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EVALUATION OF SHEAR STRENGTH OF MÉLANGE FOUNDATION AT CALAVERAS DAM

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ABSTRACT

The existing 220-foot-high Calaveras Dam, located within 1,500 feet of the active Calaveras Fault, is a composite hydraulic fill and rolled earthfill dam. The existing dam was found to have inadequate seismic stability and the potential to undergo very large seismic deformations. Alternative studies to remediate or replace the dam determined that a replacement dam should be constructed downstream of the present structure.

The new Calaveras Dam will be a modern earth- and rockfill dam that will be founded on Franciscan mélange in the valley bottom and right abutment. Franciscan mélange, which covers a large part of northern California, is a classic example of a rock formation that exhibits block-in-matrix characteristics. Block-in-matrix rock is comprised of an assemblage of harder stronger rock blocks within a matrix of softer weaker rock. Previous studies have shown that evaluating the shear strength of block-in-matrix rock on the basis of the strength of the weaker matrix alone can be overly conservative. For example, at Scott Dam in northern California, the shear strength of the Franciscan foundation was shown to be a function of the proportion of harder blocks in the rock mass.

This paper describes the geologic studies, geotechnical characterization, laboratory testing, and engineering evaluation utilized to obtain the shear strength parameters for use in stability analyses of the new dam foundation. The process described will be useful to dam design practitioners for evaluating the shear strength of block-in-matrix foundations.

BACKGROUND

The San Francisco Public Utilities Commission (SFPUC) is replacing the existing Calaveras Dam, which it owns and operates, with a new dam due to the inadequate seismic stability of the existing dam. The new 220-foot-high Calaveras Dam will have an upstream shell of compacted rockfill, a wide clay core that would allow for future expansion and a downstream shell of earthfill (see Figure 1). Chimney and blanket filters will provide for the collection of seepage through the core and up through the downstream foundation as well as protection against piping of either core or foundation

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materials. The replacement dam is designed to be operable after the maximum credible earthquake having a moment magnitude of 7¼ on the Calaveras Fault, located 0.3-mile west of the dam site. The resulting peak ground acceleration at the site is 1.1g.

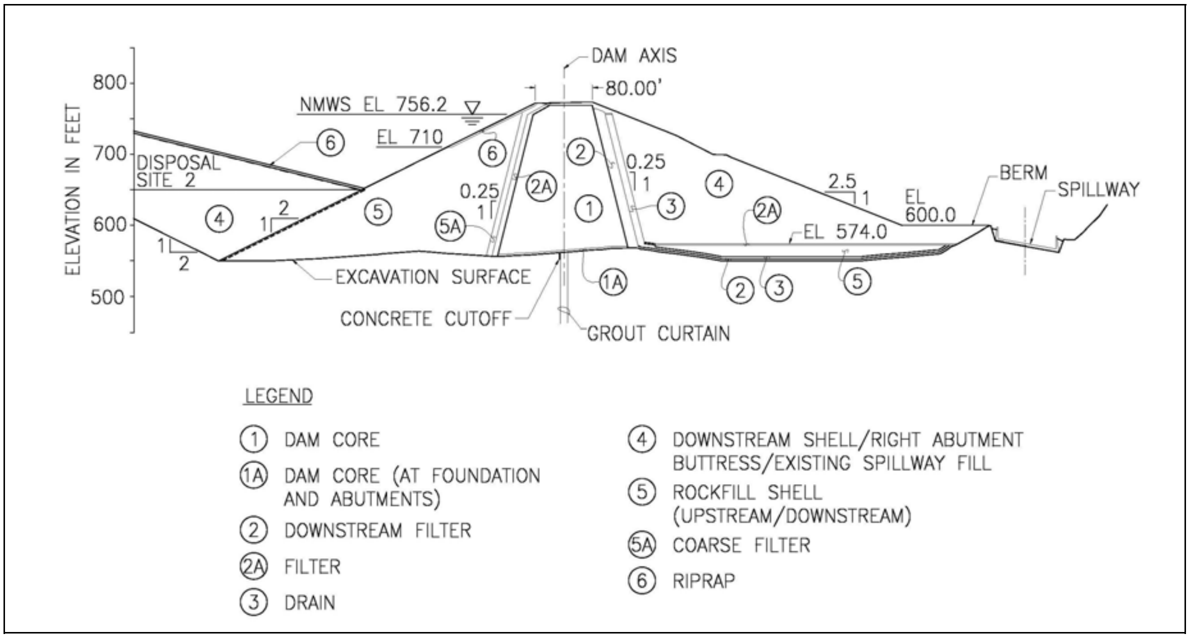

Figure 1. Section of Replacement Calaveras Dam

The foundation will be Temblor Sandstone in the left abutment and Franciscan mélange in the valley bottom and the right abutment. Geologist Dr. J. C. Branner described the chaotic nature of what would become known as the Franciscan in the right abutment area during a review of the geology of Calaveras Dam in 1918 as follows:

"Some of the tunnels driven into this hillside were supposed to have ended in hard rock in places, but in every instance… it was found that the hard rock struck was nothing more than a big loose block in a jumbled up mass of rock fragments and clays … Geologically, that area is thoroughly discouraging." (Branner, 1918)

In order to perform stability and seismic deformation analyses for the replacement dam, characterization of the foundation materials, including determination of shear strength, was required. Characterization of the Temblor Sandstone, a calcareous feldspathic marine sandstone with thin shale and conglomerate interbeds was performed using standard rock mass engineering procedures. However, Franciscan mélange is an example of a geologic material that exhibits block-in-matrix characteristics. Other examples of block-in-matrix geologic materials are colluvium, fault and shear zones, decomposed granite or residual soils containing core stones, and some agglomerates. These materials contain inclusions (blocks) that are sufficiently stronger than the surrounding matrix such that during shearing, the failure surface generally passes tortuously around the blocks. Evaluating the shear strength of block-in-matrix rock on the basis of the strength of the weaker matrix alone can be overly conservative, but, on the other hand, evaluation using standard rock mass engineering procedures may be inappropriate because these procedures do not properly account for the failure mechanism observed in these types of rocks.

CHARACTERIZATION OF BLOCK-IN-MATRIX ROCKS

Characterization of block-in-matrix rocks requires knowledge of the proportion, distribution and orientation of blocks in the rock mass, the strength of the matrix and contact between the matrix and blocks, and the fabric of discontinuities in the rock mass. The strength of block-in-matrix rock is considered to be independent of the strength of the blocks (Lindquist and Goodman, 1994; Medley, 2008). Perhaps the most significant of these properties are the proportion and orientation of blocks within the rock mass. Tools to estimate the proportion and distribution of blocks are generally limited to borings and surface mapping, which have been shown to be likely to represent the volumetric proportion of blocks in the rock mass (Medley, 1997; Haneberg, 2004) with limited accuracy. The orientation of the blocks and the fabric of the discontinuities can be evaluated through field investigations. The strengths of the matrix and contact between the blocks and matrix can be assessed together through laboratory testing.

Franciscan mélange, like other mélanges around the world, is a heterogeneous mixture of harder more competent blocks within a sheared matrix or weak rock that is characterized by scale independence wherein small scale samples of the material have been shown to resemble the large scale rock mass (Medley and Lindquist, 1995). In mélanges, this scale independence can cover up to 7 orders of magnitudes with blocks ranging from millimeter-sized to thousands of meters in size (Medley, 1994). Because of this scale independence, it is possible to model the engineering characteristics of the larger rock mass of a dam foundation using smaller samples.

Blocks within the matrix are defined as those inclusions that are geomechanically significant (Medley and Lindquist, 1995) in strength and size when compared with the surrounding matrix. With respect to strength, blocks have been defined as having an unconfined strength of at least twice that of the matrix rock (Medley and Goodman, 1994). The size of what constitutes a block depends on the scale of engineering interest. The dimension of interest may be the thickness of the failure surface through a dam foundation, the height of a sloped cut, the diameter of a tunnel, or some other key dimension related to the structure being engineered. Medley (1994) proposed that the smallest and largest block size within the mélange be defined as 5 and 75 percent, respectively, of the dimension of interest.

APPLICATION TO SCOTT DAM IN NORTHERN CALIFORNIA

The work of Linquist (1994) and Medley (1994) was a part of the evaluation of the shear strength of the Franciscan foundation at Scott Dam, a 138-foot-high concrete gravity structure located in northern California. The evaluations, which are summarized in Goodman and Ahlgren (2000), included testing simulated samples of mélange and testing and evaluating samples of mélange obtained from the dam foundation.

Lindquist (1994) studied the effect of the proportion and orientation of blocks on strength of block-in-matrix rock using samples constructed in the laboratory that mimicked the block size distribution found in the Franciscan (Medley, 1994). The samples were made using bentonite/cement mortar as matrix and ellipsoid blocks of sand/cement mortar. The ellipsoidal block shape was used as blocks in the Franciscan tend to be ellipsoidal to irregular in shape. Inclusions of paraffin wax lamina were also included in the mortar to model shears within the matrix. The samples were constructed with volumetric block proportions of 30%, 50% and 70% and block orientations of vertical, 30 degrees, 60 degrees, and horizontal relative to the long-axis of the cylindrical specimens. The samples were tested in a Hoek triaxial cell at several confining loads. The testing indicated that the shear strength increased as the proportion of blocks increased between 25 percent and 75 percent. The shear strength components of friction angle and cohesion were found to increase and decrease, respectively, as the proportion of blocks increased. The results of the testing indicated that when the proportion of blocks is less than about 25 percent of the rock mass, the rock can be characterized as matrix-only. When the proportion of blocks is greater than about 75 percent of the rock mass, the rock should be characterized as a jointed rock mass.

As part of the Scott Dam study samples of the actual mélange foundation rock were also tested using a Hoek-type cell. The sheared samples were carefully disaggregated to measure the proportion of blocks assuming a minimum block size of 3/8-inch. Relationships were developed between the friction angle and cohesion and the proportion of blocks for these samples.

The proportion of blocks within the Scott Dam foundation was estimated to be 31 percent. The block proportion was based on a minimum block size of 6 inches, which was 5 percent of the potential failure zone judged to be the 10-foot thickness immediately beneath the dam (Goodman and Ahlgren, 2000). This block proportion was used in conjunction with the relationships developed in the laboratory for friction angle and cohesion as a function of the proportion of blocks in order to select the friction angle and cohesion used for dam stability analyses.

ITERATIVE PROCESS OF CHARACTERIZATION OF MELANGE FOR CALAVERAS DAM

Characterization of the mélange foundation of the new replacement Calaveras Dam was an iterative process during final design. The iterative process resulted because the schedule required that stability and seismic deformation analyses occur prior to the completion of all field and laboratory investigations. Thus, the initial estimation of proportion of blocks in the foundation and the shear strength of the mélange was based on the limited set of data available at the time. The shear strength of the mélange was re-evaluated after completion of the field and laboratory investigations to confirm that the strength parameters used in the stability and seismic deformation analyses were appropriate. The re-evaluation incorporated a re-definition of what constituted a block at the site. The following sections discuss the initial characterization and subsequent re-evaluation of the mélange.

GEOLOGIC INVESTIGATIONS AND STUDIES

Field Investigations

Field investigations of the new Calaveras Dam foundation included 40 core borings, 12 seismic refraction lines and geologic mapping performed between 2004 and 2007. The core borings were drilled using an HQ-3 wireline system; therefore, the recovered core was 2.4 inches in diameter. Generally, core recovery in the mélange was excellent. The orientations of discontinuities in the rock mass were evaluated through measurements at surface outcrops and by televiewer in selected borings. In addition, records of historic exploratory adits and geologic mapping performed between 1904 and 1913 in the area of the proposed downstream toe of the replacement dam were reviewed.

The mélange at the Calaveras dam site is characterized by a pervasively sheared block-in-matrix fabric consisting of extremely weak to weak, dark gray to black, clayey shale matrix with abundant tectonic inclusions of graywacke, serpentinite, siliceous schist, greenstone (metabasalt), and blueschist (glaucophane and amphibolite schist). The block-in-matrix inclusions range from sand-size to over one hundred feet across.

Initial Estimates of Block Proportion in the Foundation

The core borings and geologic mapping were reviewed early in the final design phase to identify zones within the Franciscan having similar characteristics based on lithology and proportions of blocks in the dam foundation area. The proportion of blocks within the mélange was estimated for each boring based on blocks with a minimum 3-inch length. Three inches was selected as the minimum block size because it is distinguishable on the boring logs and in the photographs of the cores (see Figure 2 for an example photograph of the core). A minimum 3-inch block also corresponds to an engineering scale of interest of 5 feet, which was judged to be reasonable for the thickness of a potential failure zone through the foundation of the dam. Blocks were further defined as consisting of graywacke, blueschist, greenstone, or siliceous schist (see Figure 2). At this stage of the evaluation no distinction was made for the variation in competence of the shale matrix (i.e. all shale was counted as matrix regardless of its competence). Block proportion for each of three mélange zones that were identified in the dam foundation are summarized in Table 1.

Figure 2. Block-in-Matrix Fabric (CB-43)

Table 1. Initial Estimation of Block Proportion in Mélange Zones

Foundation Zone	Total Rock Footage Drilled (feet)	Total Blocks (feet)	Block Proportion (%)
Mélange $_{(68)}$	847.1	575.9	68
Mélange $_{(38)}$	359.8	136.1	38
Mélange $_{(13)}$	276.9	36.7	13

Based on the initial evaluation, the Franciscan Complex foundation was idealized into the five zones shown in plan and in sections on Figure 3 and as indicated below.

- Ser - Serpentinite overlying Franciscan mélange (block proportion in mélange not calculated) upstream of the dam axis;
- Mél$_{(68)}$ - A band of mélange with an estimated 68 percent proportion of blocks in the central portion of the right abutment that extends across the valley striking about N 55° W;
- Mél$_{(38)}$ - Mélange shale with an estimated 38 percent proportion of blocks in the valley downstream of the dam axis;
- Mél$_{(13)}$ - Mélange shale with an estimated 13 percent proportion of blocks in the right abutment; and
- A substantial outcrop of Franciscan mélange with a high proportion of blocks exposed in the downstream right abutment.

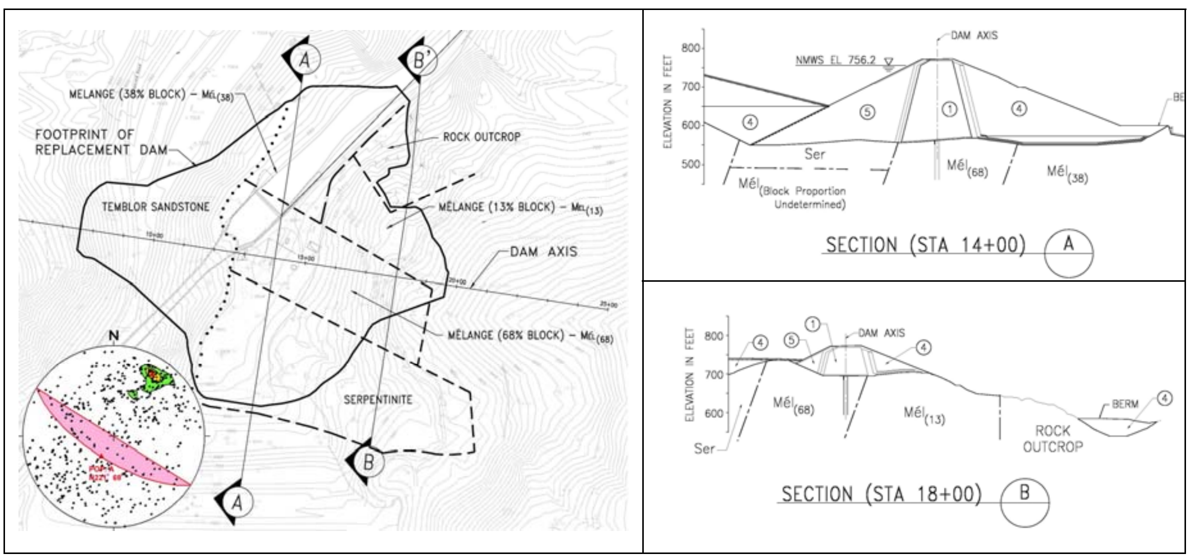

Figure 3. Idealized Franciscan Complex Model of Dam Foundation

Figure 3 includes a stereoplot of discontinuities measured in seven borings in the Franciscan. The major discontinuity set shown on the stereoplot is foliation that parallels the trend of the Mél$_{(68)}$ zone under the central portion of the dam. Surface measurements of foliation on the outcrop at the downstream right abutment toe and on outcrops further downstream indicate a northerly trend that is near vertical. The blocks are thought to parallel foliation and be nearly vertical based on exposures of blueschist blocks at the downstream toe. It is noted that the orientation of foliation and the blocks are favorable with respect to stability of the embankment because failure surfaces would necessarily have to cut across the long-axis of the blocks.

<u>Re-evaluated Block Proportions in Selected Foundation Areas</u>

During the progress of the field and laboratory investigations, it was noted that some intervals of shale, and to a lesser degree serpentinite, were far more competent than the typical soft sheared shale matrix. This greater strength was also indicated in unconfined compressive strength tests where the mean strength of the more competent shale samples was three to four times greater (820 psi) than that of the softer sheared matrix (250 psi). These more competent lengths of core, which typically included shale with quartz inclusions and shale banded with graywacke, are strong enough to be considered blocks within the significantly softer sheared shale matrix material.

Thus, the proportion of blocks in the most critical areas of the foundation, the downstream right abutment (Mel_{13}) and downstream valley bottom (Mel_{38}) (see Figure 3), were re-evaluated to include the more competent intervals of shale and serpentinite as blocks. The core was probed with a steel tool in order to identify the stronger shale and serpentinite material. During the re-evaluation it was found that most of the shale deeper than about 50 feet below the top of rock was significantly stronger than the typical matrix material. Therefore, revised block proportion calculations were made using only the upper 50 feet of each boring so as to not infer a higher block proportion in the upper portion of the foundation based on material from greater depth. Based on the re-evaluation, the block proportion in the areas described as Mel_{13} and Mel_{38} increased from 13 percent to 34 percent and from 38 percent to 55 percent, respectively.

The block proportion in the downstream right abutment area was also estimated based on geologic mapping that was performed after hydraulic mining of the area in the 1911 investigation for the Freeman Dam (the Freeman Dam axis is located downstream of the replacement dam axis). The geologic map (Figure 4) indicates that the lower portion of the abutment is comprised of large blocks of sandstone (graywacke), black shale, blueschist, and silicious schist and the upper portion of the abutment is soft shale with blocks of sandstone (graywacke), silicious schist, and black shale. The block proportion in the soft shale portion of the abutment was estimated based on the area of mapped blocks to the overall mapped area. The calculated block proportion is 28 percent, which is similar to that of the re-evaluated $Mél_{(13)}$ zone (34 percent).

LABORATORY TESTING

A total of eighteen multi-stage and six single-stage isotropically consolidated undrained (ICU) triaxial compression tests with pore pressure measurements were performed on selected samples of the mélange obtained from ten core borings. The samples were tested at confining stresses of 40, 80 and 120 psi using conventional triaxial compression test equipment. Eight multi-stage ICU triaxial compression tests from four borings were available for the initial estimation of shear strength of the mélange. The results from these eight tests were used without consideration of the possible degradation of the samples during testing.

During re-evaluation of the shear strength of the mélange it was noted that some of the samples appeared to degrade during testing. As such, the results of all of the staged tests were segregated into the three following groups:

- Tests with consistent and reasonable strength results for all three stages;
- Tests in which the first and second stage provide reasonable results but the third stage indicates some degradation of the sample during testing; and
- Tests in which sample degradation occurred after peak strength was measured during the first stage of testing.

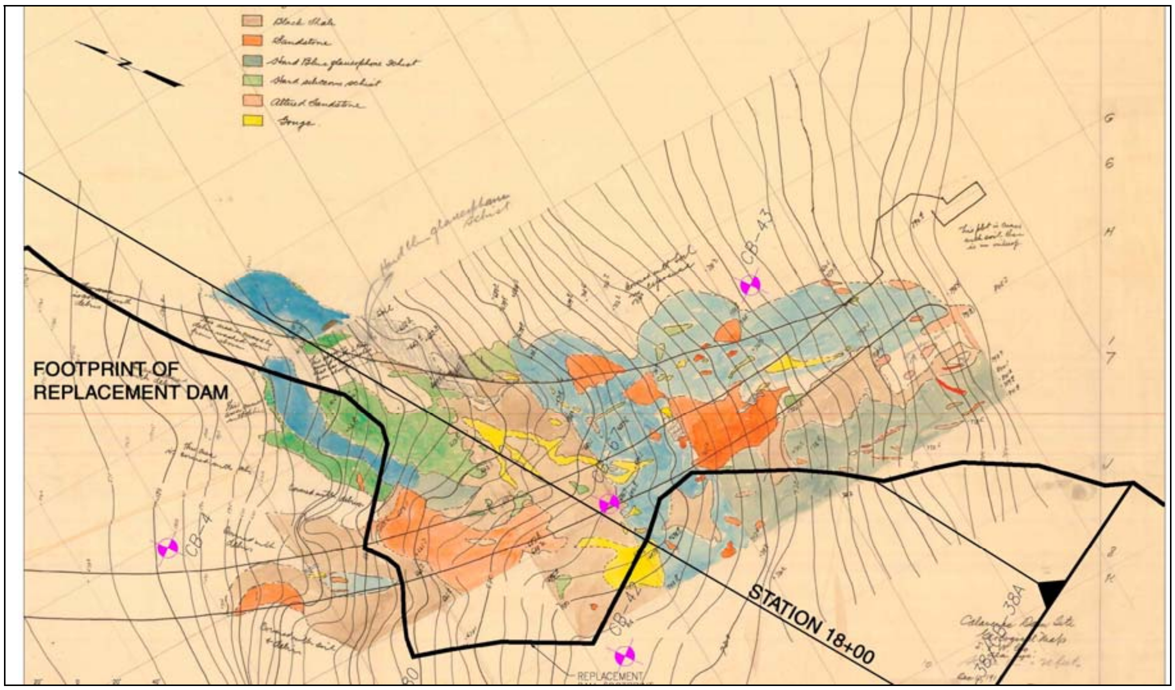

Figure 4. Freeman Dam Right Abutment Geology

The results of approximately 50 percent of the samples appeared to show some degree of degradation of strength with each succeeding stage resulting in an underestimation of the friction angle and an overestimation of the cohesion when a simple linear regression approach was used. The degradation of strength was most apparent for the stronger more brittle samples. The degradation likely represents a progression towards the residual strength of the material with each succeeding stage of the test.

In order to evaluate the strength degradation, two additional test samples were obtained near the sample locations of each of three of the staged tests (Boring CB-42 [74.6'-75.3'], CB-42 [82.4'-83.1'], and CB-78 [143.3'-144']). Each of the additional samples was selected to be as similar as possible to the nearby sample used for the staged test based on visual observation. The additional samples were then tested as single-stage tests at confining stresses of 80 and 120 psi, respectively. The results of these tests were combined with the first stage of the multi-stage tests for comparison with the results of the multi-stage tests. The comparison, as shown on Figure 5, confirmed that it was likely that some degradation of strength occurred during the multi-stage testing.

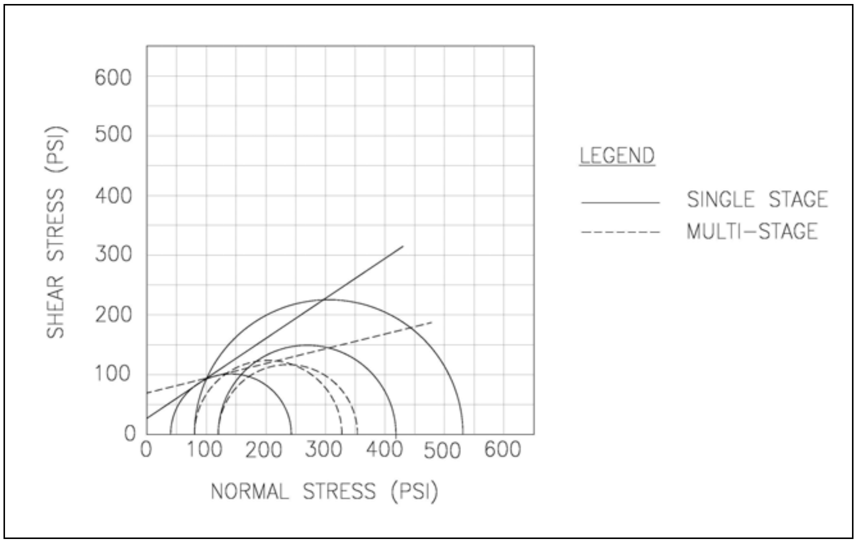

Figure 5. Comparison of Results of Multi- and Single- Stage Triaxial Compression Test Results for CB-42 [82.4']

Based on this finding, the interpretation of the shear strength parameters for the multi-stage tests for which the results indicated degradation was revised. For example, degradation was assumed when the third stage Mohr's circle fell significantly short of the linear trend set by the first two Mohr circles. For these tests the revision consisted of recalculating the shear strength parameters based on the first two stages of the test. For five of the staged tests, the degradation was significant enough after the first stage for testing that shear strength parameters could not be computed with confidence.

After triaxial compression testing, the block proportion for each test sample was estimated using the following procedure:

- The oven dried sample was weighed and then soaked for a minimum of 24 hours;
- The soaked sample was then disaggregated and washed through a #10 sieve using hand pressure;
- The plus #10 sieve-sized particles were oven-dried and weighed; and
- A particle-size analysis was performed on the plus #10 sieve-size materials.

For the triaxial test samples, the minimum block dimension was evaluated to be in the range of 0.125 to 0.3 inch, which is 5 percent of the sample diameter and height, respectively. Based on this range, the smallest block dimension was defined to be the #4 sieve size (0.187 inch). The block proportion was then estimated as the percent of the total dry weight of the sample retained on the #4 sieve. An adjustment was not made to convert the block proportion by weight to volumetric block proportion as these values are within a couple of percent of each other since the unit weights of the block and matrix material do not differ by a large amount.

The Mohr-Coulomb envelopes and the proportion of blocks measured for each of the triaxial tests are shown on Figure 6. Figure 6 generally indicates that there is an increase in shear strength with increasing block proportion.

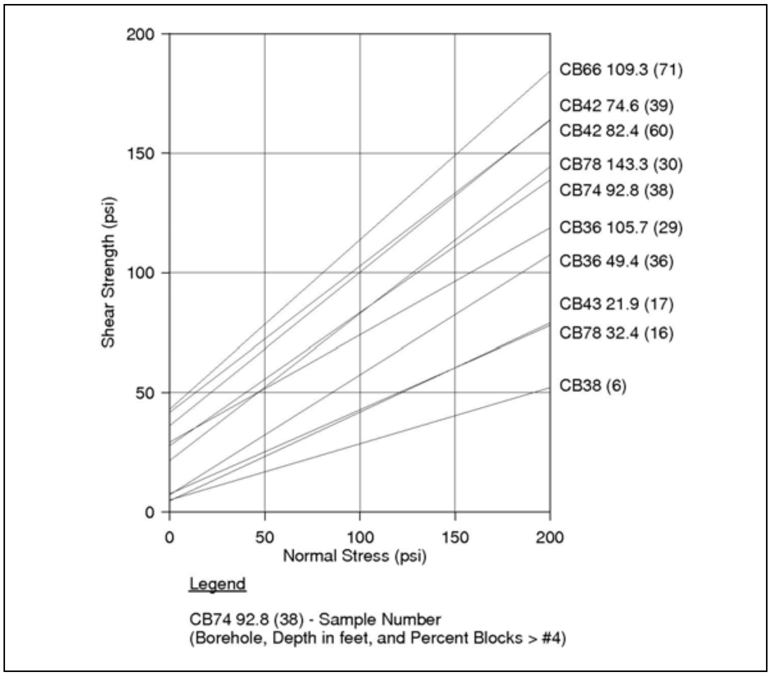

Figure 6. Results of Triaxial Tests With Block Proportions

ESTIMATION OF MÉLANGE SHEAR STRENGTH

Initial Estimate of Shear Strength

Shear strength parameters for the mélange used for stability and seismic deformation analyses were based on the initial estimated block proportions from measurements of blocks in the cores and the results of eight multi-stage ICU triaxial compression tests on mélange from four borings. Using this approach, the Mohr-Coulomb strengths for Mél$_{(13)}$ and Mél$_{(38)}$ were estimated as shown on Figure 7, which also includes the linear relationships of friction angle and cohesion intercept with block proportion for Scott Dam (Goodman and Algren, 2000) for comparison. Figure 7a indicates that the friction angle for a given proportion of blocks in the Calaveras Dam foundation is lower than at Scott Dam while the cohesion intercept shown on Figure 7b is similar for low block proportions.

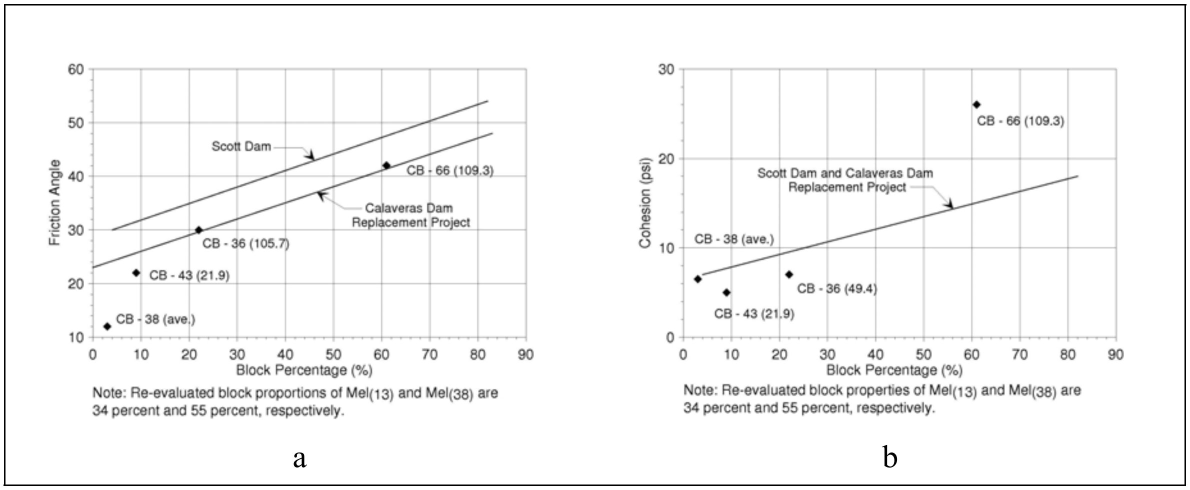

Figure 7. Initial Relationship of (a) Friction Angle and (b) Cohesion With Block Proportion

<u>Re-evaluated Estimate of Shear Strength</u>

Shear strength parameters for the mélange were subsequently re-evaluated based on an additional ten ICU triaxial compression tests and the updated proportion of blocks in the foundation as shown on Figure 8. Figure 8 indicates that there is a strong correlation between block proportion and friction angle and cohesion for the samples tested. The finding that cohesion increases with block proportion is opposite to the findings of Lindquist (1994), but similar to those found at Scott Dam (Goodman and Alhgren, 2000), suggesting that the blocks may in some as yet unknown manner contribute to the strength. Figure 8 also indicates that within the sample set tested there may be two matrix material types, each with a unique relationship between block proportion and cohesion. The first relationship represented by samples from CB-38 (average), CB-36 [49.4’], CB-43 [21.9’], and CB-78 [32.4’] is for matrix that is very soft and very weak sheared shale. The second relationship represented by the remaining samples is for matrix that is stronger sheared shale.

Figure 8a also includes points representing the five triaxial tests that were not included in determining the relationship between mélange strength and block proportion due to apparent strength degradation during the multi-stage testing. The five tests were used to test the robustness of the relationship by first estimating the cohesion intercept based on the proportion of blocks in the sample and its relationship to cohesion based on Figure 8b. The cohesion estimated based on block proportion was then used with the first stage triaxial test result for each test to back-calculate a friction angle for the first stage peak strength. The resulting friction angles were plotted against block proportion for each test in Figure 8a. As shown on Figure 8a, the data for the five tests generally lie within the range of data for the other tests confirming the correlation between friction angle and block proportion.

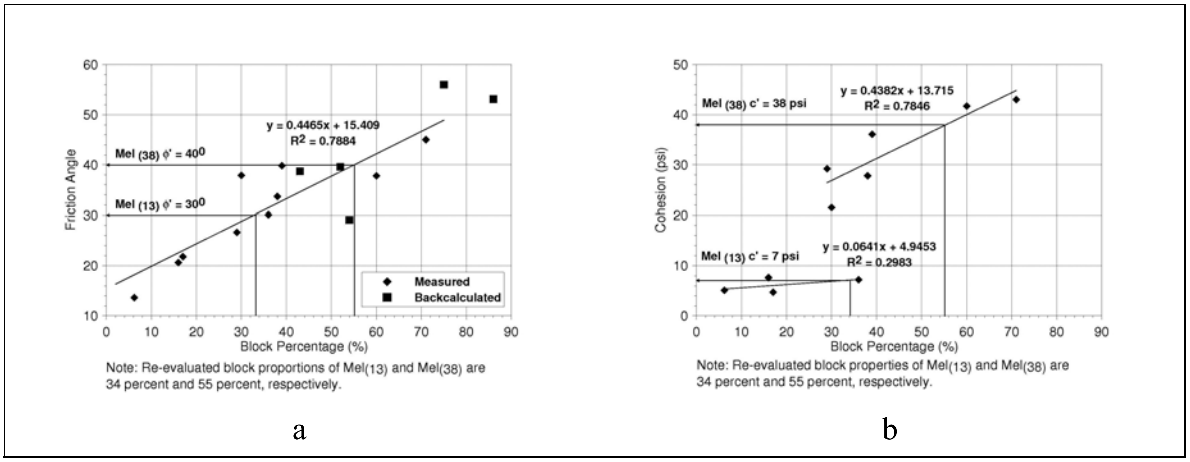

Figure 8. Re-evaluated Relationship of (a) Friction Angle and (b) Cohesion With Block Proportion

Table 2 compares the shear strength values used in the stability analyses with the re-evaluated parameters. Table 2 indicates that the parameters used in the stability analyses are conservative.

Table 2. Mélange Shear Strength Parameters Based on Block Proportions

Mélange Zone	**Initial Evaluation**			**Re-evaluation**		
	Block Proportion (%)	**Friction Angle (degrees)**	**Cohesion (psi)**	**Block Proportion (%)**	**Friction Angle (degrees)**	**Cohesion (psi)**
Mél $_{(13)}$	13	25	6.0	34	30	7.0
Mél $_{(38)}$	38	33	12.0	55	40	38.0

<u>Uncertainty Associated with Shear Strength</u>

As was previous mentioned, one of the greatest difficulties in characterizing block-in-matrix rock is assessing the proportion and distribution of blocks within the rock mass. The difficulty arises out of the low probability of intersecting the maximum dimension of blocks either at the surface in outcrop or with borings. Based on the science of stereology, given enough data, the linear block proportion (as measured in borings) will converge to the volumetric block proportion. However, the amount of drilling required is typically beyond the scope of field investigations planned for typical projects.

Medley (1994) studied uncertainties associated with estimating volumetric block proportions from core borings by constructing four physical models of mélange having known block proportions of about 13 percent, 32 percent, 43 percent and 55 percent and block distributions consistent with the Franciscan mélange. Each model was cut into ten slices and ten model borings were drawn at equal intervals across each slice, thereby “investigating” each model with 100 borings. Linear block proportions were determined for each boring. The results showed that while linear block proportions for single “borings” varied greatly, the overall linear proportion converged to the volumetric proportion. Medley (1997) used the data to further simulate typical drilling programs (significantly fewer borings) to evaluate the uncertainties associated with linear block proportions. In general, statistical analyses of the simulated drilling programs showed that the uncertainty in the estimated block proportion decreases with increased drill lengths and that uncertainty is greater when the volumetric block proportion is low.

Haneberg (2004) studied the uncertainties associated with estimating the volumetric block proportions from 2D surface expressions. His models assumed both spherically and ellipsoidally shaped blocks. He found that in most cases the proportion of blocks estimated based on the 2D surface underestimated the volumetric proportion of blocks. However, the volumetric proportion of blocks was overestimated when the orientation of the 2D surface was such that long dimensions of the ellipsoidal blocks were parallel to the 2D surface. Based on this finding, the estimation of proportion of blocks from the 1911 geologic map shown on Figure 4 may be assumed to be underestimated given that the surface that was mapped is likely not parallel to the orientation of the two long axes of the blocks.

The uncertainties associated with the re-evaluated proportions of blocks for the $\text{Mél}_{(13)}$ and $\text{Mél}_{(38)}$ zones were calculated using the relationship of uncertainty and sampling length developed by Medley (1997). The sampling length is defined by Medley to be the ratio of the total length drilled to the largest block size. The largest block size for this project was assumed to be 50 feet, which was equivalent to the depth over which the proportions of blocks in the foundation were calculated. The resulting uncertainties in block proportion were estimated to be 21 percent and 15 percent for $\text{Mél}_{(13)}$ and $\text{Mél}_{(38)}$ zones, respectively. Using these uncertainties, the proportion of blocks was reduced from 34 and 55 percent to 27 and 47 percent for $\text{Mél}_{(13)}$ and $\text{Mél}_{(38)}$ zones. Using these block proportions the low-end estimate of friction angles for $\text{Mél}_{(13)}$ and $\text{Mél}_{(38)}$ zones would be 27 and 36 degrees, respectively. These values are greater than those used in the stability and seismic deformation analyses as indicated in Table 2.

CONCLUSIONS

The shear strengths of the Franciscan mélange foundation at the new replacement Calaveras Dam were evaluated based on the results of triaxial compression testing and the proportion of blocks measured within the matrix of the sheared samples. These results were taken together with the proportion of blocks estimated in the mélange foundation to evaluate shear strength parameters for the site that could be compared to the strength parameters used in stability analyses that were developed based on a limited subset of the data. The re-evaluated strength parameters, after consideration of uncertainties associated with estimating the proportion of blocks within the foundation, were found to be greater than those used in the stability and seismic deformation analyses.

The following additional conclusions can be made based on the field and laboratory investigations and characterization of the Franciscan foundation for the new Calaveras Dam:

- Laboratory testing of mélange samples from the Calaveras Dam foundation show that the friction angle and cohesion of block-in-matrix rocks increased with increasing block proportion consistent with the findings of others (for example at Scott Dam).
- The increase in cohesion with increasing block proportion likely indicates that the blocks do have some unknown role in the strength of the block-in-matrix rock.
- Fundamental changes in the fabric of the block-in-matrix sample as the tortuous failure surfaces forms during multi-stage testing may result in degradation of the sample such that succeeding stages cannot measure the peak strength of the sample.

Considerations that should be made in the planning of field and laboratory investigations for dams founded on the Franciscan and similar mélanges and subsequent foundation characterization should include the following:

- Field investigations should be planned to provide for a greater number of borings than might normally be planned in rock masses that do not exhibit block-in-matrix characteristics.
- Geologists overseeing the field investigations in block-in-matrix rock should have a clear understanding of the importance of collecting samples that exhibit a range of block proportions for laboratory testing.
- Laboratory investigations should consider a combination of multi- and single-stage triaxial compression tests. The evaluation of multi-stage tests should take into consideration the potential for strength degradation.
- Given sufficient laboratory data from single-stage tests, develop the relationship of strength in Mohr-Coulomb space with a third dimension of block proportion.

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