Estimating Block Size Distributions of Melanges and Similar Block-in-Matrix Rocks (Bimrocks)

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ABSTRACT: Melanges and similar heterogeneous block-in-matrix rocks (bimrocks) are mixtures of hard blocks encased in weaker matrix that are formidable to characterize. Hard blocks, unexpectedly encountered, hamper excavation and tunneling construction. 1D Borings of melanges produce chord length distributions that differ considerably from the 3D block size distributions, but there is promise that rules may yet be devised to estimate reliable block size distributions of melanges from chord length distributions.

1. INTRODUCTION

Engineering geologists, geotechnical engineers and dam/earthwork/tunneling contractors are globally challenged by the characterization, design and construction problems associated with heterogeneous geological mixtures of hard blocks of rock encased in weaker matrix (block-in-matrix rocks). NOTE: In this paper the term "block" is used to sidestep geological, genetic, structural or size connotations of terms such as *boulder*, *corestone, clast,* etc.

The block-in-matrix fabric is common; indeed, the geological lexicon contains over 1000 words and terms for fragmented and mixed rocks [1]. However, the genesis of these heterogeneous rocks (as implicit in the many geological names) is, to the geological engineer, often less important than characterization and estimation of mechanical properties. To focus on the common geomechanical and characterization problems of block-in-matrix rocks, the writer introduced the term *bimrocks* [2] as a non-genetic term for melanges and other geological mixtures such as sheared serpentinites, breccias, decomposed granites, weathered rocks with corestones, and tectonically fragmented rocks such as those found in faults.

Bimrocks are "a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture" [2]. Geotechnical significance means that blocks must be stronger than the matrix, and the suggested minimum strength contrast between blocks and matrix is: $\tan \phi_{block}/\tan\phi_{matrix} \geq 2.0$ [2].

Although the geological fabric of arrays of hard blocks encased in softer matrices is common, only relatively recently has rock engineering/mechanics research been performed to provide guidelines for the characterization of bimrocks [2,3,4,5,6,7,8,9,10].

The spatial and geomechanical variability of bimrocks hampers rock mass characterizations and estimations of geomechanical and geohydrological properties. Encountering unexpected hard blocks in excavations and tunnels frequently disrupts construction [11]. For glacial tills and other soils containing boulders, procedures have been developed to estimate their sizes and frequency [12,13,14,15,16] and contribution to geomechanical properties [8]. This paper shows why there are currently few, if any, reliable procedures to estimate block size distributions for bimrocks from boring data, although there are promising hints of possible future rules that will allow such estimates.

2. MELANGES

Melanges (from *mélange*, French for "mixture") (Figure 1) are amongst the most troublesome bimrocks. Lessons learned from research into melanges may be applicable to bimrocks formed by geological fragmentation, such as fault rocks, lahars, weathered rocks and breccias.

Melanges are complex mixtures of strong blocks embedded within weaker matrices. Melanges exist in over 60 countries [2], generally in mountainous regions associated with tectonic subduction zones. Melanges are typical of the Franciscan Complex ("the Franciscan") of northern California [17], and in other tectonic jumbles of western North America [18]. From an excavation/tunneling point of view, melanges are similar to fault rocks, decomposed granites, glacial tills, breccias and lahars, since they contain hard blocks that surprise contractors and owners, and result in construction claims.

Fig. 1. Typical Franciscan melange. Scale bar is 1.5 m. [2]

Blocks in Franciscan melanges are composed of graywacke, intact siltstone/turbidites, greenstone, limestone, cherts and exotic metamorphic rocks, often in puzzling geological juxtaposition. The matrix rocks of Franciscan melanges are shale, siltstone and serpentinite, generally sheared. Shears pass around blocks in sinuous, tortuous fashion, and are generally most frequent around large blocks. Franciscan blocks are roughly ellipsoid with minor:major axes of about 1:2, where measured [2]. Block surfaces may be slickensided and polished. Small blocks can sometimes be plucked out of the matrix by hand [2].

In melanges, volumetric block proportions between about 25 percent and 75 percent control the overall strength of melange rock masses [7,8,9,10]. The volumetric proportion of blocks in a bimrock is of interest to the earthwork or tunneling contractor excavating through melange, glacial till, decomposed granites and other heterogeneous mixtures of hard blocks and soft matrices.

The range and frequency of block sizes is also of interest because levels of effort and economic penalties for excavation and tunneling construction are related to the size of any unexpected blocks encountered. In glacial tills, block sizes may be limited to a meter or so, but in a melange, blocks range in size between millimeters and hundreds of meters.

3. STEREOLOGICAL CONSIDERATIONS

In practice, the estimation of the volumetric proportion of blocks in a bimrock, a 3-Dimensional (3D) property, depends largely on 2-Dimensional (2D) geological mapping, and 1-Dimensional (1D) measurements of exploration drill core/block intersection lengths (chords) [2,4,19]. The volumetric block proportion is related to the linear block proportion (ratio of total length of chords to total length of drilling), subject to uncertainties [19]. The estimation of 3D block size distributions from 1D chord length distributions is a more complex problem than that of estimating block volumetric proportion, and the uncertainties are even greater, although at present not quantified.

The *maximum observed dimension* (d_{mod}) characterizes block sizes measured from 2D maps and outcrops (Figure 2). In 1D drilling exploration, the chord length of intersection between the drill core and the block characterizes the size of blocks. Chords and d_{mod} will generally be shorter than the maximum dimensions of blocks (Figure 2). Hence, 1D chord length distributions underestimate the actual 3D block size distributions, as shown later in the paper.

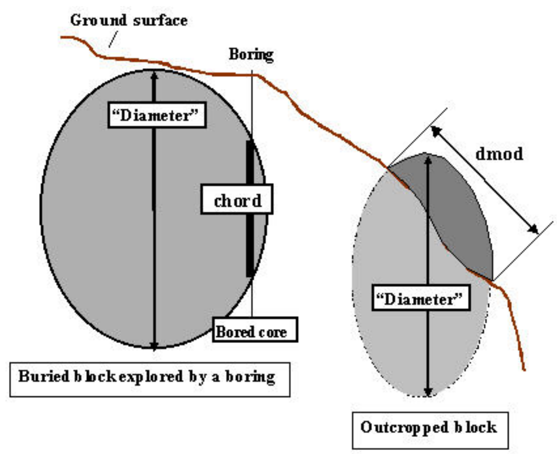

Fig. 2. Chords and d_{mod} compared to block "diameter" [4].

Estimation of 3D particle size distributions from measurements in 1D and 2D are considered by *stereology*, a discipline blended from geometrical statistics, mathematics, microscopy, image analysis and empirical research. Stereological techniques "unfold" (extract) 3D particle size distributions from measurements taken in 2D [21,22,23] using mathematical relationships [24,25,26]. A software program used for unfolding 2D microscopic crystal size measurements (*CSD Corrections 1.2*, from http://wwwdsa.uqac.uquebec.ca/~mhiggins/csdcorrections.html [25]) was creatively used to estimate melange block sizes from 2D measurements recovered by image analysis of face conditions in an Austrian tunnel [27].

Little help is available to solve the more difficult problem of unfolding 3D size distributions from 1D chord distributions. Some insight is gained from considering the probability distribution of randomly sampled chords from a single sphere: the distribution is monotonically triangular, with a minimum probability of zero and a maximum probability of about 0.61, at the diameter of the sphere [24]. However, the probability distribution for chords intersecting a population of many spheres of different diameters (such as air bubbles in concrete, or vesicles in basalt) is a complex nest of triangular distributions superimposed one on another, as illustrated in several stereological texts [21,22,23].

The intersection of a certain size sphere by sampling 1D scanlines or borings creates chords varying from some maximum (equivalent to the actual diameter of the sphere) and a *tailing* of gradually smaller chords. In a histogram, each of the chords in any given size class contains not only the chords equivalent to the diameters of spheres which are proper members of that class, but also all the tailings chords of larger spheres. The largest size class may or may not actually contain the diameter of the largest sphere. Graphical and analytical techniques unfold the size distributions of chords through spheres [21,22,23], but these methods are inappropriate to populations of the ellipsoidal to irregular blocks in bimrocks. (NOTE: A Bayesian statistics approach is available to estimate boulder size distributions from chord length distributions [15]).

4. MELANGE BLOCK SIZE DISTRIBUTIONS

For blocky rock masses, 3D block size distributions are generally estimated for the purposes of geotechnical design, blasting procedures and ore processing. Unlike weight-based soil particle size distributions, block size distributions must be estimated on the basis of measurements from 2D mapping or 1D scanlines or borings.

3D block size distributions in rock masses generally obey negative exponential rules, where there are very few large blocks and an increasing number of small blocks. With weathering of blocky rock, it is also expected that the block size distributions of corestones is exponential. Exponential size distributions of boulders in glacial tills were encountered during construction of the Storebælt project in Denmark [12] and excavation of Toronto's subway [13].

Block size distributions in blocky rock masses can also be described by negative power law [28] (fractal) distributions, where the absolute value of the negative slope of the frequency/size relationship (plotted as *log-histograms* with logarithmic axes) is also termed the *fractal dimension*. Many geological processes create fragmented systems that are characterized with power law relationships [29,30], including the block size distributions of Franciscan melanges [31] and other fragmented blocky rock masses [28], although the geometry and meaning of "blocks" differs.

Medley [2] measured the maximum observed dimension (d_{mod}) of about 1900 blocks from geological maps and outcrops of Franciscan melanges. The areas (A) containing the measured blocks ranged over 7 orders of magnitude. Block sizes, as measured, ranged between millimeters and tens of kilometers. The size distributions of the blocks at various scales were rendered dimensionless by dividing the measured block sizes by the square root of the area containing the blocks ($\sqrt{A}$). For each area reviewed, the numerical frequencies of blocks were converted to relative frequencies, where the total number of blocks measured for that area was divided into the number of blocks in each class. Geometric size classes were established in which each successive class was double the range of the previous class (i.e.: 0.025-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.8). Figure 3 shows the data as a set of log-histograms (the value at the end of each size class is indicated).

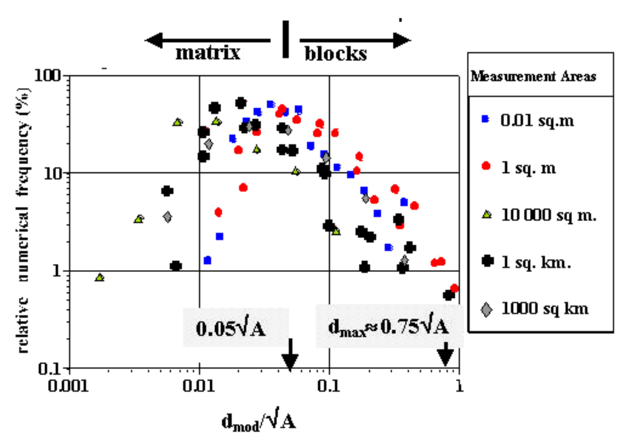

Figure 3. Compilation of log-histograms of block sizes of 1900 blocks in Franciscan melanges ranging mms to kms [1]

Despite the extreme range in block sizes, Figure 3 shows that individual block size distributions are similar in appearance: the peaks of the curves occur at about $0.05\sqrt{A}$ at relative frequencies of between 30 percent and 50 percent. To the left of the peaks, block relative frequencies are lower because the blocks become too small to measure and the size classes become narrower. To the right of the peaks, the largest blocks occur at about $d_{mod}/\sqrt{A}=1.0$. Accordingly, based on the data, the largest possible block in Franciscan melange at <u>any scale of interest</u> is about equivalent to $\sqrt{A}$ in size. However, since more than 99 percent of blocks are smaller than $0.75\sqrt{A}$, this size is defined as the largest reasonable block size, d_{max}.

Figure 3 also shows that at any scale explored, blocks will be encountered in the Franciscan. Thus, Franciscan melanges are scale-independent [31]. So: What is block and what is matrix? In answering this question, Medley [2] defined the block/matrix limit <u>at any scale</u> to be $0.05\sqrt{A}$, because blocks smaller than $0.05\sqrt{A}$ constitutes less than 1 percent of a Franciscan melange rock mass and make little contribution to the mechanical properties of the rock mass. Furthermore, since melanges are scale independent, the block/matrix threshold can be related to the scale of engineering interest by a *characteristic engineering dimension* (L_c) such as a tunnel diameter, footing width, laboratory specimen diameter, $\sqrt{A}$ and so on. When scaled by L_c the block matrix/threshold is thus $0.05L_c$ and the largest block, d_{max}, is $0.75L_c$ [2,4].

The melanges shown in Figure 3, measured from 2D maps and outcrops, have a range of fractal dimensions (or slopes) between 1.1 and 1.7, with an overall value of about 1.3. In 3D, the fractal dimension is simply estimated by adding 1.0 to the 2D fractal dimension [30,31], hence the overall Franciscan melange fractal dimension is 2.3. For Franciscan melanges, for some n blocks in a size class, there will be $2n^{2.3}$ or, about 5, in the previous class, or about 1/5 in the next larger class [31].

The implication of this finding is that rough estimates of block size distributions can be made using some given range of block size and number as a starting point, and successively multiplying the numbers in each size by 5 if one starts with a number of large blocks and works backward through the distribution, or by 1/5 if one starts with a number of small blocks. A check on the estimated blocks size distribution can be made by assuming individual block geometries (such as ellipsoids), calculating the total volume of blocks, dividing that total by the explored rock mass volume and comparing the resulting block fraction with the block volumetric proportion (estimated from the block linear proportion) adjusted for uncertainty [4,20,31]. This method is approximate but is a good starting point for preliminary "What If?" analyses.

5. INSIGHT FROM PHYSICAL MODELS

Medley and Lindquist gained insight into bimrock properties by using physical models [9,20]. Using models, Lindquist discovered the relationship between block volumetric proportion and melange strength [9]. Medley used physical models to identify and accommodate the uncertainty between estimates of block volumetric proportion based on block linear proportions generated from chord measurements [20]. Medley and Lindquist's findings significantly contributed to the success in understanding geomechanical properties of melange in the foundation of Scott Dam, CA [7]. For this paper, new data were recovered from photographs and graphics of the models.

5.1. Lindquist Models

Lindquist fabricated over 100 triaxial specimens (150 mm in diameter and 300 mm high) of model melange and tested these to failure in multistage testing [9,10]. The model melanges were mixtures of hand-made blocks of relatively high-strength concrete, within matrices of low strength concrete. The specimens contained volumetric block proportions of about 30 percent, 50 percent and 70 percent, with block orientations (angle between long axes of blocks and vertical specimen axes) of 0 degrees, 30 degrees, 60 degrees and 90 degrees (Figure 4). Specimens required between 1190 blocks (70 percent block proportion) and 425 blocks (30 percent block proportion).

Lindquist selected a 3D block size distribution to model a Franciscan melange with a fractal dimension of 2.0. Block sizes ranged between an average large block size of about 1165 mm to an average small block size of 12 mm size, which was considered the block/matrix boundary. Four size classes were selected: 10 mm-19 mm, 19 mm-38 mm, 38 mm-75 mm, and 75mm-150mm. The relative frequency of blocks in each of these size classes was about 75.3 percent, 18.9 percent, 4.7 percent, and 1.2 percent, respectively.

The circumferential surfaces of 14 of the triaxial specimens were traced onto transparent kitchen film, and developed (folded out) (Figure 4). The tracings were photographed, and using image analysis, several block parameters were measured [2]. Figure 4 shows two of the tracings: one of a low block proportion melange with vertical blocks (block/chord orientation of 0 degrees); and the other of a high block proportion specimen with blocks oriented horizontally (90 degrees).

Each tracing was also sampled with 10 vertical scanlines and chords were measured. The chords were used to generate block linear proportions and 1D chord length distributions to compare with the known block volumetric proportions and 3D blocks size distributions.

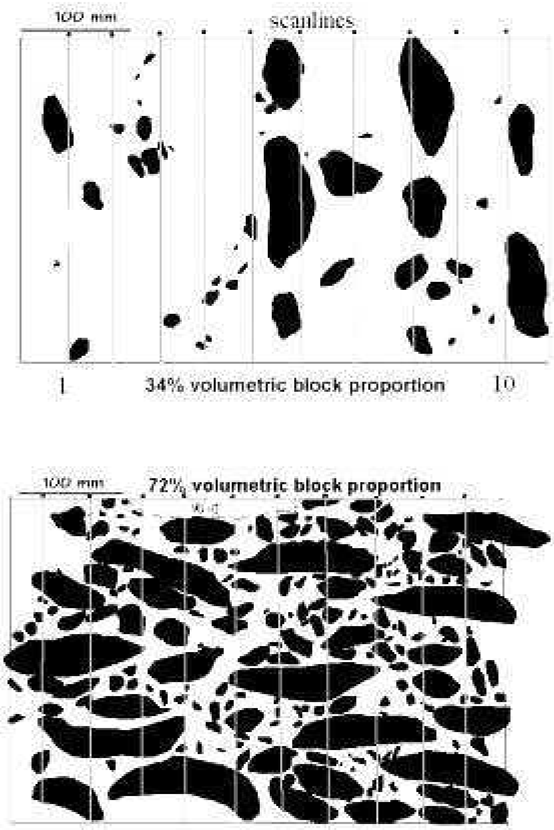

Fig. 4. Tracings of two Lindquist [1994] triaxial specimens of melange sampled with 10 vertical scanlines (thin white lines) to measure chords Top: low block proportion, vertical blocks. Bottom: high block proportion, horizontal blocks. [2]

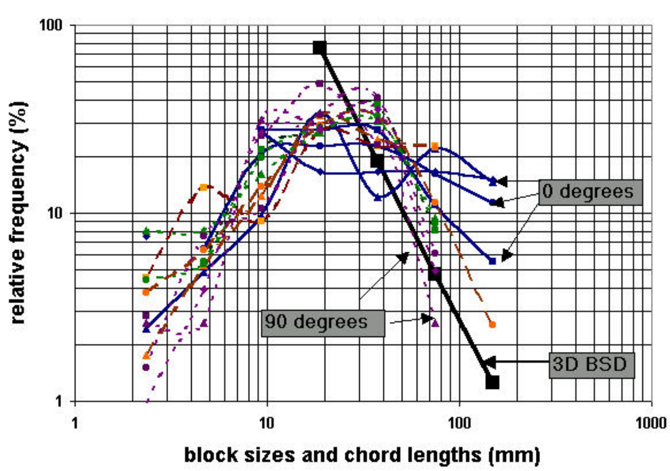

Fig. 5. Log-histograms of relative frequencies of 1D chord lengths compared to parent 3D block size distribution (bold line) from tracings of Lindquist specimens.

Figure 5 shows that the original 3D ("parent") block size distribution is poorly indicated by the 1D chord length distributions, invalidating any assumption that chord length distributions reliably map actual 3D block size distributions. However, the peaks of the individual chord length distributions correlate well with the high relative frequency of the smallest size blocks in the parent 3D distribution. Hence, the peaks in chord length distributions may identify the block/matrix threshold size, although there is a large difference in the relative frequencies of chords and blocks at the peaks.

The tailing of the chord length distributions extends for three size classes smaller than the smallest size class of the parent 3D size distribution. In other words, chord lengths were generated that were smaller than the original smallest blocks.

Chord length distributions for the 0 degrees block/scanline orientations poorly mimicked the parent 3D block size distribution, for chord lengths larger than the original smallest block size. However, the chord length distributions for the 90 degree orientation, for chords larger than the block/matrix threshold, generally mimicked the parent distribution. This is because many more chords were generated as the borings intersected the larger blocks two to three times (Figure 4). The resulting chord lengths were approximately equivalent to the minor axis of the blocks, which being about half the length of the major axis, resulted in chords that were assigned to the largest classes, which are generous in range.

In many cases large chords were measured that were assigned to the same size class as the parent 3D distribution. This observation suggests that chord length distributions could indicate d_{max}, even if the relative frequencies of the chords were higher than those of the parent blocks.

5.2. *Medley Models*

The Lindquist models [9] provided chord data for various proportions and orientations of blocks, but measurements were limited to 10 scanlines per specimen, measured at the circumferences. To better understand uncertainty between scanline data and known model properties, Medley [20] fabricated physical models to research uncertainties in estimates of block volumetric proportions generated from exploration drilling. The data were reviewed for this paper to understand the sources of uncertainties in estimates of block size distributions based on chord length distributions.

Four physical models were constructed of mixtures of Plaster of Paris matrix and blocks fabricated of

Play-Doh (children's Plasticene), clay and brown rice [20]. Block volumetric proportions (13 percent, 32 percent, 42 percent, and 55 percent), block shape (ellipsoidal), block size distribution (modeled as typical Franciscan with fractal dimension 2.3) and block orientation (generally vertical, or 0 degree orientation) were controlled.

The models were approximately 1110 mm to 150 mm high, 100 mm wide and 170 mm long. The plan area (A) of the models was about 17000 mm^2. The largest blocks were constructed to be about 0.75√A in largest dimension, or about 98 mm long. Blocks ranged in size between 95 mm and 3.5 mm. Blocks were fabricated within 5 size classes between 0.05√A (3 mm-6 mm) and ranging through 0.8√A (48 mm-96 mm). All models had the same relative frequency of blocks: 79.7 percent for 0.05√A, 16.2 percent for 0.1√A, 3.3 percent for 0.2√A, 0.7 percent for 0.4√A at and 0.1 percent for 0.8√A. The total number of blocks in each model ranged between about 2200 for the 13 percent model and about 7350 for the 55 percent model.

Plaster of Paris and the blocks were mixed and, once the models had cured, each model was sawn into 10 slices. Each slice was photographed and the photographs scanned (Figure 7). Ten model vertical "boreholes" were drawn on each scanned photograph (Figure 7) and the proportion of blocks in each boring was measured, to produce 100 linear proportions for each model. These exhaustive data sets became the basis for a statistical analysis of uncertainties in estimates of block volumetric proportions [20].

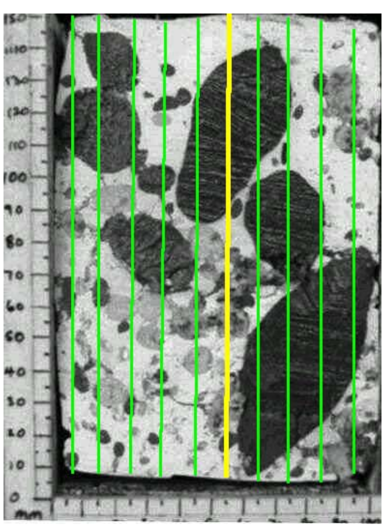

Fig. 7. Typical slice from 42 percent model, with 10 model "borings" (widths exaggerated for clarity). Thicker, lighter line is "centerline"[after 20].

For this paper, the chord lengths were measured for all 400 model borings and compared to the known block size distributions. The numbers of chord lengths were: 238 for the 13 percent model, 622 for the 32 percent model, 806 for the 42 % model and 723 for the 55% model (which was 40 mm shorter than the other models). The numbers of chords thus ranged between about 10 percent and 15 percent of the actual numbers of blocks in each model.

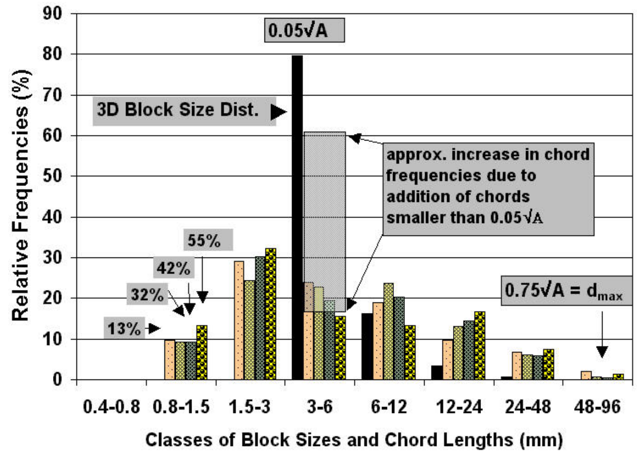

Fig. 8 Conventional histogram of original 3D block size distribution (black bars) for four models of physical melange, and chord length distributions generated from 400 model borings. (Note: 0.8 mm is actually 0.75 mm). Thick shaded bar at 3-6mm class schematically shows sum of relative frequencies for classes smaller than 0.05√A..

Figure 8 and Figure 9 show that despite the considerable amount of sampling (15500 mm per model, or more than 170 d_{max}) there is little match between the original 3D block size distribution and the 1D chord length distribution. The tailing effect is well demonstrated: chord lengths were generated that were smaller than the size of smallest parent blocks of 3mm-6mm.

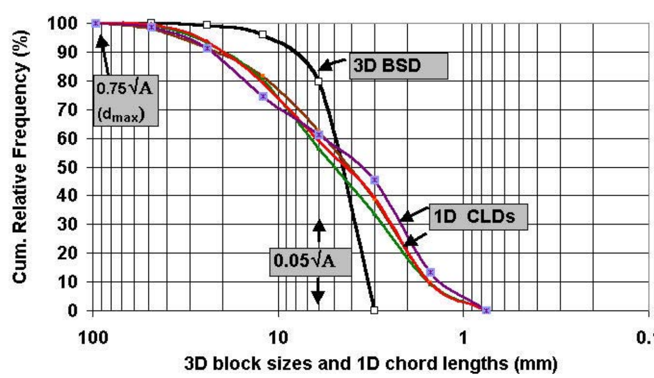

Fig. 9. Parent 3D blocks size distribution and 1D chord length distributions for the four Medley models, plotted in the style of a "particle size distribution".

Although the greatest number of parent blocks is for the smallest size (relative frequency 80 percent), there are much fewer chords at this size. This is expected given the small geometrical probability of encountering a small block with a boring, even if there are many of them. On the other hand, the larger blocks are more likely to be encountered because of their size, although not generally through the longest dimension. Furthermore, the relative frequency of larger chords is greater than the relative frequency of blocks for the same size classes, because a few large chords in a relatively small total number of chords inflate the relative frequency of chords.

Figure 8 suggests that some unfolding of the chord distribution could be performed, by adding all the relative frequencies of the chords smaller than the smallest block size (i.e. 0.75 mm-1.5 mm and 1.5 mm-3.00 mm) to the relative frequencies of the smallest block (3.0mm-6.0mm, or 0.05√A). This can be done with confidence for the model data because the small chords were generated from larger blocks. In practice, though, there would actually be blocks of the same small size in addition to the small chords. But if we care only about blocks greater than the block/matrix threshold size, the addition of chords smaller than the block/matrix threshold increases the relative frequencies of the 3.0mm-6.0mm class by about 40 percent to a total of 60 percent, which is less than the 3D relative frequency of 80 percent, but is still an improvement.

5.3. *Working With Data From Few Borings*

Generally, geo-practitioners work with relatively few borings to characterize rock masses. Accordingly, each Medley model was explored with 10 borings along the centerline of the model (Figure 7) much as a volume of melange would be explored if a tunnel or excavation were contemplated. The total length of sampling was between 15 times and 20 times d_{max}, which would be more than sufficient for purposes of estimating block volumetric proportion in Franciscan melange [20] but is clearly insufficient (Figure 10) to estimate the 3D block size distribution.

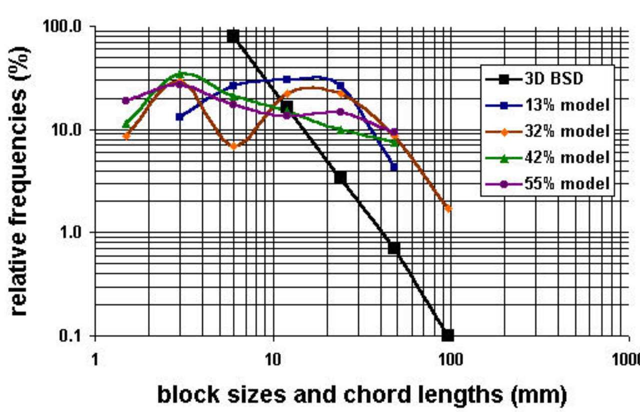

Fig. 10. Chord length distributions based on chords measured from 10 "centerline" model borings for each Medley model

Figure 10 shows the log-histograms of the "centerline" chord data, which have broad peaks poorly correlated with the 3-6 mm size (0.05√A), the smallest size class of the parent 3D distribution. The flat curves are a result of limited data and also the generally vertical orientation of the blocks (see Figure 5 for similar behavior of 0 degree data from Lindquist models). The largest measured chords from the centerline borings were smaller than the largest block size class at about 90-95 mm (d_{max} or, 0.75√A): only the 42% percent model yielded chords for the largest block size.

Figure 10 indicates that, on the basis of the few borings normally performed in geotechnical exploration, it would be foolish to assume that 1D chord length distributions reliably represent actual 3D block size distributions.

6. CONCLUSIONS

There is little equivalence between 3D block size distributions and 1D chord length distributions generated from measurements of block/boring intersections, regardless of how much drilling, and how many chords are generated.

Promisingly, there are indications that 1D chord length distributions could be converted into estimates of the 3D block size distributions. For example: the peaks in chord length distributions may indicate the block/matrix threshold, and the size of the largest block, d_{max}, may be indicated.

Before incorporating such observations into simple rules to convert 1D chord length distributions into 3D blocks size distributions, the statistical uncertainties (i.e.: errors) must be identified. Ongoing work suggests that the uncertainty depends on many factors, the most important being: block shapes, block volumetric proportions, block orientations and total length of sampling.

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