Shear Strength Characterization and Back Analysis for a Landslide Complex

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ABSTRACT

Future phases of landfill expansion at a municipal solid waste landfill in Southern California required the characterization and mitigation of a 16-hectare complex of coalescing pre-existing landslides in sedimentary bedrock. Traditional back-analysis of the entire slide mass yielded unreasonably low values of slide plane shear strength. A hybrid approach, which combined laboratory testing for site-specific validation and application of empirical correlations, with back analysis of a retrogressive failure geologic model, resulted in a realistic evaluation of slide plane shear strength. A limit equilibrium model developed to simulate the progressive nature of the failure, correctly predicted the geometry of each stage of the failure accompanied by a corresponding factor of safety at or less than unity, thereby validating both the progressive nature of the failure and the shear strength parameters. Numerical analysis using FLAC was an additional verification of the progressive failure.

Introduction

Future phases of landfill expansion at the Frank R Bowerman (FRB) municipal solid waste (MSW) landfill in Orange County, California require the characterization and mitigation of a 16-hectare complex of coalescing and pre-existing landslides. This complex of rotational and translational landslides occurs through sandstone, siltstone and claystone of multiple geologic formations underlying the site. The recent landsliding occurred in three stages over a 2-year period. The initial stage occurred in June 2000, when existing rotational landslides in the toe area were reactivated by site grading. The central portion of the landslide complex failed as a translational landslide in February 2002, followed by a third stage in September 2002. The entire landslide complex is currently active and roughly 640 meters long, 300 meters wide and up to 70 meters deep. The elevation difference between the highest headscarp area and the slope toe is approximately 110 meters. Partial headscarp removal and installation of horizontal drains has lowered the rate of movement of the landslide, but the slide continues to move.

To design an effective stabilization scheme, the shear strength parameters of the slide plane material(s) had to be determined. This was complicated because traditional back-analysis of the entire slide mass yielded unreasonably low values of slide plane shear strength. This paper describes a hybrid approach to obtain a realistic estimate of the landslide plane shear strength. The approach combines laboratory testing of slide plane material for site-specific validation of the Stark et al (2005) correlations that relate index properties to residual shear strength, and back analysis using a retrogressive failure model to validate the shear strength parameters. This approach resulted in a realistic evaluation of slide plane shear strength which was used to design remedial measures.

Landslide Characteristics

The geometry of the active landslide complex was determined by monitoring a network of over twenty-four inclinometers and surface monuments, supplemented by various subsurface investigations, downhole geophysics, and geologic mapping. The elevations corresponding to the deflection depths measured in the inclinometers were contoured to locate the active basal slip surface of the landslide. Surface geologic mapping and data from inclinometers was used to establish the multiple headscarps of the landslide complex.

The displacement vectors from the inclinometers suggested the landslide mass was not moving at the same rate nor in the same direction (Figure 1): the toe area (southern block) of the landslide was moving in a south-southeasterly direction at a relatively fast rate of about 1.6 meters/year; the central block was moving in a south-southwest to south direction at a rate of 75 to 100 mm/year; and the northern (upper) block was moving in a southwest direction at approximately 30 mm/year. This data shows the landslide is not moving as a monolithic mass, but is a combination of multiple landslides occurring in a progressive manner.

Laboratory Testing and Validation of Strength Correlations

The main basal slip surface of the landslide complex cuts across a range of materials. Similarly, the multiple headscarps of the landslides cross different material types. There were also other potential weak planes within the landslide mass including weak bedding planes, clay seams, joints, and fault planes. As a result, it was not practical to characterize the residual strength of each of the different materials using torsional ring shear tests. Therefore the following testing strategy was followed:

- Torsional ring shear tests (ASTM D6467) were performed on a limited number of “validation” samples selected from various formations and materials traversed by the basal slip surfaces, and other weak planes
- Site-specific validation of the Stark et al. (2005) strength correlation (that relates liquid limit (LL) and clay size fraction, to drained residual and fully softened shear strength), by comparing the results of the “validation” torsional ring shear tests to correlation predictions

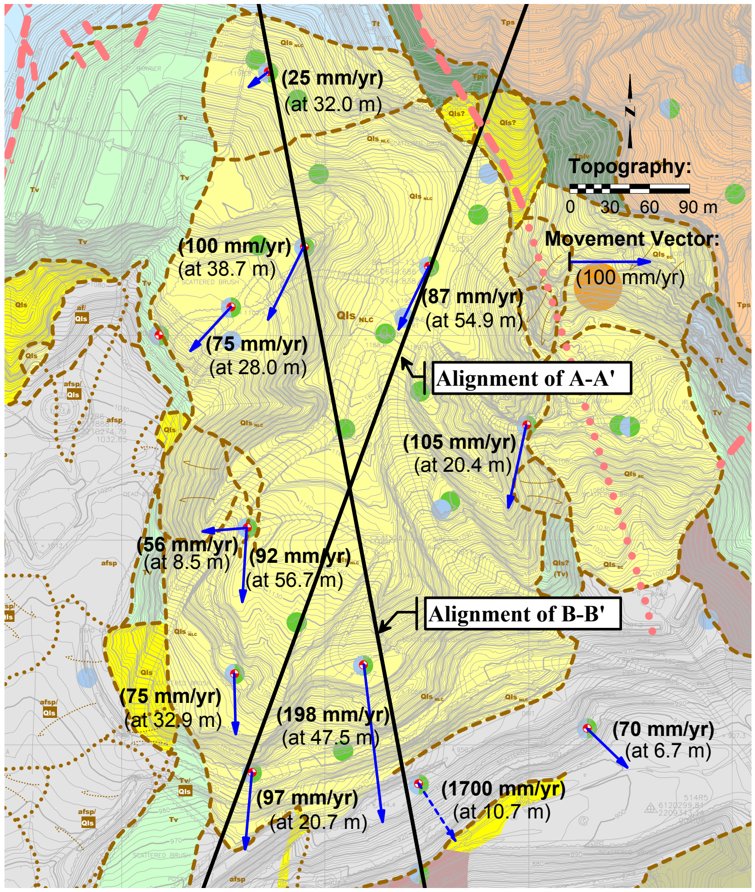

Figure 1. Landslide Movement Vectors

- Characterizing the many materials along the various slip surfaces by performing inexpensive index property tests on a relatively large number of samples from each weak plane, and averaging them
- Estimating the average residual and fully softened shear strength parameters (stress dependent strength envelopes) for the various weak planes, based on the average index properties, and using the validated Stark et al. (2005) residual strength correlation.

A total of seven test samples, representing the range of basal slip surface materials encountered at the site, were selected for validation shear testing (Table 1). The samples include materials from the main landslide basal slip surface, landslide headscarp, intact clay seams, and joint infill, with LL ranging from 20 to 136. The torsional ring shear tests were multi-stage, consolidated-drained, residual tests on remolded samples (air dried, screened through #40 sieve and prepared at its LL), sheared at 0.018 mm/min in accordance with ASTM D6467. In the Stark et al (2005) correlations, the stress dependent residual shear strength is presented in terms of secant friction angles at low, medium and high normal stresses of 100, 400 and 700 kPa, respectively. In the site-specific test program (Table 1), each sample was tested at three different effective normal stresses, roughly of the same order as the three normal stresses used in the Stark et al. (2005) correlations.

Table 1. Laboratory Torsional Ring Shear Tests Vs. Empirical Correlations

Material	USCS	ASTM Test Method			Φ'$_{res}$ (deg) from Ring Shear Tests			Φ'$_{res}$ (deg) from Correlation		
		LL	PI	CF% (<2μm)	145-190 kPa	290-380 kPa	575-775 kPa	100 kPa	400 kPa	700 kPa
Clay Seam[1]	CH	136	90	49	4	4	4	7	6	5
Clay Seam[1]	CH	130	96	34	6	5	5	8	7	6
Clay Seam[2]	CH	70	45	18.5	9	9	9	12	10	9
Slide Plane[2]	CH	60	34	31	8	8	8	16	13	10
Backscarp[2]	GM	44	14	16	15	15	15	21	18	15
Backscarp[1]	SC	34	11	17	33	32	31	30	29	28
Joint Infill[1]	SM	NP*	NP	11	33	32	31	32	31	29

Note: LL = Liquid Limit as per ASTM on material passing the No. 40 sieve; CF = Clay Fraction as per ASTM; NP = Non Plastic; Φ'$_{res}$ = Effective stress residual secant friction angle; Ball mill corrections as per Stark et al (2005) were applied to LL and CF (on all samples other than the SC) prior to applying residual strength correlations.
* for non plastic soils a liquid limit value of 20 (lower bound value in chart) was assumed
[1] samples tested at normal stresses of 145, 290, and 575 kPa
[2] samples tested at normal stresses of 190, 380, and 775 kPa
Detailed results of the torsional ring shear tests (ASTM D6467) including stress-displacement and vertical displacement curves, and shear envelopes are not included due to space limitations, but are provided in AES (2010).

Table 1 indicates that at the lower range of normal stress, (~100 kPa) the Stark et al (2005) correlations generally overestimate the residual secant friction angle. In the medium range of normal stress (~400 kPa) the correlation and testing are closer, and tend to underestimate the residual friction angles for the less plastic materials (lower LL values) and overestimate them for the more plastic materials (higher LL). At the higher normal stress (~700 kPa), the comparison between the laboratory torsional ring shear residual strength values and those from the empirical correlation are in good agreement.

The landslide basal slip surface at the FRB site is generally about 30 to 70 meters deep (corresponding effective normal stresses on the slip surfaces in the 500 to >775 kPa range). Thus, for the stress range of interest, the Stark et al. (2005) correlation provides a reliable prediction of the residual strength for the basal slip surface materials. For the shallower slip surfaces (headscarp and joints to depths up to about 30 m), the materials are different from the basal slip surface materials and consist generally of SC and SM materials with LL in the range of 20 to 50. For such materials the Stark et al (2005) correlation provides reasonable prediction of residual strength even at the medium ranges of normal stress. Figure 2 compares the predicted secant residual friction angle values with the measured values for the seven samples. All of the measured values at high levels of normal stress and most of the measured values at medium levels of normal stress fall within ±20% of the predicted secant residual friction angles. Figure 2 also shows the measured and predicted residual values versus the corresponding LL values. The latter figure also shows the range of LL values measured on samples from the actual landslide basal slip surface. These plots illustrate the validity of the Stark et al. (2005) correlations between index properties and residual strengths for the stress range and material (LL) range of interest at this site.

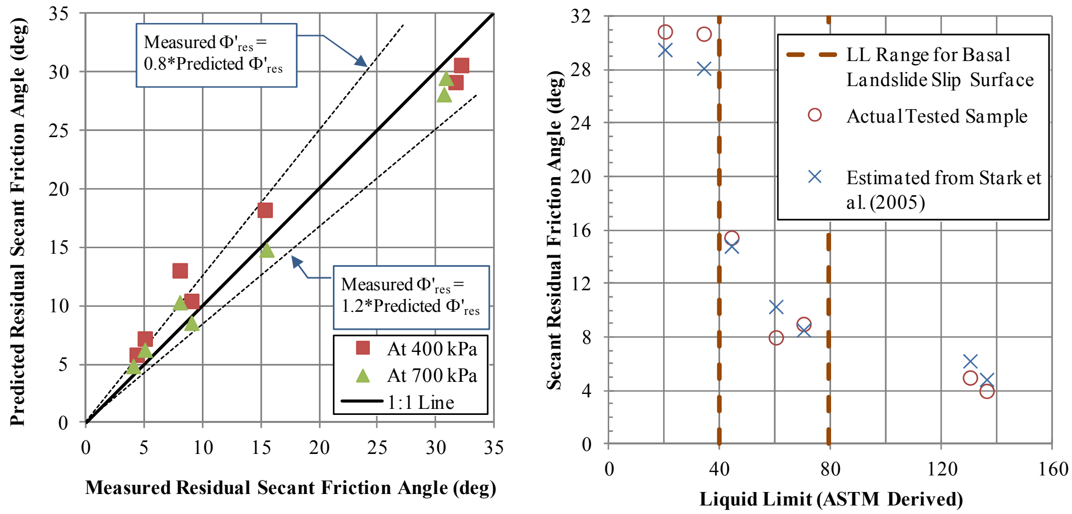

Figure 2. Comparison of Measured and Predicted Secant Residual Friction Angles.

The shear strength of various weak/slip plane materials on site were then estimated by testing several samples from each weak/slip plane to obtain the average index properties, and using the Stark et al (2005) correlations to estimate the corresponding average residual and fully softened strengths. Residual strengths were used for analyses involving pre-existing slip planes, i.e. landslide shear surfaces, headscarps, and faults. The fully softened strength was used for potential failure planes in materials that had not experienced prior shear movement.

Table 2 shows the LL and clay fraction for nine samples obtained from the basal slip plane of landslides. The exact depth of the slip plane was identified based on the depth of inclinometer movement/shear, and the corresponding sample was obtained from the recovered continuous core. The materials from the basal slip plane consist of CL and CH materials with LL from 40 to 79 and clay fraction (percentage finer than 0.002 mm) from 14 to 40 percent. Table 2 also shows the estimated residual shear strength (secant friction angles corresponding to different ranges of effective normal stress). Based on the stress-dependent secant friction angles and assuming zero cohesion, a non linear strength envelope representing the average residual strength, was developed for the basal slip plane (Figure 3). Along with the non linear strength envelope, the linear best fit line is also shown: average secant friction angle of 12 degrees. This is comparable to slide plane shear strength values typically used in the local area for landslides in sedimentary rock. In comparison, an extensive torsional shear test program on naturally occurring landslide materials in Japan by Tiwari and Marui (2005), indicates that materials with the same range of LL (40 to 79), plasticity index (19 to 47) and clay fraction (14 to 40%) as the FRB basal slide plane materials, had residual friction angle values ranging from 7.8 degrees to 25.8 degrees with an average of 14.5 degrees (from 34 samples).

Table 2. Estimated Residual Strengths using Stark et al. (2005) Correlation

Sample	USCS	Sample Depth (m)	ASTM Test Method			Φ'$_{res}$ (deg) at		
			LL	PI	CF% (<2μm)	100 kPa	400 kPa	700 kPa
Basal Slide Plane	CH	47	60	34	31	16	13	10
	CH	34	65	43	40	10	9	6
	CH	56	79	45	30	11	9	8
	CH	55	52	29	24	18	16	12
	CH	58	50	24	27	19	16	13
	CH	28	77	47	37	10	8	6
	CL	39	45	21	21	21	18	15
Slide Plane-East Canyon	CL	20	45	19	18	21	18	15
	CL	16	40	19	14	22	20	16
Slide Plane-Average			57	31	27	**16**	**14**	**11**
Slide Plane-Range			40 - 79	19 - 47	14 - 40	10 - 22	8 - 20	6 – 16

Note: LL = Liquid Limit; CF = Clay Fraction; Φ'$_{res}$ = Effective stress residual secant friction angle. Ball mill corrections were applied to LL and CF prior to using correlation

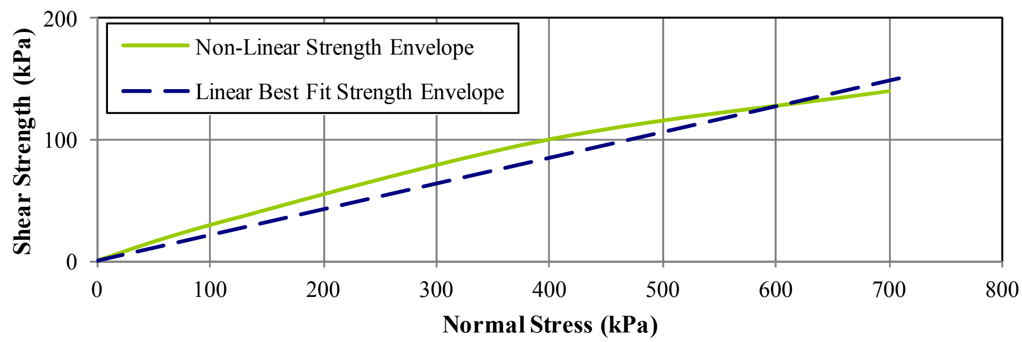

Figure 3. Effective Stress Residual Strength Envelope for Basal Slip Surface

Using a similar process, stress dependent strength envelopes were developed for other weak plane materials including headscarps, bedding planes and joints. Figure 4

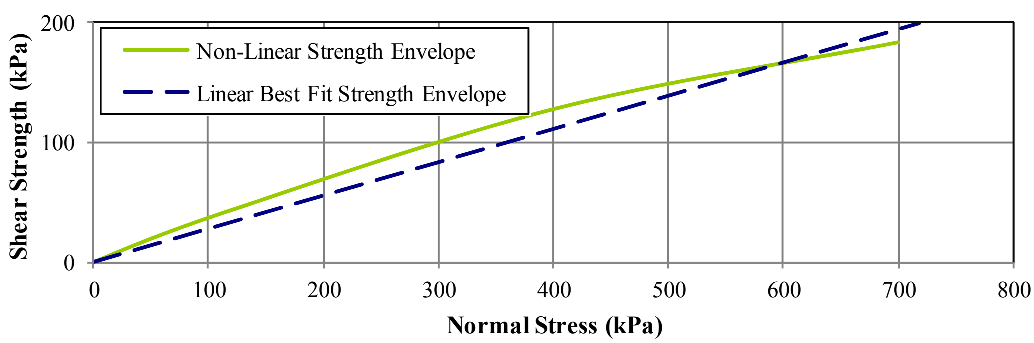

Figure 4. Residual Strength Envelopes for Landslide Headscarp Materials

shows the stress dependent strength envelope for headscarp materials (LL ranging from 34 to 51 and clay fraction ranging from 13 to 17 percent).

Back Analysis

Back analyses of the landslides in the complex were performed to validate the shear strength parameters estimated based on the laboratory test program. Two cross sections roughly aligned along the central axis of the landslide complex were used for back analysis (Figure 1). Figure 5 shows one of the cross sections, illustrating the current grade, the interpreted basal slide surface, and a series of increasingly larger landslides (total of 5) progressing from the toe to the backscarp area of the landslide complex. Based on slope inclinometer data, each of these landslides is occurring along the main basal slide plane with headscarps occurring at increasing distances from the slope toe, i.e. in a retrogressive fashion. The first landslide is a relatively small failure near the slope toe while the 5th headscarp represents the uppermost limits of the landslide complex. The 4th landslide (measured from the toe, see Headscarp 4) represents the currently active limits of the landslide complex based on ongoing inclinometer deflections. Movement along the upper portion of the landslide complex represented by the 5th headscarp had slowed significantly as a result of the unloading of the headscarp area.

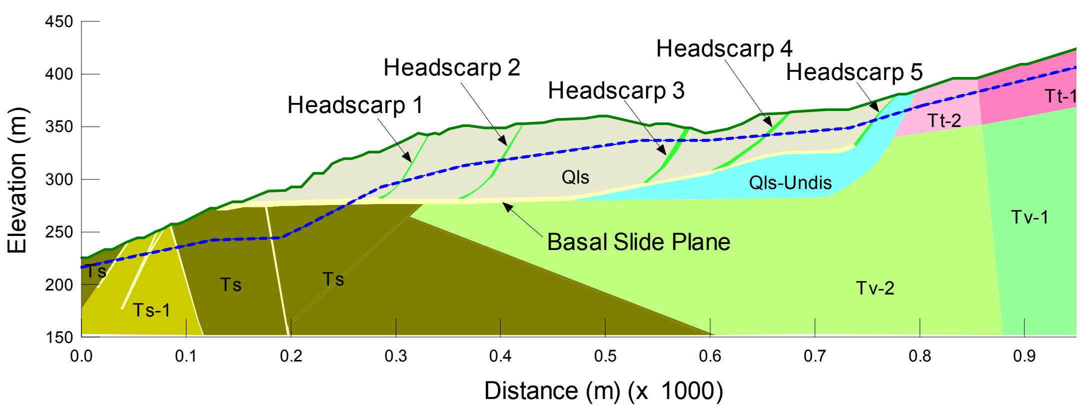

Figure 5. Typical Cross Section through Landslide Complex.

These five landslides were back analyzed using the estimated residual shear strength parameters for the basal slide plane and various headscarp materials. To simulate the actual failure mechanisms, the failure surface was forced along the basal slide plane and the program was allowed to search for the critical headscarp geometry. The search yielded a minimum factor of safety (FOS) of 0.9 (Table 3) and the critical failure surface based on the search coincides with observed headscarp location (headscarp of 1st landslide measured from the toe). This result validated the choice of shear strength parameters for the toe failure. However, when the entire currently active landslide complex (from the toe through the 4th headscarp) was analyzed with these parameters, the FOS was 1.3 to 1.4 (Table 3), which is inconsistent with an active landslide.

Table 3. Summary of Back Analysis

Description	Failure Surface	Static FOS	Remarks
First Stage of Landslide	Local Failure Near Toe (1st Stage)	0.9	Coincides with observed scarp
	Entire Active Landslide Complex	1.3 - 1.4	-
Second Stage of Landslide (After 1st Toe Slide)	Local Failure (2nd Headscarp)	0.8	Coincides with observed scarp
	Entire Active Landslide Complex	1.1	-
Third Stage of Landslide (After 2nd Toe Slide)	Landslide Through Mid-Section of Complex	0.9	Coincides with observed scarp
	Entire Active Landslide Complex	0.9	-

Note: FOS = Factor of safety

The chronology of the landslide complex development consists of at least three stages of movement. The initial stage consisting of reactivation of existing landslides in the toe area of the landslide complex followed by subsequent stages where the backscarp migrated retrogressively over time towards the central and upper portions of the landslide complex. The current displacement vector patterns observed in the inclinometers (Figure 1) also suggest that the landslide is not moving as a single mass, but is progressive, with the lower portion of the complex moving at a faster rate of movement (and slightly different direction), followed by landslides progressively increasing in size, and moving at a progressively lower rate of movement.

To simulate the effect of this retrogressive slide, the initial back analyses of the toe failure (first stage) was followed with subsequent back analyses (Stages 2 and 3) that account for the slope toe having already moved. Two different cross sections were used for the back analysis. For the first stage failure, Section B-B' oriented parallel to the first stage of failure was used. For the subsequent stages of failure, Section A-A', slightly oblique to B-B' and oriented parallel to the second and third stages of failure, was used. When the toe area moves, it separates from the rest of the slide mass and no longer provides lateral resistance (along the slide plane) to potential deep-seated slide movement. This separation, allows the upslope segment of the slide to move independently. The toe area of the upslope segment, however, is still affected by the gravity load imposed by the downslope segment failure mass. This phenomenon was simulated in the stability analyses by assuming separation between the upslope and downslope segments of the landslide along the basal slide plane, while still allowing for the gravity load from downslope segment to act on the upslope segment.

The results of the back analysis of the retrogressive failure are summarized in Table 3. After the first stage toe failure, back analysis (computer search) for the critical second stage failure resulted in a critical failure surface that coincides with the observed headscarp and a FOS of 0.8 (Figure 6). The corresponding FOS for the entire active landslide complex decreased to 1.1 from 1.3 to 1.4 at this stage. When this back analysis was repeated for the third stage (following the occurrence of the first two slides), the critical failure mechanism is a slide through the mid section of the landslide complex (roughly coinciding with the observed headscarp) with a FOS of 0.9. The corresponding FOS for the entire active landslide was also calculated to be 0.9 for this stage.

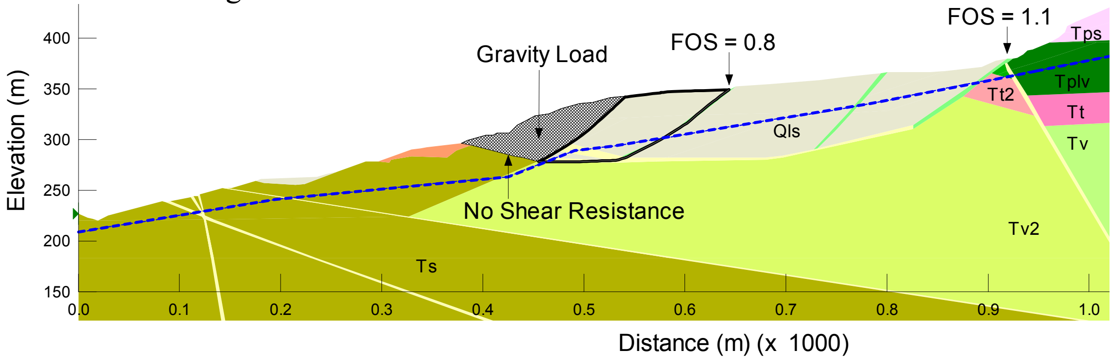

Figure 6. Retrogressive Failure Model – Stage 2 (Section A-A')

The limit equilibrium model developed to simulate the retrogressive nature of the failure, correctly predicts the geometry of each stage of the failure accompanied by a factor of safety less than unity (0.8 to 0.9), which validates both the retrogressive nature of the landslide and the shear strength parameters. However, a FOS less than unity does not imply that the slide plane shear strength is underestimated, for the following reasons:

- The back-analyses represent post-failure conditions of slide masses that are currently moving and not at incipient failure. At incipient failure, the geometry is likely different from that assumed and is not reliably known. Also, the shear strength in the backscarp area would be the gross landslide debris strength and not the residual strength used in the back analysis.
- The back analyses ignore shear strength resistance offered by the previous stage toe failure mass on the landslide mass upslope. In reality, there will be some resistance offered. If this resistance is accounted for, the calculated FOS will increase.

FLAC Model Simulations

Numerical simulation using the FLAC (Fast Lagrangian Analysis of Continua) software was performed to confirm the retrogressive failure mode. The landslide geometry with the interpreted basal slide plane and the multiple headscarps were modeled using FLAC. The residual shear strengths were assigned to the basal rupture plane and along each headscarp, and the landslide was allowed to deform under gravity load. Snapshots of the deformation at various points in the analysis shows the deformation initiating along the headscarp closest to the slope toe and then retrogressing to the next headscarp further upslope as the deformation accumulated. Figure 7 shows the deformation pattern at a certain point in the analysis where the deformations at the toe area (Headscarp 1) are on the order of meters, while deformations on the order of several centimeters have initiated along Headscarp 2.

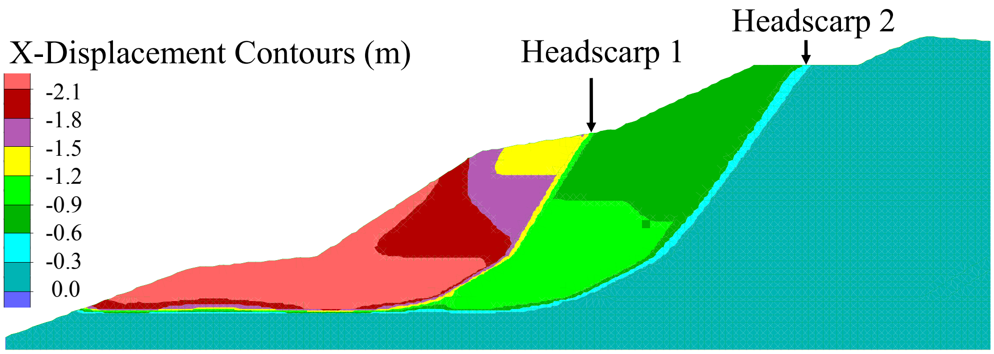

Figure 7. FLAC Model Simulation of Retrogressive Failure

Conclusions

The following conclusions can be drawn from this study:

- A hybrid approach to estimating the drained residual shear strength of preexisting slide planes in sedimentary bedrock is presented.
- Stark et al. (2005) correlations, evaluated for a wide range of site materials (LL from 20 to 136 and clay fraction from 11 to 49 percent), shows good agreement with measured ring shear values at high normal stresses (575 to 775 kPa), reasonable agreement at mid level normal stresses (290 to 380 kPa), and marginal agreement at low normal stresses.
- Back analysis without consideration of the retrogressive nature of the landsliding can result in unrealistic estimates of slide plane shear strength.
- When the retrogressive failure mechanism is modeled accurately, back analysis and the Stark et al. (2005) residual strength correlation yields comparable results.
- This study also reinforces the importance of calibrating correlations with site specific data.

Acknowledgement

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