UNIVERSITY OF NEVADA/RENO/5-7 JUNE 1995

Rock Mechanics Proceedings of the 35th U.S. Symposium

Edited by

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A. A. BALKEMA / ROTTERDAM / BROOKFIELD / 1995

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The engineering significance of the scale-independence of some Franciscan melanges in California, USA

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ABSTRACT: Block size distributions were determined for several Franciscan melanges contained within regions with measured areas (A) ranging between cm^2 and km^2. The data were plotted as log-histograms and were found to be individually fractal and, when normalized, collectively scale-independent. Hence, blocks will be encountered in melanges at all scales. A block/matrix threshold size for a Franciscan melange rock mass of any scale is defined as $0.05\sqrt{A}$. A tentative generic fractal dimension of 1.3 for Franciscan melanges allows rough estimates to be made of the block size distributions of Franciscan melange rock masses, given A and the volumetric proportion of blocks.

DEDICATION TO PROFESSOR RICHARD E. GOODMAN: We dedicate this paper to our teacher, Professor Richard E. Goodman, whose contributions to Rock Mechanics and Geological Engineering have ranged between the laboratory and dam sites, and so can aptly be called "scale-independent".

1 INTRODUCTION

A melange body (French: *mélange*, or mixture) is a mixture of relatively strong inclusions (*blocks*) of rock, ranging in size between sand and mountains, embedded within a weaker matrix of sheared argillite, shale, siltstone or serpentinite. Melanges, which often appear as sketched in Figure 1, have been identified in the mountainous regions of over 70 countries (Medley, 1994a) and are represented in northern California by the Franciscan Complex (the Franciscan), part of which is shown in Figure 2. The fabric of melanges ranges between *broken formations* which contain blocks of sandstone, intact shales or coherent sandstone and shale sequences within disrupted shales matrices, through *tectonic melanges*, which have thoroughly sheared argillaceous matrices and contain blocks of sandstones, cherts, greenstones, limestones and *exotic* high-grade metamorphic rocks (e.g.: blueschists).

Melanges are part of the large family of block-in-matrix rocks that Medley (1994a) called *bimrocks*, which are mixtures of rocks composed of *geotechnically significant blocks*, within bonded matrices of finer texture. Geotechnically significant blocks are mechanically superior to a matrix and have size distributions and volumetric proportions that directly influence the overall mechanical properties of the bimrock at the scales of engineering interest. Many geologic processes produce the vast range of block-in-matrix rocks (described by Laznicka, 1988), although only those with geotechnically significant blocks may be regarded as bimrocks *similar* to melanges (e.g.: olistostromes, broken formations, sheared serpentinites, serpentinite melanges, and possibly lahars, tillites and fault breccias)

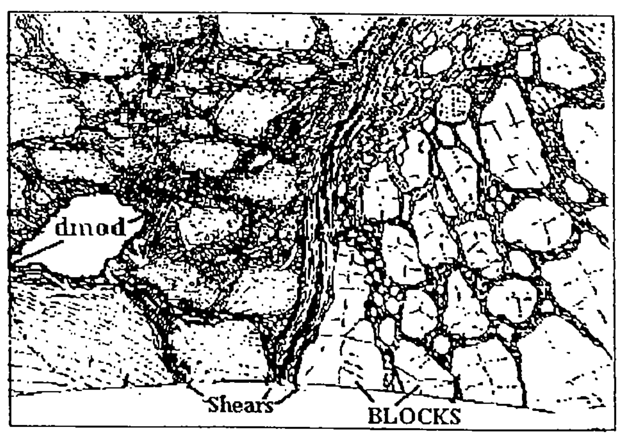


Figure 1 Franciscan melange in road cut shows blocks enclosed by shears. Sizes are characterized by d_{mod}. (After Medley, 1994b; courtesy Dr. David D. Rogers)

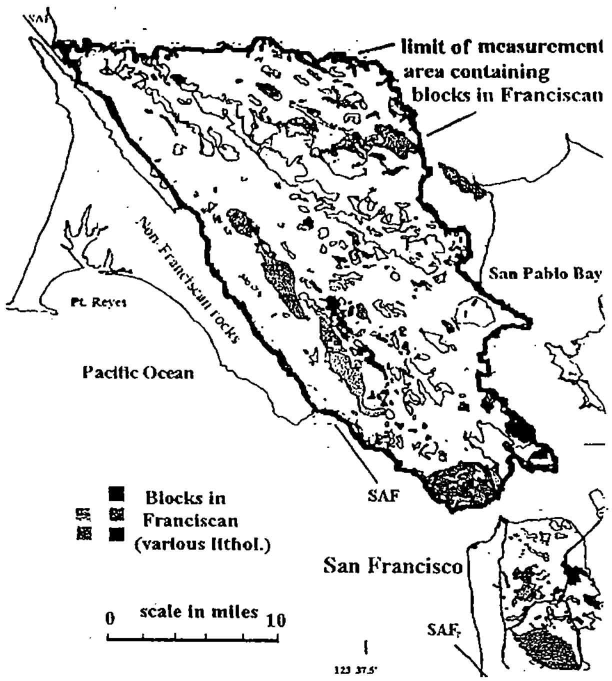


Figure 2 Blocks in the Franciscan north of San Francisco. Area enclosing measured blocks is over 900 km^2. (From Medley, 1994a; after Ellen and Wentworth, in press)

Blocks in melanges tend to be spherical or ellipsoidal and are often organized in sub-parallel trains, as shown by the northwesterly trend of steeply-dipping large blocks in the Franciscan of California in Figure 2. Approximately 60 to 75 percent of the blocks in the Californian melanges studied are composed of graywacke sandstone, with the remainder being lesser proportions of greenstones, chert, unsheared siltstones, limestones and exotic high-grade metamorphic rocks (Medley, 1994a). The matrix rock of melanges is commonly pervasively sheared with densities that may exceed 800 per meter (Savina, 1982).

Melanges are geotechnically intractable because of their chaotic spatial variability and the weak, often soil-like matrix materials. The great mechanical contrast between blocks and matrix frustrates good core recoveries, reliable laboratory test results and accurate geotechnical characterizations. Conventionally, engineers design on the basis of the weak matrix, but Lindquist and Goodman (1994) showed that for block volumetric proportions between about 25 percent and about 75 percent the mechanical properties of a melange are simply and directly related to the block volumetric proportion. Below 25 percent, a melange will have the mechanical properties of the matrix; and above about 75 percent, the mechanical properties of a melange mass approaches that of blocky rock or fractured rock with discontinuity infillings. The use of these findings requires estimates of the block volumetric proportion and Medley and Goodman (1994) outlined a method using measurements of block intercepts in drill core.

In this paper we propose a criterion so that blocks may be discriminated from matrix prior to inefficiently measuring all blocks intersected in drill core, exposed in outcrops or portrayed on maps.

Regardless of block proportions, the common practice of describing melange as "sheared *x* with boulders of *y*" or "*x* with ledges or interbeds of *y*" results in contentious earthwork construction since much effort must be expended to penetrate and remove unexpectedly large and competent blocks. We here propose a way to estimate block size distributions sufficiently well to forewarn an earthwork or tunneling Contractor. Such estimates may have significant contractual benefits.

2 APPARENT SCALE-INDEPENDENCE OF SOME FRANCISCAN MELANGES

2.1 *Self-similarity of individual log-histograms*

As shown by Cowan (1985), if images of melanges like those in Figure 2 and Figure 3 are compared they appear alike, despite greatly differing scales. Physical systems that can be formally shown to have such likenesses are referred to as *self-similar* or *fractal* (Mandelbrot, 1983). Lindquist (1991)[1] determined that the block size distribution of blocks at an outcrop of a Franciscan melange at Caspar Beach (Mendocino, California, in Coastal Belt Franciscan) was fractal and then replicated the blocks size distribution in physical model melanges (Lindquist, 1994a). Lindquist (1991) used a method described by Sammis and others (1987) and Sammis and Biegel (1989) who demonstrated the fractal particle size distributions of a fault gouge. Medley (1994a) extended the work of Lindquist (1991) and determined that the block size distributions of a variety of Franciscan melanges at many scales were also fractal, using the following procedure:

1) The d_{mod}s or *maximum observable dimensions* of over 1900 blocks, were measured from a variety of two-dimensional sources. As shown in Figure 1 and Figure 3, d_{mod} is the length of the longest vector measurable in a two-dimensional exposure. Note that d_{mod} is rarely the same as the longest possible axis in three dimensions, nor even the longest distance that could be measured if the blocks were

[1] E.S. Lindquist; "Fractals-Fractures and Franciscan". Term Paper for CE 280; *Rock Mechanics*; Dept. Civil Eng., Univ California, Berkeley; Prof. R. Goodman, Instructor.

Table 1 Summary of data from several sources used in the study

Location	Source	Area (A)	√A	0.05√A	No. blocks	shortest d_{mod}	longest d_{mod}	D Fract. Dim
Caspar Beach	photo	454 cm^2	21.3 cm	1.07 cm	286	0.19 cm	5.6 cm	1.44
Caspar Beach	photo	0.11 m^2	0.33 m	1.65 cm	79	0.36 cm	9.8 cm	1.1
Caspar Beach	photo	0.29 m^2	0.53 m	0.027 m	229	0.006 m	0.12 m	1.67
Caspar Beach	photo	2.26 m^2	1.5 m	0.075 m	173	0.019 m	0.95 m	1.3
Caspar B each	photo	7.92 m^2	2.81 m	0.14 m	173	0.04 m	1.98 m	1.65
Caspar Beach	photo	18.92 m^2	4.35 m	0.22 m	158	0.04 m	2.49 m	1.46
Lone Tree Slide Marin Co., CA	field meas. (Medley, 1994a)	32 892 m^2	181 m	9.05 m	117	0.3 m	15.2 m	1.2
Walker Ck, Marin Co., CA	Reid (1978)	1.17 km^2	1.08 km	54 m	94	4.8 m	222 m	1.58
Three Peaks, Marin Co., CA	Peterson (1979)	1.26 km^2	1.12 km	56 m	124	2.4 m	65.3 m	1.32
York Mtn, San Luis Obispo Co., CA	Seiders (1982)	3.43 km^2	1.85 km	93 m	181	12 m	2.04 km (but 1.44 km used)	1.06
Marin Co., CA	Ellen & Wentworth (in press)	916 km^2	30.3 km	1.52 km	314	125 m	17.1 km	1.56

cut by other surfaces. Only those blocks that were completely contained within an area of interest were measured, as shown in Figure 3. Blocks intersected by the frame of a photograph or map were *partial blocks* and were not measured. The work of measuring blocks from photographs of outcrops of Franciscan melange at Caspar Beach was facilitated by digitally scanning the images and exploiting image analysis software to determine the d_{mod}s automatically (Medley, 1994a). A product of the computer-assisted work is shown in Figure 3. Additional manual measurements were made from geologic maps of the Franciscan prepared at scales of between 1: 250,000 and 1:4800 by Ellen and Wentworth (in press), Peterson (1979), Reid (1978), Seiders (1982); and from the 38,000 m^2 area of the Lone Tree Slide, a site described by Medley and Goodman (1994). Several features of the data are summarized in Table 1.

2) The irregular-shaped regions that enveloped complete blocks were defined (as shown in Figure 3) and the areas (variable A) measured. Photographs were planimetered by image analysis. The areas ranged between a few square centimeters and over 900 square kilometers.

3) Block size (d_{mod}) classes were chosen that incrementally doubled (e.g.: ....0.5 cm, 1, 2, 4, .., 64, 128 cm), and were labeled with the magnitude of the larger number bracketing the class (*endclass*). The selection of endclasses was standardized by initially calculating 5 percent of the square root of the area containing the blocks (0.05√A), and defining this length as a *node* (e.g.: for the sequence above, the node is 4 cm, if A is 6400 cm^2). Endclasses smaller than the node diminished by incremental halves and endclasses. larger than the node incrementally doubled. The small bar in Figure 3 graphically shows the length of 0.05√A representing the minimum block size for the area portrayed. Table 1 lists values of (0.05√A).

4) The number of blocks for each endclass was counted, and a frequency histogram plotted using log-log axes. Such plots are *log-histograms*, a term

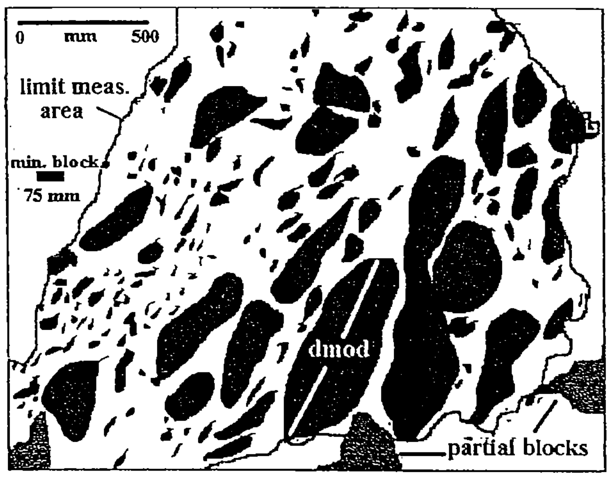
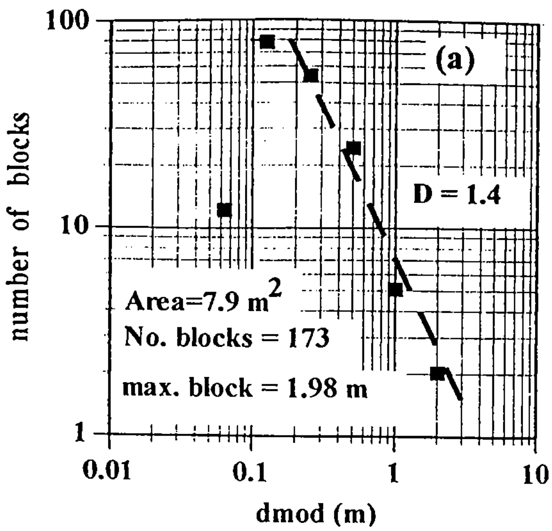


Figure 3 Blocks in melange at Caspar Beach, Mendocino. Only the d_{mod} s of complete blocks were measured in the area of 2.26 m^2 (A). Block threshold size shown by bar (0.05√A=75mm).



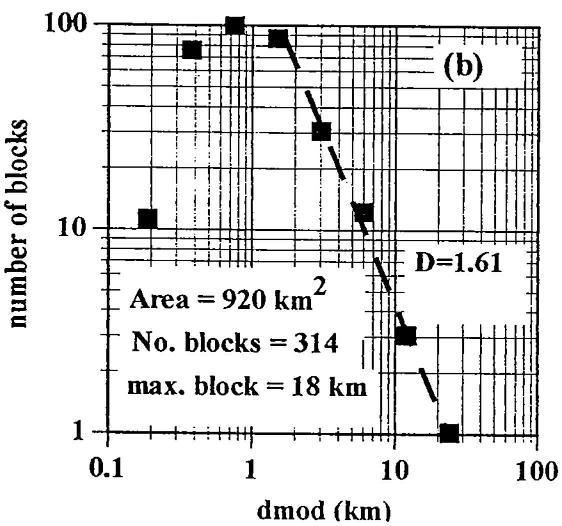


Figure 4 Log-histograms of block sizes from two disparate sources and measurement areas (m^2 and km^2): a) shows data from the same outcrop as image in Figure 3; b) shows data from source geology maps used in the preparation of Figure 2; (both from Medley, 1994a).

adopted from Bagnold and Barndorff-Nielsen (1980). The ordinates were either the number of blocks (numerical frequency) for each endclass, or else the relative numerical frequency (the number of blocks in an endclass divided by the total number of blocks in the sample population). Data points were plotted at the larger end of the endclass division.

Figure 4 contains two log-histograms; one generated from d_{mod}s measured from the outcrop shown in Figure 3; and the other from the detailed geological maps of Ellen and Wentworth (in press) used to draw Figure 2. The parabolic shapes of the log-histograms are composed (from left to right) of an *ascent limb*, a *peak* and a *descent limb*, which are described below:

1) The *ascent limb* is the result of undercounting (sample censoring) of blocks that were small relative to the scale of measurement, and so were under-represented (under-counted) for various reasons. For example, identification and measurement of small blocks was limited by the resolution of original and scanned photographs, and by the poor contrast of the gray scales pixels representing the blocks and matrix. And, on geologic maps, only the population of blocks above some minimum size were represented due to limits on the detail normally shown on geological maps, whatever the scale. The slope of the ascent limb and the location of the peak of the log-histograms depended on the source and quality of data measured. Table 1 shows that the shortest d_{mod}s were generally much smaller than 5 percent of the square root of the measurement areas ($0.05\sqrt{A}$). Severe block undercounting generally occurred for block d_{mod}s smaller than about $0.01\sqrt{A}$ to $0.025\sqrt{A}$. In order to make bias-free comparisons of the block size distributions from disparate sources at different measurement scales, measurements smaller than $0.025\sqrt{A}$ were censored from the data sets.

2) The *peaks* show the greatest number (or relative frequency) of blocks in the log-histograms. Block size d_{mod}s were large enough to be properly measured if their d_{mod}s were longer than the block size endclass, at the peak (defined as d_{peak}).

3) The linear trend of data points to the right of the peak, (*descent limb*) indicates that the block size distribution is *fractal* for the array, or follows a power law relationship with a negative exponent. The absolute magnitude of the slope of a best-fit line through the data points is the fractal dimension, D, which is also the absolute value of the exponent of the power law . The fractal dimensions of the log-histograms ranged between 1.1 and 1.7.

A particular style of log-histogram common to two or more melanges does not represent a unique deformation path, since the protolith rocks may have suffered different histories that resulted in similar block size distributions (as shown by Figure 4 where genetically dissimilar broken formations and tectonic melanges. show similar log-histogram shapes). Nevertheless, as discussed by Medley (1994a), the characteristics of log-histograms may be signatures useful to geologists in their study of melanges.

2.2 *Scale-independence of Franciscan melanges*

The log-histograms shown in Figure 4 are similar in appearance although the block sizes represented by them differed by more than 4 orders of magnitude. Consequently, the several log-histograms that we constructed were collectively compared by normalizing them in the following manner:

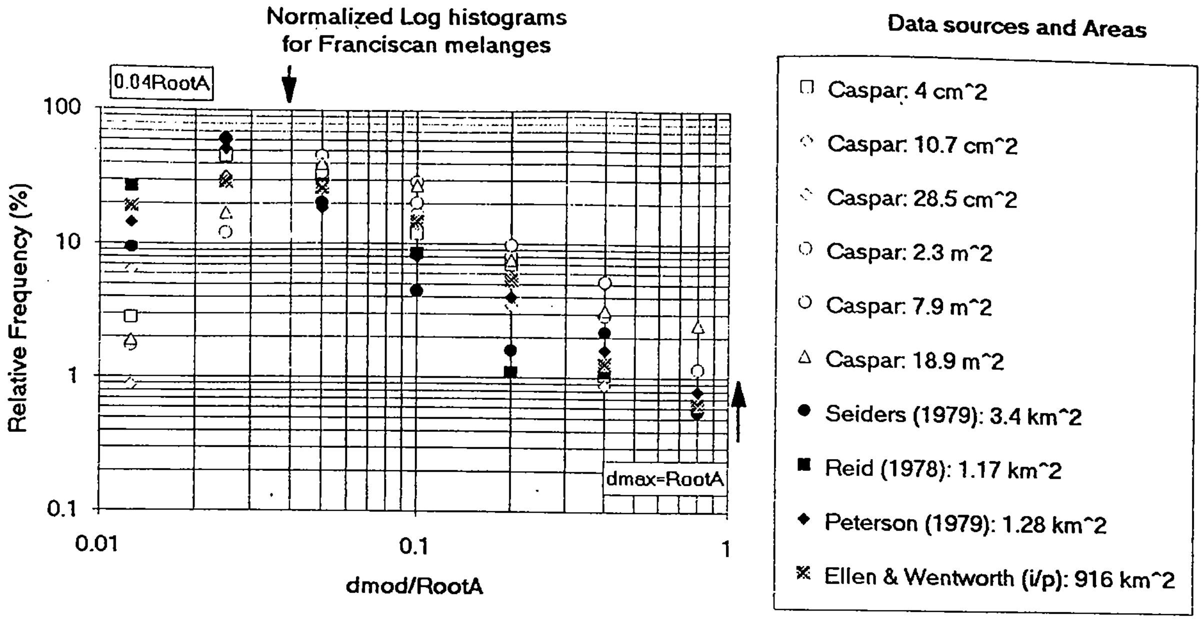


Figure 5 Compilation of log-histograms for Franciscan melanges. RootA is $\sqrt{A}$.

1) The relative numerical frequency of blocks was computed because the number of blocks measured in a measurement area depended on the areal proportion of blocks (areal density). Use of the relative frequency removed the dependence.

2) Block size endclasses for log-histograms were rendered dimensionless by dividing them by $\sqrt{A}$, where A was the area containing the blocks measured from each source, as listed in Table 1.

The normalized data are plotted in Figure 5. Remarkably, the individual log-histograms, with d_{mod}s ranging over 7 orders of magnitude, collapsed to a well-defined constellation, the general shape of which is similar to any one of the contributing log-histograms.

3 THE SIGNIFICANCE OF THE FINDINGS

We acknowledge that inferences drawn from log-log plots can be unreliable; nevertheless, some important conclusions can be made about the several melanges studied which could be boldly generalized to all Franciscan melanges *if* Figure 5 is taken to be representative of them:

1) The individual block size distributions are fractal and thus show that there is order in the apparent chaos of melanges. Consequently, the geotechnical characterization of melanges should not be avoided just because they are "complex" or "chaotic".

2) The fractal form of the constellation of normalized block-size distributions suggests that the Franciscan melanges studied are scale-independent over 7 orders of magnitude regardless of the scale of measurement, the nature of their fabric (broken formation, tectonic melange, etc), or even their location within the Franciscan. However, natural fractal phenomena are typically self-similar between upper and lower fractal limits and these limits were apparently not reached for the Franciscan melanges studied. We expect that further research will discern such limits but suspect that they are probably outside the range of scales of engineering interest (centimeters to tens of meters).

The scale-independence of the melanges studied was of fundamental significance in our research since it allowed the mechanical properties of real melange rock masses to be investigated by the use of physical model melanges (Lindquist, 1994b). Also, methods of characterizing melanges were developed using photographs (or *graphic models*) of melange outcrops and physical model melanges (Medley (1994b).

3) The scale-independence of Franciscan melanges means that blocks will be encountered at all scales of engineering interest, from laboratory specimens to in-situ melange rock masses. Furthermore, small blocks assigned to a matrix at site scale will be blocks in their own right at the scale of laboratory specimens. Since Lindquist and Goodman (1994) showed that the overall strength of a melange can be expressed as the strength of the matrix plus an increment that depends on the volumetric proportion of blocks, the strength of the matrix, if determined by laboratory tests, must be measured from representative specimens that should contain blocks. However, the performance of such tests requires specimens of generous size (greater than 150 mm diameter) and adjustments will generally need to be

made to conventional drilling, core-recovery and testing procedures. The problems of collecting and testing good-quality specimens of intact melange and similar bimrocks are worthy of further research.

4) $\sqrt{A}$ seems to be an effective dimension with which to normalize d_{mod} data, although the reasons for this are not clear and should be researched.

5) For small relative frequencies (less than 1 percent), the extrapolated trend of the aggregate descent limb of Figure 5 intercepts the $d_{mod}/\sqrt{A}$ axis at approximately 1.0. Hence, a "maximum block size", d_{max}, was defined as $d_{max} \approx \sqrt{A}$. This approximation provides an *expected* value, not a *certain* one. In our data set, only one d_{mod} exceeded the $\sqrt{A}$ representing the source area (Seiders, 1982: see Table 1), and was censored. Generally the largest d_{mod}s were significantly smaller than $\sqrt{A}$, although they were automatically and misleadingly included in the wide $0.8d_{mod}\sqrt{A}$ endclass (actually 0.4 to 0.8 $d_{mod}\sqrt{A}$).

6) A peak in the plot of the Figure 5 histogram occurs at $d_{mod}\sqrt{A}$= 0.04, which rounded to $d_{mod}/\sqrt{A}\approx 0.05$, defined a "peak block size" or $d_{peak} \approx 0.05\sqrt{A}$. Thus, for any scale of measurement, a minimum block size or block/matrix threshold is:

$$d_{peak} = 0.05d_{max} = 0.05\sqrt{A},$$

and also represents the "node" for log-histogram endclasses, as described in the previous Section. This rule was confirmed by Medley (1994a) who showed that for a typical fractal distribution of spherical blocks, blocks less than $0.05d_{max}$ constituted more than 95 percent of the total number of a given volume, but contributed less than 1 percent of the block volumetric proportion. Since Lindquist (1994a) found that larger blocks dominated the mechanical behaviour of physical model melanges, blocks less than $0.05d_{max}$ ($0.05\sqrt{A}$) probably have negligible influence on the mechanical properties of a melange rock mass at the engineering scale under consideration.

As an alternative, for those situations where the design geometry is known, Medley (1994a) also defined the block/matrix threshold as 5 percent of a *characteristic engineering dimension* (ced), or some meaningful length that describes the scale of a rock mass; e.g.: test specimen diameters, footing widths and tunnel diameters.

The definition of the block/matrix threshold presented here helps to answer the question:"*What is block and what is matrix?*" for melanges, where blocks intercepted in drill core, or exposed in outcrop, may range from millimeters to tens of meters in size. Once the scale of engineering interest has been decided (designated by d_{max}, $\sqrt{A}$, or a characteristic engineering dimension), there is no need to measure any blocks with lengths less than 5 percent of these scaling dimensions. Unfortunately, the censoring of the myriad of small blocks will lower the total lengths of block intercepts in drill core; which will in turn depress estimates of block volumetric proportions.

4 ESTIMATING BLOCK SIZE DISTRIBUTIONS

4.1 *The value of predicting block size distributions*

The problem of estimating block size distributions from the lengths of block intersections in drill core was reconnoitered by Medley and Goodman (1994), and requires much more research. However, we here propose a way to roughly estimate the block size distribution in a melange rock mass that could be helpful to engineers and earthwork Contractors. The method is similar to an approach developed by Medley (1994a), in which the relative numerical frequency of blocks in a melange was assumed to be the same in two dimensions (2D) as it was in three dimensions (3D), and which predicted a block size distribution for the excavation at the Lone Tree Slide (Marin Co., California) that closely matched the earthwork Contractor's experience.

For some site with an area of magnitude A, Figure 5 shows that blocks with d_{mod}s of greater than $0.05\sqrt{A}$ are certain, and blocks greater than $0.4\sqrt{A}$ are likely. Hence, the larger a site area, the greater the probability of finding blocks sufficiently large to hinder construction, if they are unexpected. The exhumation of blocks greater than 1 m requires bulldozers; blocks greater than about 3 m require blasting; and hard blocks of rock can deviate the course of TBMs and retard tunneling progress. If Owners could forewarn Contractors of the likelihood of large blocks in melanges, there would be some encouragement to develop contingency measures. For example, if encountered as expected, large blocks above a certain critical size could be left intact in excavations; exploited as sources of aggregate; or even used to anchor tie-backs in landslide stabilizations.

4.2 *Development of the method*

Blocks with d_{mod}s less than d_{peak} were censored from the data shown in Figure 5 and the relative numerical frequencies of the remaining data were adjusted. Figure 6 contains a re-plot of the data, through which a best-fit line yielded a fractal dimension of about 1.3. We offer this as a preliminary and generic fractal dimension for Franciscan melanges, recognizing that we determined a range of fractal dimensions between 1.1 and 1.7 for individual melanges. The trend of the best-fit line intercepts the $d_{mod}/\sqrt{A}$ axis intercept at 1.0 and confirms the approximation $d_{max} \approx \sqrt{A}$ stated above.

Figure 6 is based on data measured from two dimensional (2D) sources but a three dimensional (3D) fractal dimension (D_{3D}) can be estimated from the 2D fractal dimension (D_{2D}) by adding 1.0 (i.e.: $D_{3D} = D_{2D} + 1$), as explained by Sammis and others (1987). Since the overall D_{2D} for the Franciscan melanges studied appears to be 1.3 (Figure 6) then the overall D_{3D} is about 2.3. The operation is equivalent to adding 1.0 to the exponent of a negative power law relationship; that is, for n blocks of some endclass size (d_{mod} or $d_{mod}/\sqrt{A}$), there are $n^{2.3}$ blocks within the previous endclass size. The D_{3D} and power law exponents ranged between 2.1 and 2.7 for the individual melanges that we studied.

An objection to this procedure is that it predicts the 3D properties of a melange using data generated from a 2D source with a particular block areal proportion, which may not be representative of the 3D block volumetric proportion. However, as discussed by Medley (1994a), it is a fundamental principal of stereology that the block areal proportion of blocks is equivalent to the block volumetric proportion (given certain sampling conditions).

As an example of the technique proposed here, suppose that mapping of a site (or use of the rule $d_{max} \approx \sqrt{A}$) suggests that there is one block of about 200 m, and drilling or geological mapping indicates that there are another 2 blocks with a d_{mod}s between 50 m to 100 m (endclass of 100m). Then use of the term $n^{2.3}$ (where n is an endclass) predicts that there will be approximately 5 blocks with d_{mod}s of 25m to 50m (endclass of 50 m); 42 blocks with d_{mod}s of 12.5m to 25m (endclass of 25 m), and so on. A range of minimum and maximum numerical frequencies for each endclass can be estimated by substituting 2.1 and 2.7 for the exponent 2.3 in $n^{2.3}$.

Since typical block shapes for Franciscan melange are ellipsoidal with major axis:minor axis ratios greater than 2:1 (Medley, 1994a), estimates may be made of the individual volumes of the blocks in each block size endclass. The summed volumes of the individual blocks could then be compared to the total volume of blocks found by multiplying an estimate of the volumetric proportion of blocks (from measurements of blocks from drill core, using the method described by Medley and Goodman (1994), with the volume of melange being considered. Matching of the two estimates of total block volumes will require iterative adjustments in the absolute numerical frequency of smaller block sizes.

The approximate block size distributions estimated may not match the distribution of block intercepts measured from the drill core (chord length distributions) due to sampling difficulties resulting from low block volumetric proportions, the total length of drilling and the relative orientation of blocks

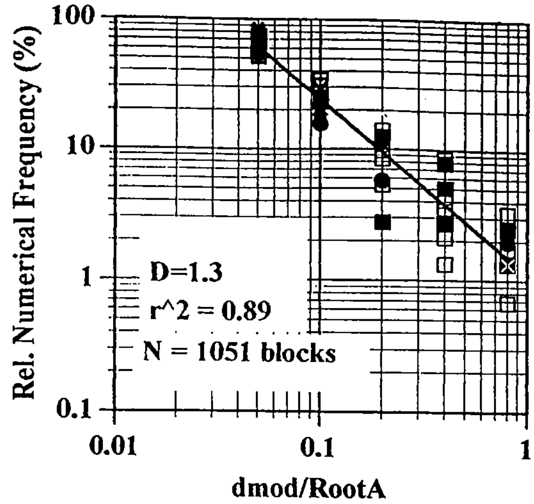


Figure 6 Replot of all d_{mod} data larger than $0.05\sqrt{A}$. Symbols and sources as in Figure 5

and drill holes. The problems were researched by Medley (1994b). but were not completely resolved.

Essentially then, all that is required to estimate the possible block size distribution at a site in Franciscan melange is the value of $\sqrt{A}$ (i.e.: d_{max}) and an estimate of the volumetric proportion measured from drill core. Although the procedure proposed here needs to be verified by experience, it requires little additional effort than that normally expended on geotechnical investigations in melange.

5 SUMMARY AND CONCLUSIONS

In the chaos of Franciscan melanges there is order, as shown by individual fractal log-histograms of melange block size distributions measured from disparate sources with scales ranging over seven orders of magnitude. Since chaotic melanges appear to have some order, geotechnical engineers should characterize melanges and similar fragmented and mixed rocks and soils in the same disciplined fashion in which they characterize more tractable geologic materials.

Collectively, the several log-histograms demonstrated the scale-independence of Franciscan melanges when normalized by the square roots of the areas containing complete blocks ($\sqrt{A}$). It was discovered that the length $0.05\sqrt{A}$ can be used to discriminate blocks from matrix at any scale, and the size of the largest block can be estimated as $d_{max} \approx \sqrt{A}$. The findings mean that blocks are always found in melanges, whatever the scale of engineering interest, and that laboratory test procedures must be adapted to accommodate blocks in test specimens.

The overall two dimensional fractal dimension of the Franciscan melanges studied is about 1.3, and in three dimensions is 2.3 (but ranges between 2.1 and 2.7). Consequently, rough estimates can be made of the block size distribution for a site once the area and volumetric block proportion are known.

The discovery of fractal block arrangements for other bimrocks (and bimsoils) implies that the techniques outlined in this paper could have broad application for geotechnical engineers.

ACKNOWLEDGMENTS

Much of the researched presented here was performed for our PhD dissertations performed at the University of California at Berkeley, and supervised by Professor Richard Goodman. We are grateful for the financial support of the Civil Engineering Department of the Pacific Gas & Electric Co. of San Francisco; and for Lindquist, the additional support of a grant from the National Science Foundation.

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