APPENDIX N

GEOTECHNICAL MODELING OF SLOPE STABILITY
JOHNSON CREEK LANDSLIDE INVESTIGATION
LINCOLN COUNTY, OREGON

Prepared for DOGAMI by

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ABSTRACT

The Johnson Creek Landslide has become the focus of an extensive, multi-agency investigation, with the goal of identifying internal and external controls on the rate of slide movement. It is anticipated that continued monitoring of this active Coast Range landslide will reveal patterns in slope movement related to factors such as rainfall, groundwater conditions, and toe erosion. As more is learned about the characteristics of the slide more effective methods of remediation can be developed and implemented. The mechanics of the Johnson Creek slide are complicated by the existence of highly weathered and fractured marine sedimentary rocks, complex groundwater hydrology adjacent to the shear zone, highly heterogeneous geotechnical properties, and failure kinematics that involves the interaction of several blocks within the slide mass. Prior geotechnical investigation and stability analyses have focused on one fairly well defined failure surface located near the center of the slide mass. In order to highlight the influence of geotechnical uncertainty on the computed stability of the slide a small project was initiated to supplement the geotechnical stability analyses performed for DOGAMI by Landslide Technology (2004). Additional analyses using standard of practice, limit equilibrium methods for assessing slope stability have been conducted in order to evaluate the influence of the following parameters on overall slide mass stability: (a) drained shear strength parameters, (b) piezometric surface and threshold pore pressure required for slope movement, (c) influence of water-filled tension cracks on toe stability, and (d) evaluation of the impact of translating pore pressure pulses, or waves, on overall stability. The results of these analyses are discussed and compared to those performed by Landslide Technology, where applicable. Additionally, the results are discussed in terms of the inherent limitations, applicability, and overall relevance to the investigation. Recommendations are provided for additional analyses, field investigations, and instrumentation.

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1.0 INTRODUCTION

The investigation of the Johnson Creek Landslide began in the fall of 2002 with the intention of characterizing the controlling factors that influence the occurrence and rate of slide movement, as well as developing innovative methods of mitigating the slide hazard in a cost effective manner (Priest, and others, 2005). In the summer of 2004, Dr. George Priest of DOGAMI provided a small grant to Professor Stephen Dickenson of the Geotechnical Engineering Group at Oregon State University (OSU) to supplement the slope stability analyses performed by Landslide Technology (2004). The Landslide Technology investigation represents the most thorough geotechnical site characterization and stability investigation that has been performed to date. The analyses were largely confined, due to limited subsurface data, to one cross section located near the center of the slide mass. The strengths and limitations of the initial analyses were well documented, and recommendations were provided for additional investigation. The small pilot study undertaken here is aimed at expanding the slope stability modeling previously performed using standard 2D limit equilibrium methods. Professor Dickenson and two students, working on term projects focused on a critical re-evaluation of the Landslide Technology report, field reconnaissance including both ground traverses and aerial inspection, supplementary review of geotechnical characterizations of regional Coast Range landslides, and an extensive suite of slope stability analyses using the commercially available program XSTABL. The results of this study are intended to supplement the earlier work of Landslide Technology (2004), and to provide guidance for future geotechnical investigations of the Johnson Creek landslide.

A brief description of the slide and history of the investigation is given here based on the main body of the text in this open-file report and on descriptions by Landslide Technology (2004). The Johnson Creek Landslide is located on the Oregon Coast less than 0.5 km south of Otter Rock. The slide consists of three major geologic units, namely a fractured sandstone of the Miocene Astoria Formation to depth and an overlying Pleistocene marine terrace sand deposit approximately 3 to 6 meters thick. The terrace deposits overlie a 0.3- to 2-meter (1- to 6-foot) layer of orange, decomposed Astoria Formation, which in turn, overlies gray, unaltered Astoria Formation bedrock. The structural dip of the Astoria Formation at the site has been measured in nearby exposures at 15 to 20 degrees to the west. The Astoria Formation at the headwall of the landslide strikes N5W ± 2°, and dips to the west 17° ± 1.

The recent history of the Johnson Creek Landslide includes a study conducted by ODOT in the 1970s, which included six borings and inclinometers installed from 1972 to 1976 (**Figure 1**). The inclinometers installed by ODOT were pinched off within a few years and provided limited data. A report was prepared by ODOT in 1979 that discussed the results of the investigation and provided options for containing the. In 2002, Landslide Technology conducted an investigation that included three borings with three sets of inclinometers and piezometers. The Landslide

Technology report documented three slide events consisting of two slow events and one fast event, which in January 2003 sheared off all three of the inclinometers. Since January 2003 there have been three minor periods of slide movement, all three of which occurred in the winter of 2003-2004.

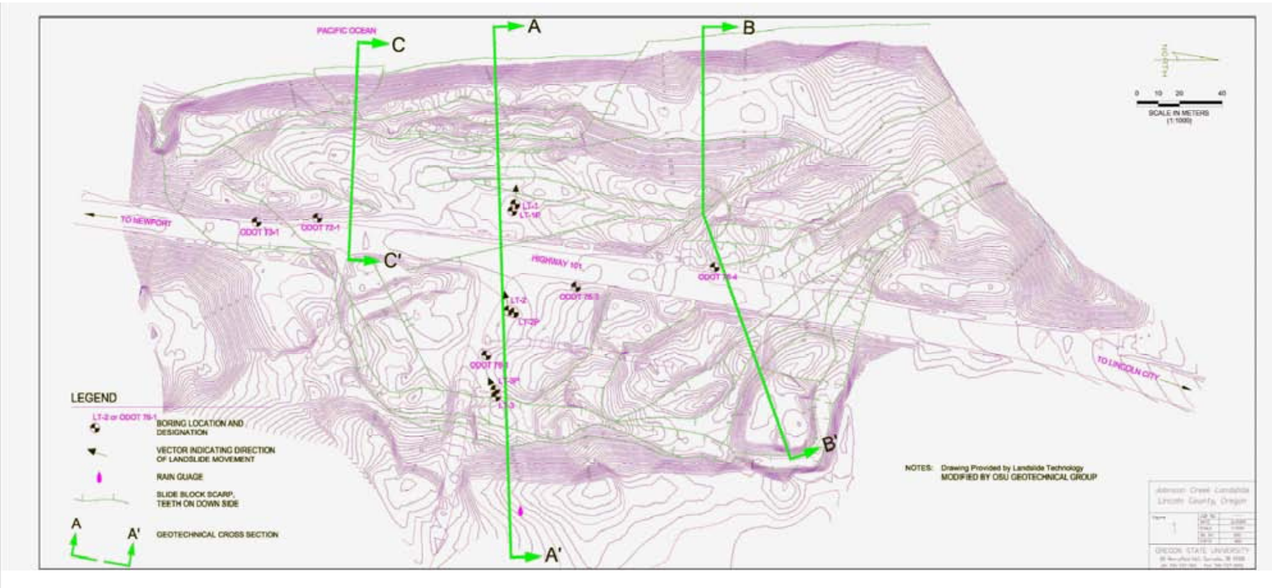

Figure 1. Site plan showing locations of cross sections used for analysis. Slide block boundaries (thin green lines are from Landslide Technology (2004).

The investigations to date have identified the key controls on slide initiation and rate of movement, provided estimates of average soil strength parameters across the shear zone, as well as estimates of the threshold pore pressures required for "fast" and "slow" movement. Sensitivity studies by Landslide Technology (2004) have shown that the greatest reduction in factor of safety occurs from severe storm events (-9%) and the loss of toe support (-7%); loss of toe support can be from cliff erosion, sliding at the toe, removal of beach sand due to seasonal wave climate and more long term littoral cell migration. In addition to the analyses mentioned above, insights into the mechanics of the slide have been raised. There is substantial evidence that the slide may be moving as three blocks as opposed to a coherent slide mass. If indeed the slide is moving as separate blocks, the 2D modeling approaches employed thus far are limited in the ability to effectively model the kinematics of the slide. The significance of this is discussed in the Conclusions section of this report.

The DOGAMI investigation has included data collection and monitoring of the slide for a 5-year period. The scope of the extensive investigation:

- Project management, including contracting, reporting and convening periodic meetings of a technical steering committee consisting of ODOT and DOGAMI personnel.
- Field data collection (geologic mapping, logging and stratigraphic interpretation of drill hole samples, collection of piezometer, rainfall, extensometer, and inclinometer data.)
- Geological and geotechnical interpretation of data.

- Publication of three reports, the LT report (Landslide Technology, 2004), an interim report after about two years (Priest and others 2005), and a final report that will be prepared in 2007 at the end of five years of data collection.

This small study contributes to the comprehensive DOGAMI investigation by confirming the back-calculated residual strength parameters from the 2004 Landslide Technology report, providing additional stability analyses of other sections of the slide as well as examination of different piezometric surfaces, and by providing recommendations for future geotechnical studies of this landslide.

2.0 MODELING EFFORTS

2.1 Model Set Up

2.1.1 Cross Sections

To evaluate the portions of the slide that may be moving differentially, three different cross sections were used in our analyses. Cross sections A-A', B-B', and C-C' are intended to represent the slide blocks of the entire slide mass (**Figures 2 and 3**). A brief discussion of the development of each slide follows:

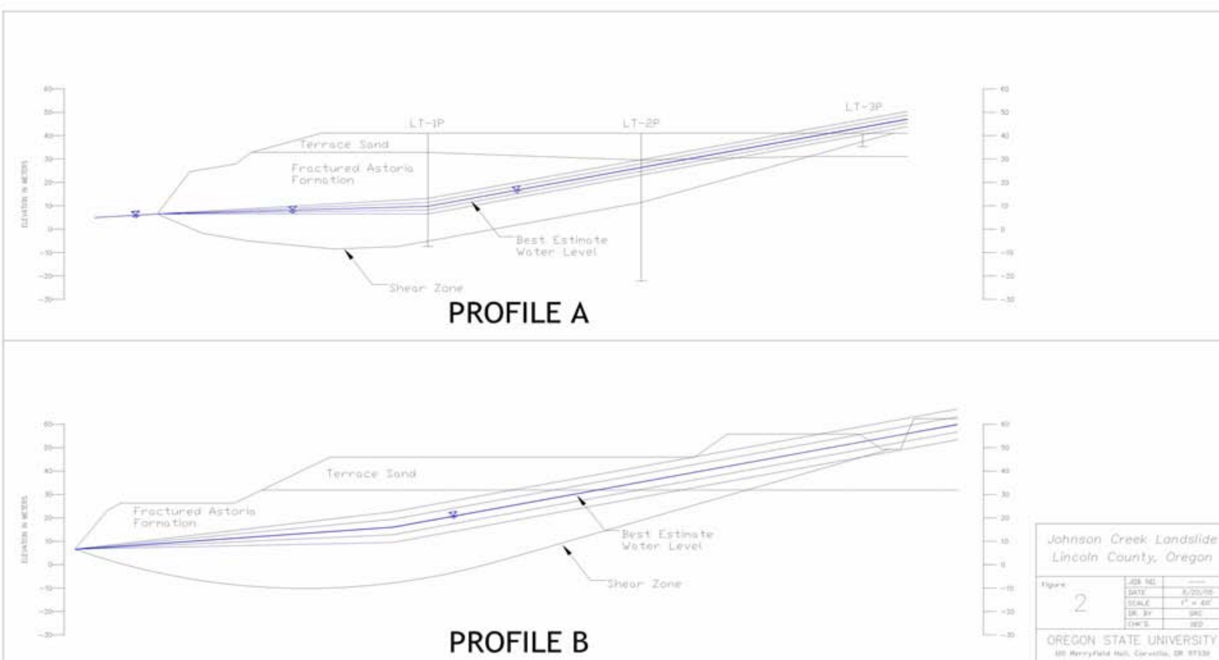

Figure 2. Cross Sections A-A' and B-B'.

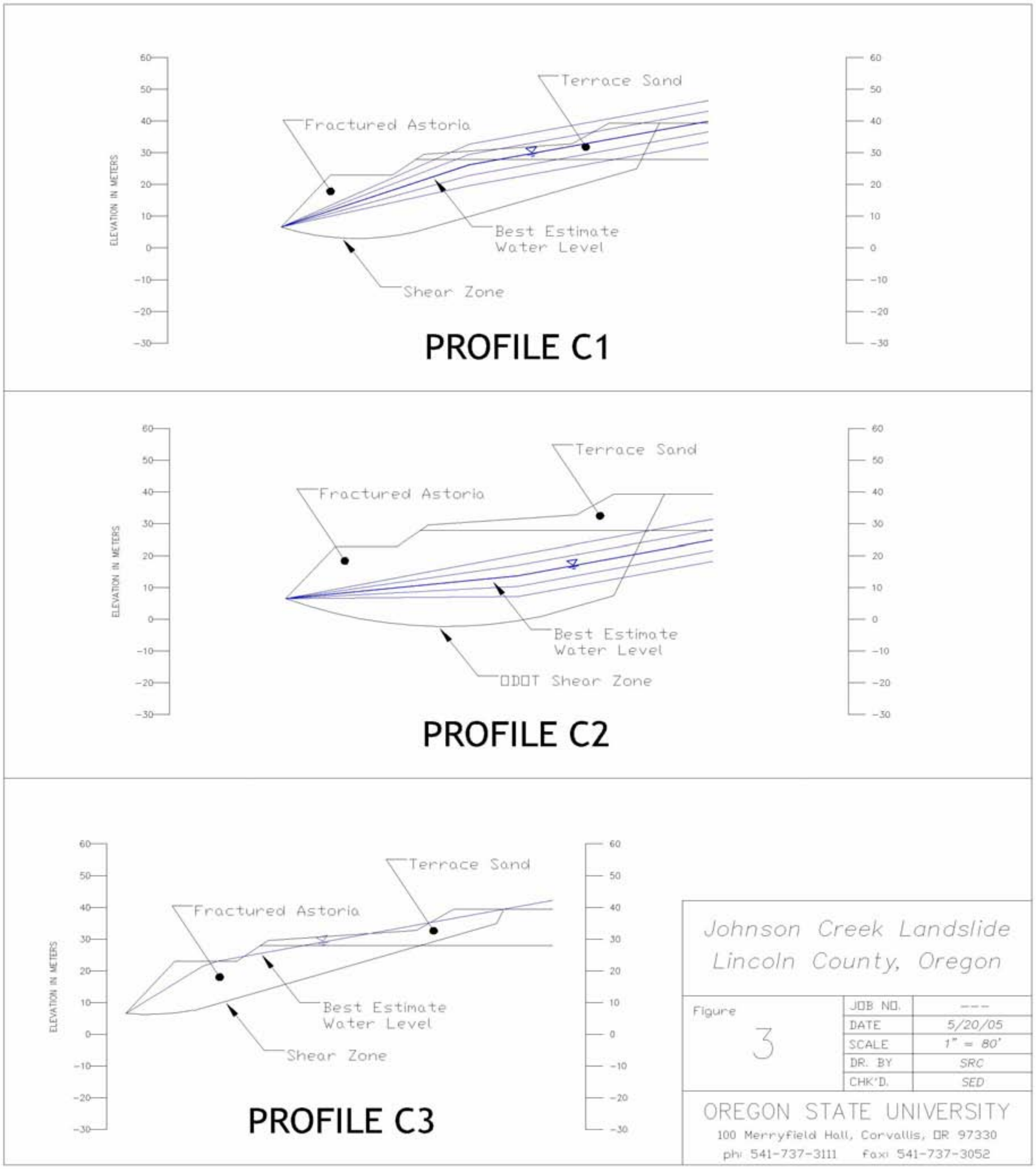

Figure 3. Cross Section C-C'.

Cross Section A-A'

Representing the centermost portion of the slide, cross section A-A' (**Figure 1**) was developed from the Landslide Technology (2004) exploration data. The configuration of the slide plane was established by Landslide Technology and adopted for this study after additional review of available instrumentation data.

Cross Section B-B'

Representing the northernmost portion of the slide, cross section B-B' (**Figure 1**) was developed to evaluate this area's overall stability and sensitivity to piezometric head increase. The slide geometry is oriented in the direction of the predominant movement of the slope. There is a small bend (approximately 20 degrees) in the section, which follows the movement vectors and the steepest slope gradient obtained from the topographical survey. Although the incorporation of the bend in section is not strictly correct for 2D limit equilibrium analyses, this is considered to impart only a very minor error in the computed margin of safety.

The shear zone associated with this slide plane was extrapolated from the data of Landslide Technology (2004) used in cross section A-A' and an ODOT exploration point (76-4) from a 1976 borehole that produced a boring log and an inclinometer data point. Naturally when data is extrapolated, as is the case here with shear zone and piezometric surfaces, there is some level of uncertainty as to the accuracy of the extrapolated data. However, based on the relative differences observed in the data both could vary by approximately +/-5 feet.

Cross Section C-C'

This cross section was developed to analyze the southernmost "block" of the slide and intersected a small toe failure. Three different shear zones were analyzed and are designated C1, C2, and C3; all have a common feature of a steeply dipping slide plane at the head scarp. Shear zone C1 was extrapolated using the exploration and inclinometer data from the Landslide Technology report, and is similar in shape to the shear zone used in cross section A-A'. Shear zone C2 was developed using nearby ODOT exploration and inclinometer data points 73-1 and 72-1; this failure surface is more deep seated than C1 and C3. Shear zone C3 represents a shallow failure that is nearly linear along the length of the block.

2.1.2 Slope Stability Software

This study focused on the application of limit equilibrium procedures for evaluating the stability of the Johnson Creek Landslide. Analyses were performed using the commercially available program XSTABL that is the same slope stability program employed by Landslide Technology (2004). XSTABL is a program that employs rigid body mechanics in the solution of circular and wedge slip surfaces. The program searches for the critical surface exhibiting the lowest margin of stability (expressed as the factor of safety against sliding). This approach does not account for the cumulative effect of multiple water-filled tension cracks or interaction between blocks within the overall slide mass.

Spencer's method (1967) was used to evaluate slope stability in our residual strength parameter and piezometric surface parametric study. Spencer's method, in short, is a force and moment equilibrium method that assumes the resultant slide force inclination is the same for every slice. A box search method was used for the stability analysis at the toe of the slope. This is a force and moment equilibrium approach that generates random points within the user specified search box. Details on the XSTABL program can be found at the following website: http://forest.moscowfsl.wsu.edu/4702/xstabl0.html.

2.2 Parametric Studies

In order to evaluate the influence of various parameters and slope configurations on the stability of the slide mass a series of sensitivity analyses were performed. The parameters that were evaluated included:

1. Drained strength parameters (φ' and c').
2. Location of the piezometric surface and pore pressures along the failure plane.
3. Influence of water-filled tension cracks on toe stability.
4. Influence of translating pore pressure waves on the stability of the slide.

These evaluations highlighted the relative contributions of the various parameters on overall stability. This work supplements the Landslide Technology's analyses by confirming their back-calculated residual strength parameters, providing analysis of additional cross sections, bounding the residual strength parameters, and evaluating slide toe stability.

2.2.1 ϕ' & c'

The purpose of the parametric study was to bound the "average" Mohr-Coulomb residual strength parameters associated with the shear zone. Analysis was performed using Spencer's method in the computer program XSTABL (Section 3.1.2). Residual strength parameters c' and ϕ' were back calculated for fixed factor of safety (FOS) value equal to 1 along the three cross sections (**Figures 2** and **3**) used in this study. Residual strength parameters were determined by performing the stability analysis for piezometric surfaces corresponding to the best estimate threshold level and variations of this level from +2 meters to -2 meters.

In order to obtain the representative strength parameters (c' and ϕ') for stability analyses the soils in the shear zone should be sampled and tested. While theoretically advantageous, the variability of the soils along the slide plane, combined with the difficulty and cost associated with obtaining samples, requires that the strength parameters be estimated from back-calculation using the best estimate configuration of the slide plane and 2D limit equilibrium methods. Since unique values of both c' and ϕ' cannot be determined for a given slide geometry, one approach is to select a value of one and solve for the other in an analysis of the slope stability for marginally stable equilibrium (FOS = 1.0). This method has been employed in this study. The combinations of c' and ϕ' that yield FOS = 1 are shown in **Figures 4** to **6**. It should be noted that the representative values of c' for residual strength along slide planes in materials commonly found in the Oregon Coast Range are very small (commonly less than 50 psf). If this value is assumed, as a maximum upper bound, then appropriate values of ϕ' are in the range of approximately 5.5° to 6.0°. The parametric analyses for c' values greater than 100 psf were only performed to establish the representative trends in c' and ϕ'.

The residual strength parameters determined in this study are consistent with those determined by Landslide Technology (2004) along cross section A-A'. The residual strength parameters provided in the Landslide Technology report of c'=0 and ϕ'=6.5° represent an average across the entire shear zone. For comparison, the case of c' = 0 in this study yielded ϕ' = 5.9° at the threshold piezometric surface. Thus, the average friction angle estimate from Landslide Technology and this study are for all intents and purposes equivalent. The small difference in the values is more than likely due to the slight geometric variations in the two respective slope stability models.

The residual strength parameters determined for the shear zone along cross section B-B' are very similar to cross section A-A'. The similarity is not surprising considering that the geometry of cross section B-B' is similar to cross section A-A' and that the shear zone was extrapolated from the Landslide Technology data located along section A-A'. For piezometric surfaces at -4m and +4m of the best estimate level, residual friction angles of 5.7° and 8.3° were calculated (**Figure 5**). The best estimate residual friction angle of 6.9° is consistent with the previous results associated with cross section A-A'.

The residual strength parameters are highly dependent on geometry of the slip surface used in the analysis. Shear zone C1 yields maximum residual friction angles of 14° to 23° (see **Figure 6**) for the extreme water levels of -4m and +4m, respectively. By examining the extrapolated head values used in the stability analysis (**Figure 3**), it is clear that the piezometric surface provides a significant pressure head increase and corresponding reduction in the effective normal stress with each step change in the piezometric surface. As a result, the residual friction angle must be increased to maintain the factor of safety of 1, thereby contributing to the variability of residual strength with these runs. Shear zone C2 was developed from ODOT data and has the deepest shear zone out of the three piezometric surfaces. This, however, tends to reduce the sensitivity of the back calculated strength parameters to increases in the piezometric head due to the large normal stresses over the shear zone. The maximum residual friction angles ranged from 9° to 11° for -4m and +4m fluctuations of the best-estimated piezometric surface, respectively. Shear zone C3 is the shallowest (with respect to the ground surface) of the three cases and subsequently has the largest residual friction angle out of the three cases. Additionally, the piezometric surface approximately follows the surface geometry; this further decreases the normal stress and requires a significant increase in the residual strength to maintain a factor of safety of 1. Generally speaking, the trends associated with the three shear zones are consistent with the model and analysis method.

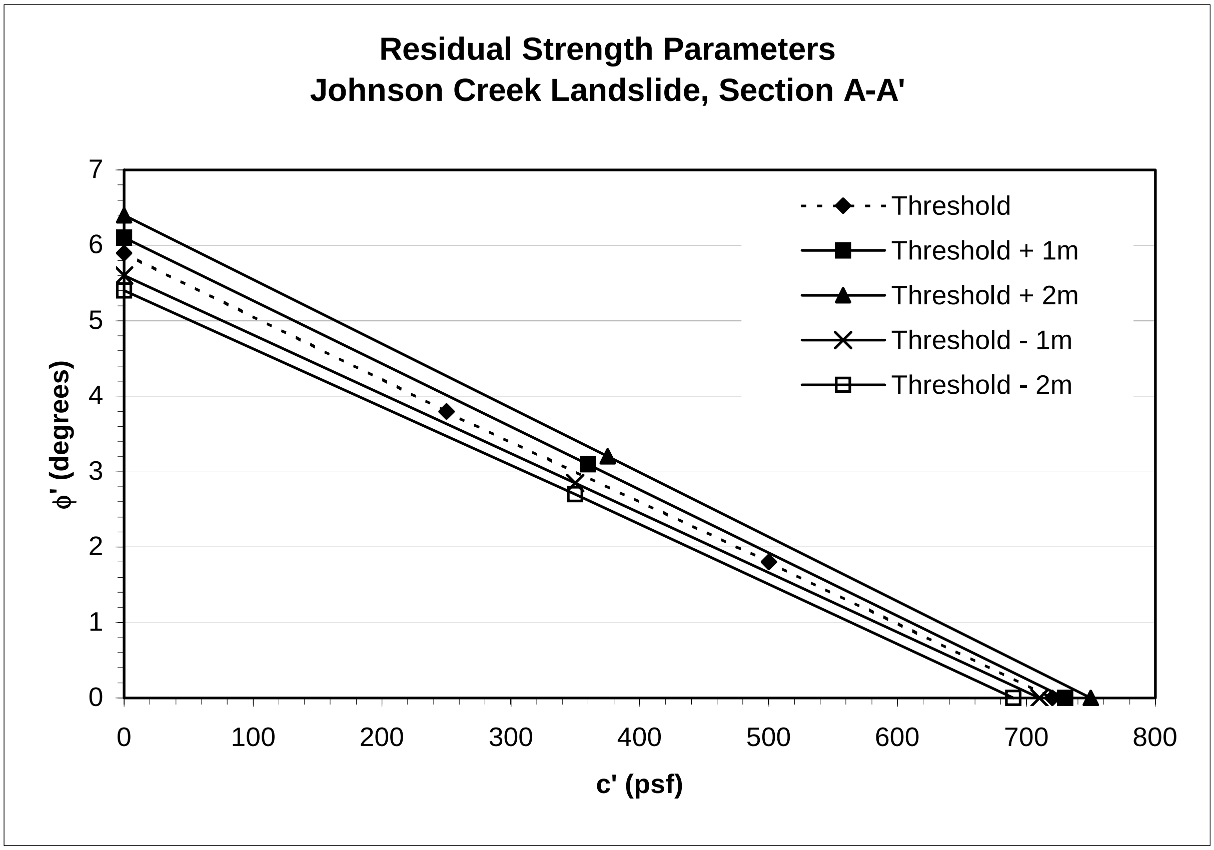

Figure 4. Cross Section A-A' Parametric Study

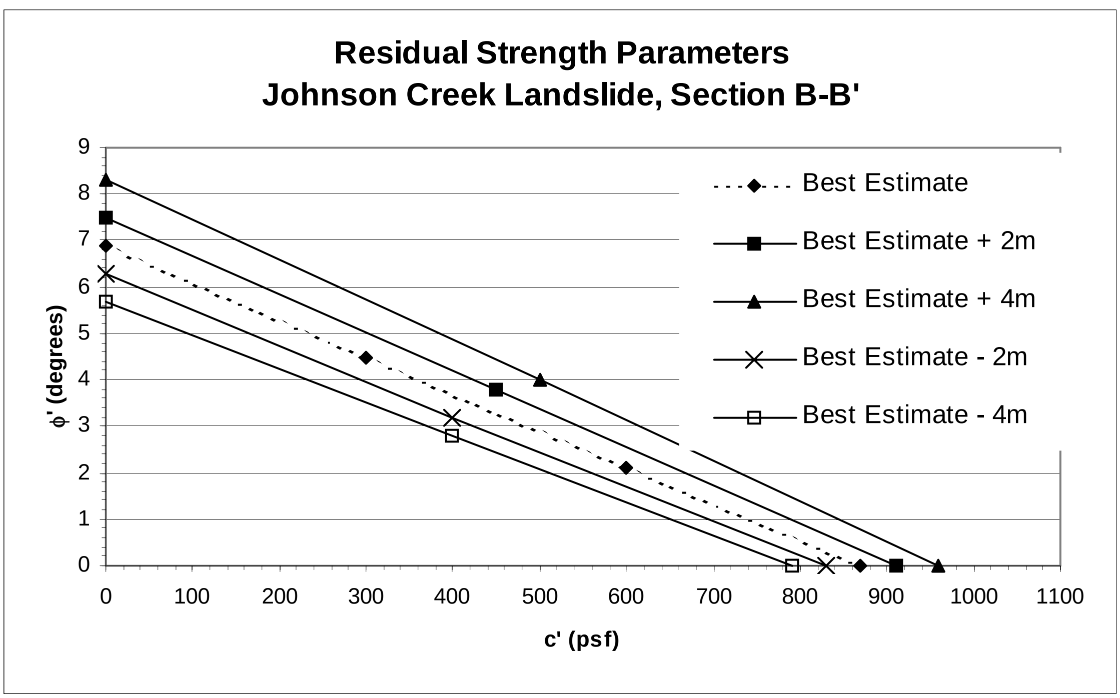

Figure 5 Cross Section B-B' Parametric Study

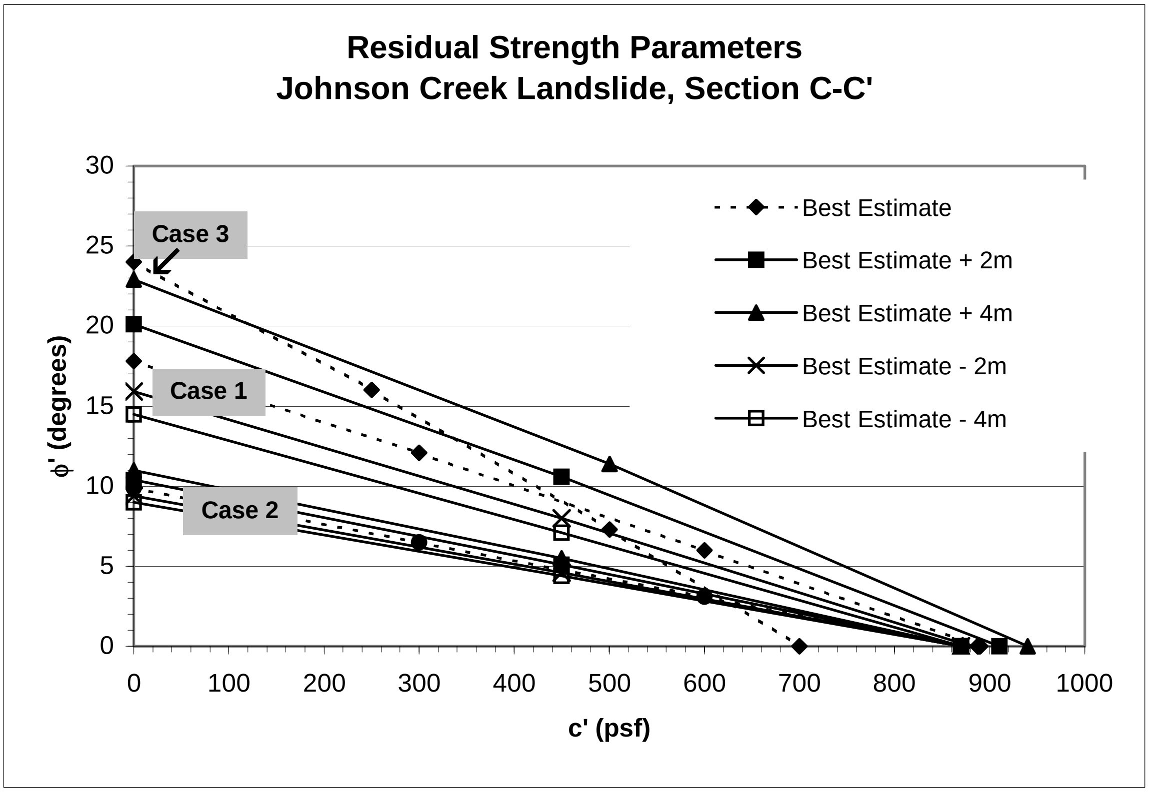

Figure 6. Cross Section C-C' Parametric Study

2.2.2 Piezometric Surface

The fractured and interbedded nature of the weathered sedimentary rocks at the site, combined with near-vertical tensional cracks and internal slide planes greatly complicates the groundwater regime in and adjacent to the slide mass. Optimally, an extensive vertical and lateral array of piezometers would be employed to obtain data that could be used to generate real-time, 3-D plots of the pressure heads within the slide mass and immediately beneath the slide plane. As it currently exists there are only three piezometers at the site. The relatively small number of instruments poses significant limitations in the groundwater characterization required for slope stability analyses. The three existing instruments are recording pore pressures above the slide plane. As a result, the pore pressures used in the slope stability calculations may not be truly representative of the conditions across the shear zone. This is particularly important when considering the response of the piezometric surface during storm events may not be representative of what is occurring at the depth of interest.

The piezometric surfaces vary greatly across the shear zone and little data beneath the slip plane exists. It appears that above the slide plane the pore pressures are controlled by infiltration of water through cracks and fissures from above, while below the slide plane the pore pressure is governed by seepage from deeper geologic units. The occurrence of the pore pressure peaks is not coincident. In fact, the peak pore pressures beneath the slide plane may lag rainfall peaks by weeks or months.

Unfortunately, piezometric data does not exist through cross sections B-B' and C-C'. By necessity we estimated the location of the piezometric surfaces at these two locations. To address the considerable uncertainty associated with the piezometric surface estimates, we performed a sensitivity study to evaluate the influence of the piezometric surface elevation on the stability of the slide mass. The piezometric surface was varied form the best estimate value by +- 4m. As previously discussed in 2.2.1, the influence on stability of the piezometric surface was most pronounced at Section C-C' and less pronounced at Section B-B' due to the respective geometries of these sections.

2.2.3 Toe Failure & Tension Cracks

To evaluate the influence of tension cracks in the slide mass slope stability analyses were performed at the toe of cross-sections A-A' and B-B' for varying tension crack depths completely filled with water. The search routine employed in the limit equilibrium model locates all critical surfaces through the tension crack therefore the interaction effects of multiple tension cracks could not be determined from this analysis. However, this analysis did examine the influence of slope stability versus the depth of the tension crack filled with water provided some insight to the threshold tension crack depth.

The results of our analyses indicate there is a bilinear relationship in the percent change FOS for tension crack depths up to 10 feet in cross section A-A' and 15 feet in cross section B-B' (**Figure 7**). Past these respective "threshold" tension crack depths there is an increase in the slope of this curve indicating a relatively rapid loss in stability.

The significance of these results is that the depth of tension crack filled with water at the toe of the slide may be influencing the stability of the larger slide mass. An additional analysis was performed with the critical toe section removed from the previously stated analysis performed on cross section A-A' with best estimate threshold water levels. The factor of safety prior to removing the failed toe section was 1.0. After removing the critical toe section, a stability analysis was performed and the factor of safety against sliding dropped to 0.87. This represents a 13 percent decrease in the factor of safety and implies the performance of the toe has a significant influence on the stability of the slide mass.

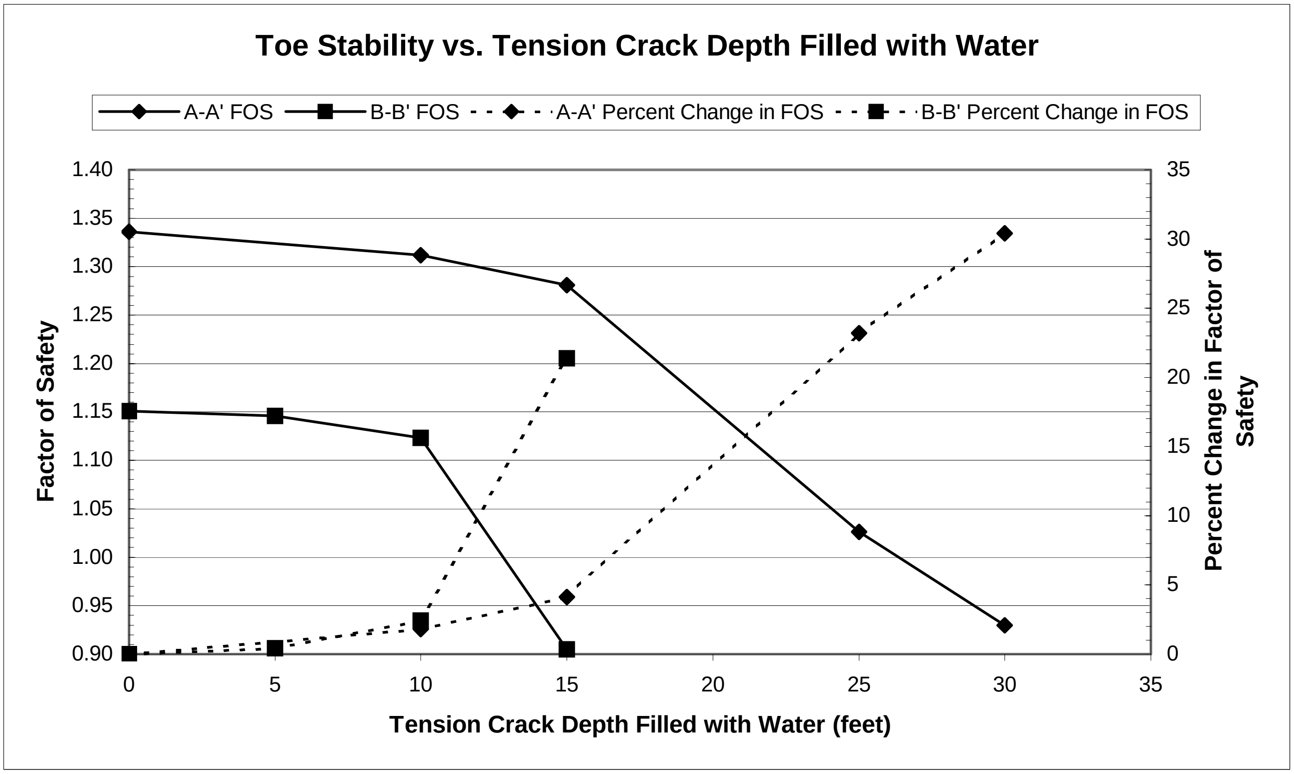

Figure 7. Analysis of Toe Stability with Varying Tension Crack Depth Filled with Water

2.2.4 Pressure Wave Analysis

In depth evaluation of the piezometer data demonstrates that the pore pressures rise first at the top of the slope and progressively increase with distance down slope (see the main body of this open-file report). The rise and fall of pore pressure adjacent to the shear zone moves down slope in the form of a long-period wave. This pulse, or pressure wave, influences the stability of the slide mass by reducing the effective normal stress and shear strength of the section of the slide where this pulse is present.

Based on the analysis of progressive piezometric head increase, a suite of slope stability analyses were performed on cross section A-A' with step increases in the piezometric surface (**Figure 8**). The base model for this analysis was developed from the information provided in **Table 1** for the fast movement case. The initial head values for the analysis were taken from the initial values provided in **Table 1**. All head values used were referenced to the failure plane to ensure consistency throughout the analysis. To model the pressure wave, the piezometric head was increased from normal to "fast movement levels" in increments approximately equal to 1/5 of the total shear zone length. The increases were cumulative and by the end of the analysis the results matched the factor of safety estimates from Landslide Technology (2004) for the extreme storm case. The results of the slope stability analyses are shown in **Figure 9**.

The overall percent change in slope stability from normal winter values to severe storm values is 9 percent, this compares very well to the Landslide Technology estimate of 9.2 percent. The analysis shows that 50 percent of the 9 percent change in factor of safety occurs over the eastern (upslope) 25 percent of the slide plane. As shown in the **Figure 9**, there is a non-linear decrease in factor of safety that transitions to a relatively linear change over the remaining 75 percent of the slide plane. The non-linear decrease in factor of safety is not thought to be a physical phenomenon but rather a manifestation of the computer program's analysis technique with high water pressure levels and low normal stresses. Examining the trend of factor of safety versus incremental pressure increase suggests a linear relationship could be extrapolated back through the point associated with LT-3P to a FOS value equal to 1.0.

Given the relatively high change in factor of safety associated with the head increase associated with the sever storm level, investigating options to maintain the head levels at their normal winter levels appears to be warranted. Although the FOS increase with horizontal drains is 1 percent (Landslide Technology, 2004), this dewatering scheme proposes lowering the normal winter water table by approximately 3 feet. From a limit equilibrium stand point lowering the water table does not improve the FOS significantly, however, if severe water levels could be mitigated or water level could be maintained at "normal" winter levels this option would, in effect, provide an increase in FOS of the 9 percent; the difference associated between normal winter levels and the severe storm levels.

Table 1. Threshold values of initial pressure head, pressure head at movement, and depth to elevation head (water table) for slow and fast slide movement. Pressure head is in meters above the slide plane (taken from the main body of this open-file report).

Drill	Initial Head (m) .	Initial Head (m) .	Pressure Head (m)	Pressure Head (m)	Depth to Elevation Head (m)	Depth to Elevation Head (m)
Site	Slow Mvmt	Fast Mvmt	Slow Movement	Fast Movement	Slow Movement	Fast Movement
LT-1	6.5	6.9	7	~9.0-9.7	19.3	~16.6-17.3
LT-2	9.2	9.4	9.4	~12	8.6	~6
LT-3	4.5	4.6	~5.0	~6.5	~1.6	~0.1

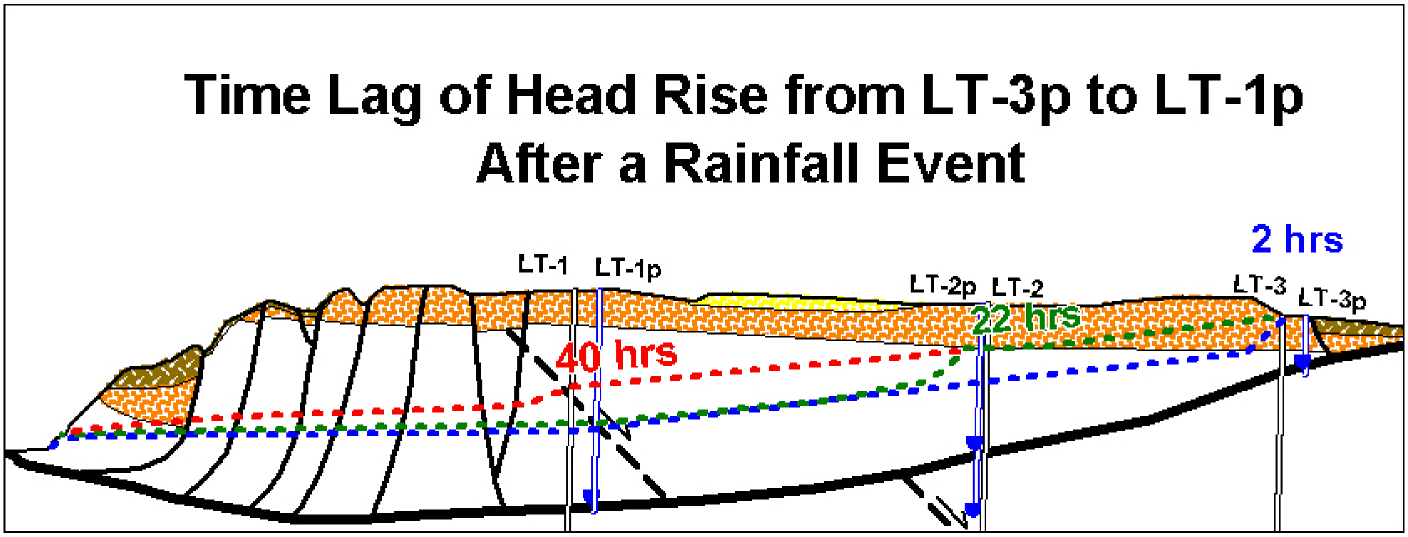

Figure 8. Schematic illustration of progressive rise in piezometric head from east-to-west after a typical rainfall event (Priest and others, 2006).

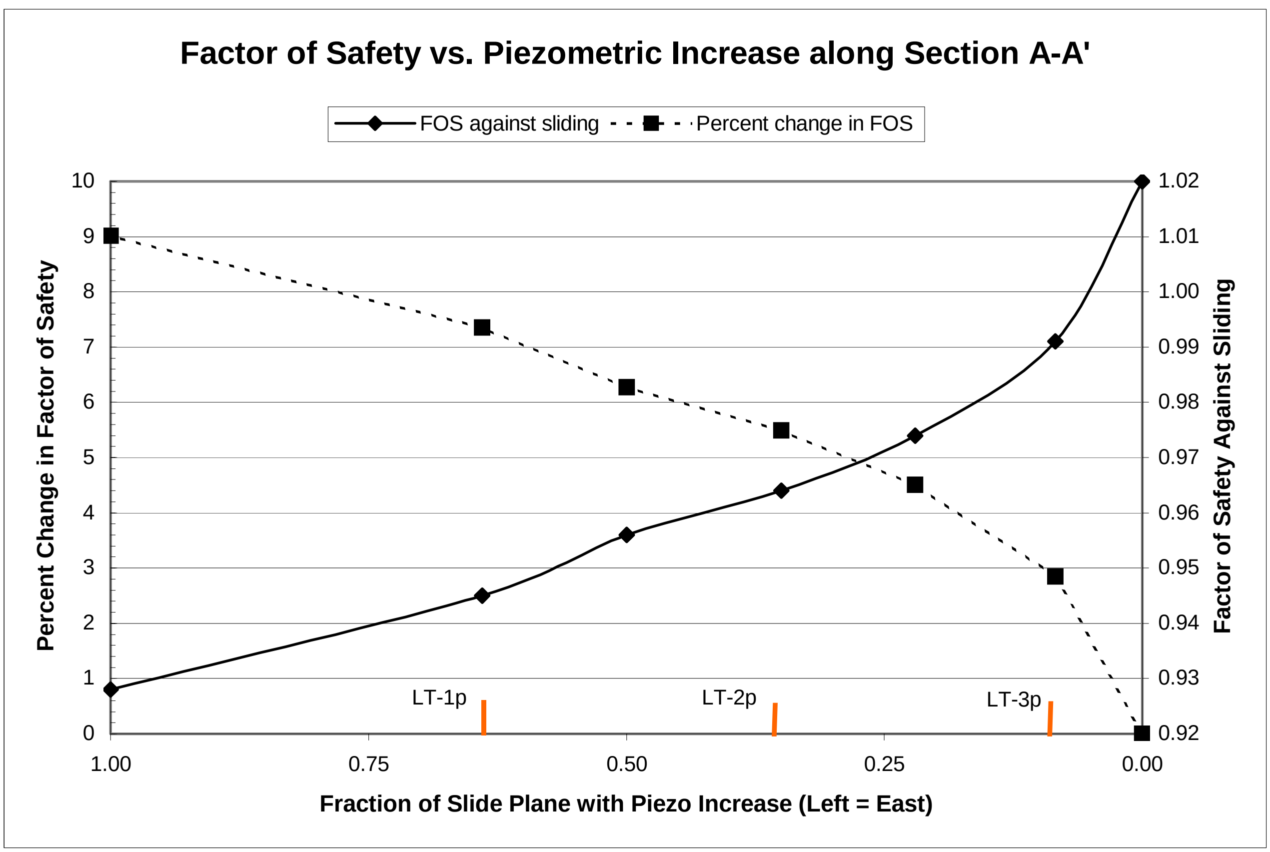

Figure 9. Factor of Safety versus Piezometric Increase along Shear Zone A-A'. (Note that left is actually west in this diagram).

3.0 CONCLUSIONS

On the basis of independent slope stability and parametric analyses the average residual strength parameters provided in the 2004 Landslide Technology report are reasonable for the Johnson Creek Landslide. Furthermore, analysis of a severe storm event yielded the same factor of safety percentage decrease as Landslide Technology's. The residual strength parameter variation for c' = 0 gives ϕ' values do not appear to be extremely sensitive to changes in the piezometric surface. Thus, potential errors in the analytical results based on the range of likely strength parameters are probably small. The sensitivity of the overall decrease in factor of safety associated with an increasing piezometric surface, however, was found to be significant. This observation is consistent with the Landslide Technology's slope stability analysis report and the correlation of movement events with piezometric spikes outlined in the main body of this open-file report.

Tension cracks appear to affect the stability of the toe when cracks are within the 10-foot to 15-foot range and are completely filled with water. Slope stability analysis shows that there is a 13 percent decrease in factor of safety associated with the removal of the critical toe surface obtained in the tension crack portion of the analysis. Based on the contribution that the toe has on the global stability, the use of a buttress system as recommended in the Landslide Technology report and the in the main body of this open-file report certainly warrants serious consideration.

Given the relative importance of the piezometric surface and toe stability on the overall stability of the slide mass, addressing both of these issues will be critical to successful remediation. Rather than focusing on the modest improvement (1% per Landslide Technology, 2004) lowering the piezometric surface provides, one approach should consider maintaining the "normal winter" levels which ultimately provides a net factor of safety increase of approximately 9 percent over the piezometric surface representing a significant rainfall event. Toe stability, too, should be addressed since there is a significant decrease in the factor of safety associated with the failure/erosion of the toe section. Even if dewatering measures were successfully implemented, the slope would likely become unstable and move regardless of the piezometric water levels.

Although these analysis were performed using standard of practice limit equilibrium methods, there are significant shortcomings associated with these models. For instance, in the case of this landslide there are many factors that influence the stability of the mass concurrently. These variables include the kinematics influence of individual blocks, time dependent increase in the piezometric surface, seepage effects, multiple tension cracks, and the accumulative effects associated with all of these occurring with in a given time frame. In addition to modeling limitations, there is a very limited base of geotechnical data for this landslide. Despite the shortcomings of the limit equilibrium analysis methods, they provide a powerful tool in illustrating the relative influence that hydrologic and geotechnical parameters have on the stability of the slide. In our opinion, these methods are appropriate given the limited data available, and they provide insight into the problem and facilitate the evaluation of potential remediation strategies.

4.0 RECOMMENDATIONS FOR FUTURE WORK

4.1 Field Investigation and Monitoring

In our opinion, there exists the need for additional fieldwork and in situ exploration if the mechanics and causative factors of the slide are to be more completely understood. Given the area of the slide mass, the variable subsurface conditions (e.g. fracturing, soil strengths, stress state, etc.), the complexity of the slide movement, and complex piezometric conditions, there is a need to further investigate these unknowns since they are ultimately influencing the behavior of the slide. Clearly the resources available to this project will dictate the degree to which the various hydrologic and geotechnical controls are characterized. A prioritization strategy is needed.

It appears that a research and monitoring emphasis on the groundwater regime would yield tremendous insights on the initiation and rate of slope movement. A program of extensive instrumentation is highly recommended. As an example, one approach to addressing these unknowns would be to install approximately 10 piezometers and inclinometer tubes throughout the slide. Cross sections B-B' and C-C' would be ideal candidates for 4 piezometer and inclinometer sets. The two remaining piezometer and inclinometer sets would then be placed along cross section A-A', particularly near the toe where conditions are not well defined to this point in the investigation. Optimally, the piezometers should be placed immediately above and below the shear zone. The assertion that this material may be imposing a confined aquifer type of condition would be of great importance in evaluating the net pressure effect on the slide plane after a storm event.

The long-term survival of the piezometers is a key consideration. This is especially true for instrumentation located below the shear zone. It is recommended that a system of wireless piezometers be used below the slide plane. A wireless system could be used to transmit data across the slide plane even after the slope has moved enough to damage the borehole casing (i.e., slope inclinometer tubing). Data would be transmitted from the piezometer located beneath the slide plane to a receiver suspended in the borehole immediately above the shear zone. Wireless systems such as this have been developed for use in physical model testing using the geotechnical centrifuge. They have been show to be rugged and reliable for these applications. The Geotechnical Engineering Group at Oregon State University is pursuing field applications for this technology and it appears that the Johnson Creek landslide could be a test bed for evaluating the applicability of this wireless instrumentation.

4.2 Laboratory Investigations

The benefits of additional laboratory testing are judged to be minimal. The heterogeneity of the slide mass materials (lithology, weathering, and pattern of discontinuities) precludes extensive characterization by laboratory tests alone. It appears that a more significant contribution would be made by focusing on drilling and field logging of the materials in order to characterize the locations of the shear zone and piezometric surface, as well as the nature of the soil and rock adjacent to the slide plane. These efforts would be pursued during the placement of the in situ instrumentation.

One aspect of laboratory testing that may be worthwhile would be additional characterization of the porosity and permeability of intact specimens of the weathered rock located near the slide plane. These data would be useful in subsequent hydrologic modeling; however, these properties would have to be modified to account for the rock mass characteristics (i.e. discontinuities, variability in the degree of weathering, etc).

4.3 Modeling

The use of more sophisticated models at this point in the study would not likely provide a better understanding of the behavior of this slide. A 3-D FEM/FDM model could be created based on the surface surveys and subsurface conditions as they are currently understood; however, uncertainties associated with the morphology of the slip surface, the hydrologic regime, geologic structure within the slide mass, and the kinematics of the various blocks within the overall slide mass would significantly limit confidence in the modeling results. If more advanced modeling is pursued, it is recommended that simple models be prepared and validated prior to applications involving all of the relevant parameters that can be reasonably modeled. The application of simple models, along with appropriate simplifications using informed judgment, may yield insights on the kinematic aspects of the slide that are not well defined using the 2-D limit equilibrium models. The ultimate goal of performing coupled hydrologic-geotechnical stability modeling is considered extremely worthwhile.

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