PRELIMINARY GEOTECHNICAL-ENGINEERING SLOPE-STABILITY INVESTIGATION OF THE PINE RIDGE LANDSLIDE, TIMBER LAKES ESTATES, WASATCH COUNTY, UTAH

by

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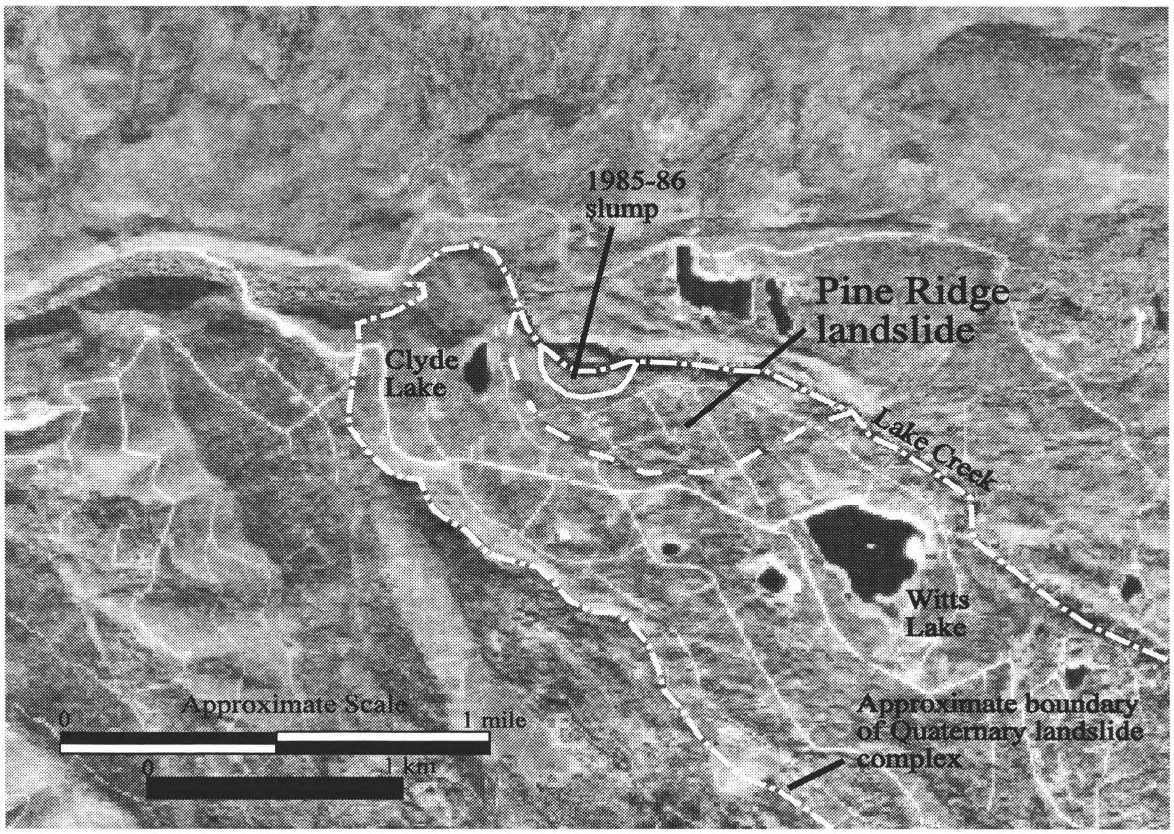

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FORWARD

The purpose of a preliminary geotechnical-engineering slope-stability analysis is to use state-of-the-art computer programs to estimate slope stability in areas where we have few detailed engineering test data. The technique uses engineering-geologic judgement, rather than expensive and difficult-to-obtain test data, to constrain and make a "best" estimate of site conditions for input into the analysis. We apply this technique to the Pine Ridge landslide because lots were already platted and many sold and developed prior to identification of the landslide, and no single subdivider remains with the responsibility to perform the needed detailed geotechnical-engineering slope-stability analysis. Individual lot-by-lot studies cannot address the stability of this large, multi-lot landslide, but a better understanding of the relative hazard is necessary for Wasatch County and Timber Lakes land owners to make prudent land-use decisions.

We have used our "best" engineering-geologic judgement to estimate site conditions, and have not assumed "worst-case" conditions as is typically done when few data are available. As such, this analysis is meant to be reasonable but not overly conservative. In particular, our analysis of residual-strength conditions assumes that ground water or the piezometric surface was at or near the ground surface when slumping initiated in 1985-86. If ground-water levels were actually lower, then the actual residual strengths could be lower than those estimated and presented in the report. Similarly, we define a boundary delineating where a more detailed study is needed based on our "best" estimates of soil and ground-water conditions. We include a zone of uncertainty along this boundary to indicate the possible range in conditions.

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ABSTRACT

The Pine Ridge landslide is a late Holocene slide in Timber Lakes Estates, Wasatch County, Utah. Approximately 114 lots, some currently with homes, are on or immediately abut the slide. Partial reactivation of the slide in the form of deep-seated slumping took place sometime in 1985-86 following an unusually wet period. Geomorphic evidence suggests recurrent late Holocene movement in the 1985-86 slump area that has likely caused a reduction of shear strengths to residual values adjacent to slip surfaces in the slump. Our analyses indicate that average residual shear strengths (Ø'r) of the glacial till in the slump range between 21 and 27 degrees and are consistent with residual strength values of similar soils reported in the literature. Lower strengths are possible, however, particularly in the lower slump block. Slumping likely triggers at high ground-water levels in which the phreatic or piezometric surface is less than 10 to 20 feet (3-6 m) below the ground surface in the upper part of the slump. At slightly lower ground-water levels, the slump is likely metastable.

The northern toe area of the Pine Ridge landslide is being modified by active debris sliding. Debris sliding results in short-term southward migration of the steep slope along Lake Creek and may threaten existing homes constructed too close to the crest of the slope because sliding does not necessarily result in a long-term stable slope configuration.

We believe the northern part of the slide, outside of the 1985-86 slump area, is also susceptible to partial reactivation by deep-seated slumping. Shear strengths in this area likely range between residual and peak values. Even if peak shear strengths prevail in the northern part of the slide, our results suggest the till is susceptible to deep-seated slumping at high ground-water levels. We believe the likelihood of future movement of the entire slide is low; however, this does not preclude the possibility of movement if the area experiences earthquake ground shaking or if a deep weak layer is present. Our analyses suggest that earthquake-induced sliding may be triggered under a combination of conditions that include high ground-water levels, shear strengths below peak values, and horizontal ground accelerations above a critical threshold level.

INTRODUCTION

The Pine Ridge landslide is the largest of several deep-seated late Holocene landslides in Timber Lakes Estates (figure 1). In either the winter or early spring 1985-86, a part of this slide reactivated as a deep-seated slump. The slump is about 11 acres (4.4 ha) in area and caused damage to a mobile home/cabin. Approximately 114 lots, some currently with homes, are on or immediately abut the Pine Ridge landslide. Presently, individual septic-tank soil-absorption (STSA) systems are used for sewage treatment and add water to the slide mass. Although home construction continues, no assessment of the cumulative affect of development, particularly STSA systems, on the overall stability of the slide has been performed. Such information is important to prudent development in the slide area.

4.9cm map = 5km ground

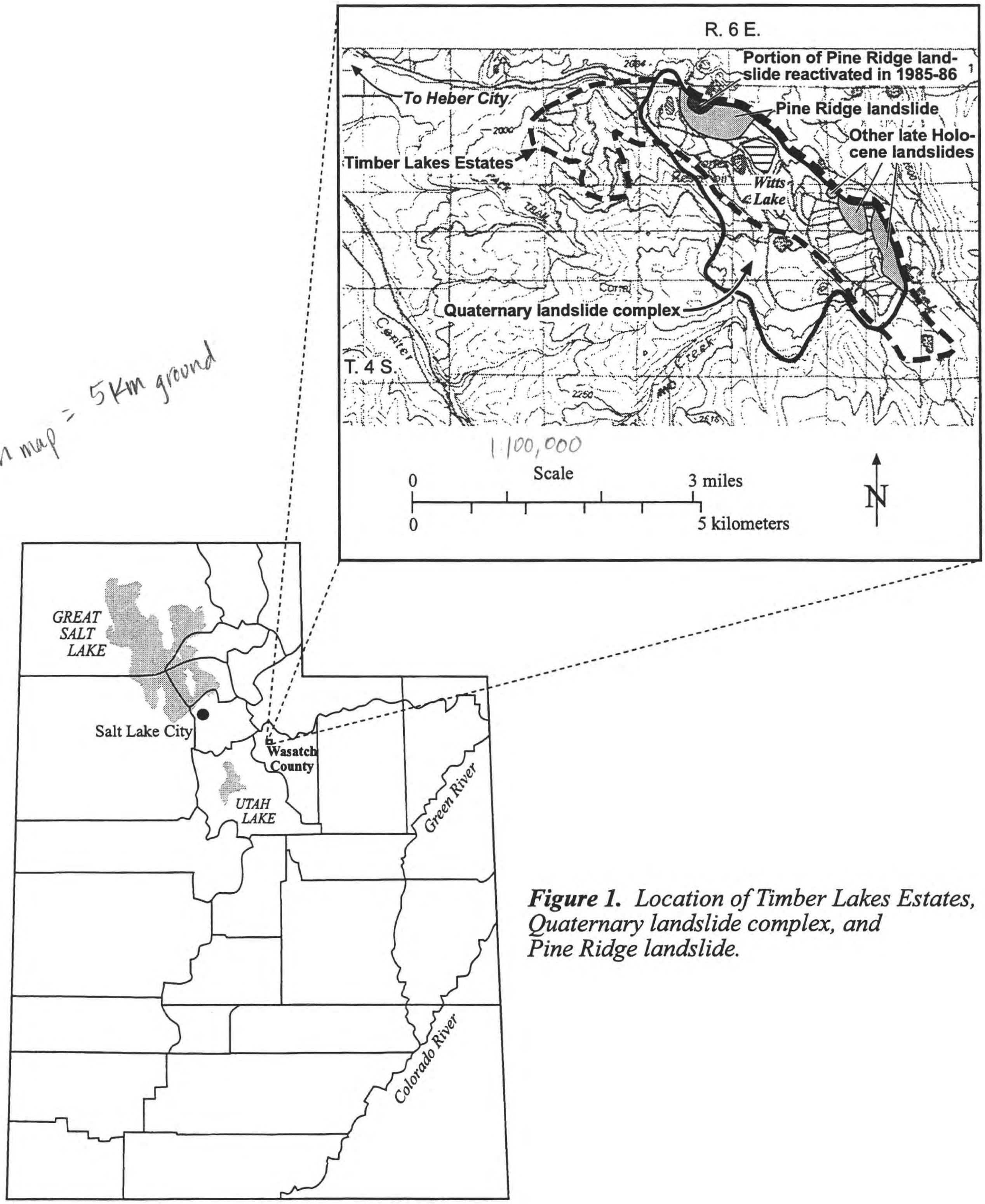


Figure 1. *Location of Timber Lakes Estates, Quaternary landslide complex, and Pine Ridge landslide.*

Previous lot-specific studies by consulting geologists and engineers have revealed little concerning the overall stability of the Pine Ridge landslide or the conditions leading to its partial reactivation in 1985-86. Despite extensive home construction in Timber Lakes Estates, geotechnical information useful in understanding the landslide's stability is lacking.

As part of this study, we obtained limited soil information from field observations and results of laboratory tests on soil samples we obtained from shallow foundation excavations and test pits used for percolation tests. We also constructed three topographic profiles using a clinometer and fiberglass tape to define the general slide geometry. With this information, we performed preliminary geotechnical-engineering limit-equilibrium slope-stability analyses (Hylland, 1996) of the slide using PCSTABL5M (Federal Highway Administration, 1988) and XSTABL5 (Sharma, 1996) programs. We consider this investigation to be only preliminary in nature because of the absence of information on soil shear strength and depth to ground water and rock.

In the sections that follow, we describe the physiographic and geologic setting and physical characteristics of the Pine Ridge landslide, discuss probable conditions leading to its partial reactivation in 1985-86, analyze its static stability, and consider the implications of our results to understanding the overall stability of the slide.

SETTING, GEOLOGY, AND DESCRIPTION OF THE LANDSLIDE

Setting

Timber Lakes Estates is in the Lake Creek drainage about seven miles (11 km) east of Heber City in Wasatch County, Utah (figure 1). The Pine Ridge landslide is in the north-central part of the subdivision and north-northwest of Witts Lake (figures 1 and 2). The slide formed on a north-northeast-facing slope in the Lake Creek drainage and is crossed by two minor north-northwest-flowing drainages in its eastern half (figure 2). These drainages presently flow from Jones Reservoir and Witts Lake.

Geology

The landslide is underlain by Pinedale-age glacial moraine deposits (Baker, 1976; Bryant, 1992) and sits in a deep-seated, Quaternary landslide complex (figures 1 and 2) within these deposits. Landsliding within the complex possibly involves the underlying Tertiary Keetley Volcanics (Hylland and Lowe, 1995); however, the depth to the top of the volcanics is unknown. Southward-tilted Jurassic sedimentary rocks including the Nugget Sandstone and Twin Creek Limestone, underlie the volcanic rocks. The maximum age of the Pine Ridge landslide is interpreted to be late Holocene (Hylland and Lowe, 1995), but part of the slide reactivated as a deep-seated slump in 1985-86.

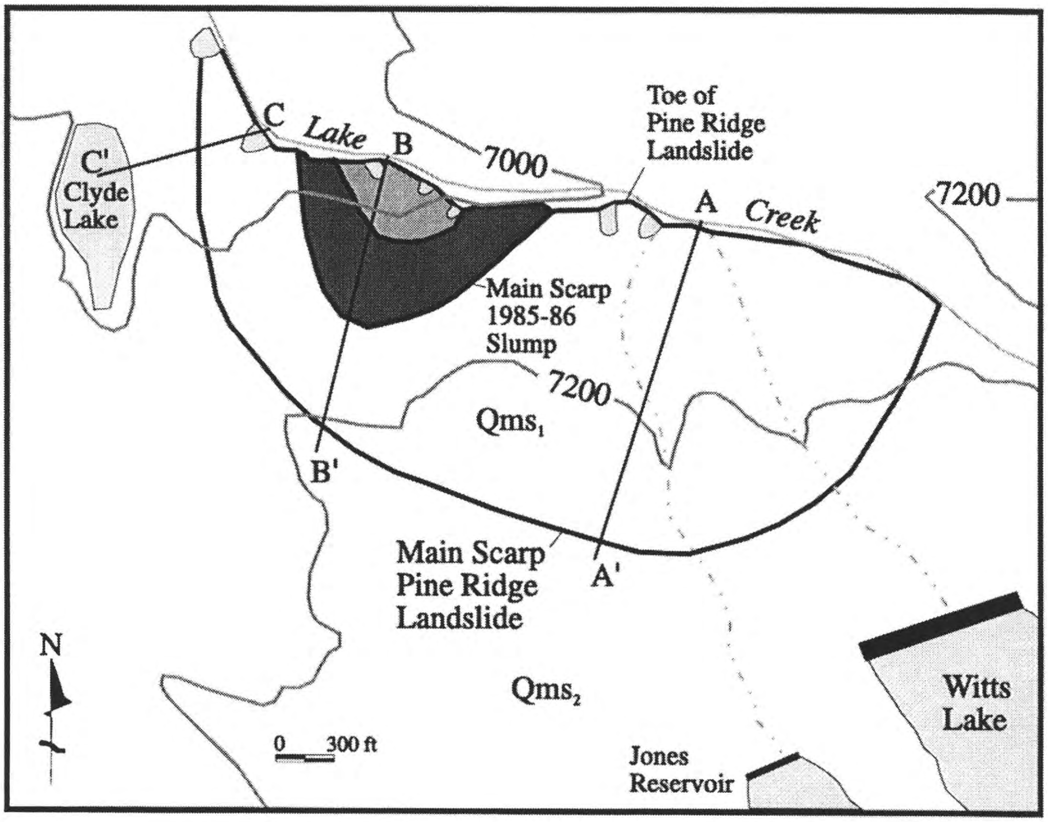


Figure 2. *Map of Pine Ridge landslide and surrounding area showing locations of profiles A-A', B-B', and C-C'. Lower slump block (medium shaded area) and main body (darker shaded area) of 1985-86 slump also shown. Drainages discharging from Jones Reservoir and Witts Lake cross the eastern part of the slide. Debris slides (lightly shaded areas) along Lake Creek are as mapped by UGS geologist Mike Lowe (unpublished mapping).* Qms_1 *= late Holocene landslide deposits;* Qms_2 *= late Pleistocene-Holocene(?) landslide and undifferentiated deposits. Elevations in feet above mean sea level.*

Our understanding of the subsurface geology of the Pine Ridge landslide is limited by the lack of borehole data in the area. Our field reconnaissance of natural exposures and shallow excavations suggests that the majority of the slide mass is glacial till that is relatively homogeneous at the scale of the landslide. Soil classifications of the glacial till samples collected in Timber Lakes Estates range from clayey or silty gravels with sand (GC or GM) to clayey or silty sands with gravel (SC or SM), and, on average, are clayey gravels with sand (GC) (table 1). These soils contain between 10 and 30 percent cobbles and boulders that are primarily

Table 1.
Classification and gradation of glacial till at Timber Lakes Estates.

Sample No.	Unified Soil Classification	% Gravel	% Sand	% Fines
PRL1	SM[1] - silty sand with gravel	38.6	44	17.4
425FS[2]	GM[3] - silty gravel with sand	42.5	38.3	19.2
425FD	GC - clayey gravel with sand	56.7	26.3	17
425BS	SM[3] - silty sand with gravel	18.8	49.6	41.6
425BD	GC - clayey gravel with sand	50.1	31.2	18.7
Average	GC - clayey gravel with sand	41.3	37.9	22.8

[1] No Atterberg limits performed on fines.
[2] Gradation results and soil classifications for 425-series samples from RB&G Engineering, Inc., Provo, Utah.
[3] Atterberg limits plot above A-line indicating GC and SC classification may be appropriate.

andesite and sandstone and are likely derived from the Keetley Volcanics and Nugget Sandstone, respectively. The glacial till is likely cohesionless based on its granular texture and lack of cementation. Engineering properties of the glacial till are presented in tables 2 and 3. The main slip surface of the slump may involve the underlying Keetley Volcanics; however, the depth to and characteristics of the glacial till/volcanics contact are unknown.

Description

The main body of the landslide is generally bowl-shaped in plan view as viewed toward the north-northeast (figure 2). In maximum dimension, the slide is about 4,000 feet (1,220 m) wide and 1,800 feet (550 m) long from toe to main scarp, and covers an area about 600,000 square yards (500,000 m^2) or 124 acres (50 ha). The depth to the main slip surface is unknown, thus volume estimates for the slide are not possible.

Table 2.
Summary of engineering properties of glacial till in Pine Ridge landslide.

Sample No.	Moisture Content (%)	Dry Density (pcf)	In situ Density (pcf)	Saturated Density (pcf)	Void Ratio e	Porosity n (%)
PRL1	11.9	--	--	--	--	--
PRL2	15.6	--	--	--	--	--
PRL3	16	--	--	--	--	--
PRL4	4.4[1]	116	121.2	135.4	0.45	31
PRL5	5.3[1]	114.7	120.8	134.7	0.47	32
PRL6	2.5[1]	118.2	121.2	136.9	0.43	30
Average	14.5[2]	116	121	136	0.45	31

[1] Samples collected from dry subaerial exposures.
[2] Excludes samples from subaerial exposures.

Table 3.
Summary of glacial till densities in Pine Ridge landslide.

Percent boulders and cobbles	Dry density[1] (pcf)	In situ density[1] (pcf)	Saturated density[1] (pcf)
None	116	121	136
10	119	124	137
15	121	125	138
20	122	126	138
25	124	127	139
30	125	129	139

[1] Calculated densities based on andesite:sandstone ratio of 3:1. Measured average andesite density = 147 pcf; measured average sandstone density = 146 pcf.

The landslide has a somewhat subdued main scarp (figures 2 and 3) that is, however, easily discernable on aerial photographs along most of its trace. In the eastern part of the slide (profile A-A'), the main scarp is about 25 feet (7.6 m) high and slopes to the northeast about 22 degrees. In the central part of the slide (profile B-B'), the main scarp is 45 feet (13.7 m) high and

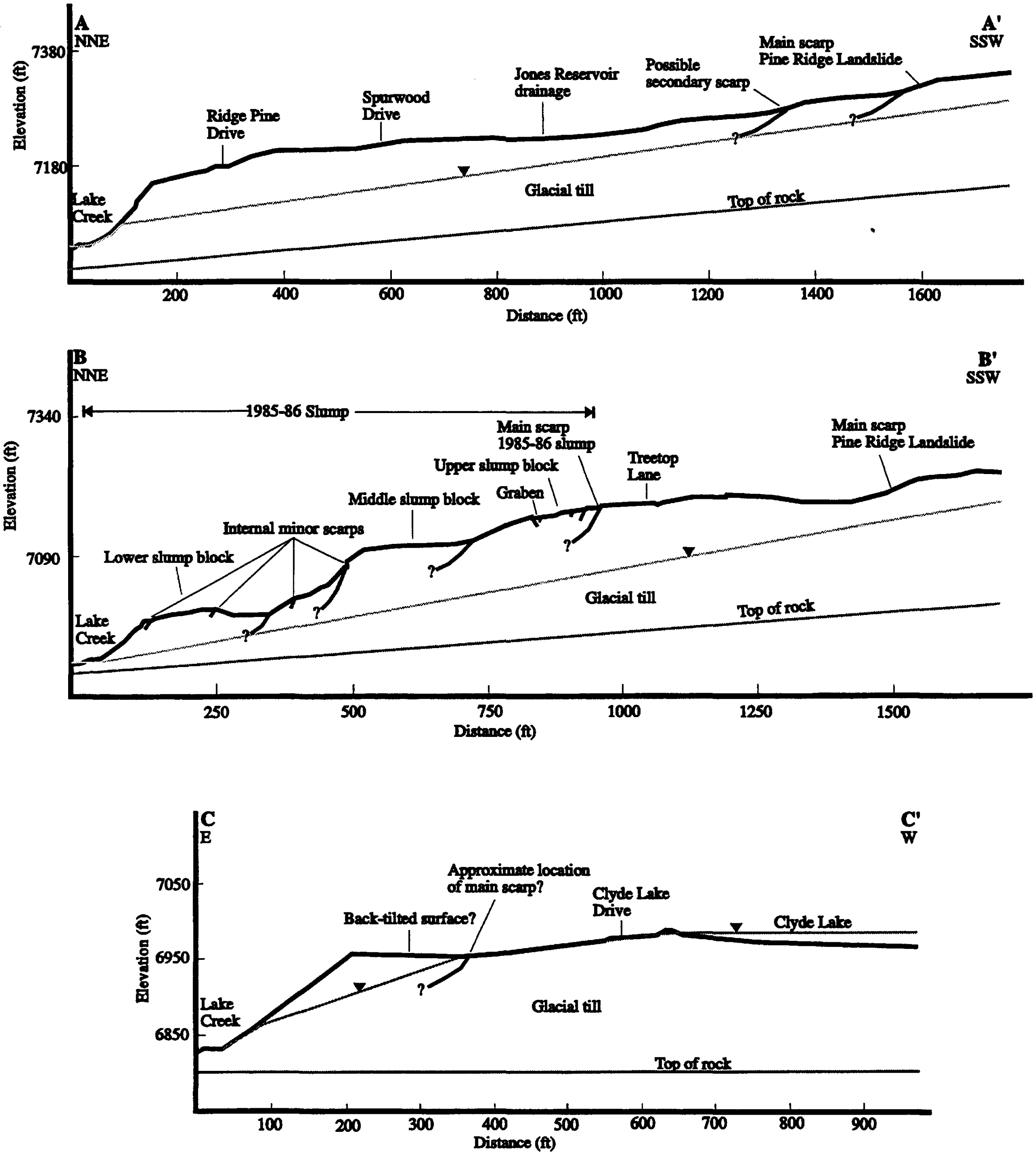


Figure 3. Profiles across the Pine Ridge landslide. Profile A-A' (top) is in the eastern part of slide and crosses the Jones Reservoir drainage. Profile B-B' (middle) is in the central part of slide and crosses 1985-86 slump. Profile C-C' (bottom) is in the northwestern part of slide and ends in Clyde Lake. Locations of profile lines are shown on figure 2. Depth to top of rock is shown as estimated for slope-stability analyses. Profiles A-A' and B-B' show estimated ground-water levels at the time the profiles were measured (summer to fall). Profile C-C' shows estimated ground-water levels when Clyde Lake is at high-water level.

slopes to the northeast about 24 degrees. In the northwestern corner of the slide (profile C-C'), the scarp is not easily located. However, we estimate the slip surface intersects the ground surface about 120 feet (37 m) west of the crown of the active debris slide area in the steep slope abutting Lake Creek. Near the crown, the ground surface dips about 5 degrees west and away from Lake Creek over a distance of about 60 feet (18.3 m). About 140 feet (43 m) west of the crown, the ground surface begins to slope to the east at about 8 degrees. We interpret the west-sloping ground to be a back-tilted surface resulting from rotation caused by movement of the slide. We also believe that the lack of expression of the scarp on the northwest flank of the slide reflects mostly local strike-slip rather than dip-slip movement on the flanks of the slide during landsliding.

In addition to the main scarp, geomorphic evidence suggests the existence of secondary scarps. In the east part of the landslide (profile A-A'), we interpret a possible secondary scarp approximately 260 feet (79 m) northeast of the main scarp. The secondary scarp is about 16 feet (4.9 m) high and slopes about 17 degrees northeast. In the northern and central part of the slide, episodes of partial reactivation of the slide by deep-seated slumping have resulted in numerous secondary scarps. The scarps in this group related to the 1985-86 slump are discussed in more detail below.

The toe of the Pine Ridge landslide consists of a very steeply sloping front that is actively being modified by shallow debris slides. Maximum local slopes at the toe range from 38 (profile C-C') to 49 (profile A-A') degrees. Local relief (Lake Creek to crest of abutting steep slope) ranges from 129 feet (39.3 m) (profile C-C') to 74 feet (22.6 m) (profile B-B'). Numerous recent shallow debris slides exist in the toe of the landslide. These debris slides typically involve movement of topsoil, thin colluvium, and underlying glacial till, and generally cause the removal of mature vegetation, consisting of mixed aspens and conifers, where present. The maximum depths of failure surfaces of these debris slides are typically less than about 13 feet (4.0 m). Shallow debris sliding may temporarily cause flattening of the overall local slope as material moves downward and laterally into the zone of accumulation. However, our profiling indicates that the upper part of the slope is generally as steep after debris sliding as before. Eventual erosion of slide debris from the toe by Lake Creek during high-flow periods each spring completes the cycle of slope modification. The net result of this process is a lateral migration of the slope of about 10 to 15 feet (3.0-4.6 m) with no significant change in local slope gradient after erosion of slide debris at the toe.

Sometime in 1985-86, about an 11-acre (4.4-ha) area of the landslide reactivated as a deep-seated slump (Hylland and Lowe, 1995) (figure 2; figure 3, profile B-B'). The main scarp of this slump extends for about 2,000 feet (610 m) and ranges from about 2 to 15 feet (0.6-4.6 m) high. A part of the composite main scarp with approximately 1 foot (0.3 m) of vertical displacement passes directly under a mobile home/cabin, which has been kept level by placing jacks and shims beneath the steel frame of the cabin on the downdropped landslide block. The 1985-86 slump contains several internal secondary scarps, two of which form a small graben that is about 110 feet (34 m) north of the main scarp. Two other secondary scarps within 50 feet

(15 m) of the main scarp and intercepted by profile B-B' are part of a set of en echelon secondary scarps that merge with or eventually become the main scarp in the eastern flank of the slump.

Overall, the 1985-86 slump has a complex geometry. In profile, the slump is benched and can be separated into three slump blocks (figure 3, profile B-B'). The lowest and northernmost block is approximately 95 feet (29.0 m) above Lake Creek, at its highest point, and is about 360 feet (110 m) long from toe to upper bounding scarp where it is crossed by profile B-B'. At least two internal scarps formed in the lower block during slumping in 1985-86. In addition, a presumably contemporaneous scarp formed in the northern slope near Lake Creek as a result of shallow debris sliding. The middle slump block is relatively flat, ranges from approximately 200 to 210 feet (61-64 m) above Lake Creek, and is about 180 feet (55 m) long where it is crossed by profile B-B'. The middle and lower slump blocks are separated by a zone of both active and inactive scarps. The total local relief across this zone is about 120 feet (37 m) where it is crossed by profile B-B'. We interpret this relief to be the result of downdropping of the lower block during multiple episodes of slumping. Two of the five scarps in the zone moved during slumping in 1985-86. The upper and southernmost slump block is approximately 275 feet (84 m) above Lake Creek, at its highest point, and is about 230 feet (70 m) long where it is crossed by profile B-B'. Internal deformation during slumping in 1985-86 formed five scarps within the block. Two of these scarps bound a graben that is about 20 feet (6.1 m) wide and about 2 feet (0.6 m) deep where it is crossed by profile B-B'. Displacement is greatest on the antithetic, southwest-facing scarp that bounds the graben on the northeast. The upper and middle slump blocks are separated by a single inactive scarp with about 47 feet (14.3 m) of local relief along profile B-B'.

ANALYSIS OF THE CAUSES OF SLUMPING IN 1985-86

Unfortunately, we have no eyewitness accounts of the 1985-86 slumping, thus the conditions that triggered the movement can only be inferred. Slumping in 1985-86 came near the end of an unusually wet period in Utah with higher than average precipitation in the Timber Lakes area. Presumably soils were saturated or nearly saturated at the time of movement, and the upper few feet of soil could have been frozen. There are no accounts of significant earthquakes in the area during the time period that movement initiated (Brown and others, 1986; Nava and others, 1990), thus failure likely occurred under static conditions.

Profiling and mapping of the 1985-86 slump indicated that not all pre-existing scarps reactivated. In addition, recent movement does not account for the total relief across internal secondary scarps and the overall benched topography of the slump, suggesting recurrent late Holocene movement of the slump.

We used PCSTABL5M and XSTABL5 limit-equilibrium slope-stability programs to evaluate, or back-calculate, the static conditions that triggered slumping in 1985-86. Based on the rotational nature of the slumping, we assumed slip surfaces were circular. We used the

Simplified Bishop Method in the analyses because this method has been shown to provide accurate results (the results are neither conservative or non-conservative) with the least variability (Robinson, 1995). In addition, we required the slip surfaces to coincide with the scarps at which movement occurred in 1985-86 and to toe in either Lake Creek or downslope slip surfaces. These requirements somewhat constrain the slip-surface geometries and likely yield adequate approximations of the actual slip surfaces to allow determination of failure conditions during slumping in 1985-86. We used the present topography in our analyses because of the negligible differences between pre- and post-failure topography.

Three separate models were analyzed in our evaluation of slumping in 1985-86 (figure 4). In model 1, movement of two independent slip surfaces forms scarps A and B in the boundary zone between the lower and middle slump blocks. Movement of a displacement-dependent slip surface forms the main scarp. The slip surface is displacement dependent because it toes in the upper part of the downslope slip surface and movement of the upper and middle slump blocks is dependent on movement of the lower block toward Lake Creek. Moderately shallow rock in the upper part of the slump controls the depth of this slip surface. Model 2 is similar to model 1 except that the depth to rock does not control the depth of the uppermost dependent slip surface. In model 3, movement of two dependent slip surfaces forms scarps A and B. Movement of a deep-seated independent slip surface that toes in Lake Creek forms the main scarp. This slip surface also acts as a detachment for the two shallower slip surfaces. In all three models, the same critical (having the lowest factors of safety) slip surfaces form scarps A and B, however we evaluated three possible critical slip surfaces that could have formed the main scarp.

Without information on ground-water conditions during slumping in 1985-86, we were not able to independently back-calculate probable soil shear strength of the slump blocks. Instead, we were only able to estimate shear strength as a function of ground-water conditions. Figure 5 shows the range in estimated shear strength as a function of the head (vertical height of ground water) above the critical slip (failure) surface. The results suggest that if shear strengths are relatively low, either ground-water-table (unconfined ground water) or non-artesian confined ground-water conditions were possible at failure. However, if shear strengths are high, artesian confined ground-water conditions would have been necessary to initiate failure.

Although artesian ground-water conditions may have existed during slumping, some indirect evidence suggests such conditions were unlikely. Slumping resulted in the formation of numerous internal scarps and ground cracks in the slump blocks. Along the main scarp, tree roots stretched across the scarp document extension. For artesian conditions to have existed, the base of the confining layer would have to be shallower than the critical slip surface of the slump. Propagation of the slip surface upward to form the main and minor scarps (see figure 4) would have breached a confining layer. If artesian conditions had existed, subsequent extension across the main and possibly other minor scarps would likely have allowed upward flow of ground water and resulted in the formation of springs. We are not aware of any reports of springs along the scarps that might suggest that artesian conditions existed during slumping. Other indirect

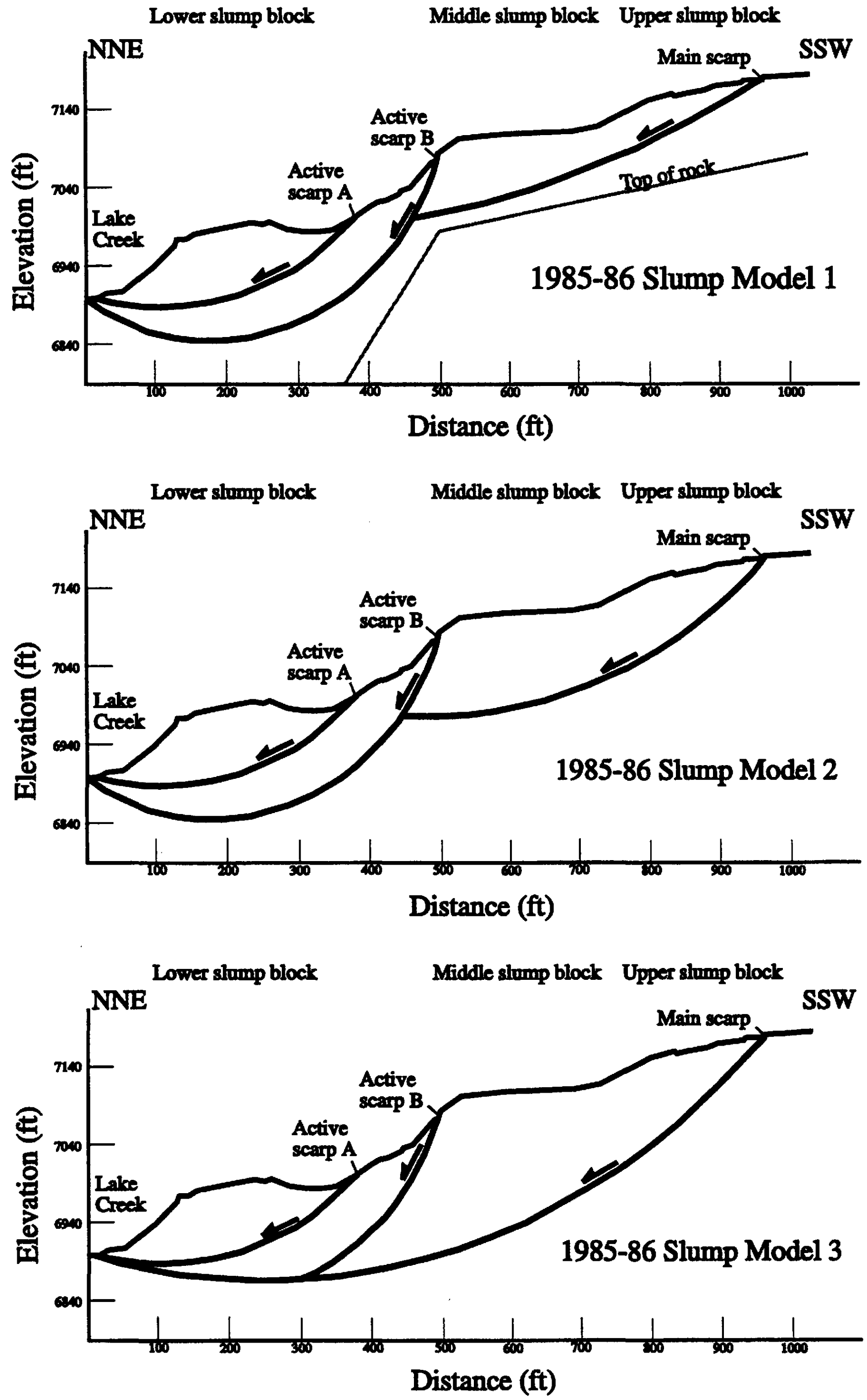


***Figure 4.** Landslide models used in slope-stability analyses of the 1985-86 slump. In model 1, movement of two independent slip surfaces forms scarps A and B in the boundary zone between the lower and middle slump blocks. A displacement-dependent slip surface forms the main scarp and toes in the upper part of the slip surface that forms scarp B. Moderately shallow rock controls the depth to the slip surface. Model 2 is similar to Model 1 except that the depth to the upper slip surface is not controlled by the depth to rock. In Model 3, movement of two dependent slip surfaces forms scarps A and B. Movement of one independent slip surface forms the main scarp. The deeper slip surface toes near Lake Creek and acts as a detachment. Rock is assumed to be relatively deep.*

evidence against the likelihood of artesian conditions includes the lack of stratification in most exposures of the glacial till and the low probability that a low-permeability layer could be laterally continuous for the distances necessary to create artesian pressures in the slide.

On this basis, we believe that upper bound shear strengths can be defined by where artesian conditions are required to initiate slumping (see figure 5). Because the onset of artesian conditions is also equivalent to the worst-case unconfined ground-water conditions (entire thickness of soil above slip surface is saturated), the upper bound shear strengths are likely the best estimate of shear strengths in the slump (table 4). The range in estimated shear strengths is consistent with published residual shear strengths of glacial tills and similar soils (figure 6). We infer from this that the probable episodic movement history of the slump, and particularly the lower slump block, has caused shear strengths to approach their residual values at least adjacent to slip surfaces. Shear strength likely increases with distance from slip surfaces and may reach peak values in the centers of slump blocks.

Table 4.
Summary of back-calculated residual shear strengths in 1985-86 slump.

Feature formed by slip surface	Residual shear strength (Ø'r)[1] (degrees)
Minor Scarp A	23
Minor Scarp B	19
Average (scarps A and B)	21
Main Scarp - range	26-30
Average (main scarp)	27
Average residual shear strength	24

[1] Glacial till assumed to be cohesionless. Shear strength at onset of artesian ground-water conditions.

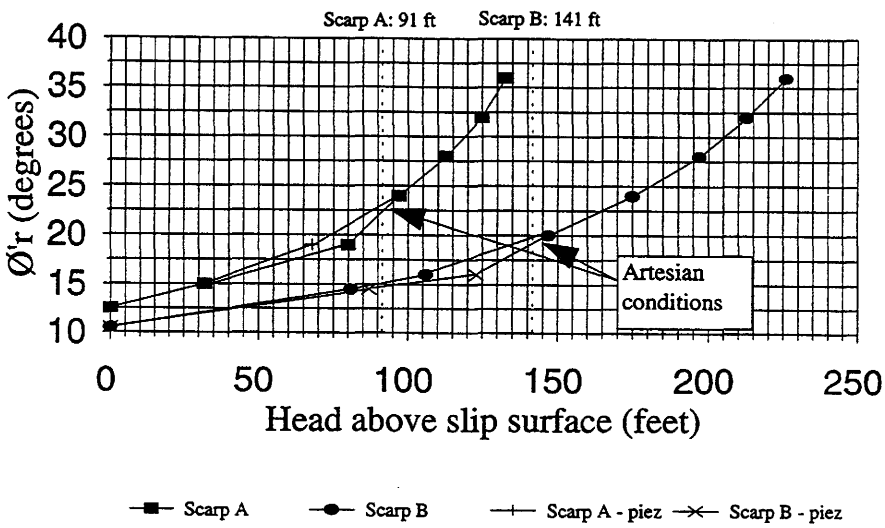
ESTIMATION OF PEAK SHEAR STRENGTHS OF THE GLACIAL TILL

Geologic evidence suggests the remainder of the Pine Ridge landslide is less active than the 1985-86 slump. The evidence for this includes:

1. the subdued nature of the main and minor scarps, and

2. the absence of other local deep-seated slumps in the toe area indicating partial reactivation similar to the 1985-86 slump.

a. Scarps A & B of 1985-86 slump



b. Main scarp of 1985-86 slump

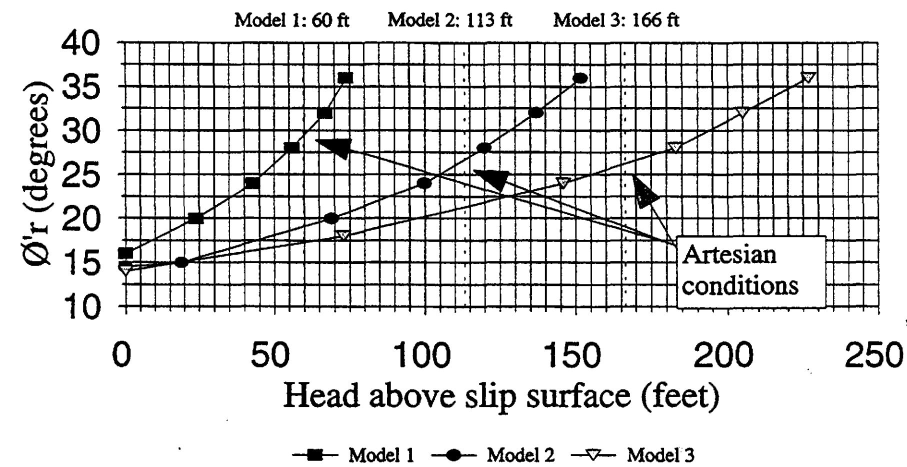


Figure 5. *Estimated shear strengths of glacial till in the 1985-86 slump. Shear strength (Ø'r) as a function of head (height of phreatic or piezometric surface) above slip surface as measured at centerline of the local slump. (a) Shear-strength estimates for two independent slip surfaces that formed scarps A and B. Alternate curves show slight variation in results using PC-STABL5M program option to selectively define piezometric surface. Option can be used to simulate confined ground-water conditions where the piezometric surface is below ground surface and gives results similar to the method used. (b) Shear-strength estimates for three possible slip surfaces (models 1-3) that could have formed main scarp. Minor differences in estimated shear strengths at onset of artesian conditions suggest results are not highly dependent on model selected.*

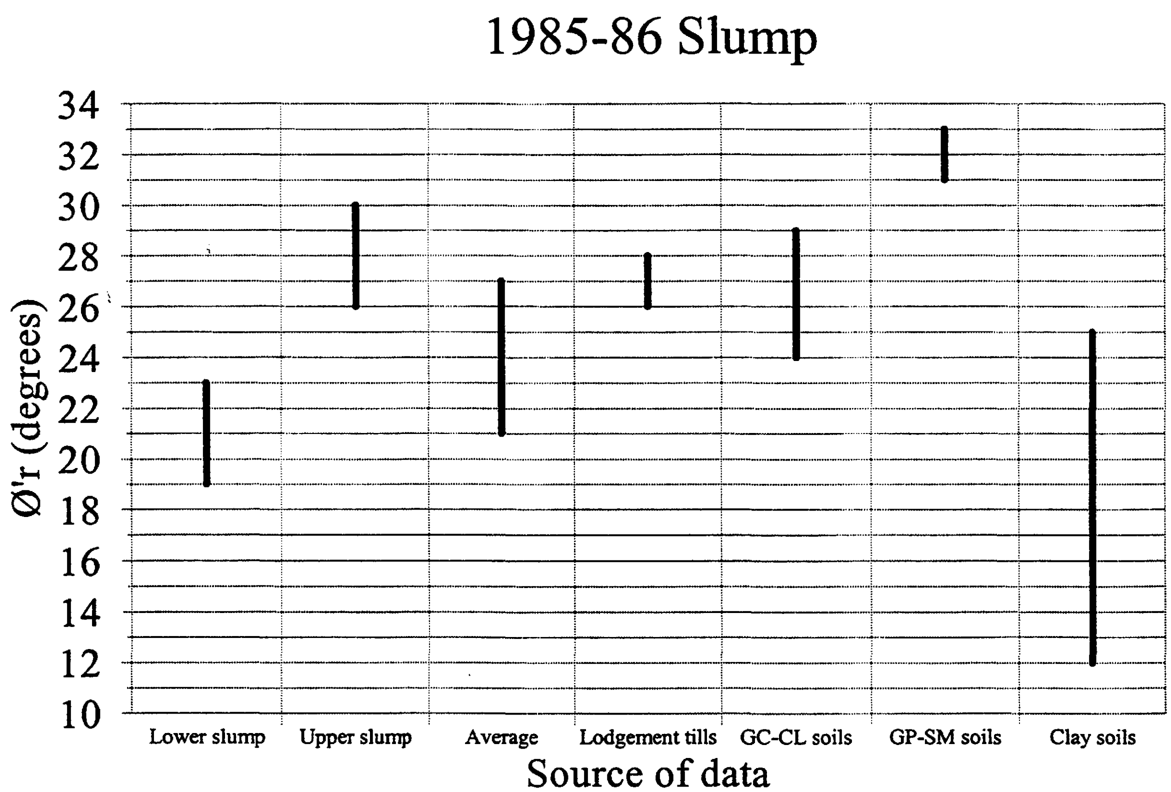


Figure 6. *Comparison of estimated residual shear strengths in the 1985-86 slump with published data. Upper bound of average residual shear strengths (Ø'r = 21-27 degrees) of glacial till in slump falls within published ranges for lodgement tills and soils with Unified soil classifications of GC-CL. Lower bound of average falls within upper part of range for clay soils and may be consistent with multiple episodes of reactivation in lower part of slump. Range of residual shear strengths for lodgement tills from Eyles (1983); for GC-CL soils from Vaughan and Walbancke (1978); and for GP-SM and clay soils from Renteria (1994).*

Because reactivation, if it has occurred, has likely been less frequent in the Pine Ridge landslide outside the 1985-86 slump, we infer that estimated residual shear-strength values may not be applicable to this area (figure 7). Our preliminary analysis indicates that if residual shear strengths prevailed throughout the slide, other local unstable conditions would most likely exist, and thus supports our assumption that somewhat higher strengths exist outside the 1985-86 slump area.

We estimated peak shear strengths of the glacial till by back-calculating failure conditions of three debris slides along Lake Creek crossed by our three topographic profiles (figure 8). Although debris sliding along Lake Creek causes movement of overlying topsoil and colluvium, we observed the slip surfaces cut mostly through the underlying glacial till, thus providing an opportunity to estimate the peak shear strength of the till. In the northwesternmost debris slide C, we profiled both the pre- and post-failure topography from Lake Creek to the crest of the steep slope above the slide. Pre-failure topography was estimated for debris slide A, whereas post-failure geometry was used for slide B because only minor movement was evident.

Although the glacial till is likely cohesionless, the presence of mature vegetation in the debris-slide areas along Lake Creek may impart some root cohesion at shallow depths. Roots do not directly affect the angle of internal friction (Ø'p) of soil, but root cohesion needs to be accounted for to back-calculate Ø'p using limit-equilibrium methods. On the steep slopes along Lake Creek, mature conifers and aspen have roots that extend down through a relatively thick sequence of glacial till. This morphology corresponds to U.S.D.A. Forest Service soil-root classification Type D (Denning, 1994) with an estimated root cohesion of 20 lbs/ft^2 (0.96 kpa) (Hammond and others, 1992).

As in our analysis of slumping in 1985-86, we were not able to independently back-calculate probable shear strength of the glacial till in the absence of information on ground-water conditions when debris sliding initiated. Instead, we were only able to estimate shear strength as a function of ground-water conditions. Figure 8 shows the likely ranges of ground-water levels at the initiation of sliding. Figure 9 shows estimated peak shear strength as a function of the degree of saturation of the critical slip surface. Seeps that we observed in debris slide A during the late fall appear to define lowest ground-water levels. Elsewhere, low ground-water levels are assumed to be below or in the toe or foot of the slide.

The range in estimated peak shear strengths (Ø'p) for the glacial till in debris slides B and C is consistent with published ranges in Ø'p for undifferentiated tills and soils with Unified soil classifications ranging from GP to SM (table 5, figure 10). However, the range in peak shear strength determined for the glacial till in debris slide A exceeds the published range reported for these soil types. Although shear strength in this location may be anomalously high, it is more

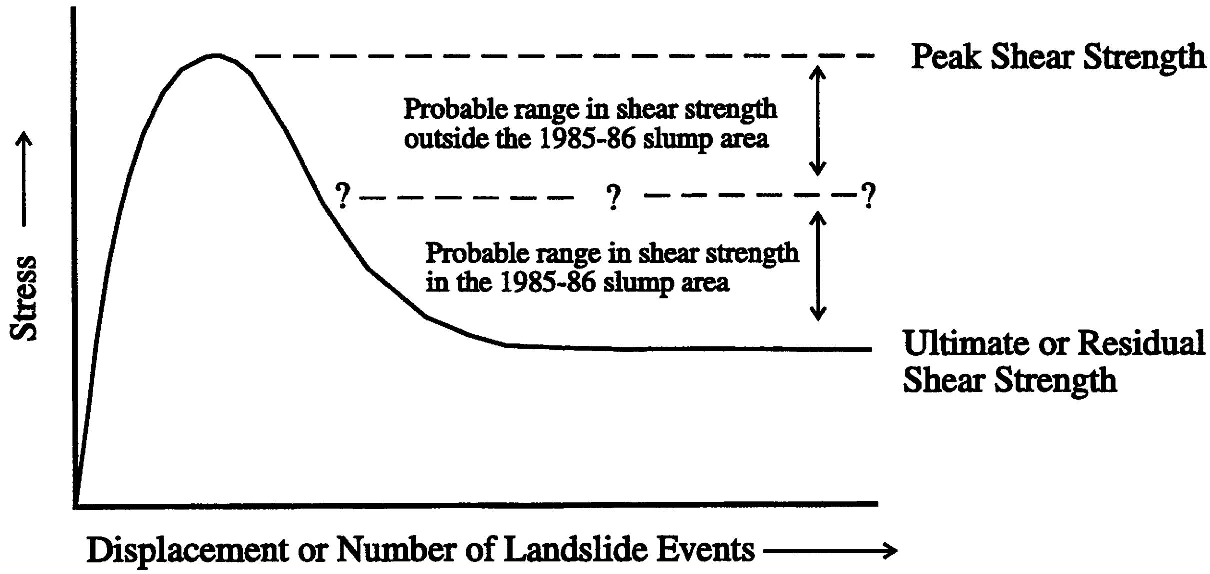


Figure 7. *Conceptual diagram showing relation between shear strength and repeated movement along a landslide slip surface. Landslide movement causes shear strength to move along curve from left to right. Eventually, repeated movement, as in the 1985-86 slump area, reduces strength to lowest possible (ultimate) value. Geologic evidence suggests fewer landslide events have occurred outside the slump area and therefore we speculate that shear strengths are somewhat higher. Modified from Jibson and Harp (1996)*

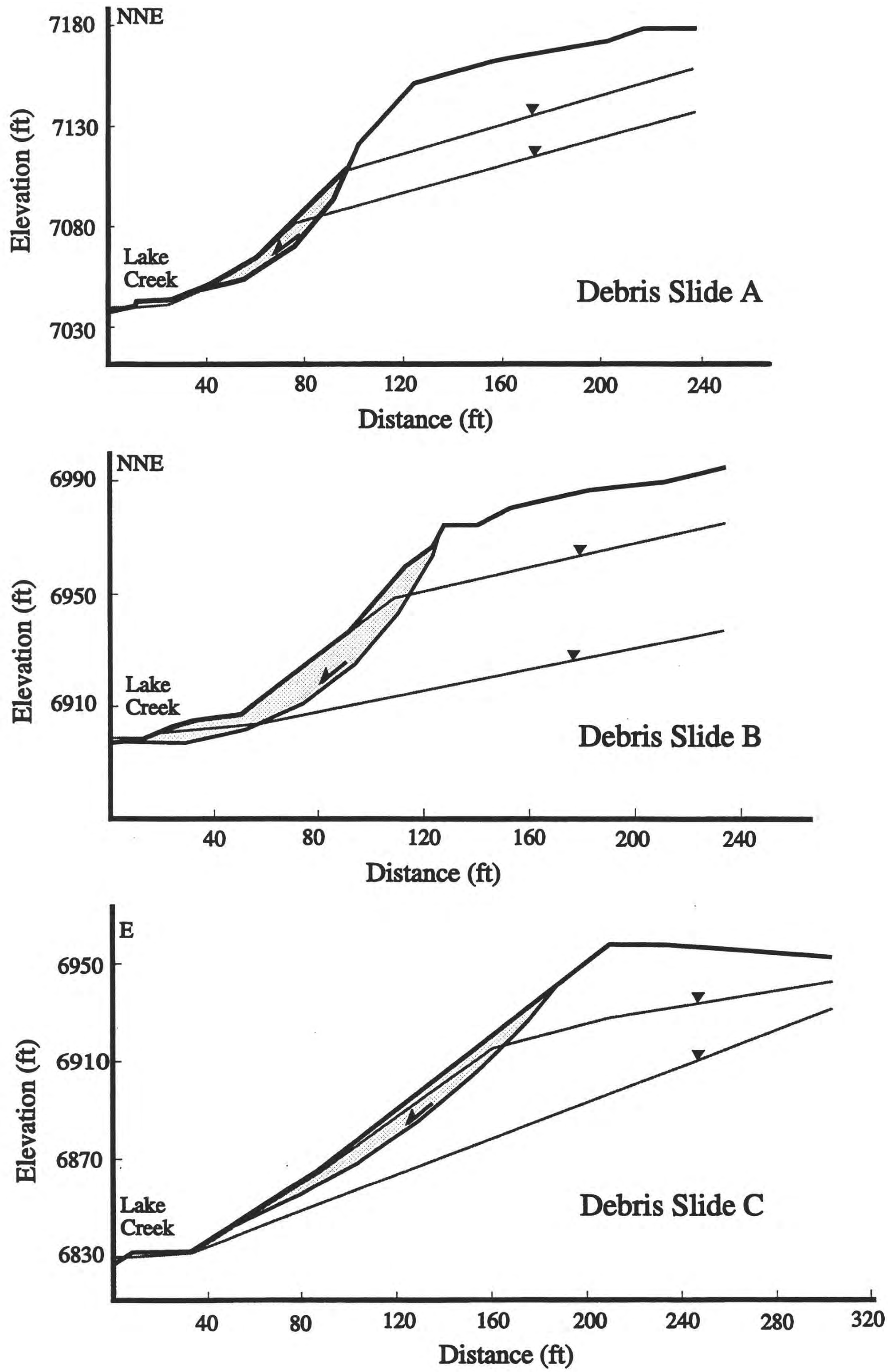


Figure 8. *Debris slides along Lake Creek used in slope-stability analyses. Debris-slide letter designation corresponds to profile line that crosses debris slide. Probable ranges of ground-water levels when debris sliding is triggered are shown.*

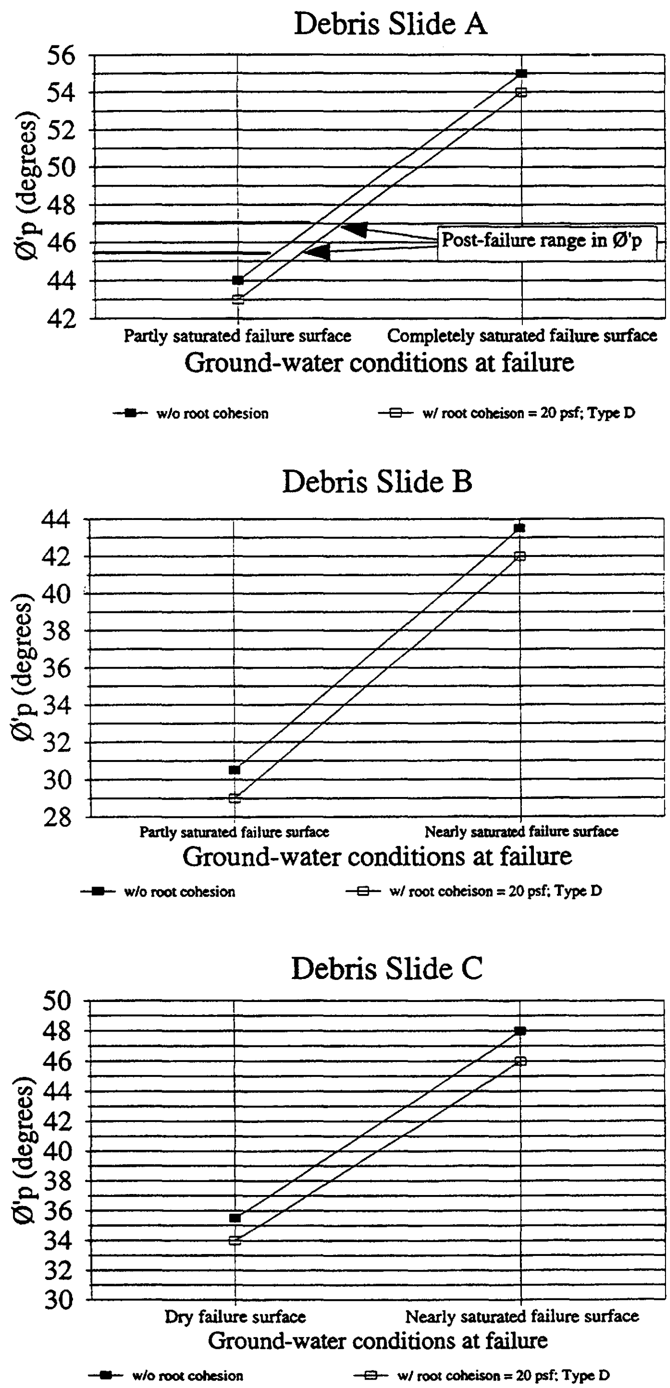


Figure 9. *Estimated peak shear strengths of glacial till. Shear strength as a function of ground-water conditions when debris sliding initiated (see figure 8). Plots show range in estimated peak shear strength (Ø'p) with (lower line) and without (upper line) the contribution in total shear strength from supplemental root cohesion. Estimated post-failure range in Ø'p is likely upper bound of shear strength in debris slide A and assumes slide is presently metastable.*

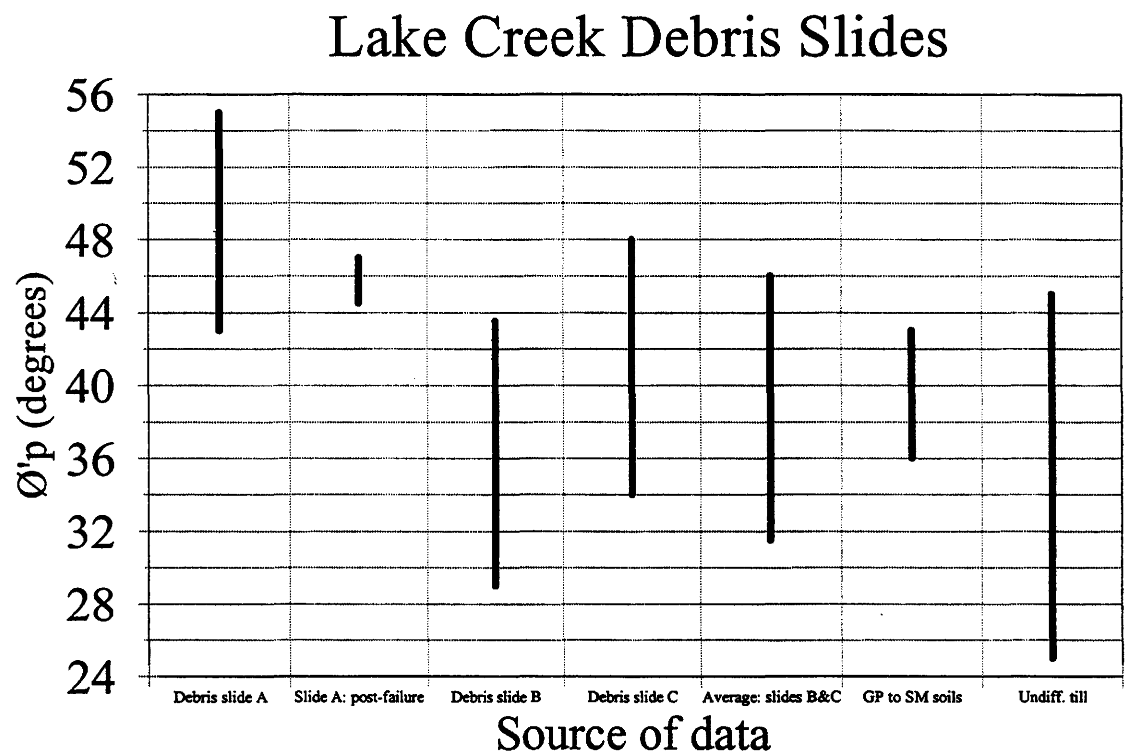


Figure 10. *Comparison of estimated peak shear strengths of glacial till with published data. Ranges in estimated shear strength derived from analysis of debris slides B and C generally fall within published ranges for undifferentiated glacial till and soils with Unified soil classification of GP to SM. Apparent high shear strength of till in debris slide A may be anomalous or could possibly reflect uncertainties regarding degree of saturation of slide or metastable state. We regard shear strength determined assuming metastable post-failure conditions as the upper bound of peak shear strength at that location. Range of peak shear strengths for GP to SM soils from Rose (1994); for undifferentiated tills from Kazi and Knill (1969) and Hammond and others (1992).*

Table 5.
Summary of back-calculated peak shear strengths in three debris-slide areas.

Debris slide	Peak shear strength (Ø'p) (degrees)
Slide A	43-55
Slide A - metastable (post-failure)	44.5-47
Slide B	29-43.5
Slide C	34-48
Average: Slides B & C	31.5 - 46
Representative average value	39

likely that the high values reflect uncertainties regarding the degree of saturation of the slide or the slide's metastable state. Our limit-equilibrium slope-stability analysis of the slide in its present configuration yields a lower range in estimated shear strength if we assume the slide is presently metastable (the factor of safety equals one but the slide is presently motionless or imperceptibly creeping).

We must also clarify that the uppermost shear-strength values (upper half of ranges in table 5 and figure 10) in all three slide areas reflect the assumption that debris sliding initiates only at the highest ground-water levels. We believe this requirement may be inconsistent with the observed low ground-water levels in the dry season despite the large number of debris slides along Lake Creek. In our opinion, debris sliding may be triggered at ground-water levels perhaps one-third to one-half as high as the highest levels portrayed in figure 8. Thus, probable shear strengths are more likely to fall within the lower half of the range shown in table 5 and figure 10.

STABILITY UNDER STATIC CONDITIONS

The stability of the Pine Ridge landslide is the critical issue to future land-use planning in the slide area. Future reactivation of the entire Pine Ridge landslide could cause movement on the main or possibly pre-existing minor scarps, and possibly form new minor scarps. A more likely scenario is the partial reactivation of the northern part of the slide by deep-seated slumping, such as occurred in 1985-86.

We believe the range in estimated average shear strengths (Ø'r,p = 24-39 degrees) likely brackets actual shear strengths of the glacial till in the landslide, although local strengths in the 1985-86 slump could be less (see table 4). Using these values and assumptions regarding seasonally high ground-water levels, we estimated the relative stability of the slide for two scenarios:

1. reactivation of the main slip surface causing movement of the entire slide, and

2. deep-seated slumping similar to that in 1985-86 (partial reactivation).

Stability of the Entire Landslide

The results of our analyses suggest that the slide as a whole is relatively stable even during high (non-artesian) ground-water levels. The apparent stability of the entire slide is consistent with both the relatively flat slope of the slide and the subdued nature of its main and minor scarps outside the 1985-86 slump area (table 6). Movement of the entire slide may be triggered by artesian conditions, but only if considerably high artesian pressures exist such that

Table 6.
Summary of landslide characteristics related to stability.

Profile	Pre-Failure Slope	Post-Failure Slope	Maximum main scarp slope	Residual strength required for instability (Ø'r)
A-A'	5.6H:1V (18 %)	6.0H:1V (17 %)	2.5H:1V (40 %)	12 degrees or less
B-B'	4.7H:1V (21 %)	5.1H:1V (20 %)	2.2H:1V (45 %)	16 degrees or less

the piezometric surface is tens of feet (3+ m) above the ground surface. We strongly caution that our evaluation does not preclude the possibility of movement of the entire slide, particularly if an underlying weak layer, with shear strengths much less than our lower bound estimated value, exists at depth. The right-hand column in table 6 shows that for the entire slide to be unstable, actual residual strengths would need to be as low as 50 percent of our estimated value. Detailed investigations with geotechnical boreholes would be required to confirm the existence of a weak layer. Excluding the possibility of a weak layer at depth, we believe the likelihood of future movement of the entire slide, under static conditions, is low. We discuss the potential for earthquake-induced movement in a later section of this report.

Potential for Partial Reactivation

1985-86 Slump

The recent movement of the 1985-86 slump indicates that this part of the Pine Ridge landslide is active. Our analyses suggest that shear strengths of the glacial till near the slip surfaces have reached residual values, most likely as the result of recurrent movement of the slump. The most recent movement in 1985-86 was likely triggered by high ground-water levels or artesian pressures following an unusually wet period. The critical issue for future land-use planning of undeveloped lots on or abutting the slump is the potential for continuing movement in the near future.

An understanding of the stability of the 1985-86 slump requires consideration of the differences in the failure models (see figure 4). In models 1 and 2, movement of the entire slump is dependent on movement of the lower slump block toward Lake Creek. However, our analyses suggest that either the phreatic (unconfined ground water) or piezometric (confined ground water) surface would locally have to be above the ground surface for slumping to initiate, assuming we have not overestimated the lower bound shear strength of the till. Profile B-B' (see figure 3) shows that the lower slump block is mound shaped with a sag between it and the scarp zone that separates the lower and middle slump blocks. Under unconfined ground-water conditions, the upslope sag elevation is the likely high ground-water level in the lower slump block assuming that the phreatic surface slopes downward to Lake Creek. Without ponded surface water in the sag, the likelihood of completely saturated conditions in the mound part of the lower slump block is low, but such conditions appear necessary for independent slumping of the block. The simplest scenario where slumping appears possible is when a piezometric surface (confined ground water) is at or slightly above the ground surface (onset of artesian conditions on top of the mound). Another possibility is that unconfined ground water exists and that the near-surface soils are frozen, including in the steep slope adjacent to Lake Creek, and act as a barrier to downslope ground-water flow. In such a scenario, ground water could back-up and fill the overlying soils in the mound because the frozen ground prevents seepage in the steep slope near Lake Creek or surface ponding in the sag. Artesian pressures could likely build up temporarily beneath the frozen surficial soils. Such requirements for slope failure appear to restrict independent slumping of the lower block to the winter months when frozen ground conditions are possible.

Our results indicate that slumping could be triggered at high ground-water levels in model 3 in the absence of artesian ground-water conditions. Metastable conditions are approached during seasonal high-water levels each spring if ground water rises to within 10 to 20 feet (3-6 m) of the ground surface. Movement appears possible under such high-water conditions if actual shear strengths are closer to the lower end of our estimated range of strengths in the slump (see figure 4). These results imply a continued landslide hazard exists during high-water conditions in and around the 1985-86 slump. Our analyses using model 3 suggest that the area up to at least 200 feet upslope of the main scarp of the 1985-86 slump could be susceptible to deep-seated slumping (factor of safety is likely less than 1.5).

Northern Pine Ridge Landslide

In addition to the 1985-86 slump, the remaining northern part of the Pine Ridge landslide may also be susceptible to deep-seated slumping (partial reactivation) at high ground-water levels. We evaluated the stability of the northern part of the slide assuming shear strengths fell somewhere within the range of average residual and peak values (Ø'r,p = 24-39 degrees). Figure 11 shows the approximate boundary between the northern part of the slide where we believe deep-seated slumping is possible (factor of safety is likely less than 1.5), and the southern part of the slide which is, in our opinion, relatively stable under static conditions (factor of safety is likely greater than 1.5). The boundary line in figure 11 is located midway between boundaries determined using the average residual and peak shear strengths and assuming the depth to rock does not control slope stability.

POTENTIAL FOR EARTHQUAKE-INDUCED MOVEMENT

Our analyses suggest that movement of the entire Pine Ridge landslide is unlikely under static conditions, thus movement may only be triggered by earthquakes that cause significant ground accelerations in the slide mass. In a recent study of the Witts Lake dam (see figure 2), AGRA Earth & Environmental (AGRA) (1995) estimated the mean peak horizontal ground acceleration (PHA) in the slide area using a deterministic method to be 0.28 g. The PHA would result from the maximum credible earthquake on the Round Valley faults located about 8.4 miles (14 km) to the southwest. Actual PHA values may exceed that estimated by AGRA (1995) (David Marble, Utah Division of Water Rights, written communication, 1997). AGRA (1995), using probabilistic distance methods and a 200-year recurrence interval, also estimated a PHA of 0.08 g from a random background earthquake in the Wasatch Front region or in Seismic Source Zone 38 (Algermissen and others, 1982) in which the slide and dam are located. Pechmann and Arabasz (1995) showed that probabilistic distance methods underestimate PHAs by a factor of 1.7 to 3.0 for a recurrence interval of 200 years. This suggests the PHA for a random background earthquake and a 200-year recurrence interval could range from 0.14 to 0.24 g.

We evaluated the potential for earthquake-induced landsliding using a pseudostatic approach within the range of possible PHAs described above. We assumed that only horizontal acceleration acts on the slide mass and in a direction toward Lake Creek. We also only evaluated earthquake ground shaking during periods of relatively high ground-water levels. Figure 12 shows the results of the pseudostatic analysis of the entire slide (profiles A-A' and B-B') and the 1985-86 slump. Assuming residual shear strength conditions prevail along the pre-existing slip surface of the slide, earthquake-induced movement of the entire slide is possible if ground acceleration exceeds 0.15 g. Higher ground acceleration values are required to induce movement if shear strengths are closer to peak values. If shear strength values (Ø') exceed approximately 33 degrees, then earthquake-induced landsliding would require PHAs higher than the deterministic PHA value and thus is unlikely.

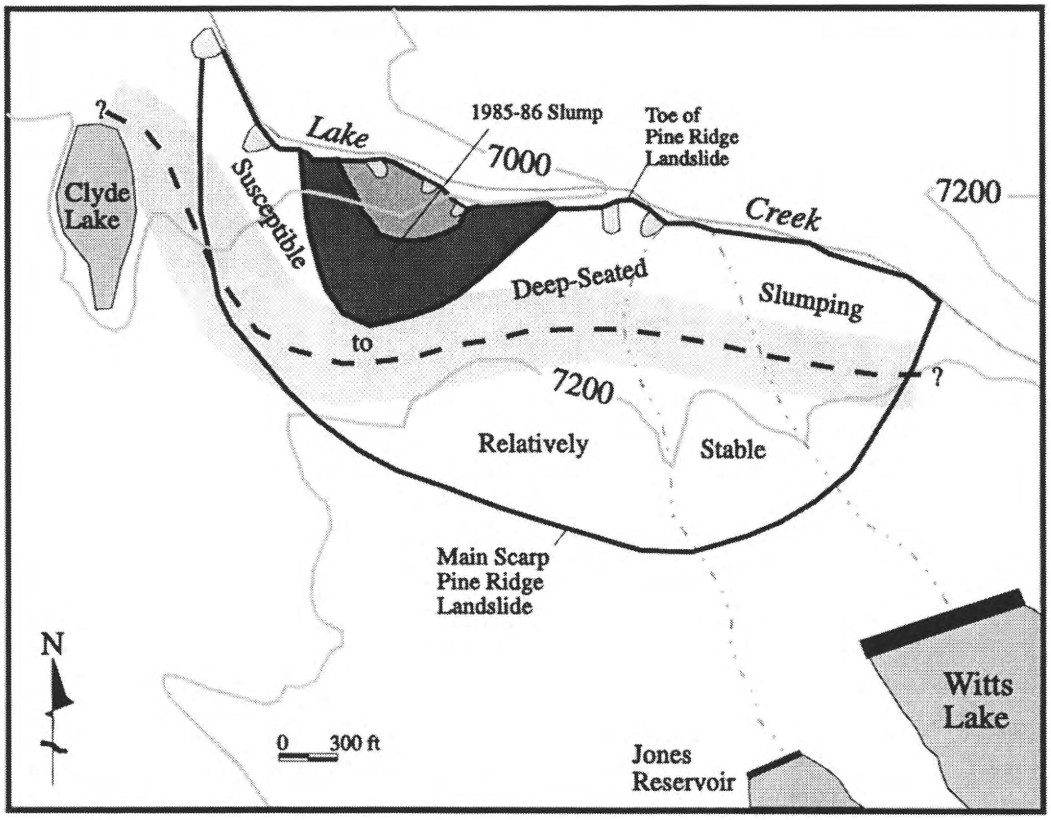


Figure 11. *Map showing area susceptible to deep-seated slumping. Results of our analyses suggest northern part of landslide is susceptible to deep-seated slumping at high ground-water levels even if shear strengths of soils approach peak values. Boundary is based on using average shear-strength value. Shaded zone surrounding boundary is zone of uncertainty regarding actual location of boundary. See figure 2 for additional explanation of base map. Elevations in feet above mean sea level.*

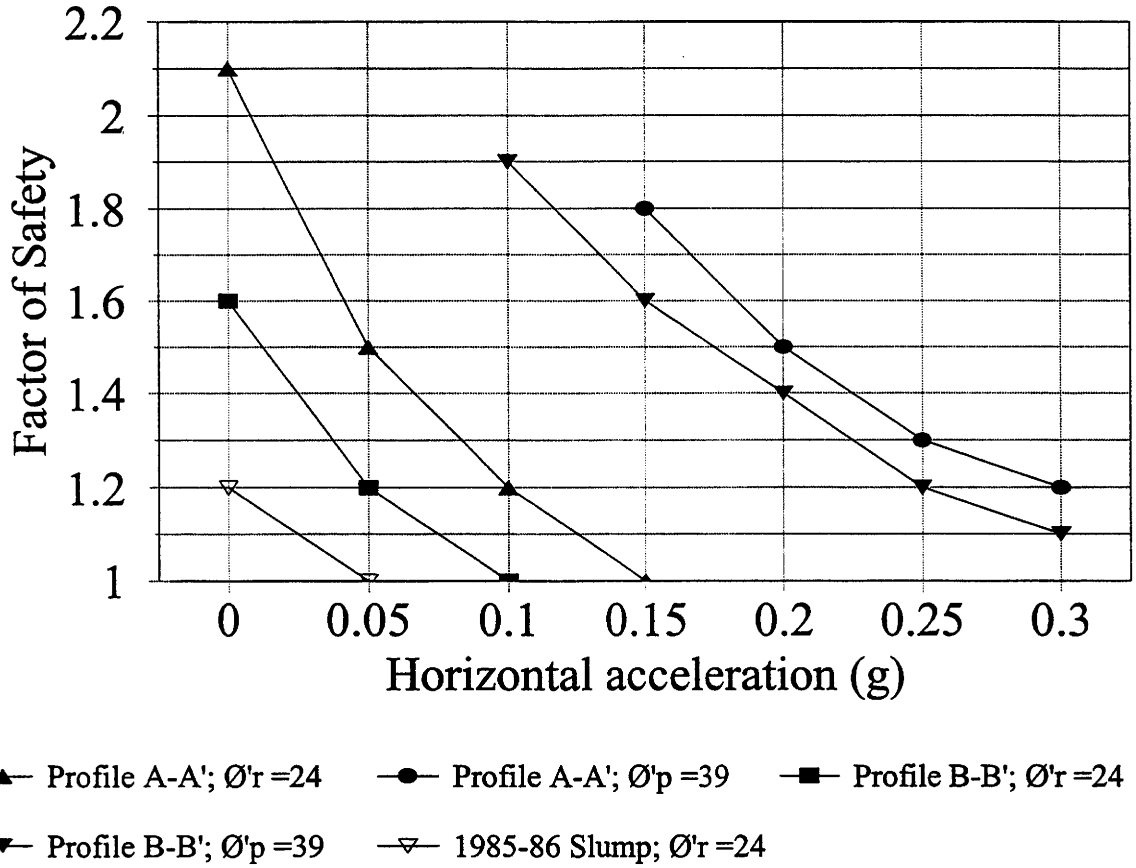


Figure 12. *Results of pseudostatic analysis of Pine Ridge landslide. Plot shows a potential for earthquake-induced movement if ground accelerations (PHAs) exceed 0.15 g assuming residual shear strengths prevail along slip surface and high ground-water levels. If shear strength values (Ø') exceed about 33 degrees earthquake induced movement would require PHAs exceeding the deterministic ground acceleration value of 0.28 g estimated by AGRA Earth & Environmental (1995).*

Once critical accelerations have been reached, earthquake-induced displacement can reduce shear strength along the slip surface and possibly destabilize the slide. Jibson and Harp (1996) showed that the small amount of coseismic displacement produced in the Springdale landslide during the 1992 M-5.7 St. George earthquake was sufficient to reduce shear strengths to residual levels and destabilize the slide. Reduction in shear strength caused the slide to become statically unstable and resulted in damaging movement exceeding that predicted for coseismic displacement alone. More detailed geotechnical data are necessary to completely evaluate this possibility for the Pine Ridge landslide.

SUMMARY

The historical movement of the 1985-86 slump indicates that the Pine Ridge landslide is susceptible to partial reactivation in its northern part. Geomorphic evidence, such as internal scarp heights that exceed the total movement in 1985-86, and pre-existing, inactive minor scarps, suggests recurrent movement of the slump. This recurrent movement likely caused a reduction of shear strengths to residual values adjacent to slip surfaces in the slump. Our analyses indicate that average residual shear strengths (Ø'r) of the glacial till in the slump range between 21 and 27 degrees, but lower strengths are possible, particularly in the lower slump block. These values are consistent with residual strength values of similar soils reported in the literature.

Movement of the 1985-86 slump is likely triggered at high ground-water levels in which ground water or the piezometric surface is less than 10 to 20 feet (3-6 m) below the ground surface in the upper part of the slump. The slump is likely metastable during or near the end of seasonal wet periods when ground-water levels are high but deeper than 10 to 20 feet (3-6 m). At some distance upslope of the main scarp of the slump, the factor of safety reaches an acceptable level.

The northern part of the landslide is being modified by active debris sliding at the toe and is susceptible to deep-seated slumping. Debris sliding results in short-term southward migration of the steep slope along Lake Creek and is not moderated by stands of mature vegetation, despite a possible contribution to overall soil strength by root cohesion. Debris sliding may threaten existing homes constructed too close to the crest of the steep slope because the process does not necessarily result in a long-term stable slope configuration. We believe the northern part of the slide is also susceptible to partial reactivation by deep-seated slumping. Shear strengths in the glacial till outside the 1985-86 slump area likely range between the average residual value and the average peak value (Ø'p = approximately 39 degrees) estimated from back-calculation of peak strengths in active debris slides. Even if peak shear strengths prevail in the northern part of the slide, our results suggest the till is susceptible to deep-seated slumping at high ground-water levels. Long-term cumulative effects of STSA systems will likely contribute to high ground-water levels.

We believe the likelihood of future movement of the entire slide is low; however, this does not preclude the possibility of movement if the area experiences earthquake ground shaking or if a deep weak layer is present. Detailed subsurface investigations would be required to determine whether such a layer exists. Our analyses suggest that earthquake-induced sliding may be triggered under a combination of conditions that include high ground-water levels, shear strengths below peak values, and horizontal ground accelerations above a critical threshold level.

LIMITATIONS

All results of this investigation are preliminary and intended for land-use planning to reduce, not eliminate, the risk from landsliding and to indicate where more detailed studies are needed. Our conclusions regarding the relative stability of the entire slide do not preclude the possibility of movement, particularly in the event of significant earthquake ground shaking during wet conditions. As geotechnical data are collected from future detailed investigations in Timber Lakes Estates, as described below, the results and conclusions presented in this report may be revised.

RECOMMENDED FUTURE STUDIES

Because of the uncertainties in this preliminary study, we recommend that a detailed geotechnical-engineering investigation be conducted to evaluate the stability of the northern part of the Pine Ridge landslide. The investigation should incorporate data from deep boreholes, laboratory soil-strength testing, and ground-water-level monitoring.

At a minimum, preliminary geotechnical-engineering slope-stability studies, similar to this investigation, should be conducted for the two large late Holocene landslides to the southeast of the Pine Ridge landslide (see figure 1). Like the Pine Ridge landslide, these areas may be susceptible to deep-seated slumping or earthquake-induced landsliding.

ACKNOWLEDGMENTS

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REFERENCES

AGRA Earth & Environmental, 1995, Geotechnical and engineering geology services - Witt Lake Dam located in Wasatch County, Utah - for Lake Creek Irrigation Company: Salt Lake City, unpublished consultant's report, 23 p.

Algermissen, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L., and Bender, B.L., 1982, Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States: U.S. Geological Survey Open-File Report 82-1033, 99 p.

Baker, A.A., 1976, Geologic map of the west half of the Strawberry Valley quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-931, 11 p. pamphlet, scale 1:24,000.

Brown, E.D., Arabasz, W.J., Pechmann, J.C., McPherson, Erwin, Hall, L.L., Oehmich, P.J., and Hathaway, G.M., 1986, Earthquake data for the Utah region - January 1, 1984 to December 31, 1985: University of Utah Seismograph Stations, Salt Lake City, Utah, 83 p.

Bryant, Bruce, 1992, Geologic and structure map of the Salt Lake City 1° x 2° quadrangle, Utah and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1997, scale 1:125,000.

Denning, Cliff, 1994, Root strength and tree surcharge, *in* Hall, D.E., Long, M.T., and Remboldt, M.D., editors, Slope stability reference guide for national forests in the United States: U.S. Department of Agriculture Forest Service Publication EM-7170-13, p. 543-558.

Eyles, N., 1983, Glacial geology: Toronto, Pergamon Press, 409 p.

Federal Highway Administration, 1988, PC-STABL5M users guide - slope stability analysis program: U.S. Department of Transportation, 131 p.

Hammond, Carol, Hall, David, Miller, Stanley, and Swetik, Paul, 1992, Level I Stability Analysis (LISA) documentation for version 2.0: U.S. Department of Agriculture Forest Service General Technical Report INT-285, 190 p.

Hylland, M.D., editor, 1996, Guidelines for evaluating landslide hazards in Utah: Utah Geological Survey Circular 92, 16 p.

Hylland, M.D., and Lowe, Mike, 1995, Landslide hazards of western Wasatch County, Utah, *in* Lund, W.R., editor, Environmental and engineering geology of the Wasatch Front Region: Utah Geological Association Publication 24, p. 121-136.

Jibson, R.W. and Harp E.L., 1996, The Springdale, Utah, landslide - an extraordinary event: Environmental & Engineering Geoscience, v. II, no. 2, p. 137-150.

Kazi, Assadullah, and Knill, J.L., 1969, The sedimentation and geotechnical properties of the Cromer Till between Happisburgh and Cromer, Norfolk: Quarterly Journal of Engineering Geology, v. 2, p. 63-86.

Nava, S.J., Pechmann, J.C., Arabasz, W.J., Brown, E.D., Hall, L.L., Oehmich, P.J., McPherson, Erwin, and Whipp, J.K., 1990, Earthquake catalog for the Utah region - January 1, 1986 to December 31, 1988: University of Utah Seismograph Stations, Salt Lake City, Utah, 96 p.

Pechmann, J.C. and Arabasz, W.J., 1995, The problem of the random earthquake in seismic hazard analysis - Wasatch Front Region, Utah *in* Lund, W.R., editor, Environmental & engineering geology of the Wasatch Front Region: Utah Geological Association Publication 24, p. 77-93.

Renteria, Rene, 1994, Strength and behavior of soil, *in* Hall, D.E., Long, M.T., and Remboldt, M.D., editors, Slope stability reference guide for national forests in the United States: U.S. Department of Agriculture Forest Service Publication EM-7170-13, p. 337-426.

Robinson, Lee, 1995, A new look at slope stability methods, *in* Caliendo, J.A., editor, Proceedings of the 1995 Annual Symposium on Engineering Geology & Geotechnical Engineering: Utah State University, no. 31, p. 124-135.

Rose, Ed, 1994, Soil weight/volume relationships, *in* Hall, D.E., Long, M.T., and Remboldt, M.D., editors, Slope stability reference guide for national forests in the United States: U.S. Department of Agriculture Forest Service Publication EM-7170-13, p. 345-376.

Sharma, Sunil, 1996, XSTABL version 5 reference manual- an integrated slope stability analysis program for personal computers: Interactive Software Designs, Inc., Moscow, Idaho, 214 p.

Vaughan, P.R., and Walbancke, H.J., 1978, The stability of cut and fill slopes in boulder clay, *in* The engineering behavior of glacial materials: Norwich, Great Britain, Geo Abstracts, p. 185-196.