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Estimating the block volumetric proportions of melanges and similar block-in-matrix rocks (bimrocks)

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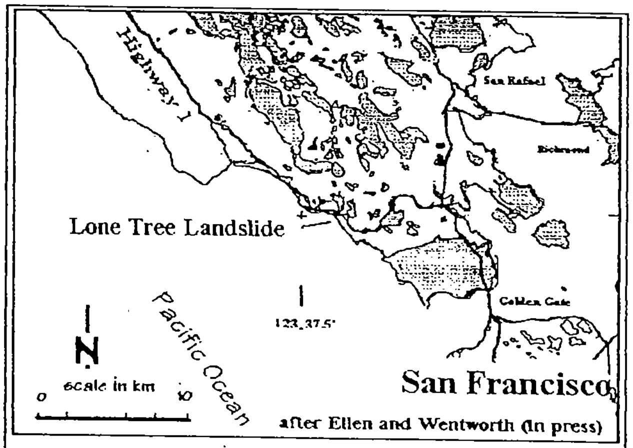
1 INTRODUCTION

Although the chaotic fabric of melange (from the French, *mélange*, or mixture) is characteristic of rocks formed within the accretion prisms of subduction zones, geologists disagree about the details of melange formation (Raymond and Terranova, 1984), as reflected in the many aliases of melange (e.g., chaotic formations, wildflysch, mega-breccia, argille scagliose and friction carpets). For engineering purposes, Medley (1994) considers melange to be a *bimrock* (block-in-matrix rock) which he defines as "a mixture of relatively large, competent blocks within a bonded matrix of finer and weaker texture", a definition that ignores rock genesis. Bimrocks similar to melange that are formed from cataclasis and fragmentation include breccias, coarse pyroclastics, lahars and tillites. Other bimrocks form from weathering (decomposed granite) or sedimentation (boulder conglomerates). Analagous soils, such as colluvium and till are termed *bimsoils*.



after Ellen and Wentworth (In press)

Figure 1: Regional -scale blocks in the Franciscan north of San Francisco, California

Melange bodies have been identified in the mountains of over 60 countries (Medley, 1994) and are exemplified by the Franciscan Assemblage (the Franciscan) a regional-scale jumble in northern California. Typically, the Franciscan contains chaotic zones of relatively strong blocks of greywacke sandstone, chert, basalts, limestone and exotic metamorphic rocks embedded within a matrix of pervasively sheared shale and argillite. The blocks range between sand particles and mountain masses, are irregularly shaped, and generally trend NNW-SSE (Figure 1). Shears are confined to the weak shale matrix, which flows around the closely jointed blocks. The sheared shale, and the sheared serpentinite bodies common in the Franciscan, are both responsible for the myriad earth-flow landslides of the Fransciscan. Also, encounters with unpredictably distributed blocks in melanges cause expensive surprises during earthwork excavations and foundation preparations.

When working with bimrocks or bimsoils, it is universal geotechnical engineering practice to design using the strength of the weaker matrix. But extensive laboratory testing of physical model melanges (Lindquist and Goodman, 1994) showed that the strength of a physical model melange increased with the volumetric proportion of blocks when the proportion exceeded approximately 30 percent as a result of the increased tortuosity of failure surfaces. Relationships between block content and overall strength have been observed qualitatively for melanges in California (Bedrossian, 1980) and Italy (D'Elia et al, 1986)

But the practical use of a relationship between block volumetric proportion and overall bimrock strength requires the determination of the in-situ volumetric proportion of blocks. In this paper, we first show that much can be learned from the study of small-scale images of melanges; secondly, that stereological methods are useful in the estimate of volumetric proportions and block size distributions; and finally, we present the results of a field application of our approach.

2 GRAPHIC MODELS BASED ON APPARENT MELANGE SELF SIMILARITY

Melanges are commonly characterized as "chaotic". But recent work (e.g., Turcotte (1992)) shows that many chaotic geological processes have a self-similar or "fractal" nature. A structure possesses self similarity if, when fragmented, each fragment is a replica of the parent whole. The fractal organization of blocks in a melange at the outcrop scale was demonstrated by Lindquist[1] when he discovered that the block size frequency distribution of the melange obeyed power laws. Plotted on logarithmic axes, the data were organized linearily: such plots are referred to here as "log-log linear". Lindquist's preliminary work has been confirmed (Medley and Lindquist, 1994; in preparation) for melanges of many scales (compare Figure 1 and Figure 2, which have a scale ratio of greater than a million). These findings have a fundamentally practical implication because, given sufficient data to define a log-log linear plot, predictions can be made about the sizes and numbers of blocks within a melange. Any predictions, though simple, are useful to geotechnical engineering designers and earthwork contractors. Up to now, no method has existed for making such predictions.

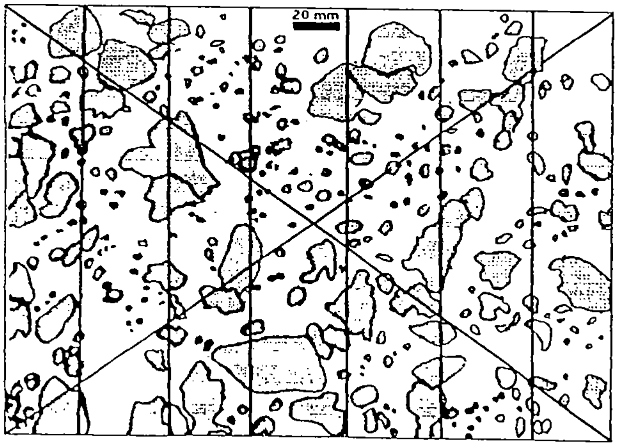


Figure 2: Graphic model of melange with scanlines. Scale bar is 20 mm long

In a melange, the discrimination between *matrix*, and *blocks*, is difficult since blocks will be found at any scale. However, for a given volume, the large blocks will contribute the most to the block volumetric proportion, thus one can select an arbitrary threshold block size of 1 percent of the maximum observed dimension of the largest block in the population

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[1] E. Lindquist, 1991: "Fractals - Fractures and Franciscan"; Term Paper for CE 280, Rock Mechanics; Dept. Civil Eng., University of California, Berkeley, California

being measured. Assuming spherical blocks and a fractal block size distribution, blocks with characteristic dimensions less than a 1 percent threshold will contribute less than 1 percent of the volume and less than 5 percent of the total surface area of the blocks in the rockmass (Medley, 1994).

Because of the apparent self-similarity of melanges, drawings and photographs at the outcrop scale are *graphic models* of larger scale melanges. Graphic models allowed us to develop characterization methods useful in estimating the block volumetric proportion and block size distributions of melanges at engineering scales. For example, Figure 2 is the hand-tracing of a photograph of melange from Caspar Headlands, near Mendocino, California. The model cross-section is 180 mm in "depth".

We used manual and computer-assisted image analysis methods to determine the areal proportions of the blocks and the block size distributions of graphic models. Block size is characterized by the length of the maximum observeable dimension of the block. The pictures were scanned and the scanned image digitized into an array of *pixels* (picture elements), each with a value of between 0 (black) and 255 (white) representing some shade of gray. Image analysis software measured the areas, perimeters and axial dimensions of the individual blocks in the images. In the case of the image of Figure 2, the sum of individual block areas yields a block areal proportion of 35.6 percent. The frequency distribution of the block sizes (maximum observeable dimensions) plots as a log-log linear curve (power law fit), as shown on Figure 4

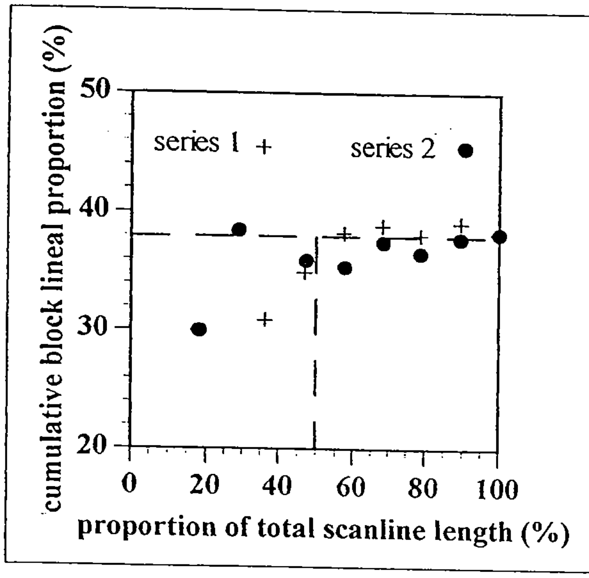

Figure 3: Lineal block proportion for scanlines shown in Figure 2. The cumulative block lineal proportion is the ratio of the sum of scanline intercepts through blocks, to the cumulative length of the scanlines. Note that the convergence of the block lineal proportion to approximately 38% which is close to the measured block areal proportion of 36%. Convergence is effectively achieved at approximately 50% of the total scanline length of 1684 mm (840mm).

In practice one rarely has the good exposure of melange modelled in Figure 2, and outcrop mapping and drill core sampling must be performed in an attempt to characterize the rockmass. The continuous detailed geological log of a borehole or the core itself, if available, are sampling *scanlines*. In the case of the graphic models, scanlines (modelled boreholes) were drawn over the graphic model of Figure 2, and measurements made of the lengths of chord intercepts through each block intersected by the scanline. The block lineal proportion for each scanline is the total length of chord intercepts along the scanline divided by the length of the scanline. If an image is sampled by a sufficient total length of scanlines, the areal block proportion is estimated. The equivalence of lineal, areal and volumeteric proportions is a fundamental law of *stereology*, using which structures are characterized by zero-, one-, and two-dimensional measurements (Underwood, 1970). The practice of making linear ("Rosiwal") traverses across microscopic images to estimate the areal and volumetric proportion of particulates within a matrix was a standard laboratory technique for petrographers, biologists and metallographers before the advent of computer-assisted image analysis.

The areal proportion of blocks in the image of Figure 2 was estimated by accumulating the block linear proportions of eight scanlines totalling 1684mm in length. The individual block lineal proportions varied between 53 percent and 30 percent. To test the influence of varying the order of scanlines, the incremental cumulative proportion (running average) and incremental proportion of total scanline length were computed separately for two series scanlines in arbitrarily chosen sequences. Figure 3 shows that the cumulative block lineal proportion converges to 38 percent, close to the block areal proportion of 35.6 percent. Convergence effectively occurs at 40 percent of the total scanline length, or some 840mm of scanline measurements.

Holmes (1921) reported a guideline to selecting a sufficient length of linear traverse for estimating the areal proportions of mineral grains in microscope images: a total traverse length of 100 times the average grain size in the area traversed was recommended. If this simple criterion is adopted for the scanline measurements of the graphic model of Figure 2 (average block size of 8.25mm), then a cumulative length of scanlines of 825 mm would be sufficient to estimate the block areal proportion. The results shown in Figure 3 validate Holmes' (1921) guideline for the graphic model since the cumulative block lineal proportion converges to the known block areal proportion, for both series of scanlines, within approximately 840 mm of scanline measurement. However, the guideline is of little use without prior knowledge of the average block diameter. Moreover, if the length of scanlines is reduced to more efficiently estimate the block areal proportion, then there will be poorer correlation between the frequency distributions of block intercept lengths (chords) and block diameters, as discussed below.

The lengths of chords across blocks intercepted by scanlines are rarely the same as the block characteristic dimensions (or "diameters"). But to simplify a complex problem, we assume that the distribution of block cross-sections in the plane of a graphic model, or the distribution of chord lengths from scanlines, is related to the true distribution of the three dimensional blocks in the parent volume. The geometric probability character of this problem and some stereological solutions are discussed by Underwood (1970). From the geotechnical viewpoint, Tang and Quek (1986) used a statistical approach to estimate the frequency distribution of boulder diameters from a frequency distribution of borehole chord intercepts through boulders. Savely (1990) used Monte Carlo simulations to determine correction factors between the frequency distribution of boulder dimensions in a cemented boulder conglomerate, and the frequency distribution of drilled core intercepts through the boulders. Correction factors range between 1.0 and 1.6 (David Nicholas, Call and Nicholas, Inc; pers. comm). Interestingly, the eight scanlines across the Figure 2 graphic model resulted in 86 chord intercepts, with an average length of 7.29 mm, but the actual average block diameter (in two-dimensions) was 8.25 mm, larger by a factor of 1.13. However, for melanges, the notion of *average* dimensions is misleading, since average block sizes are greatly skewed toward the small sizes due to the fractal distribution of blocks. Hence, chord to diameter conversions may not be as simple for fractally distributed and irregular shaped melange blocks as it appears to be for normally distributed and rounded boulders in conglomerates.

The frequency distributions of chord intercepts for graphic models and field scanlines generally plot as power-law curves (log-log linear) like that of Figure 4, which also shows the distribution of block diameters for the graphic model (mini-melange) of Figure 2. The plots of Figure 4 suggest that the distributions are related since the slopes of the plots are similar, so that an empirical and general adjustment between the frequency distributions of chord intercepts and block maximum dimensions for melanges may yet be discovered. The plots of Figure 4 show that for any given chord intercept length, the number of equivalent block diameters is many times greater; and for any given frequency, the estimates of true block dimensions will be severely underestimated if one assumes the chord dimensions to be diameters.

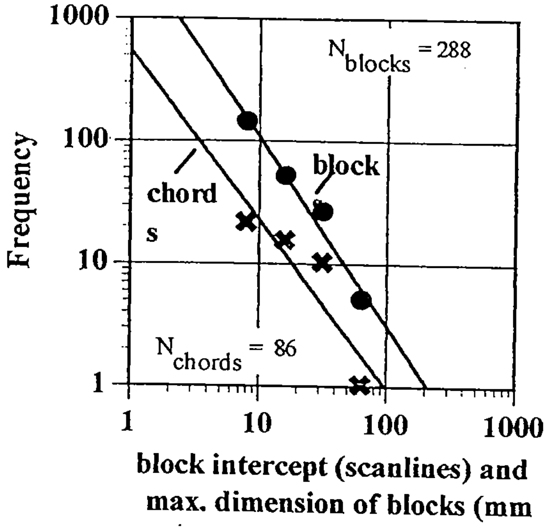

Figure 4: Plots of the block size distribution (from image analysis measurements) and the chord length distribution (from scanline measurements) of blocks shown in the graphic model of Figure 2.

3 CASE HISTORY: LONE TREE LANDSLIDE, CALIFORNIA

Shortly after the Loma Prieta earthquake in October, 1989, California Highway 1 was closed by the Lone Tree Landslide (Figure 1). The California Department of Transportation (CALTRANS) restored access by excavating 765,000 m^3 (10^6 yd^3) of Franciscan melange to an average depth of 37m(Van Velsor and Walkinshaw, 1993). Relatively intact rock was excavated from behind the interpreted landslide surface to provide stable cut slopes (Figure 5). Blocks up to 25m were blasted during the excavation work (Michael Hobbs, Ford Construction, Inc.; pers. comm).

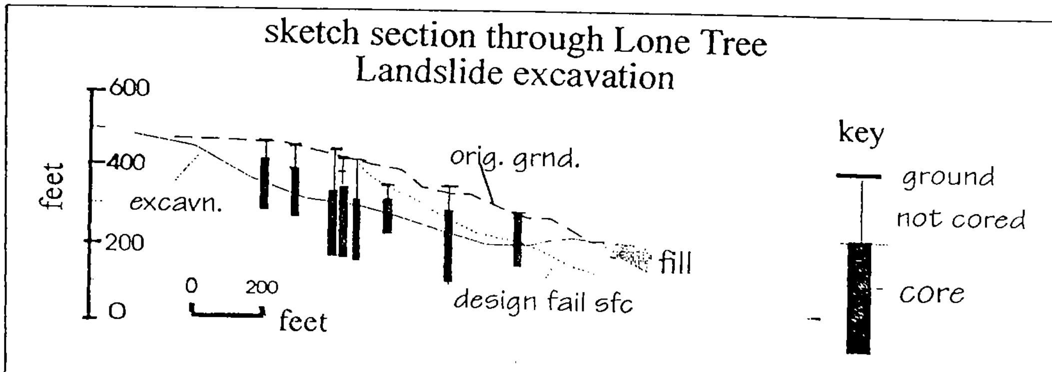

Figure 5

courtesy of CALTRANS

Prior to construction, nine exploratory borings (Figure 5) were drilled to between 37m and 82m deep to investigate the stability of the melange that would be exposed in the cut slopes. Some 375m of HQ size core (61mm diameter) was recovered, and eventually given to us for our research. Coring started some distance below the ground surface and only 82m of the core was from those borehole segments located above the future excavated surface. The core from these segments was assumed to represent the melange excavated, referred to here as the "excavation segments", and averaged 10m in length. The average length of all the core was 42m. Since the largest blocks in the vicinity of the slide are some 30m in size (maximum observed dimension), we chose the matrix/block threshold to be 0.3m using an arbitrary 1 percent criterion (as described in section 2), but nevertheless measured block intercepts in the core to as small as 5 cm in length.

Some 40 percent of the core (approximately 150m) was sufficient to show that the block lineal proportion of all the core effectively converged to approximately 21 percent (Figure 6). The longest block intercept in all the core was 7.9m, with an average length of 0.43m. The intercepts from the excavation segments core were much shorter, ranging to 9.3cm long, with an average length of 3.1cm. Some 38 percent of the excavation segments core was sufficient to estimate the block lineal proportion of approximately 4.5 percent (Figure 6). For both sets of data, the ratios of total length of lineal traverse (core) to the average intercept lengths, greatly exceed the ratio of 100 recommended by Holmes (1921). We estimate the block volumetric proportion of the unexcavated melange to be approximately 28 percent.

Medley, (1994) tested the estimate of block volumetric proportion of the excavated material as measured from the excavation segments core (4.5 percent), by measuring the areal proportion of blocks exposed in the excavation slopes. The blocks are relicts of larger blocks that had been blasted or ripped during excavation. The site (37,780 m^2, or 8.1 acres) was divided into 21 sub-areas and the maximum observed dimension of blocks greater than 1m in each sub-area was visually estimated. The block areas were estimated using the assumption that the maximum observed dimension was a circular diameter. The total areal proportion of blocks exposed on the slopes of the excavation is estimated as 4.2 percent. This proportion is remarkably close to the 4.5 percent lineal proportion estimated from measuring the core from the excavation segments. It appears that the material removed from the excavation was relatively deficient in blocks, and that much of it was landslide material, as indicated by the sheared shale in the core of the excavation segments.

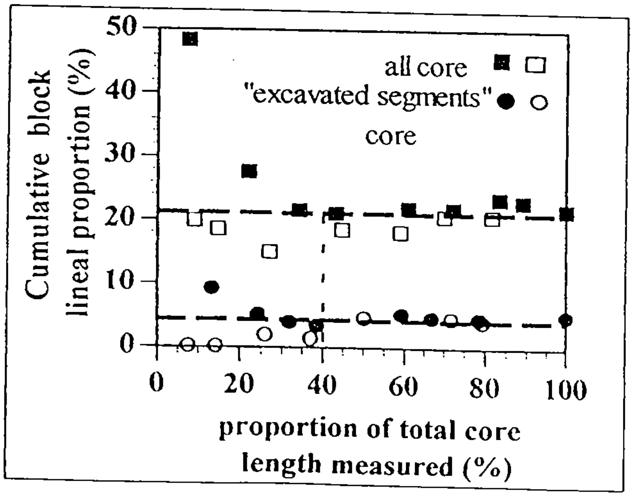

Figure 6:

Block lineal proportion for Lone Tree Landslide core: that for all the core coverges to approximately 21%, and the proportion for the core of the "excavation segments" converges to approximately 4.5%. Both plots effectively converge within about 40% of the total length of the core measured for each exercise.

Figure 7 shows the frequency distribution of the chord intercepts of the blocks measured for all the core and also the frequency distribution of the maximum observed dimensions of the blocks estimated in the field. There is reasonable correlation between the slopes of the plots of the fieldwork and core measurements (of all the core), but considerable difference between the maximum size of blocks predicted: the fieldwork predicts a block of 100m, and the core a block of 15m. Based on our work with graphic models, it is likely that the true distribution of block characteristic dimensions ("diameters") has been severely underestimated. The plot based on the measurements from the core from the excavated segments is poorly correlated with the other two, although it too plots log-log linear. The steep slope of the plot may be related to the sparse block population of the material excavated, but in a manner not yet clear to us.

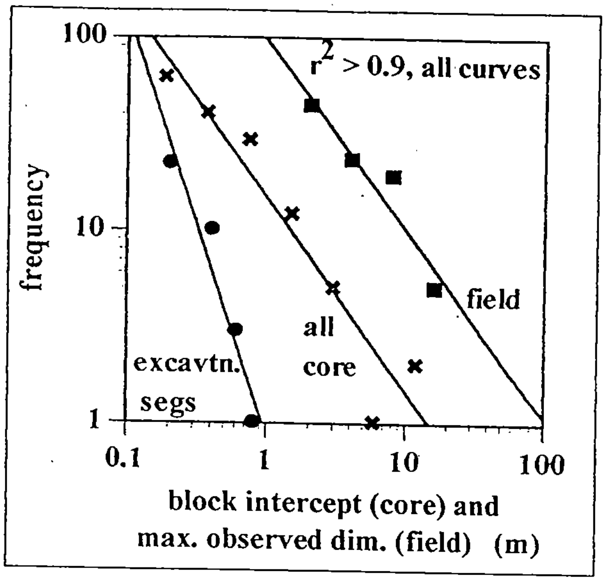

Figure 7:

Compilation of the distributions of block lengths in the "excavation segments" of core and all the core, together with the distribution of maximum observed dimensions of blocks, as mapped in the field

4 SUMMARY AND CONCLUSIONS

When working with a bimrock (block-in-matrix rock), the application of a block volumetric proportion/strength relationship requires that the volumetric proportion be estimated. The apparent self-similarity of the block distribution in melanges allowed the use of small-scale graphical models to develop a measurement technique useful for estimating the volumetric proportion of blocks by measuring the lineal proportion of chord intercepts recovered in drill core. Field mapping and measurement of drill core recovered from the Lone Tree Landslide, California, indicate that the technique may predict the in-situ proportion of blocks in a melange. Yet more work needs to be performed to allow predictions to be made about the block-size distribution of in-situ melange from chord intercepts measured from drill core.

5 ACKNOWLEDGEMENTS

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