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SHEAR STRENGTH OF FRANCISCAN COMPLEX MELANGE AS CALCULATED FROM BACK-ANALYSIS OF A LANDSLIDE

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ABSTRACT

A methodology was developed to evaluate causation of a complex landslide that occurred in Franciscan Complex melange during the winter of 1996-1997 in San Mateo County, California. Conventional back-analysis methods to evaluate shear strength parameters were insufficient because the basal failure plane traversed three materials (fill, block-poor melange, and block-rich melange). Instead, using field observations of landslide kinematics, review of available subsurface data, and previous experience with Franciscan melange, a methodology was developed that incorporates the location of critical failure surfaces generated by random search routines in PCSTABL5M as an additional constraint. The methodology was employed to evaluate the relative effects of various destabilizing modifications to the slope.

1 INTRODUCTION

In the winter of 1996-1997, a landslide occurred in San Mateo County, California that affected several homes at the head of the landslide and a county road at the toe. The original slope geometry was modified in the 1950's during development of a residential subdivision and widening of the county road. Modifications included placement of a fill embankment at the crest of the slope and a road cut at the toe. In addition, groundwater levels appeared to have been raised substantially from pre-development levels. Evaluation of landslide causation required the analysis of the relative contribution of each of these factors to destabilization of the slope.

The pre-failure slope stratigraphy included a relatively small wedge of fill at the slope crest. The remainder of the slope was composed of melange of the Franciscan Complex, (the Franciscan) a tectonically jumbled assemblage of rocks that covers over a third of Northern California. The melange had a block-in-matrix fabric, with isolated blocks of competent sandstone surrounded by a soil-like matrix of highly sheared clayey shale (Fig. 1).

This paper includes a summary of the nature and mechanical properties of melanges for those readers unfamiliar with these geologically complex, but nevertheless, globally common, block-in-matrix rock mixtures.

At the toe of the slope, the melange contained a high proportion of blocks relative to the upper portion of the slope. This uneven distribution of blocks created a substantial contrast in bulk shear strength of the melange between the toe and upslope portions of the landslide.

Site-specific shear strength data were not available for the melange. Furthermore, conventional back-analysis methods to evaluate shear strength parameters were insufficient because the basal failure plane traversed three distinct materials (fill, block-poor melange, and block-rich melange). This paper presents the methodology used to develop a slope stability model to evaluate the relative impacts of slope modifications and changes in groundwater level on stability.

2 OVERVIEW OF MELANGES

Melanges are a jumble of competent blocks of rock embedded in often pervasively sheared, soil-like shale (Fig. 1). Blocks in melanges are ubiquitous, range in size between sand and mountains, and are composed mainly of graywacke sandstone, with lesser proportions of unsheared siltstone, chert, greenstone and exotic metamorphic rocks. Medley (1994) characterized the fabric of melanges to be similar to those of breccias, decomposed granites and saprolites, and bundled these and other geologically complex rocks into the generic term bimrocks (block-in-matrix rocks).

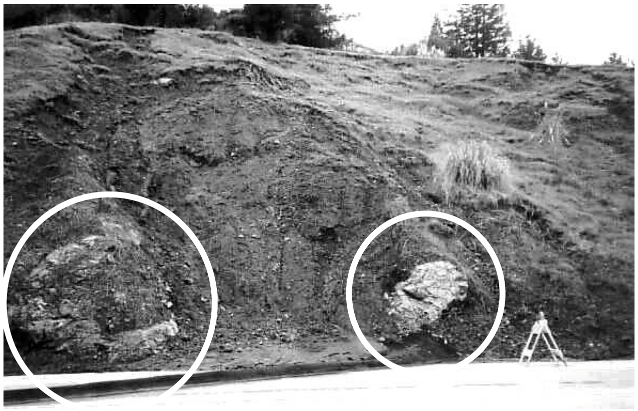

Fig. 1: Part of toe of landslide, showing typical appearance of a Franciscan Complex melange. White circles indicate large blocks of competent rock within soil-like sheared shale. Blocks shown here buttress the slopes above them.

As described in Medley (1994, 2001), blocks are found in melanges at all scales of engineering interest, and their presence frustrate conventional subsurface spatial and geomechanical characterizations. The universal approach to the strength of mixtures such as bimrocks is to adopt the strength of the weak matrix as representative of the entire rock mass. However, Lindquist (1994a,b) and Lindquist and Goodman (1994) showed that the overall mechanical properties of melange bimrocks were simply and directly related to the volumetric proportion of blocks in the bimrock. Between a range in volumetric block proportion of about 25 percent and 75 percent, the presence of blocks contributes strength to the bimrock, additive to that of the matrix. Below 25 percent, the bimrock strength (the angle of internal friction) is the same as the matrix strength, and above 75 percent, there is no further increase in strength. Given some matrix strength, the increase in friction angle can be as much as 15 degrees to 20 degrees (Lindquist, 1994). In other words, it may be geotechnically over-cautious to ignore the beneficial mechanical contribution of blocks in a bimrock. Furthermore: ignoring the presence of hard blocks of rock within a soft matrix during characterization and design will lead to unpleasant and expensive surprises during earthwork construction.

3 SLOPE STABILITY MODEL

This section describes the development of the slope stability model used to evaluate the factors contributing to failure.

3.1 Data Sources for Geologic Conditions

Topographic information was compiled from previous surveys. Historical, pre-development topography was obtained from grading plans for the residential subdivision and from topographic profiles prepared for the improvement of the road at the base of the landslide.

Stratigraphic information was interpreted from borings performed during previous investigations at the project site. In addition, surface geologic mapping was performed in the summer of 1997. Unit weights were assigned to site materials based on laboratory tests from previous investigations and prior experience with similar soil and rock in the region.

Estimated critical groundwater levels prior to failure were obtained from soil borings drilled before catastrophic failure of the slide. Additional groundwater level data were inferred from the observed performance of hydroaugers (horizontal drains) at the head of the slide and from the location and water level of the creek downslope from the landslide. The hydroaugers had been installed prior to failure due to evidence of slope instability in the year preceding the landslide.

The location of the basal failure plane (deepest slide surface) was postulated based on inclinometer data and field mapping. Post-failure inclinometer data indicated the probable depth of movement at several locations within the landslide area. The geometry of the headscarp was mapped in the field. The location of the basal failure plane at the toe was postulated based on field observation of apparent slide kinematics. Slide debris prevented direct observation of the basal failure plane at the toe.

3.2 Cross-sections Selected for Analysis

Using the information described above, several geologic cross-sections through the landslide area were prepared. Two cross-sections were selected for modeling based on the geometry of the slope, the limits and direction of landslide movement, and geologic conditions.

Cross-section A-A’ intersects the middle of the landslide and represents the portion of the landslide comprised of fill, block-poor melange, and block-rich melange (Fig. 2). Based on field observations of geologic conditions and slide kinematics, the block-rich melange appeared to have engineering properties that were distinct from the other materials involved in the landslide.

A second cross section (Cross-section B-B’, not shown) was prepared near the northern margin of the landslide and roughly parallel to Cross-section A-A’. This section was modeled to help validate the strength parameters developed for the block-poor Franciscan melange. The location of this cross-section was chosen because it is outside the apparent limits of the block-rich Franciscan melange at the toe of the slide mass. The stratigraphy within this cross-section includes a wedge of engineered fill underlain by block-poor melange.

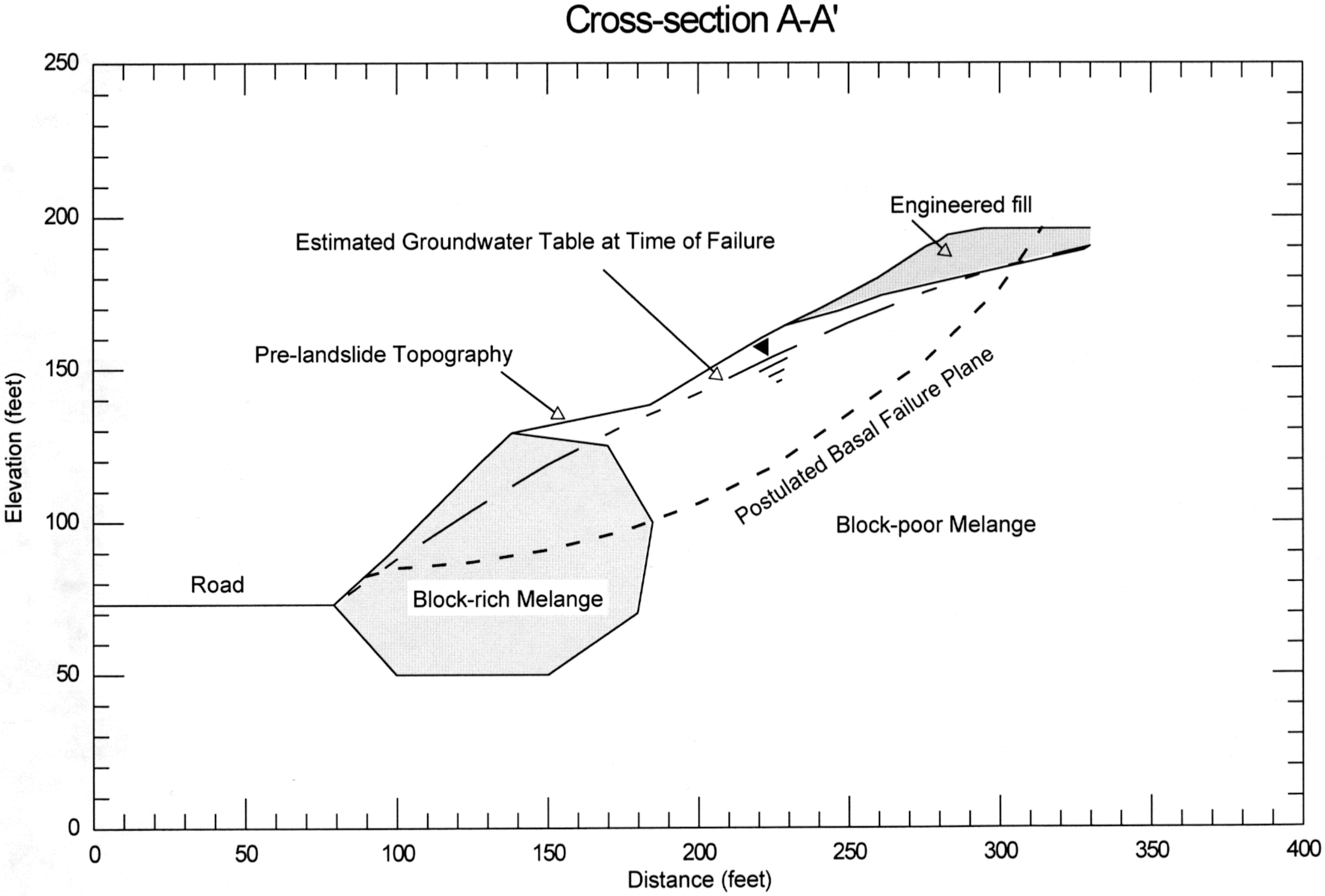

Fig. 2. Cross-section A-A' through the middle of the landslide.

The probable thickness of colluvium and residual soil at the fill/bedrock interface was estimated to be less than 5 feet. Thus, colluvium and residual soil were not differentiated from bedrock in the model because they did not constitute a significant portion of the basal failure plane. Additionally, split-spoon sampler blowcounts and unconfined compression test results from previous investigations suggested that the strength of those soils was comparable to block-poor Franciscan melange. Based on these two factors, differentiation of these materials from block-poor Franciscan melange was considered unlikely to increase the accuracy of the model.

3.3 Method of Stability Analysis

The selected cross-sections were modeled and analyzed using the computer program PCSTABL5M (Achilleos, 1988). The program gives the general solution of slope stability problems using a two-dimensional limit equilibrium method. The methods available in the program and used for this study are the simplified Bishop method of slices (Bishop, 1955) for circular failure surfaces and Spencer's method of slices (Spencer, 1967) for noncircular failure surfaces.

4 DEVELOPMENT OF SHEAR STRENGTH PARAMETERS

Shear strength parameters were derived from site data and published correlations, as well as from back-calculation methods. The methods used to develop shear strength parameters are discussed in the following sections.

4.1 Strength Data Derived from Published Correlations

As an initial step in developing shear strength parameters for the modeled cross-sections, available field and laboratory test data were compiled to derive shear strength estimates from published correlations. Data from previous geotechnical investigations at the site included standard penetration test (SPT) sampler blowcounts, unconfined compression tests, and plasticity indices.

4.1.1 SPT Blowcounts – Fill. Due to the heterogeneous nature of Franciscan Complex melange, strength correlation with highly scattered blowcount data was not attempted. The engineered fill, however, appeared to be sufficiently homogeneous to correlate blowcounts to strength. The average SPT equivalent blowcount (N) recorded by previous investigations in the fill was 10.

Since landslide geometry suggests that the native materials control the failure mechanism, effective strength (drained, or long-term condition) parameters were developed for the materials involved in the slide, including the fill. Based on correlation of SPT blowcounts to relative density and correlation of relative density to friction angle (NAVFAC, 1986), the effective friction angle (ϕ') was estimated to range between 30^o and 35^o. In addition, we assumed the fill was compacted in accordance with the recommendations of the geotechnical engineer for the residential development. If so, clayey sands compacted to the recommended relative density of 90% by the standard Proctor procedure (the standard at the time of grading for the residential development) would attain shear strengths represented by an effective cohesion intercept (c') of 230 pounds per square foot (psf) and a ϕ' of 31^o (NAVFAC, 1986).

<u>4.1.2 Laboratory Tests – Melange</u>. Results of unconfined compression tests from previous investigations were too varied to assign strength properties based solely on these results. Moreover, based on the postulated arrangement of the failure surface , the stability of the subject slope would be controlled by the long-term, drained shear strength parameters, not the undrained values obtained from unconfined compression tests.

Plasticity index tests (Atterberg Limits) were performed on a sandy clay sample from the melange during a geotechnical investigation performed prior to development. Test results of the sandy clay sample indicated a Plasticity Index of 22%, which was compared with published shear-strength correlations to identify approximate ϕ' values.

The shear strength of the melange is influenced by the volumetric proportion of the blocks (but not the strength) and the strength of matrix material. The shear strength of the clayey matrix material represents the lower bound value for the entire mass. Based on published correlations (Ladd et al., 1977; Bjerrum and Simons, 1960; Kanja and Wolle, 1977; Olsen et al., 1986), the effective friction angle, ϕ', of the matrix material could range from 10^o to 30^o, depending on how much shear strain it has experienced. Results are summarized in Table 1.

The data presented in Table 1 were used as initial estimates in iterations to back-calculate shear strengths and to check the reasonableness of back-calculated shear strength values.

Table 1. Estimated ϕ' of Melange Matrix Based on Correlations

Condition of Clay	ϕ' (degrees)
Intact (Peak)	30
Disturbed (Fully Softened)	20
Prior Failure, Ancient Slide Plane (Residual)	10

<u>4.2 Back-calculation of Shear Strength Parameters for Melange</u>

Typically, back-calculation of shear strength parameters consists of identifying a unique friction angle required to generate a factor of safety (F.S.) of 1 for the postulated failure surface through the pre-slide topography assuming a cohesion intercept of zero. However, because the basal failure plane traversed three materials, an infinite number of friction angle combinations for the fill, block-poor melange, and block-rich melange could be used to back-calculate an F.S. of 1. Acknowledging that the back-calculated shear strength parameters will not be unique, simplifications were made and additional constraints implemented to develop a set of shear strength parameters that constitute a reasonable estimate of field conditions.

To simplify the analysis, a variable was removed from the back-analysis by assuming reasonable shear strength parameters for the fill. Based on the analysis presented in Section 4.1.1, a ϕ' of 30^o and a c' of 500 psf were assigned to the fill. A relatively high c' was selected for the fill to prevent the model from generating shallow failure surfaces within the fill that would not have been useful in our analysis. Although based on observed slide characteristics, the shear strength of the fill did not appear to control the stability of the slope, a parametric analysis was performed to evaluate its importance. The results of that analysis are summarized in Section 4.2.3.

<u>4.2.1 Constraining the Possible Range of Shear Strength Parameters for the Melange</u>. As a first step, the maximum reasonable difference (hereinafter referred to as "limiting differential") in shear strengths between the block-rich and blockpoor melange was evaluated. Based on previous experience with the Franciscan Complex, a maximum ϕ' of 45^o was estimated. A minimum residual ϕ' of 10^o was estimated based on published correlations using plasticity indices and previous experience. To reduce the number of iterations required to converge to a solution, the cohesion intercept and surficial stability were neglected during this phase of the analysis. Sets of limiting differential friction angles required to back-calculate a F.S. of 1 for the postulated failure surface using Spencer's Method are shown in Table 2.

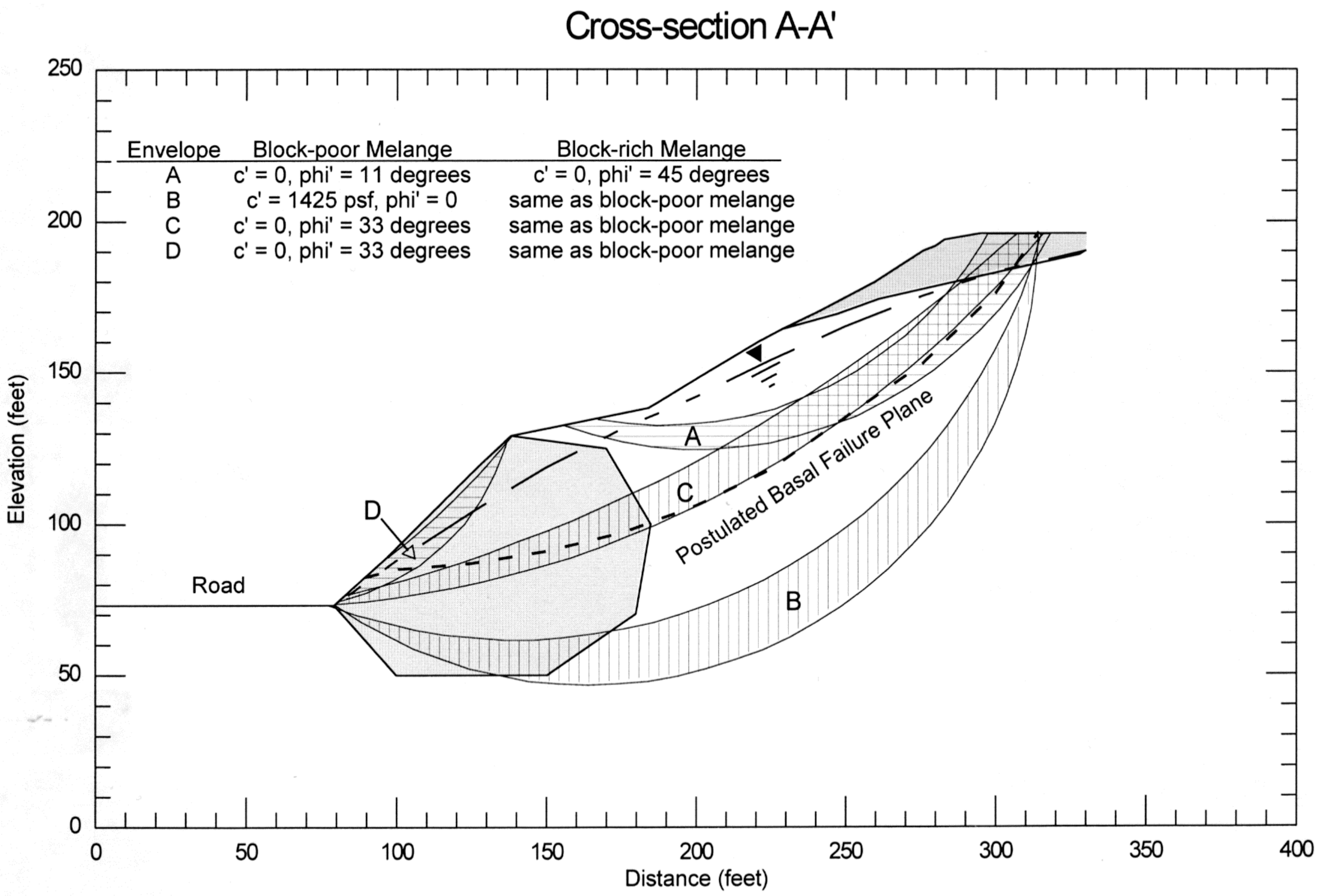

Fig. 3. Cross-section A-A' showing failure envelopes.

Table 2: Sets of Limiting Differential ϕ's

Block-rich Melange	Block-poor Melange
45° (reasonable maximum)	11°
45.5°	10° (reasonable minimum)

As shown in Table 2, the maximum difference in ϕ' between the stronger block-rich melange and the weaker block-poor melange was approximately 35°. However, results of the random search routines for failure surfaces on Cross-section A-A' by PCSTABL5M suggested that these limiting strengths may not be appropriate. Using the Simplified Bishop method of circular failure surfaces, the search routine algorithm created 500 failure surfaces spaced along specified discrete intervals. Using the strength parameters shown in Table 2, the critical failure surfaces developed were much shallower than the postulated slide plane (Envelope A on Fig. 3).

Although the postulated slide was most likely a block failure, the block search routine in PCSTABL5M was not used as an independent check because required inputs constrain the locations of failure surfaces, thereby inducing a bias that renders the check ineffective. Thus the circular search routine was used to determine the general location of the critical failure surfaces.

At the opposite extreme from the limiting differential shear strengths was the assumption that the block-rich and block-poor melange had the same strength. The shear strengths required to calculate an F.S. of 1 assuming that the block-rich and block-poor melange had uniform strength are shown in Table 3.

Table 3: Sets of Uniform Shear Strengths

c' (psf)	ϕ' (degrees)
1425	0
0	33

Based on the location of the critical failure surfaces developed by random search routines, the shear strength modeled by ϕ' = 33° and no cohesion appeared to be more plausible than c' = 1425 psf (Envelopes C and B, respectively, on Fig. 3). However, a more detailed search routine revealed that for ϕ' = 33° and no cohesion, shallow surficial failures were more critical than deeper slide surfaces similar to the postulated slide plane (Envelope D on Fig. 3). A c' of at least 200 psf was required to render the deeper failure surfaces as critical as the shallow, surficial surfaces.

Note that the F.S. of the randomly developed circular failure surfaces (calculated by the simplified Bishop method) was generally lower than the F.S. of the postulated slide plane (calculated by Spencer's method) by about 0.1. The difference is due to the use of different modeling and solving methods. Spencer's method was used to analyze the postulated slide plane because it has two advantages over the simplified Bishop method: (1) it can analyze non-circular failure surfaces and, (2) it solves for both force and moment equilibrium. Even though it resolved only the moment equilibrium, the simplified Bishop method was used for random searches, because Spencer's method often did not converge to a unique solution. Moreover, the simplified Bishop method provided solutions that were roughly equivalent to Spencer's method for circular surfaces.

4.2.2 Incorporating Cohesion Intercepts. The lack of evidence of prior failures or slumps along Cross-section A-A' indicated that the slope had performed adequately for almost 40 years. Thus, if the slopes were dry, the F.S. for surficial stability probably had been at least 1.25. Based on infinite slope analyses using reasonable intermediate ϕ' values for the block-rich melange (30° to 35°), a c' of at least 200 psf was required to maintain surficial stability of the upper 5 feet of block-rich melange, given the approximate 50° pre-failure slope at the toe of the slide area. Similarly, the required c' of the block-poor melange was calculated as 100 psf for the upper 5 feet, given reasonable ϕ' values (25° to 30°) and the pre-failure slope angle of approximately 28°.

Effective cohesion intercepts of 100 psf and 200 psf were used for the block-poor and block-rich areas, respectively, to maintain consistency of method for the remainder of the back-calculation.

4.2.3 Use of Random Failure Surface Generation Routines to Back-calculate Shear Strengths (Critical Surface Correlation). The correlation of critical failure surface locations generated by random surface generation routines with the location of the postulated actual failure plane (critical surface correlation) was used as an additional filter in refining the range of possible shear strengths.

To maintain an F.S. of 1 (based on the Spencer method and the postulated basal failure plane), an increase in the shear strength of the block-rich melange required a corresponding reduction in the shear strength of the block-poor melange. When the shear strength of the block-poor melange was too low, the critical failure surfaces developed by random search-routines daylighted above the block-rich melange. However, the postulated basal failure plane actually daylighted near the base of the slope, within the block-rich melange (as shown on Fig. 2), thus constraining the minimum shear strength of the block-poor melange and the corresponding maximum shear strength of the block-rich melange. Similarly, if the shear strength of the block-rich melange was too low, shallow surficial failures within the block-rich melange became more critical than the deeper failures that resemble the postulated basal failure plane. Sets of friction angles used in this phase of the stability evaluation are summarized in Table 4.

Table 4: Sets of Friction Angles Used for Critical Surface Correlation

Block-rich ϕ'	Block-poor ϕ'	Comments
31°	30°	Shallow failures at block-rich area are more critical
32°	29°	Possible solution
33°	28°	Possible solution
34°	26°	Possible solution
35°	25°	Possible solution
36°	23°	Critical surfaces daylight above the block-rich area

As shown in Table 4, the ϕ' of the block-rich melange ranged from 32° to 35° using a c' of 200 psf. Noting the inverse relationship between the block-rich and block-poor melanges, the corresponding ϕ' of the block-poor area ranged from 29° to 25° using a c' of 100 psf. The difference in ϕ' between the two melanges ranged from 3° to 10°. Because field observations suggested that a significant difference in strength existed between the block-rich and block-poor melanges, the set with the maximum difference in ϕ' was selected for the model.

The shear strength parameters selected for the block-poor melange were checked using a slope stability evaluation of Cross-section B-B'. The resulting F.S. of 0.9 for the postulated failure surface and groundwater level (both projected from Cross-section A-A') was considered to be reasonable given the large downslope displacement of material observed at Cross-section B-B'.

Because only a small portion (approximately 5%) of the postulated slide plane passed through the engineered fill at the top of the slope, its shear strength parameters were not included as variables in the initial iterations. Estimates of the engineered fill's ϕ' and c' (based on previous experience, field and laboratory tests, and published correlations) were considered to be reliable due to the relative homogeneity of the fill and quantity of physical data. Moreover, the small portion of the postulated slide plane that passed through the engineered fill was entirely in the active zone of the slide, so its effect on the stability was expected to be minor. Even so, the effect of changing the strength parameters of the engineered fill was later analyzed assuming that the Franciscan melange strength parameters selected for the model were correct. Decreasing the fill strength to zero had a negligible effect on the stability of the postulated slide plane.

5 MODEL SENSITIVITY TO STRENGTH PARAMETERS

The slope stability model's sensitivity to the strength parameters used was evaluated, as discussed in the following sections.

5.1 Shear Strength Parameters Selected for the Model

Based on the methodology presented in Section 4, parameters of the melange and engineered fill that were selected for the slope stability model are presented in Table 5.

Table 5: Shear Strength Parameters Selected for Slope Stability Model

Stratigraphic Unit	c' (psf)	ϕ' (degrees)
Engineered Fill	500	30
Block-poor Franciscan melange	100	25
Block-rich Franciscan melange	200	35

The back-calculated shear strength values, Cross-section A-A', and the postulated basal failure plane were used to evaluate the destabilizing effect of raising the groundwater table, cutting the toe of the slope, and placing fill at the head of the slope.

5.2 Sensitivity of Results to Strength Parameter Selection

Alternate sets of possible shear strengths (Table 4) were substituted in the model to evaluate its sensitivity to changes in shear strength parameters. Instead of parameters providing the greatest difference in ϕ' between the block-rich (35°) and block-poor (25°) melange, the sensitivity analysis used the set with the smallest difference (32° and 29°) and a set in between (34° and 26°).

The change in strength parameters did not significantly change the calculated F.S. for any of the conditions simulated with the model. The maximum standard deviation in the F.S. calculated using the three different sets of strength parameters was 0.023, which was negligible, considering the expected overall accuracy of the model.

6 CONCLUSIONS

Evaluation of landslides in complex geologic materials such as melange requires exhaustive compilation of available data and careful selection/derivation of parameters used to develop a reasonably accurate slope stability model. In block-in-matrix materials, consideration must be given to the relation between bulk shear strength and volumetric proportion of competent blocks. The study presented in this paper indicates that critical surface correlation is a feasible additional criterion that can be used to back-calculate strength parameters.

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