Observations on Tortuous Failure Surfaces in Bimrocks

By Edmund W. Medley

Although heterogeneous geological mixtures of competent blocks of rock encased in weaker matrix have long frustrated designers, contractors and owners, only recently have geotechnical design guidelines been available for characterizing geological chaos (1, 2). As a step in the process of understanding the common geomechanical behavior of the vast variety of soil/rock mixtures, the author introduced the term "bimrock" (block-in-matrix rock) to include melanges, sheared serpentinites, breccias, decomposed granites, weathered rocks with corestones, and tectonically fragmented rocks such as fault rocks (3). Bimrocks are defined as geological mixtures composed of geotechnically significant rock blocks within a bonded rock matrix of finer texture (3). The term "geotechnical significance" means that there is a sufficient volume of blocks with mechanical contrast between blocks and matrix to induce failure surfaces to pass around the blocks. The overall strength of bimrocks increases with increases in volumetric block proportions, the geomechanical advantage being due to the extra effort expended by tortuous failure surfaces forced around competent blocks (4, 5). The factor of safety for slope stability also depends on volumetric block proportion, as well as block orientations (6).

From a study of failed physical model melanges, this paper summarizes the characteristics of tortuous failure surfaces and their dependence on volumetric block proportions and block orientations and presents a preliminary guideline for estimating the thickness of potential failure zones in bimrocks.

Background on melanges and tortuosity

The most intractable bimrocks are fault rocks and melanges (from French: mélange, or mixture), exemplified by those of the Franciscan Complex of California, popularly known as "the Franciscan". Figure 1 shows an example outcrop of a Franciscan melange. Melanges occur globally in mountainous terrains, and are notorious for their role in slope instability and for providing unexpected and expensive difficulties during excavation and tunneling; and construction claims are common for unexpected "mixed face" tunneling conditions and differing site conditions claims.

Although melanges are common, only relatively recently have guidelines been presented for their geotechnical characterization (1, 7). Clues to melanges are the presence of rocks of different lithologies juxtaposed in improbable fashion (7), or the "scaly clay" fabric of intensely sheared shale with blocks, such as the "argille scagliose" of Northern Italy. Blocks in Franciscan melanges are commonly greywacke, are roughly ellipsoid with minor : major axes of 1:2

Beobachtungen an geschwungenen Versagensflächen in Bimrocks

Bimrocks (so genannte Block-in-Matrix Gesteine) bestehen aus einem Gemisch von kompetenten Gesteinsblöcken umgeben von Matrixgestein mit geringer Festigkeit, die sehr oft geschert sind und sich wie Lockergestein verhalten. Beispiele hierfür sind Melangen und Störungsgesteine. Eine vorläufige Studie bezüglich der Geometrie von über 70 Versagensflächen in physikalischen Modellmelangen deutet darauf hin, dass Zug-Druck-Linien von Versagensflächen, Blockvolumen und Blockausrichtung nur unwesentlich voneinander abhängig sind. Es ist deshalb sinnvoller, mögliche Versagensflächenbereiche zu untersuchen als potenzielle Versagensmodelle zu entwickeln. Diese Bereiche/Zonen bewegen sich in einer Größenordung von 5 bis 15 % der ingenieurtechnischen Kenngröße (wie Böschungshöhe und Dammfußbreite). Es besteht kaum eine Beziehung zwischen den beobachteten extrem uneinheitlichen Versagensflächen in Bimrock und Profilarten für die Auswahl des Trennfugenrauigkeitskoeffizienten. Eine Abhängigkeit besteht jedoch zwischen Blockvolumen und dem Größenverhältnis von Versagensflächen in Kontakt mit Gesteinblöcken.

Bimrocks (block-in-matrix rocks) are mixtures of competent blocks of rock surrounded by weak matrix rocks, which are often sheared and soil-like, and are exemplified by melanges and fault rocks. A preliminary study of the geometries of over 70 failure surfaces in physical model melanges indicates that there is little dependence between failure surface trajectories, volumetric block proportions and block orientations. Rather than attempt to model potential failure surfaces, it is more reasonable to analyze potential failure zones; the thickness of which ranges between 5 and 15 % of the characteristic engineering dimension that scales the problem at hand (such as slope height and dam footing width). There is little relationship between the observed highly irregular bimrock failure surfaces and type profiles for the selection of joint roughness coefficients. There is dependence between volumetric block proportion and the proportion of failure surfaces that contact blocks.

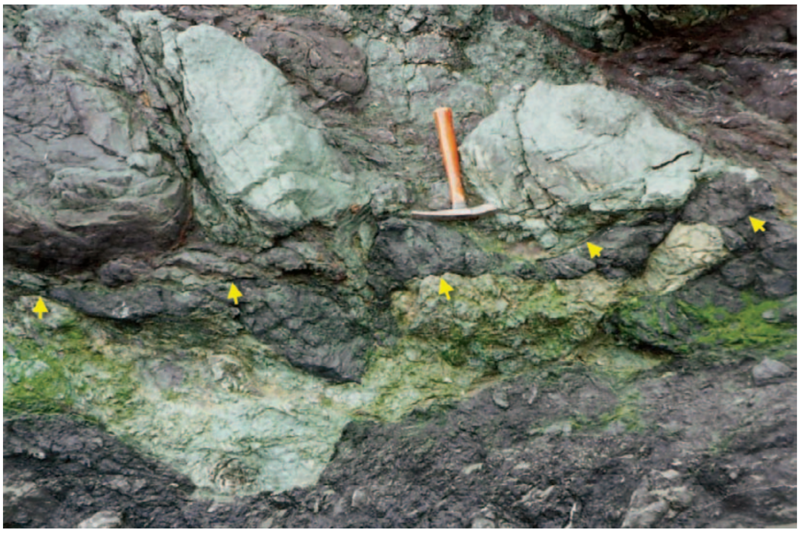

Fig. 1 Franciscan melange at Trinidad Beach, Humboldt County, Northern California. Yellow arrows indicate one of several shears.

Bild 1 *Franciscan Melange am Trinidad Strand, Humboldt County, Nordkalifornien. Gelbe Pfeile kennzeichnen eine von mehreren Scherungen.*

and greater, and often have slickensided and polished surfaces. Block shapes influence the tortuosity of failure surfaces most when coupled with the orientation of the blocks: elliptical blocks have the greatest deleterious effect on slope stability when the direction of the major axes is co-incident with the direction of shearing (6). Well-fractured blocks may have little strength contrast with matrix and should then be considered matrix. Melange rock masses can contain block-poor and block-rich regions (6).

Blocks in Franciscan melanges are found at all scales of engineering interest and the range of block sizes extends more than seven orders in magnitude, between sand and mountains (8). The author (1, 3) suggests appropriate scaling dimensions be selected over the range of scales of engineering interest, (termed the "characteristic engineering dimension") such as the diameter of a laboratory triaxial specimen, the height of a landslide, the diameter of a tunnel, or the width of a dam foundation. At the selected scale of interest, blocks are limited to between about 5 and 70 % of the characteristic engineering dimension. The materials below the 5 % limit are matrix and those above 70 % are blocky rock masses.

The overall mechanical properties of bimrocks are mainly affected by the mechanical properties of the matrix, the volumetric block proportion, the block shapes, the block size distributions and the orientation of the blocks relative to failure surfaces. When the block proportions are between about 25 and 70 %, the increase in the overall mechanical properties of bimrocks are directly related to the volumetric block proportion of blocks in the rock mass (5). Tortuosity is defined as "winding or twisted" (9) and is a property defined in medicine, groundwater hydrology and fluvial geomorphology, but is not commonly used in rock engineering.

The increase in the overall friction strength due to tortuosity can be as much as 15° to 20° above the matrix friction strength. Increases in volumetric block proportion also lead to a decrease in the bimrock cohesion. Irfan and Tang (10) identified similar relationships between volumetric block proportion and shear strength for Hong Kong colluvium containing boulders to 7 m in size.

Matrix rocks in Franciscan melanges are most often fractured and broken to completely sheared soil siltstone and shale. Shears pass around blocks (Figures 1 and 2), and may be numerically denser around large blocks. Melanges are often extensively sheared to soil: about 800 shears per meter were counted in a Franciscan melange (11). Common rock engineering terminology used to indicate the quality of the rock surfaces of rock mass "discontinuities", such as "waviness", "sinuosity" and even "roughness", do not adequately reflect the often extreme irregularity and dimensional variations exhibited by failure surfaces in chaotic melanges and fault rocks.

The block/matrix contact of melanges is generally the weakest component of the bimrock, particularly if the contact is also part of a preexisting shear and there is potential for future failure of a melange rock mass to occur along pre-existing failure surfaces. Accordingly, there is geotechnical motivation to understand the geometry and characteristics of failure surfaces in bimrocks and the contribution of block/failure contact strengths to their geomechanical properties for slope instability studies (6) or dam foundation analyses (2, 12).

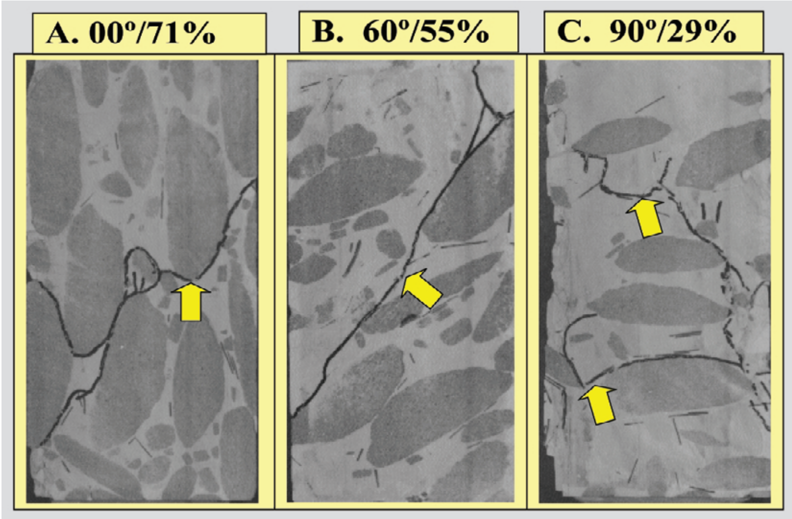

Fig. 2 Cross-sections through 150 mm diameter triaxial specimens of model melange of differing overall block orientations relative to vertical axial loading (degrees) and volumetric block proportions (%). Arrows indicate black lines of tortuous failure surfaces. Specimens as tested by Lindquist (4): A: H0150, B: M60200, C: L9050. After (3).

Bild 2 *Querschnitt durch dreiachsige Probekörper mit 150 mm Durchmesser aus typischer Melange mit unterschiedlicher Gesteinsblockausrichtung relativ zur Vertikalachslast (°) und dem Blockvolumen (%). Pfeile kennzeichnen die schwarzen Linien der geschwungenen Versagensflächen. Probekörper wie von Lindquist gestestet (4): A: H0150, B: M60200, C: L9050. Nach (3).*

Measurement of tortuosity characteristics in model bimrock

As a part of his research, Lindquist fabricated and triaxially tested over one hundred 150 mm, 300 mm high cylindrical specimens of model melange composed of mixtures of hard blocks and weaker matrix (4, 5). Specimens had one of three general volumetric block proportions (about 30, 50 or 70 %); one of four possible overall block orientations included relative to the vertical axial loading direction (0°, 30°, 60° and 90°); and one of five possible confining stress conditions ranging between 50 psf (2.5 kPa) and 250 psf (12.5 kPa). The specimens were tested triaxially to failure and some specimens were cut to reveal the internal patterns of failure. As shown in Figure 2, failure surfaces generally passed around blocks.

The block size distribution of the blocks in the bimrock mixtures conformed to a Franciscan-type, fractal (well-graded) size distribution (4, 8), with blocks ranging in size between about 115 and 12 mm. Since the specimen diameter indicates the laboratory scale of interest, the block sizes thus ranged between 75 and 8 % of the appropriate characteristic engineering dimension.

Adopting a procedure developed by the writer (3, Section 2.8.2) Lindquist documented the external patterns of failure surfaces of about 60 of his specimens (4). The specimens were wrapped in transparent kitchen "cling film" (known as Saran

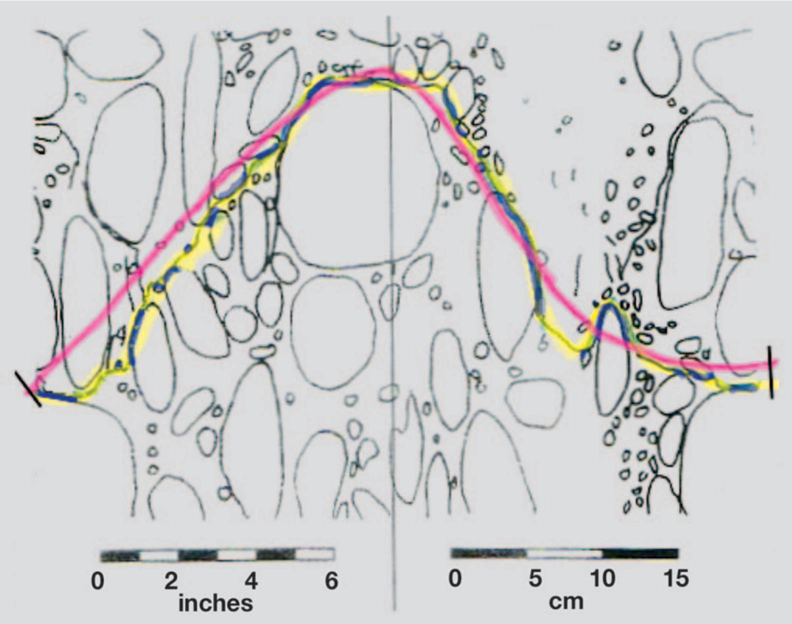

Fig. 3 Scanned tracing of circumferential surface of triaxial specimen C in Figure 2. Measurements were made of: a) the length of the tortuous failure surface (yellow highlighted line); b) the length of estimated smooth mean surface (red line); and c) total length of the block contacts along the failure surface. Specimen H0150. After (4).

Bild 3 *Umfangsabwicklung des dreiachsigen Probekörpers C in Bild 2. Messungen von: a) Länge der geschwungenen Versagensfläche (gelbe Linie); b) Länge der geschätzten ausgeglichenen Durchschnittsfläche (rote Linie); und c) Blockkontaktgesamtlänge entlang der Versagensfläche. Probekörper H0150. Nach (3).*

Wrap in the USA), and the outlines of blocks and failure surfaces traced with a felt pen. Folded flat onto white cardboard, the tracings were photocopied, as shown in the example of Figure 3. The tracings are 2D projections of cylinders, and as such there is some distortion of blocks by "stretching" in the horizontal direction, the amount being a function of block orientations (3, Section 2.8.2).

Copies of Lindquist's tracings were used in this study to investigate characteristics of the failure surfaces. The failure surfaces were expressed on the cylinder surface as irregular lines that tortuously negotiated around blocks as shown by the yellow highlighted line in Figure 3. The lines were measured using a flexible chain made of fine links that allowed it to be draped around tight bends. Once a length of the chain was placed along all of a failure surface, it was removed, straightened and measured. The length was declared to be L', the tortuous length.

A smooth line was also drawn through a path estimated to be that which the failure could have produced in the absence of the blocks, as shown by the red line in Figure 3. The template for the estimated smooth line was the simple linear pattern of failures in matrix-only specimens tested by Lindquist (4). Furthermore, it was also assumed that the actual failure surfaces deviated as little as possible from the tortuous surfaces, as a matter of energy conservation. This line was also measured manually by the chain, and declared to be L_o. For this study, it was assumed that the degree of horizontal "stretching" was the same for both the actual failure line and estimated smooth failure line. About 70 tortuous failure lines and smooth lines were measured.

The individual lengths of block/failure surface contact (tangents; blue line segments in Figure 3) were also measured, and these were totaled to produce a total block/failure contact length, identified as t.

Compilations of manual tracings of the failure lines, such as those shown in Figure 4, were sketched for specimens grouped by common volumetric proportion and block orientations (but individual confining stresses). The traces were made using a light table, with Lindquist's drawings (such as Figure 3) taped to the light table underneath the tracings. Each actual tortuous failure line was drawn relative to its companion smooth line, by continuously turning the tracing paper such that the common straight line for each group was co-incident with the underlying estimated smooth failure surface line. In this fashion, the entire tortuous failure surface line was captured as an irregular trajectory of departures from the smooth line. Some specimen sketches had more than one failure surface and these were also traced. Figure 4 shows clearly that the trajectories have very little in common, other than being invariably irregular. For comparison with rock mass joints, Figure 4 also shows six type profiles, enlarged to match the scales of the tracings, which are commonly used to select joint roughness coefficients (JRC) 10 through 20 (13). The profiles, which are standard in rock engineering, illustrate that the "roughest" surfaces normally expected when characterizing rock joints, are relatively subdued compared to the tortuous failure profiles.

Including the profiles of Figure 4, over 70 profiles were scanned. The areas (A) under the irregular trajectories were measured digitally using SigmaScan Pro, which is commercially available image analysis software (14). The length of the smooth line L_o, was also re-measured digitally.

Results and discussion

Several parameters were generated from the measurements, as illustrated in Figure 5. Although there are more than 15 parameters for the characterization of 3D surface roughness used in materials science (16), the measures used in this study were few and intuitive. A summary of the results is presented in Figure 6 and in Table 1.

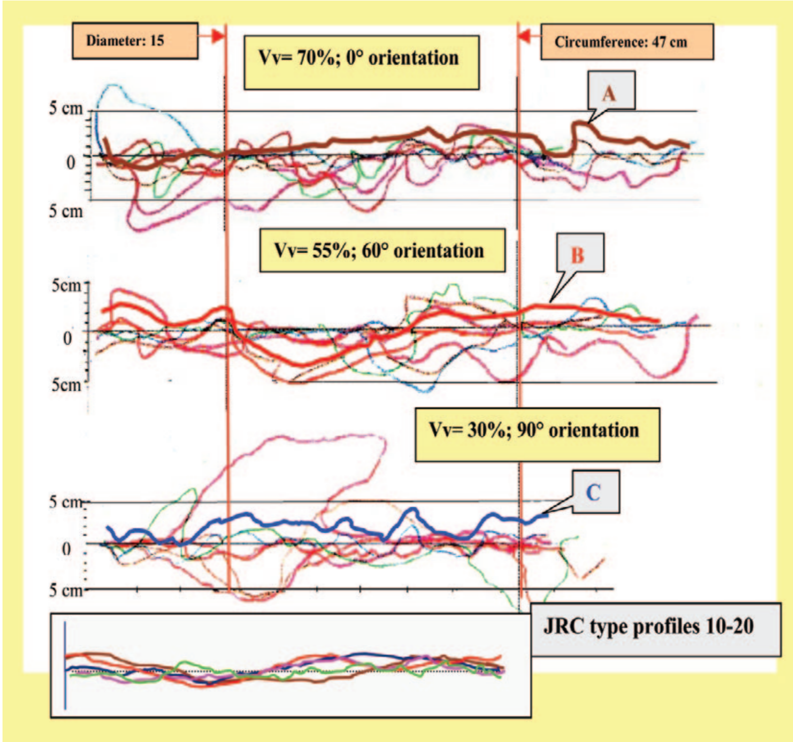

Fig. 4 Scans of traced lines of failure surfaces and compared to type profiles for JRC 10 to 20 (13). Horizontal scale same as vertical scale. Highlighted tracings of failure surfaces are for specimens shown in Figure 2 (A, B, C).

Bild 4 *Linienabwicklungen der Versagensflächen im Vergleich zu JRC Typendarstellung 10 bis 20 (13). Horizontalmaßstab entspricht Vertikalmaßstab. Hervorgehobene Abwicklungen der Versagensflächen entstammen den Probekörpern aus Bild 2 (A, B, C).*

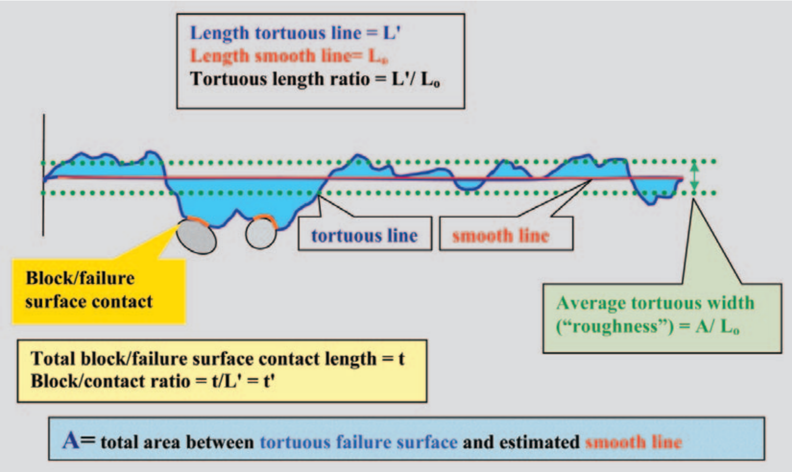

Fig. 5 Parameters measured and calculated from traced lines of tortuous failure surfaces.

Bild 5 *Kenngrößen gemessen und berechnet anhand von Abwicklungslinien der geschwungenen Versagensflächen.*

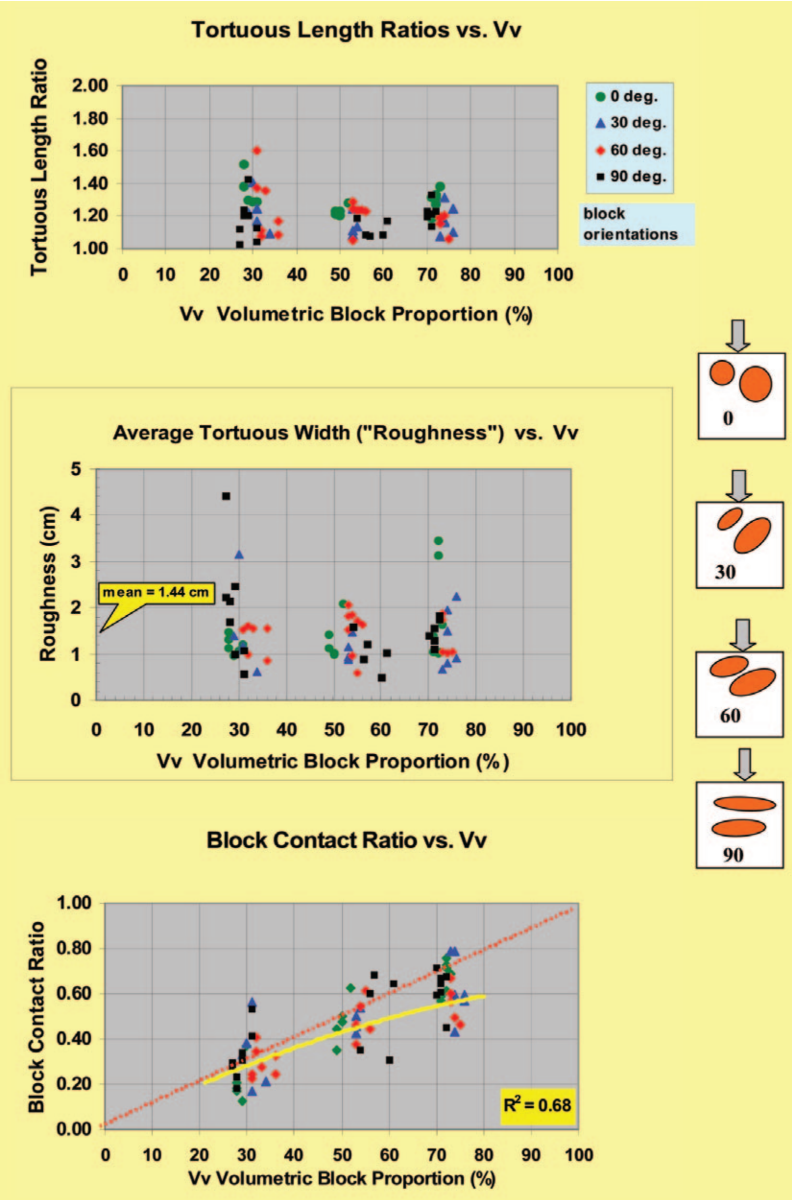

Fig. 6 Plots of volumetric block proportions and: top) tortuous length ratios; middle) block/failure surface contact ratios and, bottom) average tortuous width.

Bild 6 *Darstellungen von Blockvolumen gegenüber: oben) geschwungenen Längenverhältnissen; Mitte) Kontaktverhältnissen zwischen Gesteinsblock und Versagensflächen und, unten) mittlere Schwingungsbreite.*

One measure of tortuosity is the ratio of the length of the tortuous line connecting two points to the length of the shortest line between the same two points. This is referred to as the "tortuous length ratio" (L'/Lo) in this paper. As shown in Figure 6 (top plot), there is relatively little sensitivity between the tortuous length ratio, volumetric proportion and block orientation. For lower block proportions (about 30 %) there is more variability in the tortuous length ratio.

Overall, there is little systematic variation between the geometry of failure surfaces with block proportions and block orientations, as suggested by the results summarized in the top plot of Figure 6, together with the unruly appearance of the failure profiles shown in Figure 5. However, further work is needed to understand the reason for variations, and particularly why there is relatively little variation at about 50 % volumetric block proportion.

Based on this preliminary study, there appears to be little to be gained from attempts to predict "type failure surfaces" for use in design. Rather, it is better to accept that completely random possible profile geometries are likely and focus instead on defining failure zones, which contain a multitude of actual and potential individual shear surfaces, much like shear zones and fault zones (15).

A simple measure of a potential "failure zone" is to identify an overall mean width for many possible tortuous failure surfaces. Such an average width is used to tolerance surfaces in mechanical engineering, where surface roughness is defined as the average deviation of a surface above a mean line (17). Surface roughness (or in this case, "average tortuous width") was calculated by dividing the total of the areas between the irregular surface and the mean line (A), by the length of the mean line (or L_o, in this study), as shown in Figure 5. The length L_o used was that measured digitally rather than the manual length measured for the tortuous length ratio study described above.

Figure 6 (middle plot) shows that there is little dependence between the average tortuous width, volumetric block proportions and block orientations, although there is more variation for the lowest block proportions. A plot of areas is not shown since it would look very similar to the plot of tortuous widths, because the average mean (smooth) line length is relatively constant (Table 1: mean length about 60 cm, standard deviation about 10 cm). The mean tortuous width value for all 73 failure surfaces measured from Lindquist's triaxial specimens is 1.44 cm, with a standard deviation of 0.68 cm, shown in Table 1. Accordingly, since the triaxial specimen diameter is 15 cm, the mean tortuous width is thus approximately 10 % of the diameter plus or minus about 5 % (for one standard deviation).

This finding is of use to the practitioner, through the property of scale-independence

Table 1 Summary of Statistics.
Tabelle 1 *Zusammenfassung der statistischen Ergebnisse.*

Parameter	Unit	Symbol	Count	Mean	Standard deviation	Minimum	Maximum
Length Smooth Line*	cm	L_o	72	58.2	10.4	31.6	77.8
Length Tortuous Line	cm	L'	72	70.9	13.7	38.9	110.2
Tortuous Extension Ratio		L'/ L_o	72	**1.22**	**0.046**	1.03	1.6
Total Length block Contacts	cm	t	72	32.9	12.5	9.7	66.8
Block Contact Ratio		t/ L'	72	**0.46**	**0.18**	0.12	0.79
Tortuous Area	cm^2	A	73	84.2	37.7	24.9	225.4
Length Smooth Line**	cm	L_o	73	59.4	9.5	41.7	81
Tortuous Width	cm	A/L_o	73	**1.44**	**0.68**	0.5	4.45

* L_o measured manually, ** L_o measured digitally

common to many bimrocks over the range of scales of engineering interest. A basis for Lindquist's work (4) was that the models were scale models of real melanges, because of the scale independence of Franciscan melanges (8). In other words, Franciscan melanges and many other bimrocks, appear similar when observed within the range of scales of centimeters to hundreds of meters (7, 15). Scale-independence also applies to the geometry of pre-existing shears and induced failure surfaces. Hence, a preliminary implication of the study is that at any scale of engineering interest, once the characteristic engineering dimension has been selected (1), a first-order estimate of the thickness of a potential failure zone would be 5 to 15 % of that width.

A validation of this guideline was the selection of a 3 m thick potential failure zone below Scott Dam, California (2, 3). The dam is about 40 m high and 45 m wide at the base. Selecting the dam width as the characteristic engineering dimension for a study of possible basal shear of the dam through foundation rock. Using the preliminary rule described above, a potential failure zone would be between 2.3 m and 6.8 m thick, and the estimated 3 m thick failure zone selected was thus appropriate.

In the geotechnical analysis of a potential failure zone, consideration should be given to the strengths of the block/matrix and block/shear zone contacts. As written above, block/shear surface contacts are considered to be the weakest elements of bimrocks when shears pre-exist. Although overall bimrock frictional strength is increased for volumetric block proportions between about 25 and 75 %, there are indications that cohesive strength decreases as block proportion increases because block/matrix contacts increase (2, 4, 5). For pre-sheared matrix, is should thus be presumed that cohesion will decrease even more, although currently there are no methods available to predict the decrease.

Figure 6 (bottom) and Table 1 summarize the results for block/failure surface contact ratios (t/L'). There is some initial linear dependence between the proportion failure surfaces that are tangent to blocks, and the volumetric block proportions, but the linear dependence weakens beyond about 50 % volumetric block proportion. However, it would be conservative to assume that the linear dependence continues (as indicated by the red line on the plot). For design purposes, it may be possible to then assume that the overall cohesion of the potential failure zone be the cohesion of matrix, reduced by a factor that has a relationship to the estimated block volumetric proportion (as yet unknown). The reduction may be similar to the empirical factors used in soils mechanics for pile/soil adhesion or retaining wall/backfill. Work is underway to identify such factors (Pablo Sanz Rehermann, personal communication).

Conclusions

The study summarized in this paper indicates that there is little value in defining potential failure surfaces for bimrocks. Instead, it is both prudent and appropriate to define failure zones with thickness between 5 and 15 % of the appropriate characteristic engineering dimension. The paper also demonstrates that conventional rock engineering approaches of design, which incorporate joint roughness coefficients selected on the basis of type profiles, will be inappropriate, since the "roughness" of the failure surfaces in bimrocks far exceeds the roughness of the JRC type categories. Furthermore, the "joints" are not joints, but are relatively thick zones of rock/soil mixtures that require analysis involving soils engineering approaches.

Earlier findings from stability analyses that showed that the factor of safety is related to volumetric block proportion (6) is encouraging because commonly used analytical tools may then become useful to the practitioner investigating the slope stability of geologically complex mixtures such as melanges, fault rocks and other bimrocks. However, an important caveat must be repeated: any geotechnical prediction made of bimrock properties that are based on estimates of block volumetric proportions or block sizes are subject to considerable uncertainties, as described fully in other papers (18, 19, 20).

For slope stability studies, it also appears that the findings of this paper could possibly be integrated with conventional geotechnical analytical methods, since trial failure surfaces could be defined with thicknesses between 5 and 15 % of the characteristic engineering dimension, which for slope stability studies, is appropriately the slope height (6).

Despite the encouraging results of this preliminary study, more work must be performed, and research into case histories and practitioner experiences be extended.

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