Orderly Characterization of Chaotic Franciscan Melanges

By Edmund W. Medley

Engineering geologists and geotechnical engineers are commonly challenged by weak, heterogeneous and geologically complex mixtures of strong blocks of rock embedded in soil-like matrices. Melanges (French: *mélange*) are a common example of such complex geological mixtures. Melanges and other soil/rock mixtures are well represented in the Northern California: the Franciscan Complex contains abundant melange bodies. Elsewhere in the Northern California, the geo-professional is challenged by fault and shear zones, lahar deposits, decomposed granites, glacial tills, and colluvium. However, it is not the intent of this paper to focus on American troubles: geologically complex mixtures pose global problems. For example, melanges have been mapped worldwide (1), and the lessons learned in California are applicable globally.

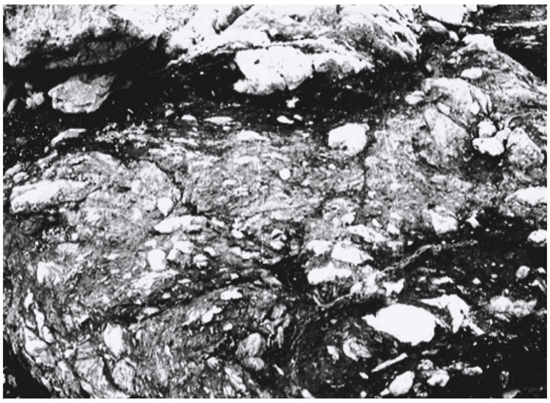


Fig. 1 Franciscan melange at Shelter Cove, Point Delgada, Northern California. Matrix is dark gray sheared shale/argillite. Light colored blocks are graywacke. Outcrop is about 1m wide.

Bild 1 *Franciscan Melange bei Shelter Cove, Point Delgada, Nordkalifornien. Die Matrix besteht aus dunkelgrauem, zerschertem (Ton/Silt-) Schiefer; helle Gesteinsblöcke sind Grauwacken. Die Bildunterkante entspricht etwa 1 m.*

Given their considerable spatial, lithological, and mechanical variability, characterization, design and construction of melanges and other rock/soil mixtures is daunting. Accordingly, practitioners often make the simplifying assumption that the mechanical behavior of rock/soil mixtures is adequately represented by the properties of the weak matrix materials and that there is no need to consider the contribution of blocks. As will be shown in this paper, such assumptions lead to improper and expensive engineering geological and geotechnical engineering mischaracterizations.

This paper has three purposes:

- The paper shows that blocks do influence the mechanical behavior of melanges and other rock/soil mixtures.
- The paper describes a scheme for the systematic characterization of block lithologies, block proportions and block size distributions to reduce inconvenient and expensive surprises during tunneling, earthwork and foundation construction.
- The paper summarizes recent research and practical experience on the geotechnical and geological characterization of melanges and other rock/soil mixtures.

Systematische Charakterisierung der chaotischen „Franciscan Melange“

Sogenannte „Bimrocks“ (Block-in-Matrix Gesteine) wie tektonische Melangen können trotz ihrer Heterogenität systematisch beschrieben werden. Die Festigkeit eines Bimrock hängt direkt vom volumetrischen Anteil von Gesteinsblöcken in der Matrix (Felsmasse) ab, so daß es erforderlich ist, diesen volumetrischen Anteil und weitere Eigenschaften der Blöcke zu bestimmen. Da tektonische Melangen Blöcke jeglicher Größenordnung beinhalten, ist es notwendig, sie in bezug auf eine charakteristische, geotechnisch interessierende Dimension (L_c) zu beschreiben wie etwa den Durchmesser eines Tunnels oder den Tiefgang einer Rutschung. Die relevanten Blockgrößen bewegen sich zwischen maximal 0,75 L_c und der definitorischen Abgrenzung gegen die Korngröße der Matrix bei 0,05 L_c. Der volumetrische Blockanteil kann aus Geländekartierung und Bohrkernuntersuchung abgeschätzt und die Aussagesicherheit kann angegeben werden. Obwohl geringe Blockanteile die Festigkeit eines Bimrock nicht beeinflussen, kann eine systematische Charakterisierung die Kosten der geotechnischen Planung und Überraschungen während der Baudurchführung vermindern helfen.

Despite their heterogeneity, bimrocks (block-in-matrix rocks) such as melanges can be systematically characterized. The strength of a bimrock is simply and directly related to the volumetric proportion of the blocks in the rock mass, which requires that volumetric block proportions and other block properties be determined. Because melanges contain blocks at all scales, a characteristic engineering dimension (L_c), such as a landslide thickness or a tunnel diameter, is necessary to describe a bimrocks mass at a particular scale of engineering interest. Block sizes range between the largest at 0.75 L_c and the block/matrix threshold at 0.05 L_c. Volumetric block proportions can be estimated from mapping and drill core and adjusted for uncertainty. Even where low block proportions do not increase the strength of a bimrock, systematic characterization will reduce expensive geotechnical design and surprises during construction.

Melanges and other bimrocks

Bimrocks

Melanges contain competent blocks of varied lithologies, embedded in sheared matrices of weaker rock (Figure 1). The fabric of hard blocks of rock within weaker matrix is fundamental in geology and there are over 1 000 geological terms for rock mixtures and fragmented rocks (2), including more than 20 aliases for melanges, such as olistostromes, argille scagliose, complex formations, friction carpet, wildflysch, megabreccia and polygenetic breccia. Attempts have been made to simplify the confusing geological lexicon associated with chaos. The Italian Geotechnical Society (3) devised a simple, geotechnically-oriented classification scheme for “structurally complex formations” which included melanges, colluvium and residual soils. Raymond (4) also attempted to simplify the confusing array of geological theories and descriptions for melanges and similar rocks. Laznicka (2) organized a Universal Rudrock Code to classify fragmented and mixed rocks. Popiolek and others (5) devised a Geotechnical Flysch Rock Mass Classification (KF) and correlated it to the Rock Mass Rating Scheme of Bieniawiski (6) for use with coherent and brecciated rock of the Carpathian Flysch in underground excavations. A companion paper in this Journal by Riedmüller and others (7) introduces an engineering geological characterization for brittle faults and fault rocks.

Because the vast collection of geological terms describing the fundamental fabric of mixed strong blocks in weak matrix tends to be confusing, Medley (1) introduced the term bimrocks, a contraction of the term “block-in-matrix rocks”, introduced by Raymond (4) to describe ”“block-in-matrix” melanges.

The word “bimrock” has no geological or genetic connotations and was defined by Medley (1) to be “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 proportion and size range of the blocks influences the mechanical properties of the strong block/weak matrix mixture at the scale of interest. There are many geological materials that can be described as bimrocks, as long as they conform to the criteria. Amplification of these criteria are presented later in the paper.

In this paper, the term “bimrock” is used wherever the results obtained from studies of melanges can be applied to the characterizations of other rock/soil mixtures, which conform to the definition of bimrocks.

Geological aspects of Franciscan melanges

Melange bodies are present in over 60 countries. Medley (1, Appendix A) lists references and

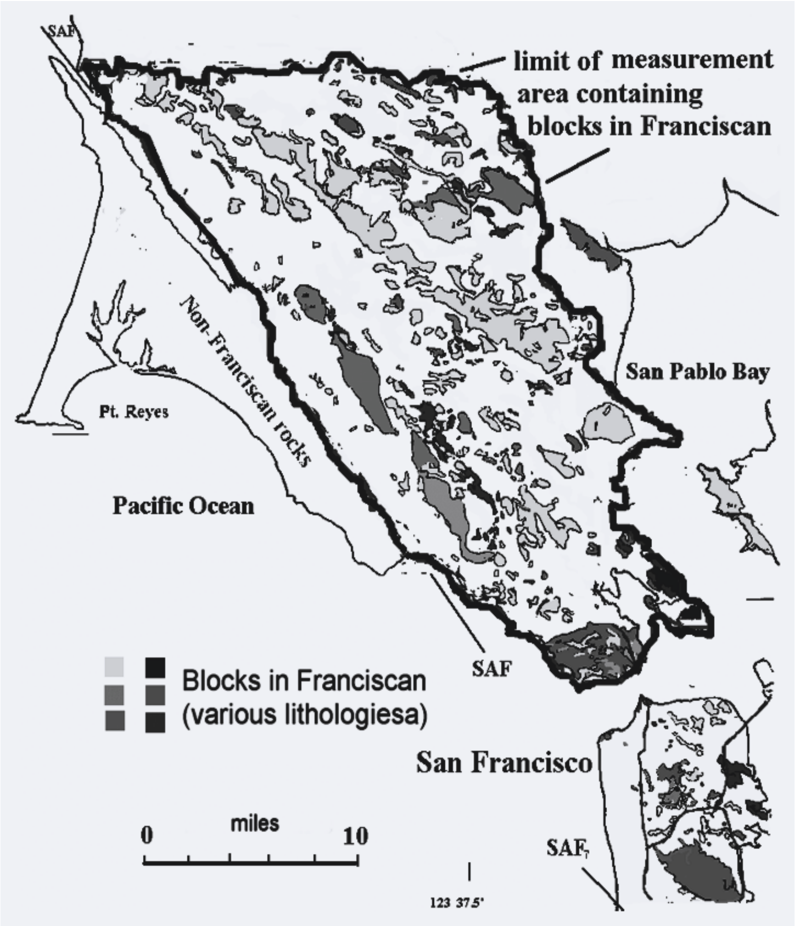


Fig. 2 The Franciscan Complex in Marin County, north of San Francisco. Mapped blocks range to nearly 20 km in length. SAF is the San Andreas fault. Area of interest within indicated boundary is about 1 000 km^2; after (1); base map after (19).

Bild 2 *Der Franciscan Complex in Marin County, nördlich von San Francisco. Die auskartierten Blöcke erreichen fast 20 km Länge. Das Gebiet innerhalb der angegebenen Grenzen umfaßt etwa 1 000 km^2; SAF: San Andreas Fault, nach (1), Kartengrundlage nach (19).*

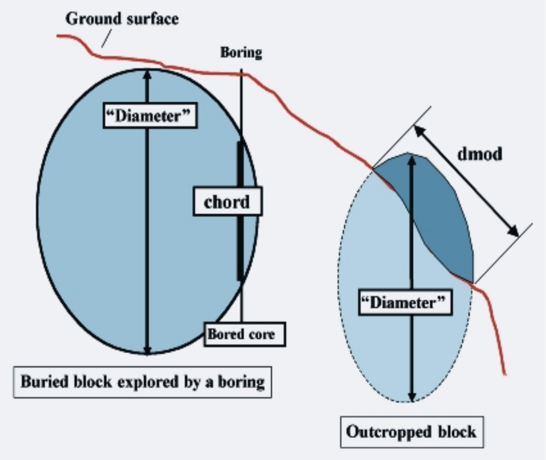


Fig. 3 In two dimensions a block has apparent block size of d_{mod}, the maximum observed dimension. In one dimension, the block size is indicated by the chord length, or intercept between a boring and a block. Only rarely is d_{mod} or a chord length equivalent to the actual “diameter” or maximum dimension of a block, and hence block sizes are generally underestimated.

Bild 3 *Im Aufschluß (2D) hat ein Block die scheinbare Größe d_{mod} (größte sichtbare Dimension), im linearen Anschnitt (1D) ist die Blockgröße durch die Sehnenlänge (chord length) gegeben. Nur selten wird durch d_{mod} oder die Sehnenlänge der tatsächliche Durchmesser oder die größte Dimension eines Blocks erfaßt, daher werden Blockgrößen generell unterschätzt.*

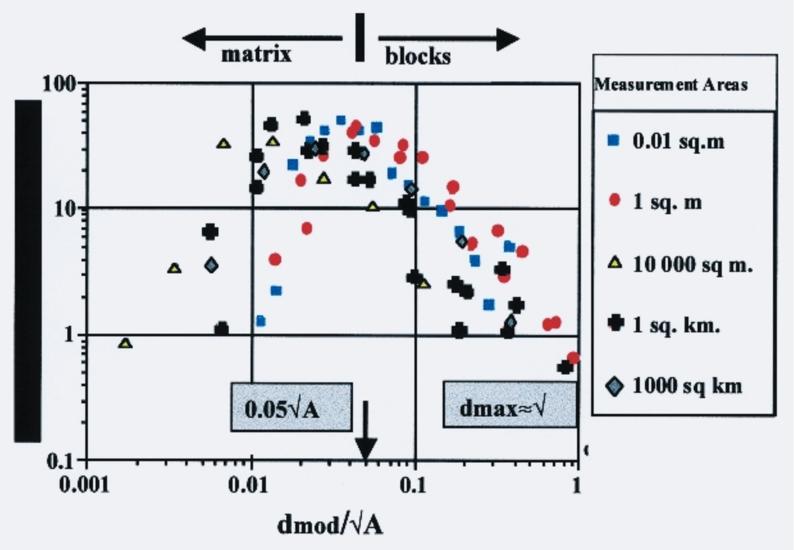


Fig. 4 Normalized block size distribution curves for 1,928 blocks measured from outcrops and geological maps of several Franciscan melanges ranging over seven orders of magnitude in scale, ranging from centimeters to kilometers (after Medley,1). The sizes of blocks are characterized by d_{mod}, the maximum observed dimension of the blocks in the outcrops and maps. The measurements of the block sizes are divided by the square root of the area (√A) containing the measured blocks to yield the dimensionless block size d_{mod}/ √A. The normalizing parameter √A is an indicator of the scale of the outcrop or geological map being measured. The relative frequency of blocks in each of the measured areas is the number of blocks in any size class divided by the total number of blocks in the measured area. The use of normalized block size and normalized numerical frequency allows the comparison of block size distributions over the extreme range in measurement scales. The data from each measurement area forms graphed plots that are similar in shape to each other, regardless of the size of the measured area. The similarity in shapes indicates that the block size distributions are scale independent. The plots peak at about 0.05 dmod/÷A, which is defined as the block/matrix threshold size at any scale. Blocks smaller than 0.05 dmod/÷A tend to be too small to measure and are undercounted. Blocks smaller than the threshold size are assigned to the matrix. The largest indicated block size is approximately equivalent to √A (at d_{mod}/√A =1), but 99 % of the blocks are smaller than about 0.75 ÷A, which is defined as the maximum block size (d_{max}) at the scale of interest.

***Bild 4** Verteilungskurven der normalisierten Blockgrößen von 1.928 in Aufschlüssen und Karten vermessenen Blöcken aus verschiedenen Vorkommen der Franciscan Melange. Die Blockgrößen umfassen sieben Größenordnungen vom cm- bis in den km-Bereich (nach Medley, 1), die Größen wurden als d_{mod} (vgl. Bild 3) aufgenommen. Die Meßwerte wurden durch die Quadratwurzel der Aufnahmefläche (√A als Normalisierungsparameter) dividiert und ergeben dadurch eine dimensionslose Blockgröße d_{mod}/√A. Die relative Häufigkeit von Blöcken in den jeweiligen Aufnahmeflächen wird durch die Anzahl von Blöcken in jeder Größenklasse, dividiert durch die Gesamtzahl der Blöcke in der Fläche gegeben. Die Verwendung normalisierter Werte für Größen und Häufigkeiten von Blöcken erlaubt den Vergleich der Blockgrößenverteilungen über den extrem weiten Bereich der Aufnahmemaßstäbe. Die graphische Darstellung der Messungen ergibt ähnliche Kurven für jede Aufnahmefläche, unabhängig von deren Größe. Dies bedeutet, daß die Blockgrößenverteilungen maßstabsunabhängig sind. Die Kurven erreichen einen relativen Extremwert bei etwa 0,05 dmod/÷A, der als Grenze für die Unterscheidung von Blöcken und Matrix für jeden Betrachtungsmaßstab definiert wird. Blöcke mit Dimensionen unterhalb dieser Schwelle sind einer Messung meist nicht zugänglich und daher unterrepräsentiert; sie werden der Matrix zugerechnet. Die maximale gemessene Blockgröße entspricht etwa dem Wert von √A (bei d_{mod}/√A =1), aber 99% der Blöcke sind kleiner als etwa 0,75 ÷A, welcher Wert als obere Grenze für die Blockgröße im jeweiligen Betrachtungsmaßstab definiert wird.*

shows maps of worldwide locations of melange bodies. Although there are over 2 000 geological references on melanges there are few references on the engineering geology or geotechnical engineering aspects. However, there were a series of works in 1993 to 1995 by the writer and his former colleagues Dr. Eric Lindquist and Professor Richard Goodman, at the University of California at Berkeley. A recent paper was published by Goodman and Ahlgren (8). In parallel with these works have been the significant contributions of Professors Gunter Riedmüller and Wulf Schubert and their colleagues at the Technical University of Graz, Austria. Geotechnical research on melanges has also been performed in Italy by AGI (3), Aversa et al. (9), and D'Elia et al. (10). An important contribution by Irfan and Tang (11) summarizes the geotechnical behavior of soil/boulder mixtures in Hong Kong, with findings applicable to other complex geological mixtures.

As indicated above, this paper specifically considers experience with melanges in Northern California, which are abundant in the jumbled Franciscan Complex (the Franciscan) that covers about one-third of Northern California. Blake (12), Raymond (4), Cowan (13), and Hsü (14) described the geology of Franciscan melanges, and Wahrhaftig (15), Blake and Harwood (16), and Wakabayashi (17) prepared useful field guides. Figure 2 illustrates the mapped appearance of the Franciscan at the scale of Marin County, north of San Francisco. Figure 1, also showing melange but at outcrop scale, shows how similar the fabric is to fault and shear zones.

The matrix of Franciscan melanges is composed of shale, argillite, siltstone, serpentinite or sandstone, and may be pervasively sheared to the consistency of soil. Blocks are not evenly distributed within melanges and congregate to form block-rich and block-poor zones (see Figure 11). The most intense shearing within melanges is often in block-poor zones adjacent to the largest blocks. Savina (18) measured as many as 800 shears per meter. Earth flow landslides commonly occur in block-poor zones.

The weakest elements in a melange are the contacts between blocks and matrix. 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. Shear surfaces generally pass around blocks via the block/matrix contacts (see Figures 11 and 12). Blocks within the shears may be entrained within, and oriented parallel to, the shears (see Figures 1 and 11).

Medley (1) estimated that in the Franciscan of Marin County, California (see Figure 2) about 60 to 70 % of blocks are graywacke, 15 to 20 % are volcanic, 15 to 20 % are serpentinite, 5 to 10 % are chert, and the remaining blocks are rare limestone and exotic metamorphic rock. Blocks may also be composed of intact siltstone and sandstone/siltstone sequences. Large blocks in Franciscan melanges range between smoothly ellipsoidal and irregular in shape and, where measured, have major/minor axis lengths in the approximate ratio of about 2:1 (1).

Block sizes

Block measurements from field mapping or drilling are invariably shorter than the true "diameter" of a block as illustrated in Figure 3. Block sizes are indicated by the length d_{mod} (the maximum observed dimension) of blocks exposed in two dimensions (outcrops or geological maps). In one dimension, block sizes are also measured from sampling lines traversing outcrops ("scan-lines" of Priest, 20), or in drill core, by the chord length formed from the interception between the block and the core.

Scale independence of block size distributions

Many rock/soil mixtures contain a few large blocks and increasing numbers of smaller blocks or, using common geological parlance, the block size distributions tend to be fractal (conforming to negative power law) or else in soils-engineering parlance as "well-graded". Medley (1) and Medley and Lindquist (21) observed fractal block size distributions at many scales of geological interest in Franciscan melanges, which supported observations of fractal size block distributions in other comminuted geological materials such as fault gouges (22), and fractured rock masses (23). In Franciscan melanges, the range in block sizes is extreme, exceeding seven orders of magnitude, between sand (millimeters) and mountains (tens of kilometers) as illustrated in Figure 4. Despite the considerable difference in scales, the melanges depicted in Figure 1 and Figure 2 show block size distributions with similar well-graded appearances.

The block size distributions of Franciscan melanges are also scale independent, meaning that blocks will always be found, regardless of the scale of interest or observation. Over a smaller range of scales, the block size distributions of other rock/soil mixtures (such as glacial tills and fault zones) also show scale independence. Because blocks will always be found in melanges, the distinction between blocks and matrix depends solely on the scale of interest. Small blocks at one scale (e.g. 1: 1 000) are part of the matrix at a larger scale (1:10 000). Likewise, large blocks at one scale of interest (e.g.: 1:10 000) are not geotechnically significant blocks at a smaller scale (e.g. 1:1 000) because they are too large to be considered as individual blocks within the rock/soil mixture. Instead, they can be considered as strong, massive and unmixed rock masses. Figure 5 illustrates the point, which is explained further below.

Characteristic engineering dimension (L_c)

Because of scale independence, any reasonable dimension can be used to scale a melange rock mass for the problem at hand. Medley (1) called such a descriptive length the characteristic engineering dimension, L_c (the "ced" of Medley (1) and later papers). The use of a characteristic engineering dimension is analogous to showing a measuring tape, coin, hand or spouse in a photograph, without which object the observer cannot appreciate the scale of the image. For example, Figure 1 could represent a melange at any scale, since it contains no clear scaling feature other than the information provided in the caption. L_c may variously be

➪ an indicator of the size of a site, such as ÷A, where A is the area of the site,

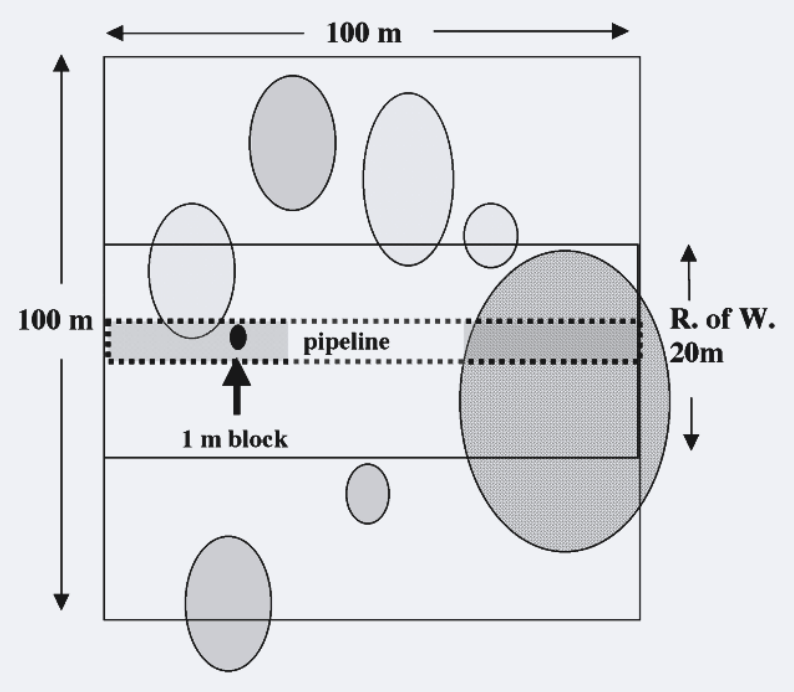


Fig. 5 Sketch showing various scales of interest for an area where a 20 m wide road and 2 m wide, 2 m deep pipeline trench will be excavated in a melange bimrock.

1) The 100 m by 100 m geological map has an area (A) of 10 000 m^2, and hence a √A of 100 m, which is taken as the characteristic engineering dimension (L_c) at the large scale of interest of the overall site. The block/matrix threshold at this scale is 5 m (0.05 L_c or 0.05 √A). Hence the 1 m block in the center of the sketch is part of the matrix. In contrast, at the scale of overall site, the large speckled rock mass at the right of the sketch is a block since it is less than 0.75 L_c (75 m) in size.

2) At the scale of the road Right of Way, L_c is the 20 m width. At this scale of interest, the 1 m block is at the block/matrix threshold (0.05 L_c) and the largest geotechnically significant block is 15 m (0.75 L_c). The large speckled block is massive rock at this scale of interest. Massive rock and blocks greater than about 1 m in size will present difficulties during mass grading of the road.

3) At the scale of the 2 m wide, 2 m deep pipeline trench, L_c can be taken as the depth of the trench. The block/matrix threshold will be 0.1 m, and the largest geotechnically significant block 1.5 m. At the local scale of interest of the trench represented by the trench depth, the 1 m block may present a problem for the trenching contractor. However, at the scale of the overall length of the trench, the speckled block is considered massive rock and will be more challenging since a significant portion of it must be excavated.

Bild 5 *Darstellung der Unterschiede im interessierenden Maßstab in einem Gebiet, in dem eine 20 m breite Straße und ein 2 m breiter, 2 m tiefer Graben für eine Pipeline im Bimrock einer Melange ausgehoben werden sollen.*

1) Die 100 m x 100 m umschreibende geologische Karte umfaßt eine Fläche (A) von 10.000 m^2, √A entspricht daher 100 m. Dies ist die charakteristische geotechnische Dimension (L_c) für das Gesamtgebiet im Kartenmaßstab. Die Grenze zwischen Blöcken und Matrix liegt in diesem Maßstab bei 5 m (0.05 L_c beziehungsweise 0.05 √A), daher ist der 1 m Block im Zentrum der Skizze ein Teil der Matrix. Hingegen stellt der grob gerasterte Fels rechts einen Block dar, da seine Größe unter 0,75 L_c (75 m) liegt.

2) Im Betrachtungsmaßstab des Straßenprojekts ist L_c die Breite von 20 m. Der 1 m Block liegt an der Größenschwelle Block/Matrix (0,05 L_c), und die größte geotechnisch signifikante Blockdimension beträgt 15 m (0,75 L_c). Der grob gerasterte Block (rechts) ist in diesem Maßstab als anstehender Fels zu betrachten. Dieser und alle Blöcke größer als etwa 1 m werden bei der Herstellung des Unterbauplanums Schwierigkeiten bereiten.

3) Im Maßstab des Aushubs für die Pipeline kann für L_c dessen Tiefe (2 m) angenommen werden. Die Größengrenze Block/Matrix liegt bei 0,1 m und für den größten geotechnisch bedeutsamen Block bei 1,5 m. Im lokalen Maßstab der Aushubtiefe kann der 1 m Block ein Problem für die Ausführung darstellen, im Maßstab der Aushublänge jedoch erfordert der grob gerasterte Block mehr Aufmerksamkeit, da er als massiver, anstehender Fels betrachtet werden und auf einer beträchtlichen Länge durchquert werden muß.

- the size of the largest mapped or estimated largest block (d_{max}) at the site,
- the thickness of a failure zone beneath a landslide,
- a tunnel diameter,
- a footing width, or
- the dimension of a laboratory specimen. The characteristic engineering dimension changes as scales of interest change on a project (as indicated in Figure 5).

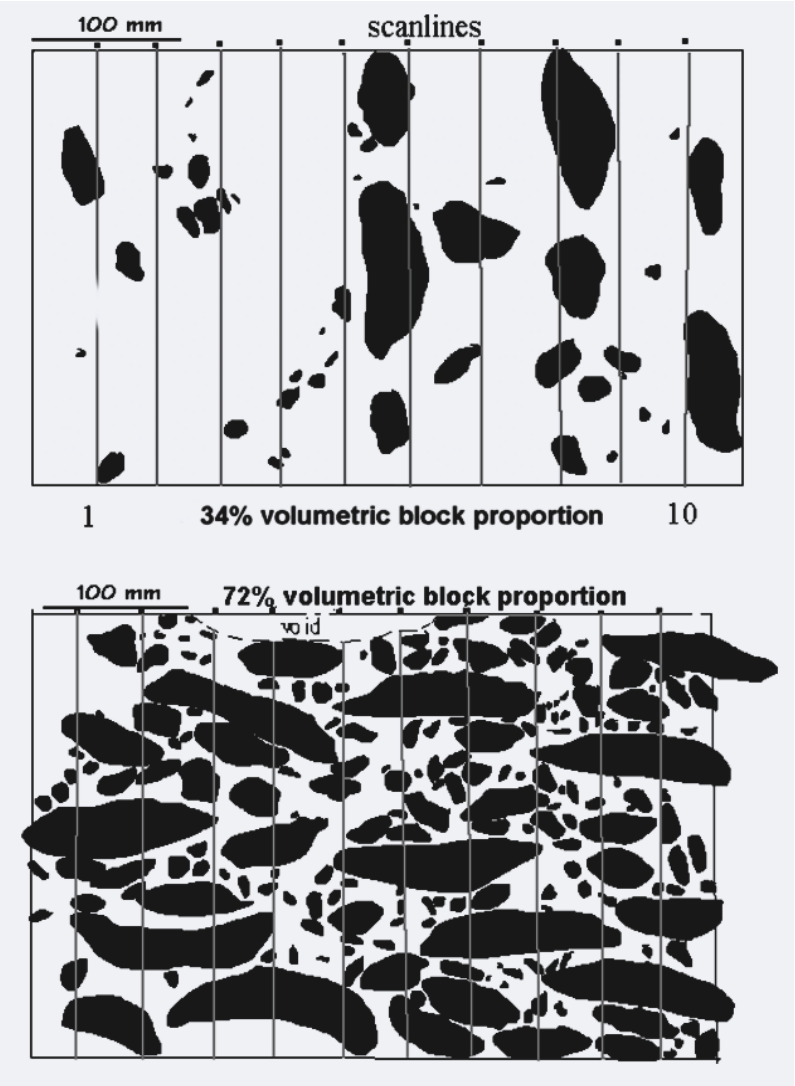


Fig. 6 Tracings of physical model melanges (1, after (25)), with known volumetric block proportions and 3D block size distributions. The tracings were measured by one-dimension (1D) model borings ("scanlines") to yield linear block proportions and chord length distributions. The upper model has a relatively low volumetric block proportion (34 %) where the scanlines are parallel to the orientation of the ellipsoidal blocks. When volumetric block proportion is low, there is less probability that a boring will intersect a block at all, and even less that it will intercept the actual maximum dimension of blocks. The lower model has a high volumetric block proportion (72 %) with blocks oriented approximately horizontal and the exploratory borings oriented vertical. Clearly, in the latter case, even though the probability is high that borings will intersect blocks, the chord length distribution cannot match the actual block size distribution, since the vertical chords are always shorter than the horizontal maximum block dimensions.

Bild 6 *Schnittzeichnungen physischer Modellmelangen (1, nach (25)) mit bekanntem volumetrischem Blockanteil und dreidimensionaler Größenverteilung. Die Zeichnungen wurden über Meßlinien (Modellbohrungen „Scanlines") vermessen, um den linearen Blockanteil und Sehnenlängenverteilungen zu ermitteln. Das obere Modell hat einen relativ geringen volumetrischen Blockanteil (34 %), wobei die Meßlinien parallel zur Längserstreckung der etwa elliptischen Blockanschnitte verlaufen. Bei geringem volumetrischen Blockanteil ist die Chance, mit einer Meßlinie einen Block zu schneiden, gering, noch weniger wahrscheinlich ist es, die maximale Dimension eines Blocks zu erfassen. Das untere Modell hat einen hohen volumetrischen Blockanteil (72 %), wobei die Längsachsen der Blöcke etwa horizontal, die Meßlinien („Erkundungsbohrungen") vertikal verlaufen. Obwohl die Wahrscheinlichkeit, Blöcke zu durchqueren, sichtlich hoch ist, wird die Sehnenlängenverteilung die tatsächliche Blockgrößenverteilung nicht wiedergeben, da die vertikalen Sehnen (Blockdurchstichlinien) immer kürzer als die maximalen Blockdimensionen sind.*

Largest and smallest geotechnically significant blocks

In Figure 4, $\sqrt{A}$ is the characteristic engineering dimension (L_c) for areas of outcrops and geological maps at scales of measurement that range from less than 0.01 square meters (portion of an outcrop) to more than 1 000 square kilometers (Marin County, see Figure 2). Block sizes are characterized by d_{mod}, which is rarely the actual maximum dimension of individual blocks. In Figure 4, block sizes for each set of data are normalized, or rendered dimensionless, by dividing the block size by the length $\sqrt{A}$ of the measured area of each outcrop or area of geological map. The relative frequency in Figure 4 is the proportion of blocks in each size class divided by the total number of blocks in each of the measured maps or outcrops. Figure 4 uses logarithmic axes in its compilation of the log-histogram depiction of the block size distributions. (The term log-histogram was first introduced by Bagnold and Barndorff-Nielsen (24).)

Figure 4 shows that, at all the scales of measurement, the largest blocks are equivalent in size to $\sqrt{A}$ (for $d_{mod}/\sqrt{A} = 1$), but about 99 % of blocks are smaller than about 0.75 $\sqrt{A}$ (0.75 L_c), which is a reasonable maximum block size (d_{max}). Accordingly, the largest geotechnically significant block (d_{max}) within any given volume of Franciscan melange is about 0.75 L_c. Blocks greater than 0.75 L_c 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. (For example, in Figure 5 the very large block at the right side of the sketch is very much larger than the scale of pipeline trench width.)

At all scales of measurement in Figure 4, the graphed data plots of normalized block sizes have peak relative frequencies at about 0.05 $\sqrt{A}$ (equivalent to 0.05 L_c). At block sizes smaller than 0.05 L_c the blocks tend become too small to observe and tend to be undercounted, although in reality there are a myriad of them, and they become obvious once the scale of observation becomes smaller. For any given volume of Franciscan melange, blocks less than 0.05 L_c in size constitute greater than 95 % of the total number, but contribute less than 1 % to the total volume of melange and thus have negligible effect on the mechanical behavior of the melange. For these reasons, the threshold size between blocks and matrix at any scale is taken to be 0.05 L_c (equivalent to 0.05 $\sqrt{A}$).

Figure 5 illustrates how a block at one scale of interest can be part of matrix at a larger scale, but massive rock at a smaller scale. Figure 5 shows that it is essential to consider the possibility of having to penetrate very large blocks when constructing linear facilities such as roads, pipelines and tunnels. Figure 5 also illustrates examples of the selection of L_c for various scales of interest for an area of bimrock.

Block size distributions based on chords

True three dimension (3D) block size distributions in bimrocks are poorly estimated by one dimension chord length distributions obtained from the limited linear sampling of typical geotechnical exploration core drilling. The degree to which chord length distributions match actual 3D block size distributions is dependent on the orientation of blocks relative to the boring directions, volumetric block proportion, and total length of drilling (Figure 6). Since observed chord lengths are almost invariably smaller than the actual block diameters (see, Figure 3), 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 3D block size distribution, as shown in Figure 7. For this reason, it is unlikely that drilling and coring into a melange can recover an actual 3D block size distribution curve. The practical consequence of underestimating block sizes from exploration drilling is that unpleasant and costly surprises are common during excavation and tunneling of bimrocks. The author is developing practical guidelines to constructing 3D block size distributions from 1D measurements.

Mechanical contrast between blocks and matrix

The mechanical contrast between competent blocks and weaker matrix forces failure surfaces to negotiate tortuously around the perimeters of blocks (see Figure 12). Sufficient contrast is afforded by a friction angle ratio ($\tan\phi$ of weakest block)/ ($\tan\phi$ of matrix) of between 1.5 and 2, as suggested by the work of Lindquist (25, 26, 27) and Volpe and others (28). Another means of identifying strength contrasts is to use rock stiffness. Lindquist (25) used a ratio of block stiffness (E, Young's modulus) to matrix stiffness, (E_{block}/ E_{matrix}) of 2.0 to generate block/matrix contrasts for physical models of melange. Satisfaction of block/matrix mechanical contrast criteria such as these are necessary for a block-in-matrix rock mass to be considered a bimrock. For strength ratios or stiffness rations 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.

A wide range of block sizes in bimrocks tends to force failure surfaces to negotiate through matrix and along block/matrix contacts in contorted, tortuous paths. The tortuosity of pre-ex

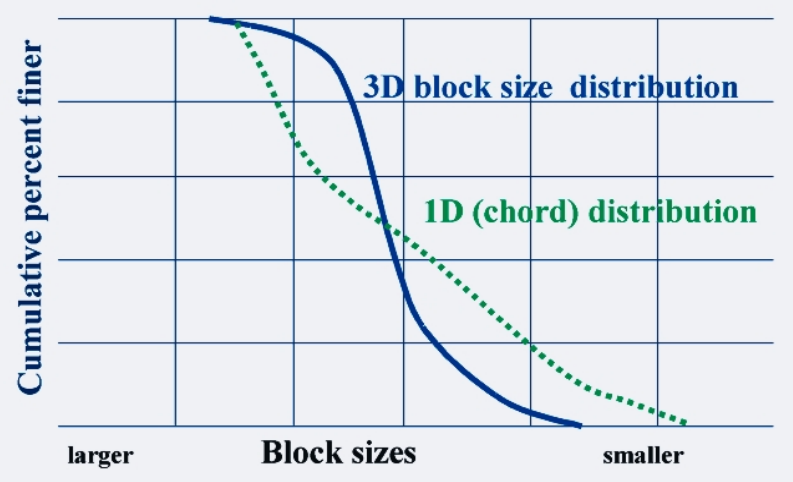


Fig. 7 Schematic block size distribution plots for physical melange models with blocks oriented vertical and parallel to the model borings, such as shown in the second case of Figure 6. 3D block size distributions for blocks (as measured by the actual "diameter") or the largest dimension in three dimensions) compared to 1D chord length distributions (as measured by the lengths of the intercepts between exploration borings and the block). Since chords are rarely equivalent to the maximum dimensions of blocks, the chord length distributions tend to be more "graded" than the parent block size distribution. The size distribution of larger blocks is underestimated by the chord length distribution, and the proportion of smaller blocks is overestimated. Indeed, smaller block sizes are predicted than are not contained in the parent rock mass.

Bild 7 *Schematische Verteilungskurven der Blockgrößen aus Modellmelangen mit den Blocklängsachsen parallel, beziehungsweise normal zu den Bohrungen, wie im Bild 6, unten. 3D Blockgrößenverteilung (Messung der tatsächlichen größten Dimensionen) im Vergleich mit der 1D Sehnenlängenverteilung. Da Sehnen kaum die maximale Dimension eines Blocks erfassen, erscheint ihre Längenverteilungskurve gestreckter als es der tatsächlichen Verteilung in der Population entspricht. Der Anteil in der Verteilung großer Blöcke wird unterschätzt, derjenige kleiner Blöcke überschätzt. Es werden sogar kleinere scheinbare Blockgrößen angegeben, als in der Ausgangsverteilung vorhanden.*

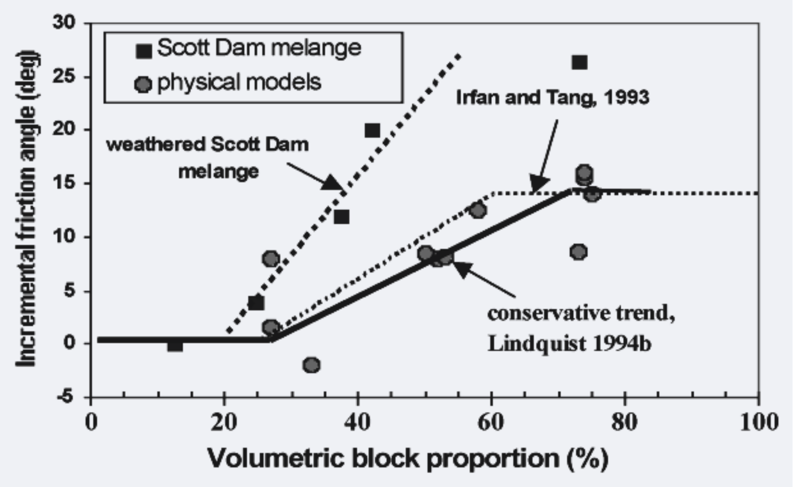


Fig. 8 The strength of bimrocks increases directly with volumetric block proportion. The increase in friction is added to the frictional strength of the matrix. There is marked similarity between the data of Lindquist (26), for physical model melanges, and that of Irfan and Tang (11), for Hong Kong boulder colluvium. However, the data obtained from laboratory testing of weathered Franciscan melange from Scott Dam (30) shows that for some bimrocks, blocks may provide considerably more incremental strength than indicated by the Lindquist and Irfan and Tang experiments. The "conservative trend" of Lindquist (26) could be used in lieu of site-specific testing of Franciscan melanges, after (39).

Bild 8 *Die Festigkeit von Bimrocks nimmt direkt proportional mit dem volumetrischen Blockanteil zu, es kommt zu einer Erhöhung der inneren Reibung über jene der Matrix hinaus. Es besteht große Ähnlichkeit in den Ergebnissen von Lindquist (26) für physische Modellmelangen und jenen von Irfan & Tang (11) für blockreichen (Schwemm-)Schutt. Die Daten aus Laborversuchen mit verwitterter Franciscan Melange vom Scott Damm (30) hingegen zeigen, daß die Blöcke erheblich größere zusätzliche Festigkeit hervorrufen können, als es die Experimente von Lindquist und Irfan & Tang ergaben. Der „konservative Trend" (26) kann anstelle von Tests an den tatsächlich in Projekten in der Franciscan Melange auftretenden Gesteinen verwendet werden.*

Fig. 9 Franciscan melange at Coleman Beach, Sonoma County, Northern California. Blocks form erosion-resistant headlands and also buttress upslope weaker block-poor melange. Several homes are threatened by cliff-top retreat of block-poor melange. The near shore is strewn with relict blocks.

Bild 9 *Die Franciscan Melange bei Coleman Beach, Sonoma County, Nordkalifornien. Blöcke bilden erosionsresistente Landzungen und Vorsprünge über blockarmer, geringfester Melange. Mehrere Häuser sind durch rückschreitende Erosion der Kliffkante in blockarmer Melange gefährdet. Der Küstenbereich ist mit ausgewaschenen Blöcken übersät.*

isting and induced shear surfaces increases shear resistance, as demonstrated by Savely (29), for boulder-rich Gila Conglomerate in Arizona; Irfan and Tang (11) for boulder-rich colluvium in Hong Kong; and Lindquist (25) for physical model melanges. When blocks are uniformly sized, failure surfaces tend to have smoother, undulating profiles (1), and hence the mixed rock mass has less shear resistance.

Relation of volumetric block proportion to melange strength

The overall strength of a Franciscan melange or other bimrock is independent of the strength of the blocks. As long as there is mechanical contrast between blocks and matrix, the presence of blocks with a range of sizes adds strength to the bimrocks mixture by forcing tortuous failure surfaces to negotiate around blocks. Strength and deformation properties of a rock/soil mixture increase directly and simply with increasing volumetric block proportions as shown in Figure 8, which is compiled from the results of Irfan and Tang (11) for boulder-rich colluvium in Hong Kong, and Lindquist (25) and Goodman and others (30) for physical model melanges and melange from Scott Dam, Northern California.

By testing over one hundred 15 cm diameter specimens of physical model melanges, Lindquist (25) determined a conservative relationship between volumetric block proportion and increased strength for physical model melanges (Figure 8). Lindquist showed that below about 25 % volumetric block proportion, the strength and deformation properties of a melange is that of the matrix; between about 25 and 75 %, the friction angle and modulus of deformation of the melange mass proportionally increase; and, beyond 75 % block proportion, the blocks tend to touch and there is no further increase in melange strength. Lindquist's results for model melanges closely matched the findings of Irfan and Tang (11) for actual boulder colluvium in Hong Kong, where some boulders were more than 2 meters in diameter.

However, as shown in Figure 8, some rock/soil mixtures may have different strength/volumetric proportion relationships, as indicated by the trend of the data for weathered Scott Dam melange. Nevertheless, the important feature of Figure 8 is that there is a simple and direct dependence between volumetric block proportions and bimrock strengths.

Lindquist (11) also determined that cohesion tends to decrease with increasing volumetric block proportion for physical model melanges. However, Goodman and Ahlgren (8) observed that cohesion inexplicably increased with volumetric block proportion for Franciscan melange

Fig. 10 Franciscan melange photographed in the spring/early summer. Mottling of lighter tones indicate blocks underlying the hillside (circled).

Bild 10 *Franciscan Melange, aufgenommen im Frühling/Frühsommer: Helle Flecken im Gelände (am Hang, durch Ringe hervorgehoben) weisen auf darunterliegende Blöcke hin.*

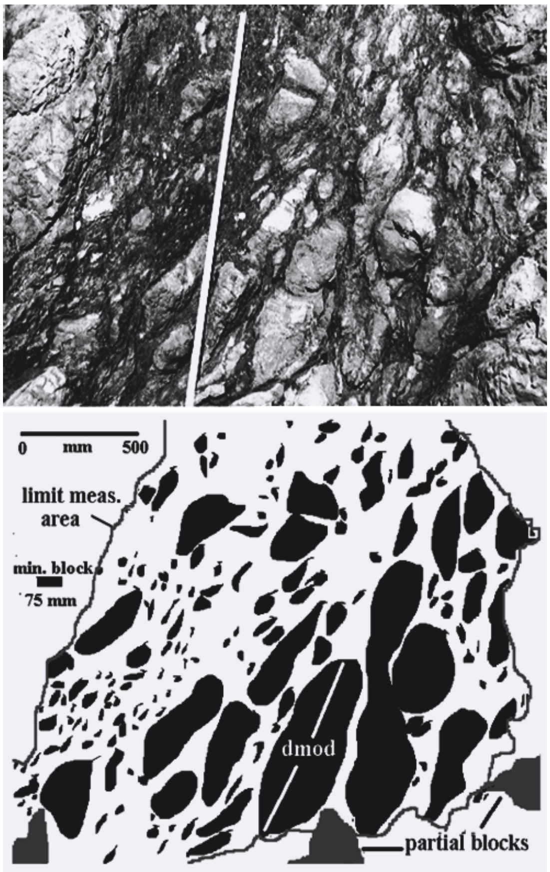


Fig.11 Photograph and sketch of outcrop of Franciscan melange at Caspar Headlands, Mendocino Co., Northern California. The scale bar in the photograph is 1.5 m long. The sketch shows the blocks discriminated by image analysis software. Block sizes are characterized by d_{mod} (maximum observed dimension). The area of measurement excludes two partial blocks at the lower right of the outcrop. At the scale of the outcrop, the size of blocks at the block/matrix threshold (75 mm) is shown by the black bar midway on left side of sketch ("min. block 75 mm"). Note block-poor and block-rich areas. From Medley (1) and Medley and Lindquist (21).

Bild 11 *Foto und Skizze eines Aufschlusses der Franciscan Melange bei Caspar Headlands, Mendocine Co., Nordkalifornien; der Meßstab im Bild ist 1,5 m lang. Die Skizze zeigt Blöcke, die durch den Einsatz von Computer-Bildanalyse herausgefiltert wurden. Blockgrößen werden durch* d_{mod} *(größte sichtbare Dimension) charakterisiert. Der Bearbeitungsausschnitt schließt zwei Teilblöcke am rechten unteren Bildrand aus. Die Größe der Blöcke an der Block/Matrix Schwelle (75 mm im Aufschlußmaßstab) ist durch den schwarzen Balken links („min. block 75 mm") verdeutlicht. Man beachte blockarme und blockreiche Gebiete. Aus Medley (1) und Medley & Lindquist (21).*

in the foundation of Scott Dam in Northern California. Because of the as yet unresolved contradiction between these finding, it is prudent to neglect any benefit of uncertain increased cohesion with increased volumetric block proportion.

Estimation of volumetric block proportion

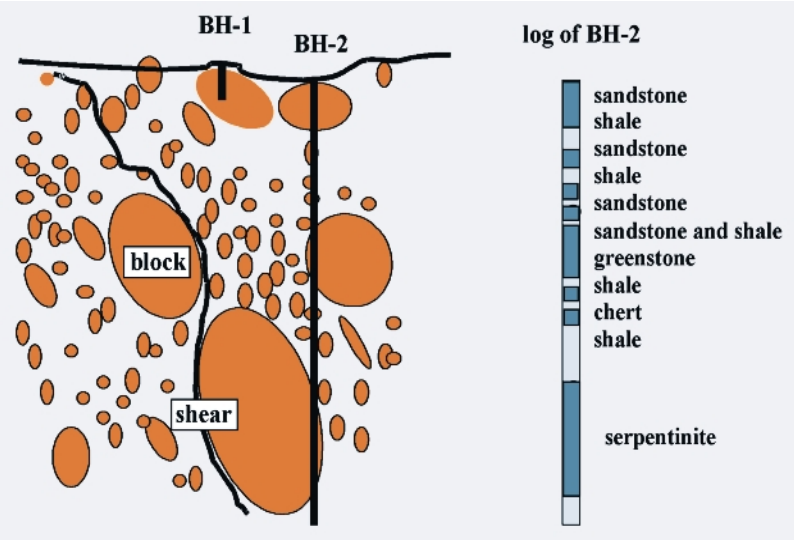
As described above, the volumetric block proportion of a Franciscan melange or other bimrock is necessary to predict the geomechanical properties. The volumetric block proportion is approximated by measuring areal block proportions from outcrops, or linear block proportions from scanlines and exploration core drilling. The areal block proportion is the sum of the measured areas of blocks to the total area of rock mass measured. The linear block proportion is the ratio of the total length of block/boring intersections (chord lengths) to the total length of sample lines. The assumption that measured areal or linear block proportions are equivalent to the required volumetric block proportions is only valid given that there is enough sampling. Such equivalence is one of the fundamental laws of stereology, an empirical and mathematical study relating point, line and planar observations to the true geometric properties of objects (31, 32).

Since blocks in melanges are not uniformly sized or distributed, the volumetric block proportion cannot be accurately determined from a few borings, but given sufficient total lengths of sampling lines (at least 10 d_{max}) the linear block proportion approaches the volumetric block proportion with an error, or uncertainty, that can be roughly estimated (1, 33, 34, 35, 36, 37).

Although the desirable minimum total length of exploration drilling is equivalent to at least 10 d_{max}, optimum geotechnical exploration is rarely performed, even when subsurface conditions are relatively straightforward. Medley (35) considered the error in estimates of volumetric block proportion based on the assumption that they are the same as the measured linear block proportions. He fabricated physical models of melange with known block size distributions and volumetric block proportions and explored the models with hundreds of model boreholes. The experiments showed that measured linear block proportions had to be adjusted by an uncertainty factor to yield an appropriate estimate of the volumetric block proportion.

Fig. 12 Shears in melanges typically tortuously negotiate around blocks at the block/matrix contacts. Sketch also shows exploration of a bimrock by borings (BH). BH-1 terminates in a block, a situation that, in Northern California, often results because the investigator identifies the block as "bedrock". The log of BH-2, shows a sequence of rocks that is not "inter-bedded sandstones and shales", because the juxtaposed presence of chert, greenstone and serpentinite suggests the presence of Franciscan melange. Note that BH-2 only rarely penetrates the "diameter" of a block.

Bild 12 *Scherflächen in Melangen nehmen typischerweise einen gewundenen Verlauf entlang der Grenze zwischen Blöcken und umgebender Matrix. Die Skizze zeigt auch die Erkundung eines Bimrock durch Bohrungen (BH). BH-1 endet in einem Block: eine Situation, die in Nordkalifornien häufig vorkommt, da der Bearbeiter den Block als Anstehendes (Grundgebirge) deutet. Das Kernaufnahmeprotokoll von BH-2 zeigt keine „Sandstein- (Ton-/Silt-) Schiefer-Wechsellagerung", weil die zusätzliche Präsenz von Radiolarit, Diabas und Serpentinit das Vorliegen von Franciscan Melange nahelegt. Man beachte, daß BH-2 nur selten einen Block-„Durchmesser" durchstößt.*



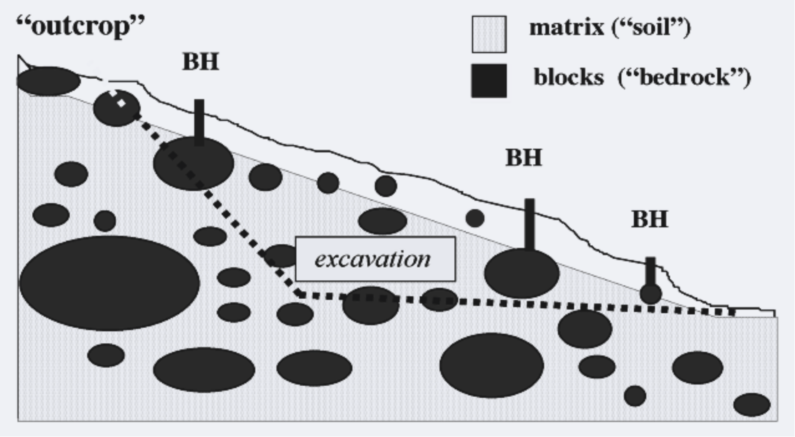


Fig. 13 Borings (BH) in melange. Borings have been terminated in rock interpreted as continuous "bedrock" rather than blocks, and the matrix as "soil" or "soil with boulders". Because of this misinterpretation, the excavation of the designed slope will be troublesome.

Bild 13 *Erkundungsbohrungen (BH) in Melange; die Bohrungen setzen in Blöcken auf, die fälschlich als Anstehendes (Grundgebirge mit durchgehender Felslinie) und die Matrix als „Boden" oder „Boden mit Findlingen" bezeichnet werden. Aufgrund dieser Fehlinterpretation wird der Abtrag der geplanten Böschung Probleme mit sich bringen.*

Uncertainty depends on both the total length of the linear measurements, such as from drilled core, and the linear block proportion itself. The uncertainty factor to be applied to the linear block proportion is both positive and negative. The actual volumetric block proportion may lie anywhere within the range defined by the adjusted lower and upper volumetric block proportions. As described by Medley (35), it is prudent and conservative to apply the uncertainty adjustment to reduce (negative adjustment) the calculated estimates of volumetric block proportions for the purpose of assigning strength parameters for a bimrock. On the other hand, because of the economic consequences of underestimating volumetric block proportions to be excavated by tunneling or earthwork construction, it is prudent and conservative to increase (positive adjustment) the calculated estimates of volumetric block proportions. (The uncertainty factor is shown in Figure 15, the use of which is described later in this paper).

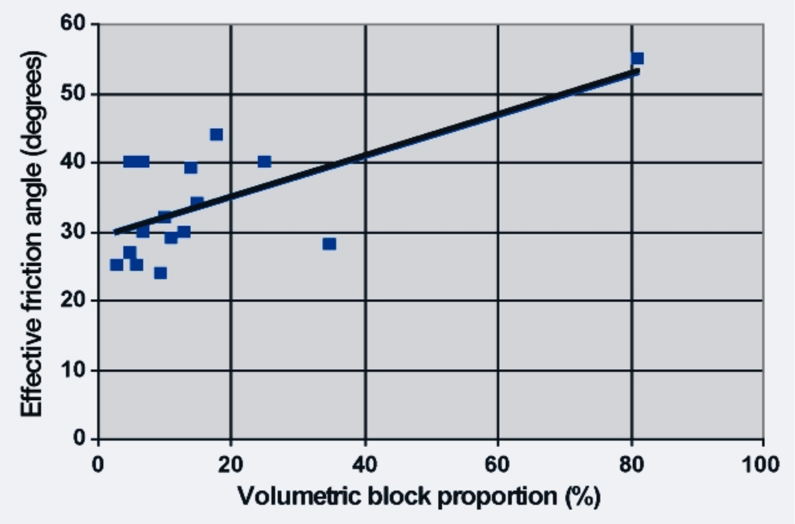


Fig. 14 Plot of effective friction angle as a function of volumetric block proportion, generated from laboratory testing of Franciscan melange specimens obtained from core drilling at Scott Dam, Northern California (8). The correlation is not good, but a straight line fit is appropriate, given prior experience with laboratory testing of bimrocks (see Figure 8). Inclusion of the sole data point at 80 % volumetric block proportion renders the best-fit line more conservative.

Bild 14 *Effektiver Reibungswinkel als Funktion des Blockanteils als Resultat von Labortests an Bohrkernproben aus der Franciscan Melange beim Scott Damm Projekt, Nordkalifornien (8). Die Korrelation ist schwach, doch kann eine lineare Abhängigkeit aufgrund vorheriger Erfahrungen mit der Laboruntersuchung von Bimrock angenommen werden (vgl. Bild 8). Die Einbeziehung des Einzelwerte bei 80 % volumetrischem Blockanteil ergibt einen konservativen Trend der Ausgleichsgeraden.*

Practical guidelines for engineering geological characterization of melanges and similar bimrocks

Elements in a program to characterize a volume of Franciscan melange or other rock/soil mixture include

- establishing characteristic engineering dimensions (L_c),
- estimating the sizes of smallest and largest blocks,
- mapping,
- exploration drilling,
- geologic interpretation,
- laboratory testing,
- estimating rock mass volumetric block proportion,
- estimating of rock mass strength, and
- estimating block size distributions.

Guidelines for performing each of these nine elements are provided in the following sections. The guidelines are derived from case histories (1, 38, 39).

Establishing of characteristic engineering dimensions (L_c)

Flexibility is exercised in the selection of L_c, as illustrated in Figure 5. For an entire site or outcrop, determine the area of interest (A). Choose L_c as equivalent to $\sqrt{A}$. For an excavation or trench use the height of the excavation. At the scale of the entire excavation or trench, measure the explored area (A) and use $\sqrt{A}$. For a landslide use a critical cross-section depth or the thickness of the failure zone, as described by Medley (1, 39) for the Lone Tree Landslide in Marin County, Northern California. For foundation footings use the foundation width. If piles or caissons will be driven or drilled through the bimrock, use the pile diameter. For tunnels, at the scale of the entire tunnel length, measure the explored area (A) and use $\sqrt{A}$. At the scale of the tunnel face, use the tunnel diameter. (Medley (1, 39) provided examples of the use of characteristic engineering dimensions for the Richmond Transport Tunnel excavated in 1994 through Franciscan melange in San Francisco). For dam foundations use the most critical of dam width, dam height, $\sqrt{A}$ of footprint area, or some minimum design dimension such as the thickness of a critical shear failure zone, as described by Medley (1) and Goodman and Ahlgren (8).

Estimating the sizes of smallest and largest blocks

As described above, geotechnically significant blocks that influence bimrock strength range between about 0.05 L_c at the block/matrix threshold and 0.75 L_c for the largest block (d_{max}). Select the most conservative block/matrix threshold that can be justified. As shown in Figure 5, blocks smaller than 0.05 L_c are demoted to matrix at an overall site scale of interest, but may still be of substantial size at a contractor's smaller scale of interest, and where excavation equipment capabilities must be considered.

Mapping

Block-poor zones in Franciscan melange landscapes are geomorphologically expressed as valleys and landslides. Block-rich regions and individual blocks form erosion-resistant outcroppings, hills, rocky protuberances and stacks and craggy headlands along rivers and coastlines (Figure 9), where they act as buttresses. Blocks may be vegetated with trees, whereas surrounding mobile, creep-prone matrix soils are sparsely vegetated. The sandier soils above blocks lose moisture more quickly than clayey matrix soils, and in the spring and early summer, large blocks at shallow depths may be identified by browning grasses and shrub vegetation overlying them. Matrix soils host greener vegetation. In air photos, the presence of near-surface blocks shows as tonal mottling (Figure 10).

At outcrops, the mechanical contrast between blocks and matrix can be established using a rock pick. Friction angles of blocks and matrix can be estimated using standard strength scales such as those provided by the Geological Society Engineering Geology Working Party (40). The geologist should observe the nature of exposed block/matrix contacts, the matrix fabric, the block lithologies, and the array and nature of the discontinuities in the blocks (1). A highly fractured block is a weak block that may have little mechanical contrast and should be assigned to the matrix. Zones of weakness in large blocks may also act as "channels" for developed failures. Shearing at different scales is common in melanges and should be mapped.

Photographs of outcrops should be taken at different scales with an indicator of the scale, such as a tape measure, included in the photograph (Figure 11). The procedure was described in more detail by Medley (1). The maximum observable dimensions (d_{mod}) of exposed blocks can later be measured, either manually or using image analysis software, as described by Medley (1) and Medley and Lindquist (21).

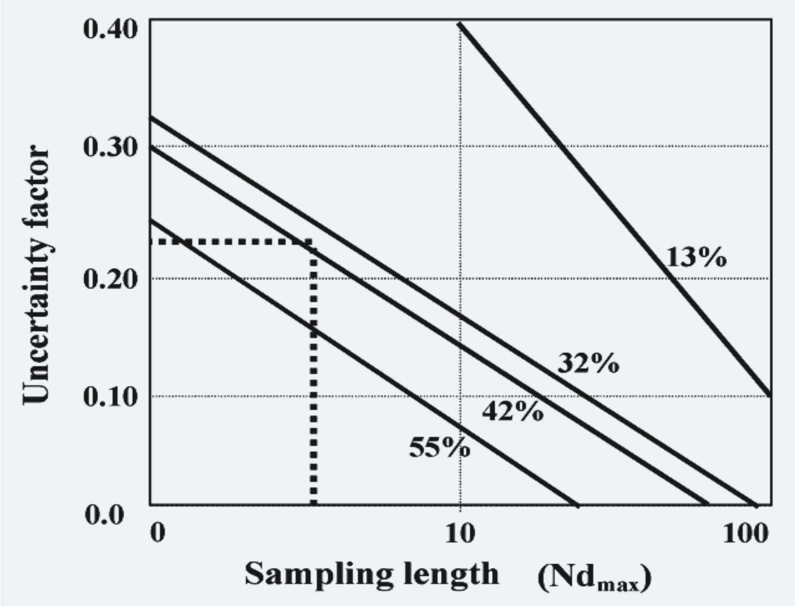


Fig. 15 Uncertainty in estimates of volumetric block proportion as a function of the length of linear measurement, expressed as a multiple (N) of the length of the largest block (d_{max}), and the measured linear block proportion (13 to 55 %). (35). The dashed line is shows the use of the graph for an example (provided in the text) at Scott Dam, where the 150 m of drill core (sampling length) was equivalent to 5 times the size of the largest block expected in the region of the dam (30 m). Hence, Nd_{max} is 5. The measured liner block proportion was 40 %. Entering the graph at Nd_{max} of 5, and intersecting the linear volumetric proportion of 40 % (interpolating between 42 and 32 % diagonal lines), gives an uncertainty factor of 0.23 (dimensionless). The uncertainty is assuming that the linear block proportion is the same as the volumetric block proportion is estimated as 40 % ± (0.23·40 %), or 40 % ± 9 %, giving upper and lower bounds of 31 % and 49 %. The actual volumetric block proportion will generally lie within the range of the lower and upper bounds. It is prudent to use the lowest estimate if the volumetric block proportion will be used to estimate bimrock strength. On the other hand, if the volumetric block proportion will be used for excavation purposes, it may be appropriate to overestimate the block proportion, in which case the upper bound could be used.

Bild 15 *Die Unsicherheit in der Einschätzung der volumetrischen Blockproportion als Funktion der Meßlinienlänge, ausgedrückt als Vielfaches (N) der Länge des größten Blocks (d_{max}) und der gemessenen linearen Blockproportion (13 bis 55 %) (35). Die gepunkteten Linien zeigen die Anwendung des Diagramms für ein Beispiel vom Scott Damm (siehe Text), wo 150 m Bohrkernlänge der fünffachen Länge des größten zu erwartenden Blocks (30 m) im Projektsbereich entsprachen, daher: Nd_{max} = 5. Der gemessene lineare Blockanteil betrug 40 %. Geht man auf der Abszisse bei Nd_{max} = 5 in das Diagramm und hoch bis zur Bestimmungsgeraden für 40 % (Interpolation zwischen 32 % und 42 %), erreicht man horizontal zurück die Ordinate bei einem (dimensionslosen) Unsicherheitsfaktor von 0,22. Die Unsicherheit, daß die lineare Blockproportion gleich der volumetrischen ist, beträgt damit 40 % ± (0,22·40 %) oder 40 % ± 9 %, was obere und untere Grenzen der Unsicherheit von 49 %, beziehungsweise 31 % ergibt. Es wird geraten, den unteren Grenzwert zur Berechnung der Festigkeit von Bimrocks zu verwenden. Andererseits kann es zur Beurteilung von Abtragsarbeiten angezeigt sein, den Blockanteil höher einzuschätzen und den oberen Grenzwert zu verwenden.*

Exploration drilling

There should be no expectation that exploration drilling will adequately intercept all, or even many, of the blocks within a mass of bimrock. As indicated above, the desirable minimum total length of exploration core drilling is about 10 d_{max}. For example, at a site where $\sqrt{A}$, equivalent to L_c, is 100 m, the largest block (d_{max}) will be about 75 m in size. Hence, at least 750 m of drilled core is preferable, but is unlikely to be drilled due to cost and time constraints. In this case, conservative adjustments to the linear block proportion must be made to provide prudent estimates of volumetric block proportions and block size distributions.

It is difficult to recover good quality core in melanges and similar rock/soil mixtures because of the abrupt variations between blocks and matrix, varying block lithologies (Figure 12), extensive shearing, and highly fractured small blocks. Alternate dry and flush drilling is considered poor practice in the drilling of bimrocks (7). Exploring of bimrocks by core drilling requires an experienced geologist, a skilled and dedicated drilling crew, and high-quality drilling equipment, although the provision of these does not preclude disappointing results: Goodman and Ahlgren (8) describe the poor sample recovery of Franciscan melange at Scott Dam, Northern California, even when using triple-barrel samplers and the Integral Sampling Method of Rocha (41) (a method in which friable rock is pre-grouted and then cored). As described by Riedmüller et al. (7), good results have been obtained faulted rocks by drilling continuously with double or triple tube core barrels and using a polymer as a flushing agent. The agent tends to prevent the disintegration of the drill core and promotes drill hole stability by the formation of a transparent filter skin on the bore hole wall.

When logging core, measure all block/core intercepts (chord lengths) greater than 2 to 3 cm long, even if the block/matrix threshold is larger. The information on small blocks will be useful for work performed at laboratory scale. The degree of alteration and fracturing, as well as the surface properties of discontinuities and their inclination to the borehole axis, should also be recorded. Estimates of the linear block proportions should be made during core logging and the core should be photographed. Wrap the core promptly since matrix, particularly in sheared melanges, may dry and slake. Examples of suggested practice in the logging of melange core is provided by several case histories described by Medley (1). Brosch et al. (42) and Harer and Riedmüller (43) were able to discriminate rockmass features using an Acoustic Borehole Televiewer combined with visual inspection of the drill cores and a computerized evaluation of the detected features.

Geological interpretation

The problems of characterizing Franciscan melanges and other rock/soil mixtures are compounded by inappropriate use of commonly used geological terms. For example, a succession of shale matrix and sandstone blocks in drill core may result in Franciscan melange being logged as interbedded sandstones and shales (see Figure 12, BH-2), which incorrectly suggests lateral continuity. True blocks of coherent sequences of shales and sandstones are generally unsheared and the shales lack small blocks as described by Medley (1). Melanges also contain juxtaposed blocks of diverse lithologies that represent improbable depositional environments (as logged in BH-2, see Figure 12). A mental picture of the spatial and lithologic variety of bimrocks, similar to Figure 12, will reduce errors in geological interpretations.

Melanges should not be described as soil with boulders, a term that can mean different things to the geologist who encounters blocks during exploration and the contractor who has to construct through or around them. Boulders are often considered to range in size between 200 mm to 2 m. A practitioner may observe blocks in outcrops or in a boring and call them “boulders”, which implies to a contractor that they can be excavated and can be considered “soil”. However, an unexpectedly large block that substantially fills a tunnel face will not likely be considered “soil” by the tunnel contractor, as pointed out by Attewell (44). Furthermore, since chord lengths usually underestimate the true “diameter” of blocks, the apparent “diameter” of observed “boulders” may actually be chord lengths close to the edge of large blocks (see Figures 3 and 12; BH-2). The excavation or penetration of blocks larger than about 1.5 to 2 m diameter may require expensive blasting or jack hammering.

Borings are commonly terminated about 1 to 2 m into bedrock as shown in Figures 12 and 13. But logging the material encountered in the borings as soil above bedrock increases the probability that the blocks will later be interpreted as continuous bedrock, which could result in erroneous slope design and troublesome excavation, as shown in Figure 13. In Marin County, Northern California, a mischaracterization similar to the one depicted in Figure 13 resulted in a landslide repair costing ten times as much as originally estimated.

Laboratory testing

Because of scale independence, laboratory specimens of melange are scale models of melange at rock mass scale. The results of laboratory testing are thus more directly applicable to in-situ melange rock masses than for many other geological materials. Specimens of melange with varying block proportions have been tested to develop relationships between block proportions and strengths at laboratory scale (8, 25, 26, 27). Specimen testing should be performed by laboratories experienced in rock testing, using multistage testing methods, where specimens of melange are subjected to several loads, each applied to the onset of increased strain at peak stress (8, 25, 26,27, 45, 46). For each specimen tested, a series of Mohr’s circles can be drawn to identify the effective friction angle and cohesion.

The volumetric block proportions of each specimen can be determined after carefully disaggregating them and wash sieving to retrieve the blocks. Given that the characteristic engineering dimensions of the laboratory specimens are their diameters, blocks are those intact inclusions that have maximum dimension between about 5 % and 75 % of the diameter of the specimens. The volume of blocks (and hence the volumetric block proportion) is measured by weighing the blocks once the specific gravity of the blocks is known. The testing of specimens with different proportions of blocks yields plots of effective friction angle as a function of volumetric block proportion, such as that shown in Figure 14. Plots can also be developed for cohesion and deformation parameters (8, 25).

Estimating rock mass volumetric block proportion

For the selected characteristic engineering dimension (L_c), identify the block/matrix threshold size as $0.05\,L_c$, and ignore all chord lengths shorter than the threshold size. Calculate the linear block proportion by dividing the sum of the chord lengths by the total scanline or total length of borings. To estimate the volumetric block proportion, the linear block proportion must be adjusted for uncertainty using a plot such as that shown in Figure 15. To use Figure 15, first estimate d_{max} (size of largest expected block), and calculate multiples (N) of d_{max} (Nd_{max}) by dividing the total length of sampling by d_{max}. Enter the graph at Nd_{max}, and for the estimated linear block proportion identify uncertainty at the left axis. Interpolate between the diagonal lines if necessary. To obtain the range of volumetric block proportions, multiply the linear block proportion by the uncertainty, and subtract the product from the linear block proportion (for the lower bound), and add for the upper bound. The lower bound is used for purposes of estimating bimrock strength and the upper for estimating block proportion for earthwork construction.

At Scott Dam, Northern California, the likely mode of dam failure was considered to be sliding along an assumed 3 m thick shear zone within the melange adjacent to the base of the dam. On the basis of field mapping, the size of the largest block (d_{max}) in the area of the dam was estimated to be about 30 m long. Because of the significance of the anticipated failure mode, the 3 m thickness of the shear zone was selected as the characteristic engineering dimension (L_c). The block/matrix threshold was calculated as 0.15 m (i.e. 5 % of 3 m).

About 360 m of exploratory drilling had been performed during the life of the dam, but only about 150 m of core had been recovered. Accordingly, the total length of coring was equivalent to about $5d_{max}$ (i.e. $150\text{m}/d_{max}$ where d_{max} was 30 m.) Inspection of drill logs and photographs of core penetrating the assumed potential failure zone indicated that the linear block proportion, for blocks greater than 0.15 m, was about 40 %. As shown in Figure 15, for a linear block proportion of 40 %, and a sampling length of $5\,d_{max}$, the uncertainty factor is about 0.23. Hence the estimated range of volumetric block proportion was 40 % ± (0.23·40 %), or about 40 % ± 9 % to yield a lower bound of 31 % and an upper bound of 49 %. Since it is prudent to take the lowest estimate of the volumetric block proportion for the purposes of estimating melange strength, the 31 % estimate is the most appropriate. As described by Goodman and Ahlgren (8), a value of 31 % was actually adopted as a conservative estimate of the average block proportion in the Franciscan melange at the base of the dam.

Estimating rock mass strength

The overall strength of Franciscan melange rock masses is determined by using the estimates of in-situ volumetric block proportion and the laboratory test plots of effective friction angle and cohesion as a function of volumetric block proportion, such as the one shown in Figure 14. It may be necessary to determine strengths for block-poor and block-rich zones within the rock mass, which may vary significantly from the overall average. In the case of Scott Dam, the friction angle was estimated to be 39 degrees for the overall volumetric block proportion of 31 % (8).

Estimating block size distributions

Although the strength of the blocks does not influence the overall strength, the lithology, discontinuity fabric, number, and size distribution of blocks are of concern to tunneling or earthwork contractors. For example, blocks greater than about 0.6 m in diameter are too large to be plucked by scrapers and must be excavated by bulldozers; and blocks larger than about 1.5 to 2 m must be blasted. Encountering blocks complicates tunneling, so there is some value in making pre-construction estimates of possible block sizes. For example, between 1994 and 1995, while tunneling through Franciscan melange for the Richmond Transport Tunnel in San Francisco, the contractor had to traverse 200 m through an unexpected graywacke block. Medley (1) had earlier predicted that the tunnel could encounter a block as large as 600 m.

Although the estimation of block size distributions from drilling data is unreliable (see Figures 3 and 7), very approximate estimations can be made for Franciscan melanges using a method described by Medley and Lindquist (21). First establish d_{max} at the appropriate scale of interest, then construct a first approximation for the block size distribution using the finding (1) that for some number of blocks (n) within a certain size class there will be about 5 n in the previous size class and 0.2 n in the following size class. Size classes are constructed such that the span of each class is twice that of the previous class. Next, starting with d_{max}, work backwards through the size distribution. (For example, if d_{max}, is thought to be 3 m, then initially assume that there is one block in the 2 to 4 m class. Hence there will be about five blocks in the 1 to 2 m class, about 25 blocks in the 0.5 to 1 m class, about 125 blocks in the 0.25 to 0.5 m class, and 625 blocks in the 0.125 to 0.25 m class. The latter class contains the block/matrix threshold size, 0.15 m (i.e. 5 % of d_{max}, 3 m). The volume of individual blocks can be estimated assuming spherical or ellipsoidal blocks. The volume of all blocks in any particular class can be estimated by determining the volume of a single block with a dimension equivalent to the average size in the class, and multiplying that volume by the number of estimated blocks in the class. Finally, the total volume of blocks in all classes, divided by the volume of bimrock being considered should match the estimated volumetric block proportion (preferably an upper bound estimate which incorporates uncertainty). If there is a difference, make adjustments to the assumed block size distribution (for example by doubling the number of blocks in the classes), and repeat the calculations until the volumetric block proportions match. This method gives approximate and conservative estimates but is useful for pre-excavation planning (34).

Conclusions

Engineering geologists and geotechnical engineers working in Northern California (and elsewhere in the world) cannot avoid encountering and working with chaotic bimrocks such as melange, faulted breccia/gouge mixtures and other rock/soil mixtures. However, despite their heterogeneity, such mixtures can be reasonably characterized for the purpose of geological engineering design and construction. Even where there is great uncertainty in the characterization, the work performed to produce broad estimates of block proportions, block sizes, lithologic proportions, bimrock strengths and deformation properties will focus the attention of geologists, engineers, owners and contractors on the difficulties that may be encountered during design and construction.

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