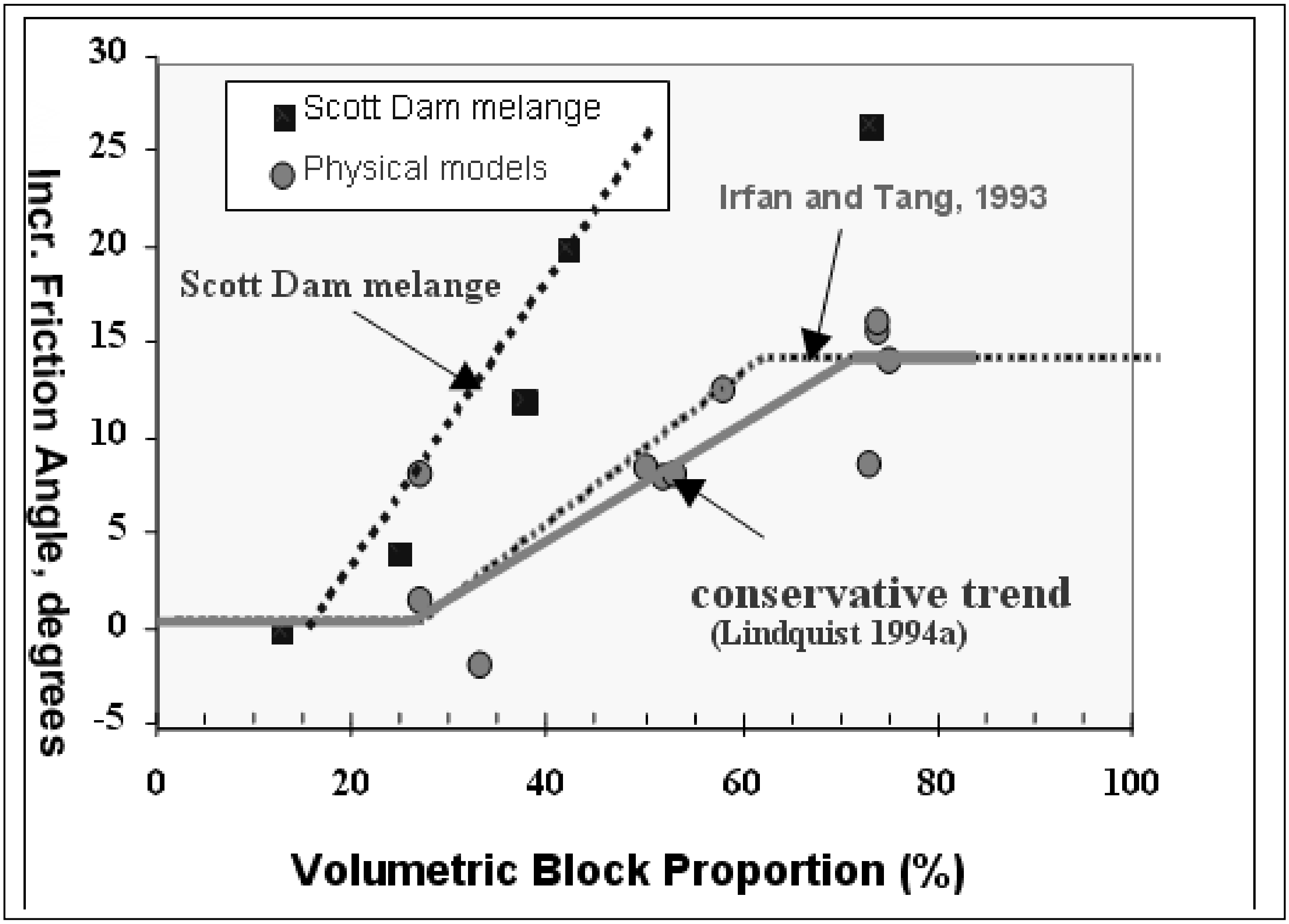
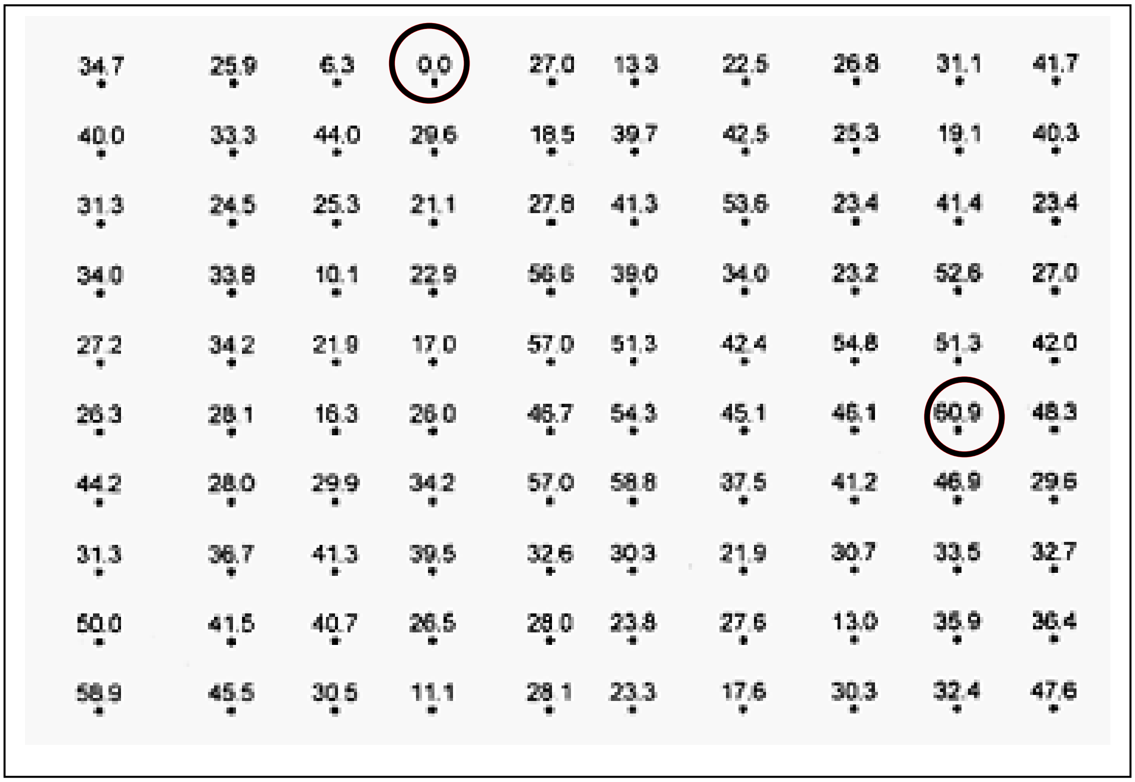


Figure 12: Strength of bimrocks increases with volumetric block proportion. The increase is added to the strength of the matrix. After Medley (1999), from data of Lindquist (1994a) and Irfan and Tang (1993).



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

Figure 13. Plan view of an array of 100 linear block proportions ranging between 0% and 61% measured for a physical model bimrock with 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 melange, 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).

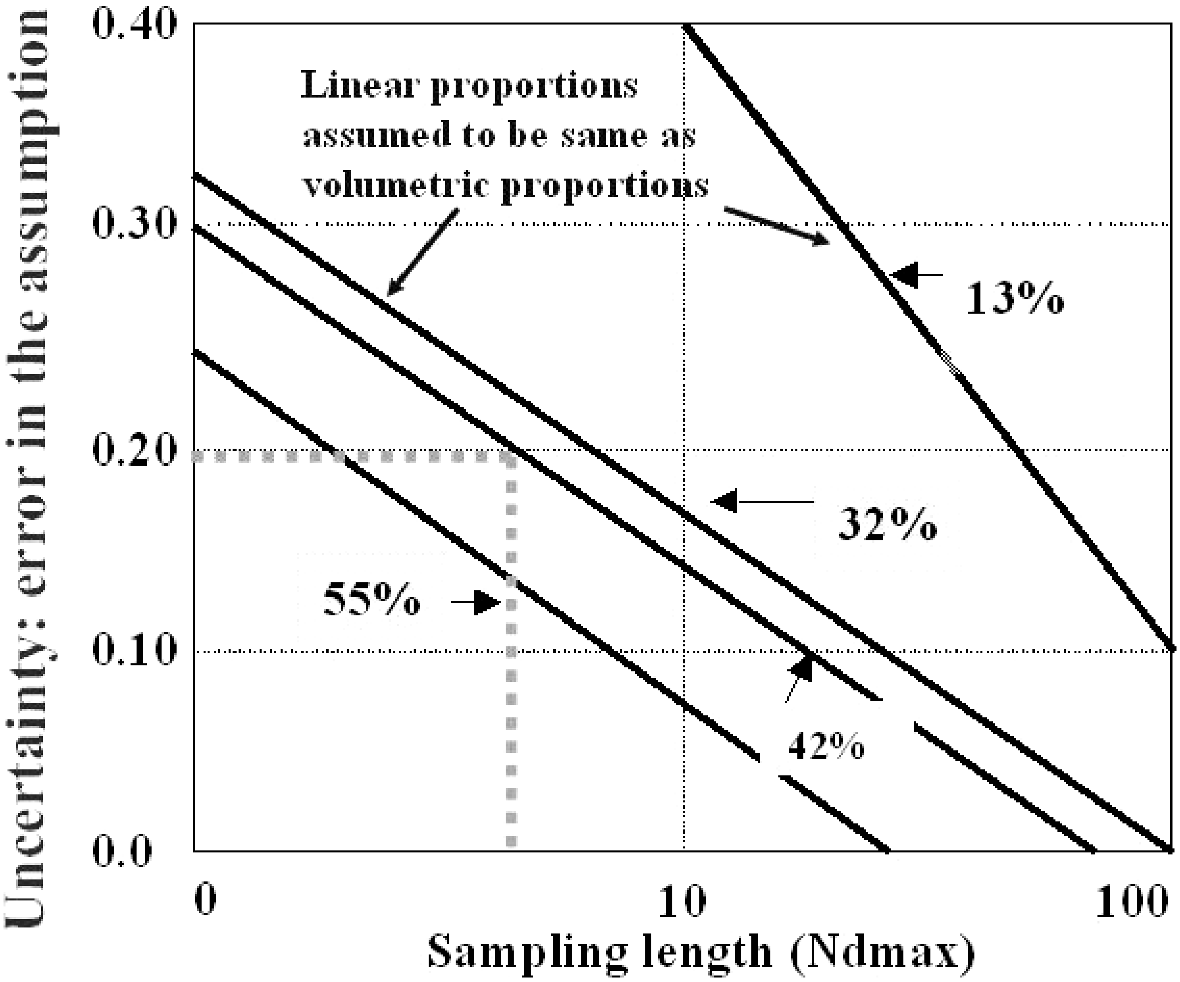


Figure 14. The plot provides the uncertainty in assuming that measured linear block proportions (13% to 55%) are assumed to represent volumetric block proportion. Uncertainty(co-efficient of variation) in estimates of volumetric block proportions are a function of the total length of linear measurement, expressed as a 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 about 5 times the size of the largest block; ie.: Nd_{max} was about 5. Based on the drilling, the linear

block proportion was about 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).

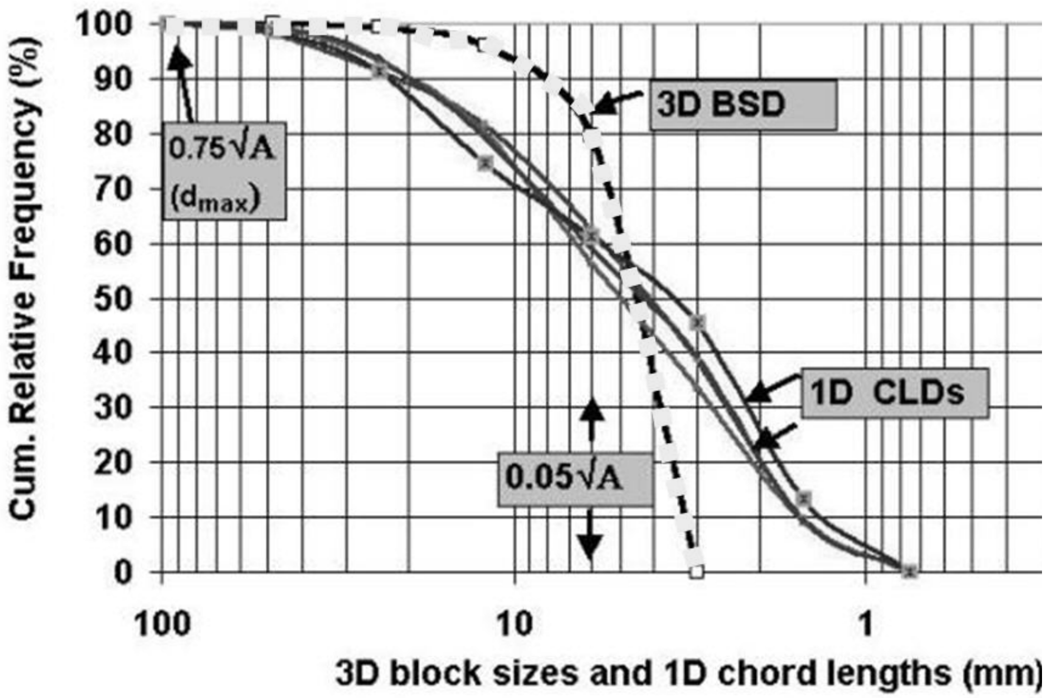


Figure 15. Comparison of true 3-D block size distribution (3D BSD) used in the fabrication of each of four physical model bimrocks. The 1-D chord length distributions (CLDs) were generated from measuring all chord lengths in 100 model borings generated for each model. Despite the 400 borings, the 1-D 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).

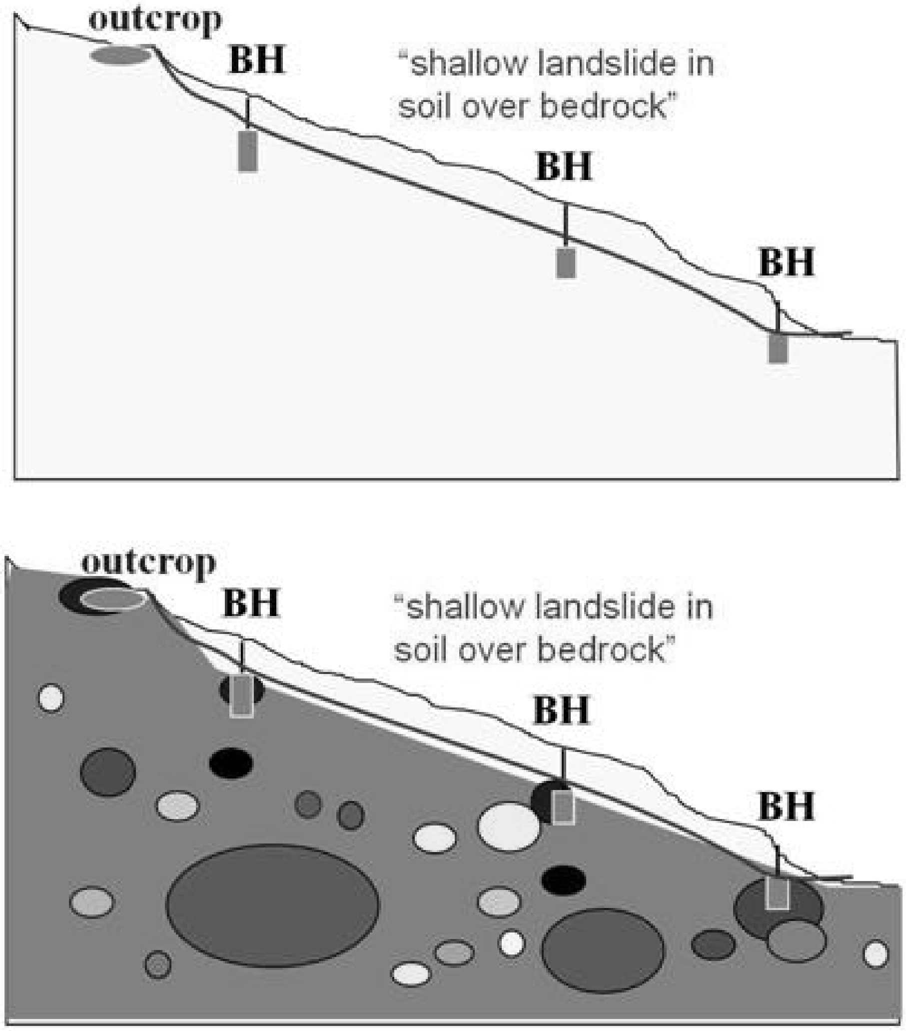


Figure 16. The upper sketch shows a geopractitioner's landslide characterization based on shallow borings and an observed outcrop - a shallow soil landslide sliding on an assumed underlying continuous bedrock surface. The lower sketch shows the actual bedrock conditions in which the borings intersected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

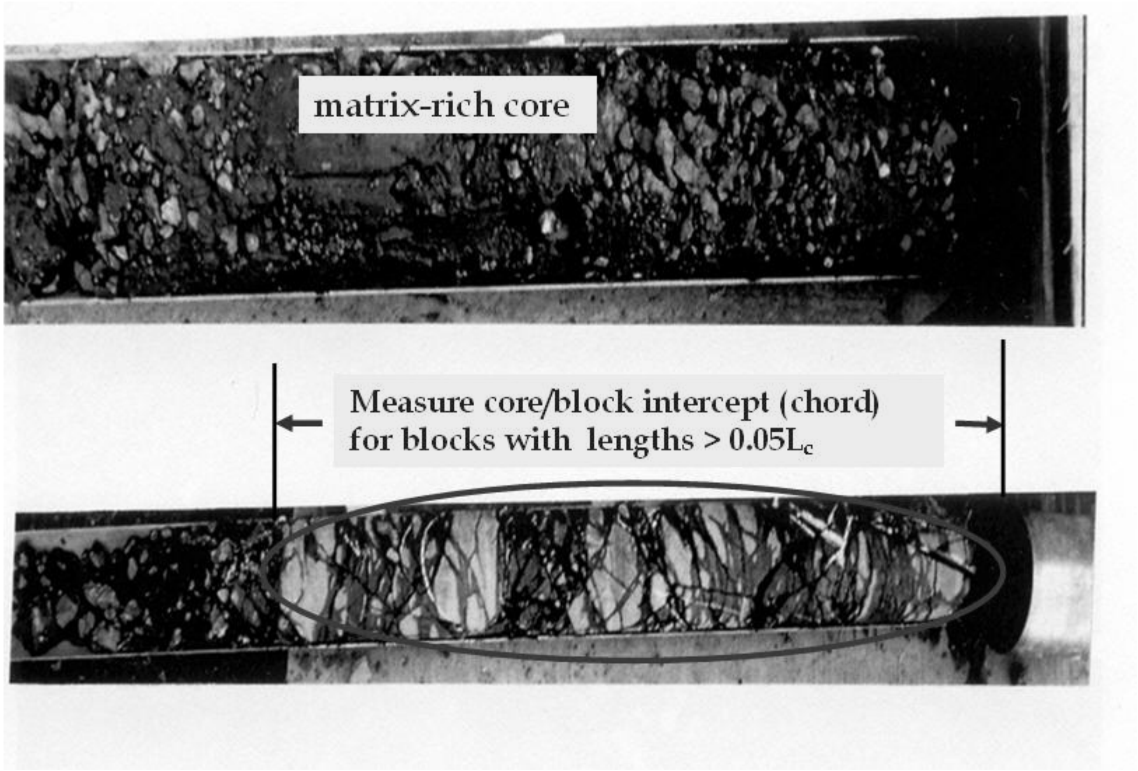


Figure 17. Typical core from an exploration boring at Scott Dam, California, showing a measurable block and matrix of sheared shale containing blocks that were smaller than 0.05 L_c (0.15m) and assigned to the matrix. Photo: Professor Richard E. Goodman.

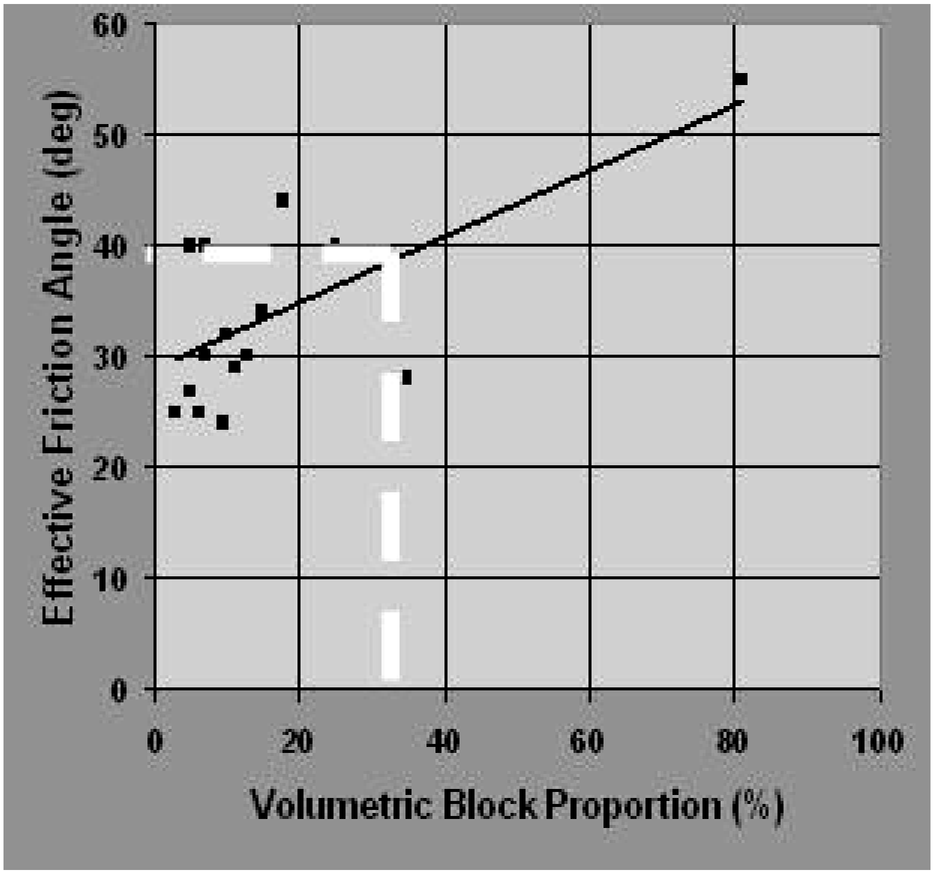


Figure 18. Plot of effective angle of friction (ϕ') as a function of volumetric block proportion, generated from laboratory testing of Franciscan melange specimens obtained from core drilling at Scott Dam, Northern California. From Medley (2001), after Goodman and Ahlgren (2000).