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R.OLIVEIRA, L.F.RODRIGUES, A.G.COELHO & A.P.CUNHA
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Using stereological methods to estimate the volumetric proportions of blocks in melanges and similar block-in-matrix rocks (bimrocks)

Méthodes stéréologiques pour l'évaluation des proportions volumétriques des blocs en mélanges et des roches de bloc-en-matrice (bimrocks)

Edmund Medley
Department of Civil Engineering, University of California, Berkeley, Calif., USA

ABSTRACT: Melanges are part of a larger family of *bimrocks* (block-in-matrix rocks), composed of hard blocks within weak matrices. Since recent work by other shows that the overall strength of a bimrock is proportional to the volume of blocks, means of estimating the volumetric proportion of blocks *in-situ* must be developed. A stereological method is described in which the volumetric proportion is estimated by measurements of block intercept lengths in drill core, and the results compared to data for a California construction site.

RÉSUMÉ: Mélanges sont une parte d'une famille plus grande de *bimrocks* (les roches de bloc-en-matrice), composées de blocs durs dans matrices faibles. Parce que les travaux récents par les autres démontreant que la force d'un bimrock est proportionnel d'après le volume des blocs, c'est nécessaire ainsi developper le moyen de évaluer le proportion volumetrique par blocs *in situ*. Une methode stereologique est décrite par lequel la proportion volumetrique est évaluée par faire les mesures de la longuer dans segments de droite dans le noyau de foret, et les sont comparés aux résultats d 'une location de construction en Californie.

1 INTRODUCTION

Melanges (from the French, *mélange*, or "mixture") are rock masses composed of competent rock blocks of varying size, embedded within a weaker argillaceous matrix. The chaotic fabric of melange is characteristic of rocks formed within the accretion prisms of subduction zones. Indeed, the presence of melanges within the sedimentary stack is considered to be necessary evidence for a subduction history. However, despite general accordance on these principal facts, many 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). In the geological literature there are abundant references to melanges, there being over 1950 references alone accessible from GeoRef (a geological literature database supplied by the American Geological Institute), but there are only rare references to melange in the engineering geology or geotechnical engineering literature.

Raymond et al (1989), included melanges within a larger geological family of block-in-matrix rocks. For engineering purposes, I abbreviated the term "block-in-matrix rock" to *bimrock* (Medley, 1994), which is defined 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 (e.g.: decomposed granite) and sedimentation (e.g.: boulder conglomerates). Similarly, mixed soils such as colluvium and till, are termed *bimsoils*.

Melange bodies have been identified in the mountains of over 60 countries (Medley, 1994), as shown in Figure 1 and are exemplified by the Franciscan Assemblage (the Franciscan) a regional-scale jumble in northern California, the

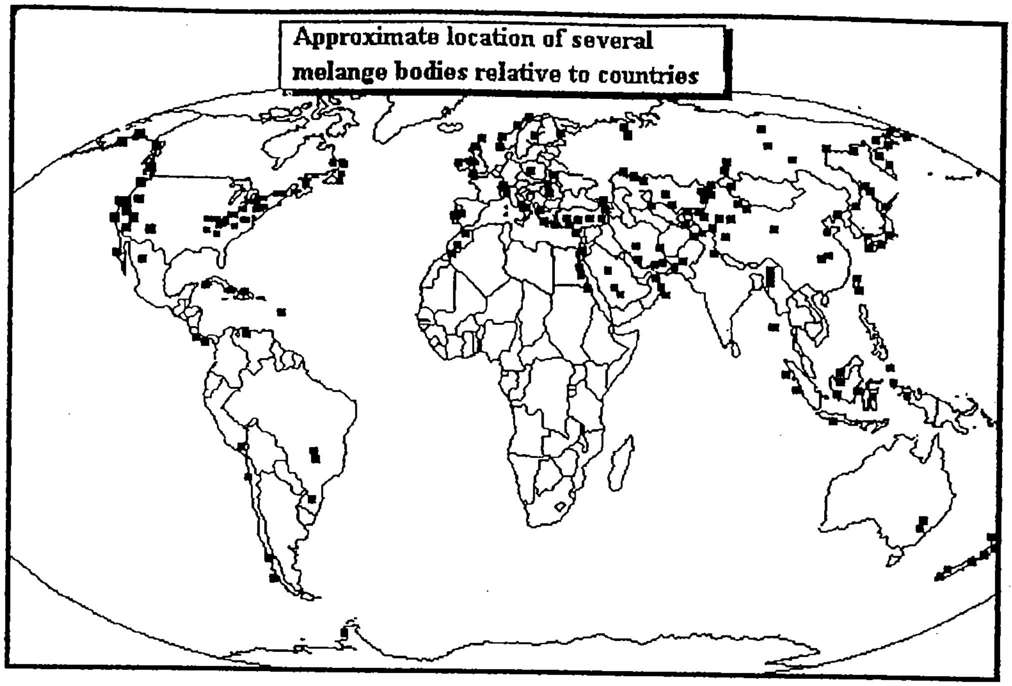
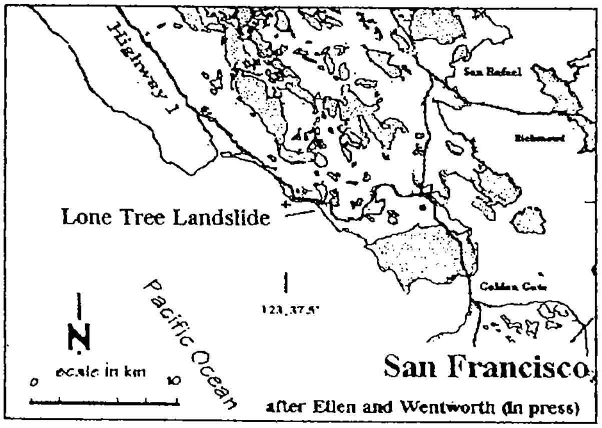


Figure 1 Approximate location of several melange bodies throughout the world

argille scagliose of the Italian Apennines, and the extensive melanges of Turkey and Iran. Typically, melanges contain chaotic zones of relatively strong blocks of greywacke sandstone, together with scarcer chert, basalts, limestone and exotic metamorphic rocks, all embedded within matrices of pervasively sheared shale and argillite. In the Franciscan of northern California, blocks sizes 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 of earth-flow landslides of the Franciscan. Also, encounters with unpredictably distributed blocks in melanges cause expensive surprises during earthwork excavations and foundation preparations. Although it is relatively easy to excavate the sheared shale using conventional earthwork equipment, blocks larger than approximately 3m in dimension generally must be blasted.



after Ellen and Wentworth (in press)

Figure 2: Regional scale blocks in the Franciscan north of San Francisco, California

When working with bimrocks or bimsoils, it is universal geotechnical engineering practice to design using the strength of the weaker matrix. But this practice may be overly-conservative if the bimrock contains a large proportion of blocks. Extensive laboratory testing of physical model melanges (Lindquist and Goodman, 1994; Lindquist, 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. Similar relationships between block content and overall strength have been observed qualitatively for melanges in California

(Bedrossian, 1980) and Italy (D'Elia et al, 1986), and in colluvium deposits in Hong Kong (Irfan and Tang, 1993).

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, I show that much can be learned from the study of small-scale images of melanges and that stereological methods are useful in the estimate of volumetric proportions. I briefly introduce the more complex problem of the determination of block and block size distributions; and finally, I present the results of a field application of my approach to estimating the volumeteric proportion of blocks at the site of a California landslide.

2 THE APPARENT SELF-SIMILARITY OF FRANCISCAN MELANGES

Melanges are commonly characterized as "chaotic". But recent work (e.g., Turcotte (1992)) showed 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 against logarithmic axes, the data were organized linearly: such plots are referred to here as "log-log linear". Lindquist's preliminary work has been confirmed (Medley, 1994; Medley and Lindquist, 1994; in preparation) for melanges of many scales (compare Figure 2 and Figure 3, which have a scale ratio of greater than a million), and also for other fragmented geological materials such as the clasts within lodgment (basal) till. 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. Within the California geotechnical community, there has not been a method for making such predictions until recently (Medley, 1994; Medley and Goodman, 1994; Medley and Lindquist, 1994).

In a bimrock with a continuous distribution of blocks, the discrimination between *matrix*, and *blocks*, is difficult since blocks will be found at any scale. However, for any given volume, the large blocks will contribute the most to the volumetric block proportion. Recognizing this, one can select an arbitrary threshold block size, such as one percent of the maximum observed dimension of the largest block in the population being measured. Assuming spherical blocks and a fractal block size distribution, blocks with largest dimensions less than a 1 percent of the threshold size 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).

3 GRAPHIC MODELS

It is difficult to distinguish the difference between tracings of the blocks shown on maps of melanges and tracings from photo-microscopic images, if there are no reference scale bars. Hence, drawings and photographs at the intermediate outcrop scale are *graphic models* of larger scale melanges. Graphic models allowed the development of characterization methods useful in estimating the block volumetric proportion and block size distributions of melanges at engineering scales. For example, Figure 3 is the hand-tracing of a photograph of melange from Caspar Headlands, near Mendocino, California. The model cross-section is 180 mm in "depth".

Manual and computer-assisted image analysis methods were used to determine the areal proportions of the blocks and the block size distributions of graphic models, block size being characterized by the length of the maximum observable 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 3, the

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[1] E. Lindquist, 1991; "Fractals-Fractures and Franciscan", Term Paper for CE 280, Rock Mechanics; Dept. Civil Engineering, University of California, Berkeley, CA, 94720, USA

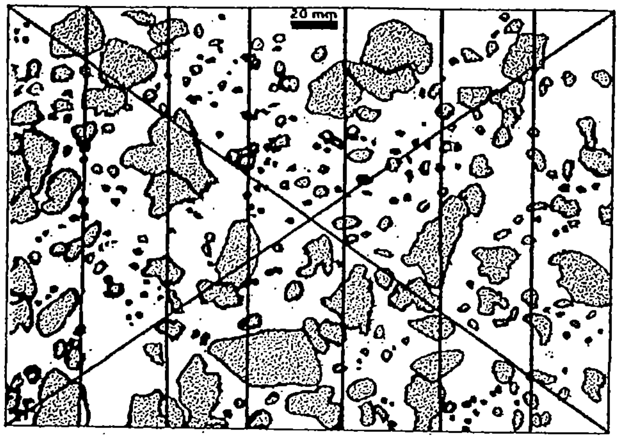


Figure 3: Graphic model of melange, showing scanlines. Scale bar is 20 mm long

sum of individual block areas yields a block areal proportion of 35.6 percent.

Additional data were collected by tracing the arrangement of blocks revealed at the surface of 14 cylindrical laboratory specimens (150 mm diameter, 300 mm long), part of a suite of 60 specimens of model melanges tested by Lindquist (1994). Lindquist fabricated the model melanges with a known distribution of block sizes, and varied both the block volumetric proportions and the orientation of the blocks. The actual volumetric proportion of these specimens, as determined from their weight densities, was compared to the estimates made from image analysis of the tracings. In general the actual volumetric proportion of blocks in the specimens was found to be approximately 30 percent higher than the areal proportion of blocks as exposed on the cylinder surfaces. The discrepancy was apparently due to the higher concentration of blocks toward the center of the specimens, but is still being investigated at the time this paper is being written (March, 1994). For the purposes of my work, I assumed that the areal proportions, as measured on the cylinder surfaces, were representative of the actual volumetric block proportions specimens, since I was really interested in how accurately the block volumetric proportions could be estimated by the linear block proportions measured from scanlines across the traced areas.

4 STEREOLOGICAL MEASUREMENTS

In practice one rarely has the good exposure of melange modeled in Figure 3, so outcrop mapping and drill core sampling must be performed in an attempt to characterize the rockmass. The continuous detailed geological log of a borehole

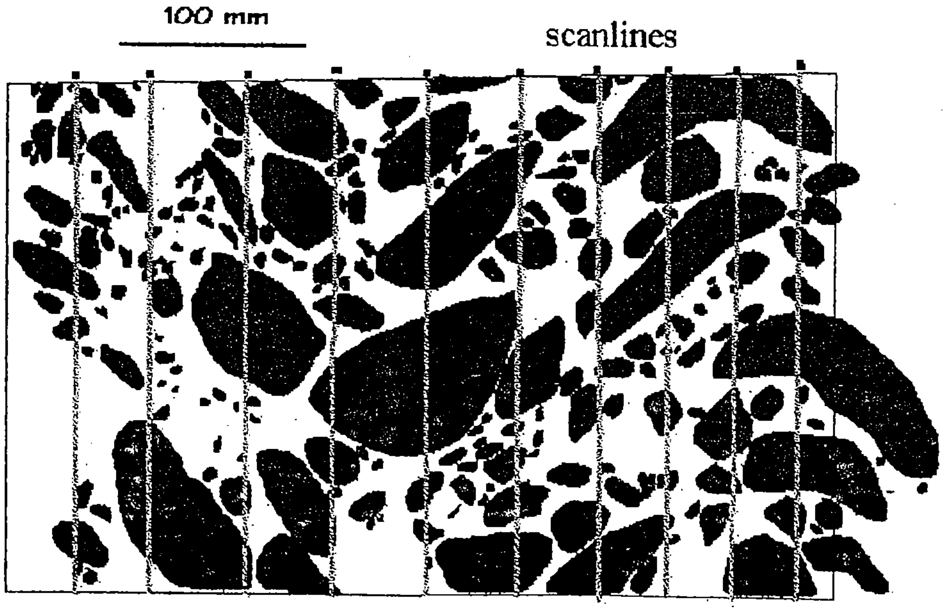


Figure 4: Unrolled tracing of surface of cylindrical triaxial specimen, showing location of scanlines. Specimen is 300 mm high. Blocks are oriented at 30 degrees to the vertical axis.

or the core itself, if available, are sampling *scanlines*. In the case of the graphic models, scanlines (modeled boreholes) were drawn over the graphic models of Figure 3 and the tracings of the surfaces of the triaxial specimens. Measurements were 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.

The equivalence of lineal, areal and volumetric proportions is a fundamental law of *stereology*, using which structures are characterized by zero- ,one-, and two-dimensional measurements (Underwood, 1970). If an image is sampled by a sufficient total length of scanlines, the areal block proportion is estimated, and if sufficient cross-sectional areas are available, the volumetric proportion is estimated. However, it is not necessary that the linear measurements be made on common planes: the investigated volume can be sampled by an arbitrary array of linear traverses in order to arrive at the volumetric proportion. The practice of making linear 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, and were commonly referred to as "Rosiwal Traverses" after the German geologist who devised the method (Rosiwal, 1898). The method was later modified to a larger scale, to allow estimate of the volumetric proportion of air bubbles in concrete test cylinders and the size distribution of those bubbles (Lord and Willis, 1951).

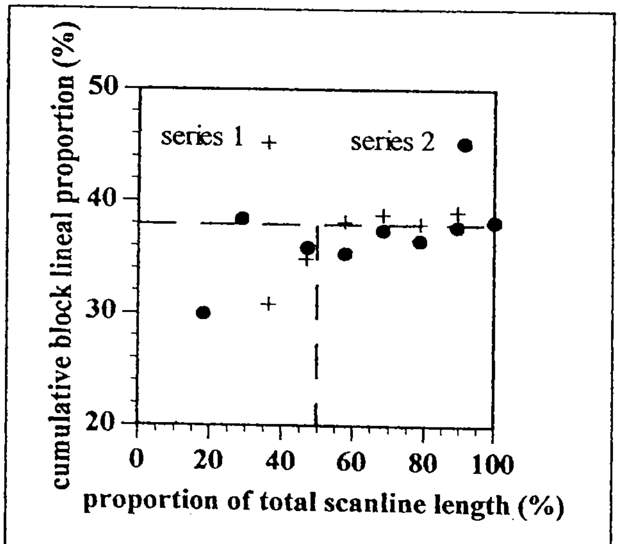


Figure 5: Block lineal proportion for the graphic model shown as Figure 3.

The areal proportion of the blocks in the image of Figure 3 were estimated by accumulating the block linear proportions of eight scanlines totaling 1684 mm in length. As shown in Figure 5, the cumulative linear block proportion is the ratio of the cumulative sum of chord intercepts measured for each scanline, to the cumulative sum of the lengths of the scanlines. Initially, the proportions will vary, but eventually the cumulative proportion converges to one value. For the image of Figure 3, the individual block lineal proportions varied between 53 percent and 30 percent. To test the influence of varying the summation order of scanline data, the incremental cumulative proportion (running average) and incremental proportion of total scanline length were computed. separately for two series of scanlines in arbitrarily chosen sequences. Figure 5 shows that the cumulative block lineal proportion converges (of the image shown in Figure 3) to be 38 percent, close to the block areal proportion of 35.6 percent. Convergence effectively occurs at 50 percent of the total scanline length, or some 840 mm of scanline measurements.

Images of the triaxial test specimens were each sampled by ten scanlines totaling approximately 3000 mm. The linear block proportions generally converged to plus or minus a few percent of the areal block proportions within approximately 40% to 60% of the cumulative scanline length. Hence, measurement of a larger suite of images confirms that at least the areal proportion (and by assumption, the volumetric proportion) of blocks exposed at a surface may be quickly estimated by scanlines.

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. But to confuse this issue, it should be reported that Krumbein and Pettijohn (1938), stated that the "it was generally said" that a total traverse length equal to 1000 times the largest particle should give a "fair" degree of accuracy). However, if Holmes' admittedly more attractive criterion is adopted for the scanline measurements of the graphic model of Figure 3 (average block size of 8.25 mm), then a cumulative length of scanlines of 825 mm would be sufficient to estimate the block areal proportion. The results shown in Figure 5 validate Holmes' 1921) guideline for the block population shown in 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 scanline measurements, or 50 percent of total scanline length. 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 briefly discussed below.

5 ESTIMATING BLOCK SIZE DISTRIBUTIONS FROM SCANLINES

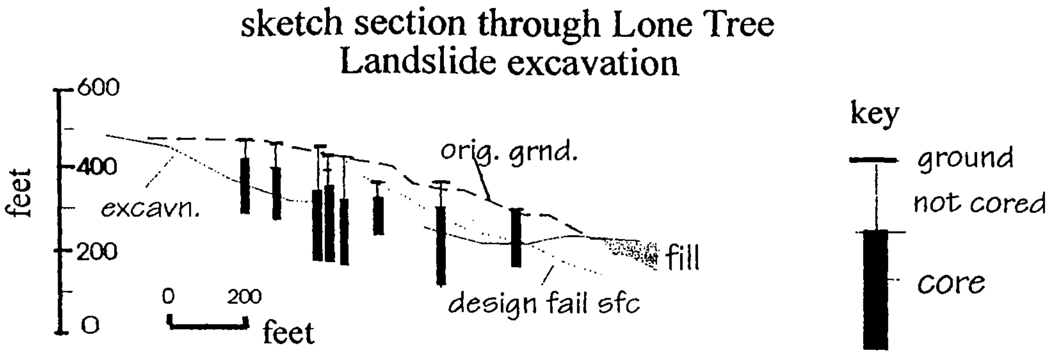
The lengths of chords across blocks intercepted by scanlines are rarely the same as the block characteristic dimensions (or "diameters"). But it can be assumed that the distribution of block cross-sections in the plane of a graphic model, or the distribution of chord lengths from scanlines, is directly related to the true distribution of the three dimensional blocks in the parent volume. The geometric probability character of this complex 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 3 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), which suggests that an empirical and general adjustment between the frequency distributions of chord intercepts and block maximum dimensions for melanges may yet be discovered. Current work shows that for any given chord intercept length, the number of equivalent block diameters is smaller; and for any given frequency, the estimates of true block dimensions will be severely underestimated if one assumes the chord dimensions to be diameters. The topic is explored further in Medley (1994) and Medley and Goodman (1994).

6 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 2). The California Department of Transportation (CALTRANS) restored access by excavating 956,000 m^3 (1.25 million 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 6). Blocks up to 30 m in exposed largest dimension were blasted during the excavation work (Michael Hobbs, Ford Construction, Inc.; pers. comm). Fill from the excavation was placed on the downhill side of the cut to buttress remnants of the landslide. It is anticipated that the fill will be removed by coastal erosion over several decades.

Prior to construction, nine exploratory borings (Figure 6) were drilled to between 37 m and 82 m deep to investigate the stability of the melange that would be exposed in the cut slopes. Some 375 m of HQ size core (61 mm diameter) was recovered, and eventually given to us for our research. Coring started some distance below the ground surface and only 82 m 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, and are referred to here as the



courtesy of CALTRANS

Figure 6: Cross-section through Lone Tree Landslide, California. Core sections recovered from above the base of the excavation line are referred to in the text as "excavation segments". Melange removed from above the base of the excavation was mostly landslide material

"excavation segments". Although much of the excavated melange was landslide material, Figure 6 shows that some of the melange removed from below and behind the assumed failure plane.

Since the largest blocks in the immediate vicinity of the slide are some 30 m in size (maximum observed dimension), the matrix/block threshold was chosen to be 0.3 m using an arbitrary 1 percent criterion (as described in section 2). Nevertheless, the block intercepts in the core were measured to as small as 5 cm in length. The data obtained by measuring the core are shown in Table 1 below.

The estimate of block volumetric proportion of the excavated material as measured from the excavation segments core (4.5 percent), was tested by measuring the areal proportion of blocks that are 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 data are summarized in Table 1 below.

Some 40 percent of the core (approximately 150) 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 7.9 m, with an average length of 0.43 m. The intercepts from the excavation segments core were much shorter, ranging to 9.3 cm 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 7). The block volumetric proportion of the unexcavated melange is estimated to be approximately 28 percent

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. The contractor has estimated that approximately 5 percent of the excavation was composed of blocks greater than 1.3m in size, (Michael Hobbs, Ford Construction; pers. comm.) which is an encouraging confirmation of the results of the study.

It appears that the material removed from the excavation was relatively deficient in blocks. Since the volumetric proportion was significantly less than 30 percent, it was geotechnically prudent and justified to assume the rockmass strength to be equal to that of the weak, sheared matrix. However, the proportion of blocks encountered was much greater than anticipated from the exploration drilling. Removal of blocks or reducing them to grade, required more effort than had originally been anticipated. But in this case, the extra blocks were welcome since they were used as protective rip-rap at the shoreline toe of the fill. Commonly, the discovery and laborious removal of blocks results in contractual disputes due to "changed conditions".

Table 1. Data obtained from measurements of Lone Tree Slide core and from field mapping

Measurement	All core	Excavation Segments Core	Field Mapping
number of boreholes	9	8	-
length of core measured	375 m	82 m	-
avg. length core/borehole	42 m	10 m	-
number of blocks	191	44	117
average block size	0.43 m		2.7 m
block proportion (>1m)	21 %	4.5 %	4.2 %
Convergence: (% total scanline)	(40%)	(38%)	-
min. block measured	0.05 m	0.05 m	0.3 m
max. block measured	7.9 m	0.093 m	15 m
max. predicted block size	15 m	1 m	100 m

There was a great difference between the maximum size of blocks predicted from the investigation of the excavation segments of core, and the maximum size of block mapped in the field. Interpretation of chord intercept data from all the core, and from the excavation segments, suggested that the maximum block sizes that could be encountered in the melange was of the order of 15 m and 1 m respectively. The maximum size measured in the field was, indeed ,approximately 15 m, but the data collected from the fieldwork further suggested that a maximum block of 100 m could be expected. Several blocks of that at least that size are prominent in the general area of the Lone tree Slide. However, judging from my work with graphic models, it seems probable to me that the true distribution of block characteristic dimensions ("diameters") is significantly different from the distribution of chord lengths. Work is underway to predict a more likely distribution of block sizes.

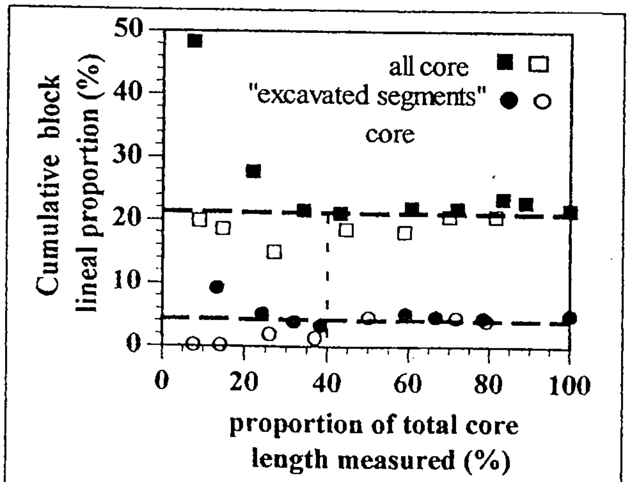


Figure 7: Block lineal proportions for Lone Tree Landslide core. Proportion for all core is approximately 21%, and for the excavation segments, approximately 4.5%

7 SUMMARY AND CONCLUSIONS

Melanges are, generally, chaotic mixtures of hard blocks embedded within sheared shales and argillites, and are members of the large family of geological materials defined as bimrocks (block-in-matrix rocks). Recent work by others indicates that the overall strength of bimrocks is directly related to the volumetric proportion of the blocks. However, the application of a block volumetric proportion/strength relationship requires that a volumetric proportion must 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 linear proportion of chord intercepts measured from drill core. Field mapping and measurement of drill core recovered from the Lone Tree Landslide, California, indicated that the technique may predict the in-situ proportion of blocks in a melange. However, more work needs to be performed to allow confident predictions to be made about the block-size distribution of in-situ melange from the same chord intercept data.

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