Landslide Investigation of Timber Lakes Estates, Wasatch County, Utah: Landslide Inventory and Preliminary Geotechnical-Engineering Slope Stability Analysis

by
Daniel P. Neuffer
Ronald L. Bruhn

MISCELLANEOUS PUBLICATION 05-9 November 2005
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

Landslide Investigation of Timber Lakes Estates, Wasatch County, Utah: Landslide Inventory and Preliminary Geotechnical-Engineering Slope Stability Analysis

Daniel P. Neuffer*
Ronald L. Bruhn

Department of Geology and Geophysics
University of Utah, Salt Lake City, Utah

*RTW Professional Engineers & Consultants
825 Railroad Street
Elko, NV 89801

Revised March 31, 2005

ABSTRACT

We produced a comprehensive, detailed landslide map of Timber Lakes Estates in Wasatch County, Utah. Landslide deposits underlie about 13% of the total area of Timber Lakes (about 3,200 acres). We mapped twenty separate landslides scattered throughout Timber Lakes based on field observations and aerial photograph and topographic map interpretation. Ten of the landslides initiated as rotational rock slides or earth slides in the Tertiary Keetley Volcanics or Keetley-derived residual material and two of the ten have evolved into earth flows. The other ten landslides occur in Quaternary glacial till or derived colluvium. Seven of these ten slides are rotational earth slides and the remaining three are translational shallow debris slides. Three landslides, the Pine Ridge, Westview, and Aspen slides, display fresh scarps and other signs of recent activity. In addition, active debris sliding commonly occurs on slopes above Lake Creek. Six landslides, the Clyde Lake, Pine Ridge, Witts Lake, Tanglewood, Blazing Star, and Aspen slides, are being undercut by Lake Creek, threatening their stability. We also mapped lithologic contacts in the northwest portion of the study area and tabulated landslide and pertinent lithologic and hydrologic data obtained through field observations, measurements, and interpretations to help characterize the landslide hazard.

We performed preliminary slope stability analyses on three landslides in Timber Lakes Estates using PC-STABL5M. We modeled the Cedar Bark slide, an earth slide-earth flow in Quaternary glacial till, the Beaver Bench slide, a rock slide in Tertiary Keetley Volcanics, and the Blazing Star slide, a rock-earth slide in Keetley Volcanics and glacial till. We modeled each landslide under three different static loading scenarios: the first scenario involved reconstructing an estimate of pre-slide topography in order to estimate peak friction angles of the material; in the second scenario, we evaluated the stability of the entire slide mass and determined residual friction angles; the purpose of the third scenario was to locate the least stable area of the landslide. Groundwater levels were varied to simulate dry, mid-level, and saturated conditions. We estimated peak friction angles of 16–29 degrees and residual friction angles of <15–23 degrees for glacial till and Keetley Volcanics at differing groundwater conditions. The range of peak friction angles from 20–29 degrees probably represents more realistic groundwater conditions. Estimated peak friction angles would be greater if pore pressures were greater than hydrostatic or if dynamic loading was induced by earthquake ground shaking. The least stable segments within the landslides were on the steepest slopes within the slides, on either the main scarp or toe. For all three landslides, these segments would probably fail in saturated groundwater conditions and possibly fail in less than saturated conditions. Under mid-level groundwater conditions, the factors of safety for the present configurations of the Cedar Bark and Blazing Star slides are less than 1.5 if friction angles are less than 23 and 22 degrees, respectively. Under saturated groundwater conditions, the factors of safety for the present configurations of the Cedar Bark and Blazing Star slides are less than 1.5 if friction angles are less than 32 and 31 degrees, respectively.

1.0 INTRODUCTION

1.1 Statement of Problem

Landslides pose significant problems to both existing and future development in Timber Lakes Estates. This subdivision is located in the drainage of Lake Creek, approximately 7 miles (11 km) east of Heber City, in Wasatch County, Utah (Fig. 1). Timber Lakes Estates is located in the foothills of the Uinta Mountains, an area with significant topographic relief, steep hill slopes, and geological deposits that are susceptible to failure by mass wasting (Biek and others, 2003). Twenty landslides are identified within Tertiary and younger deposits within the boundaries of the subdivision. Several of these slides have been active in the last 10,000 years, and are therefore Holocene in age. Some landslide activity has continued to the present day. Following several years of high precipitation, the Pine Ridge landslide was partly reactivated during 1985 and 1986, damaging a cabin (Ashland and Hylland, 1997). In total, at least five cabins in the Timber Lakes subdivision were damaged during the winter and spring of 1985–86, due to both deep-seated slumping and shallow debris-sliding (Hylland and Lowe, 1995). A landslide triggered by cutting a slope destroyed one of the cabins, illustrating that development and construction can contribute to slope failure. Active debris sliding occurs along the steep banks of Lake Creek, and there are fresh scarps, ground fissures and vegetation anomalies in several other areas that are indicative of slope instability and partial reactivation of landslides (Hylland and Lowe, 1995).

The Utah Geological Survey published four reports concerning landslides in Timber Lakes. Hylland (1995) compiled an engineering geologic map folio of western Wasatch County, including landslide hazards. Hylland and Lowe (1995) investigated landslide hazards in western Wasatch County. Ashland and Hylland (1997) produced a preliminary geotechnical-engineering evaluation of the Pine Ridge landslide. Biek and others (2003) mapped the geology, including surficial deposits and mass movements, of the Center Creek quadrangle, which includes the northwest half of Timber Lakes. In addition, consulting geologists and engineers have performed site-specific slope-stability analyses on various lots in Timber Lakes.

Prompted by concern about the risks posed to structures and residents by landslides, Wasatch County and the Timber Lakes Property Owners Association funded a two-phase landslide study of Timber Lakes. The Utah Geological Survey provided technical support. This landslide mapping project and slope stability analysis form the first and second phases of the study, respectively. This report presents a map of the landslide deposits that incorporates previous work with a new field investigation conducted during August through October of 2000, as well as preliminary geotechnical-engineering slope stability analyses of three landslides within Timber Lakes Estates. This study is consistent with Utah Geological Survey guidelines for evaluating landslide hazards (Hylland, 1996).

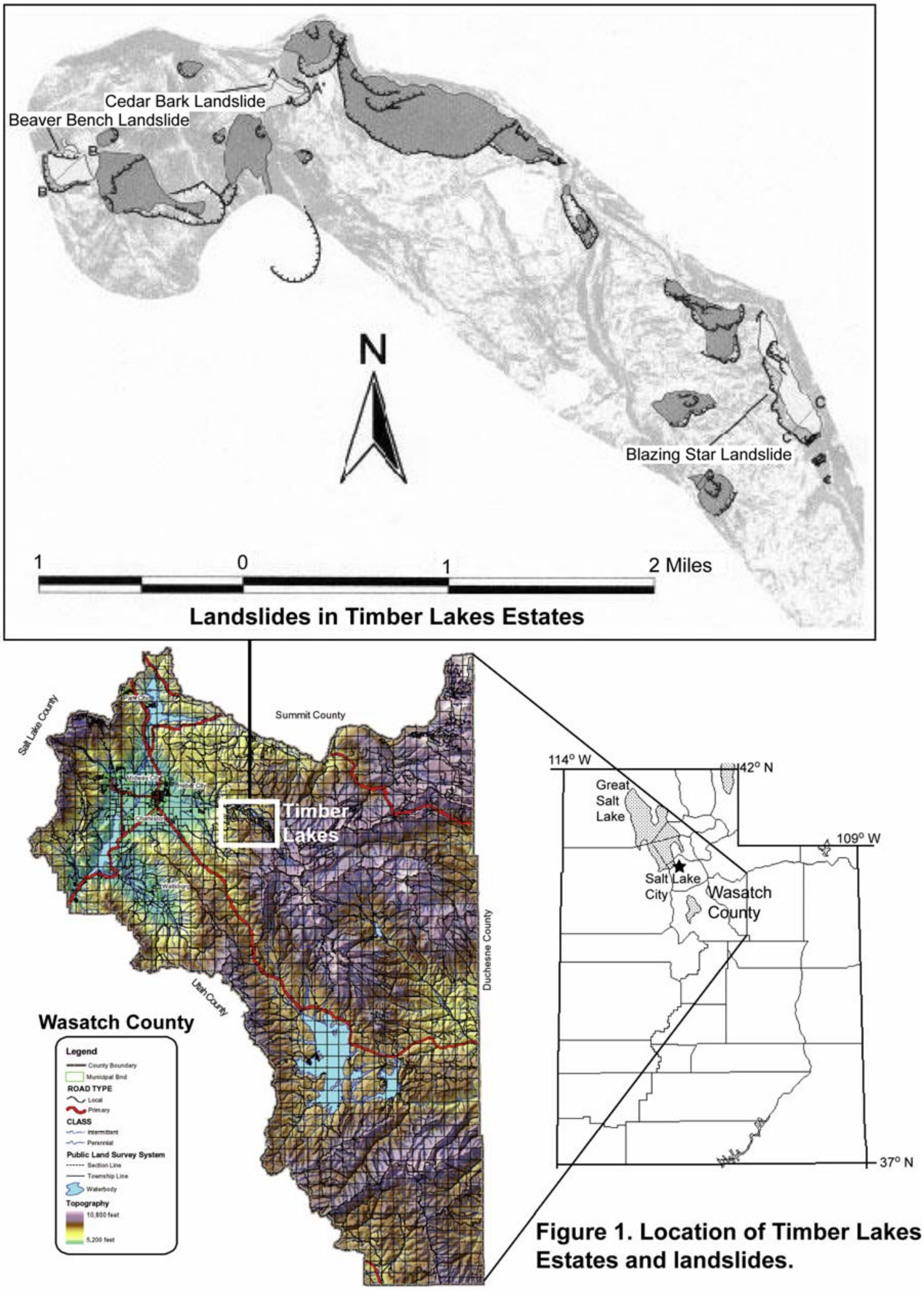


Figure 1. Location of Timber Lakes Estates and landslides.

1.2 Goals

The goals of the landslide mapping project are as follows:

- Refine the boundaries of previously mapped slides.
- Map additional slides identified through field observation.
- Identify and evaluate evidence of slide activity.

The slope stability study has several goals:

- Evaluate the geometry and stability of slides developed in various types of deposits at three localities within the subdivision.
- Constrain the peak and residual frictional properties of the slide masses.
- Evaluate the sensitivity of the slides to changes in groundwater level.
- Identify parts of slides that are most prone to failure.
- Make recommendations concerning appropriate field and laboratory work that should be done when more detailed studies are warranted.
- Present guidelines that are useful for planning development in slide prone areas.

2.0 GEOLOGIC SETTING

Timber Lakes Estates is situated at elevations of ~ 6500–8500 ft, with slope angles ranging from zero up to almost 40 degrees (on the hillsides above Lake Creek). Slopes in the subdivision are mostly north facing, but west and east aspects exist as well. In the Timber Lakes area, south-dipping Jurassic sedimentary rocks are locally exposed. The Nugget Sandstone, a fine- to medium-grained, cross-bedded eolian quartz sandstone is overlain by the Twin Creek Limestone, a thin- to medium-bedded fine-grained limestone deposited in a shallow-marine environment. Outcrops of the Nugget Sandstone are white to red-tan in color and form small cliffs and resistant benches, while the Twin Creek Limestone is light gray and is less resistant to erosion than the sandstone. The Tertiary Keetley Volcanics unconformably overly the Twin Creek Limestone and are locally greater than 2500 ft thick in the study area (Biek and others, 2003). Three members of the Keetley Volcanics, the Tuffaceous Unit, the Quartzite-boulder Unit, and the Volcanic Breccia of Coyote Canyon, have been identified in the Timber Lakes area. The Tuffaceous Unit is a white-gray to green-gray tuff, tuffaceous sandstone, and pebbly sandstone that ranges up to 720 ft in thickness (Biek and others, 2003). The overlying Quartzite-boulder Unit, an unconsolidated to poorly consolidated conglomerate consisting of quartzite pebbles to boulders, is thin and not well exposed in Timber Lakes (Biek and others, 2003). The Volcanic Breccia of Coyote Canyon, the youngest member of the Keetley Volcanics in Timber Lakes, is a thick (up to 1400 ft) sequence of volcanic conglomerate and breccia containing andesite and rhyodacite clasts with local quartzite, sandstone, and limestone clasts (Biek and others, 2003).

Poorly sorted, heterogeneous glacial till consisting of unconsolidated clay, silt, sand, and pebble- to boulder-sized clasts of volcanic rock and quartzite was deposited during late Pleistocene glaciation and overlies the Keetley Volcanics in the majority of the subdivision (Biek and others, 2003). Glacial tills are moraine deposits that formed during the late Pleistocene, as part of the Pinedale and possibly earlier glacial events. The moraines form cuspate to hummocky topography, particularly in the southeastern part of the subdivision. Hillsides are locally mantled by colluvium, which thickens in hollows or depressions in the hillsides, and accumulates at the base of slopes. Colluvium is an unconsolidated mixture of soil and rock fragments derived primarily from the older till and volcanic deposits, as well as organic material derived from dead vegetation and soil. Recent stream deposits occur along the course of Lake Creek and along small drainages elsewhere in the subdivision. There are also older stream and pond deposits distributed among the glacial moraines, but these deposits are not of primary concern for estimating slope stability because of their restricted distribution.

Landslides in the Timber Lakes Estates subdivision occur in the Keetley Volcanics, glacial till, and colluvium. Many slides have developed in two or more of these deposits. There are no large landslides identified within the Nugget Sandstone or Twin Creek Limestone. However, fractures in these rocks may provide preferential pathways for the movement of groundwater. In some areas, water may percolate into the unconsolidated deposits through channel-ways in subjacent fractured bedrock. Groundwater seeps and ephemeral ponds are distributed throughout the subdivision.

3.0 MAPPING METHODS

We first mapped contacts between Jurassic strata and overlying Keetley Volcanics in the northwest part of the study area where the Jurassic Twin Creek Limestone and Nugget Sandstone are exposed (Plate 1, Sheet 1). The purpose of the bedrock mapping was to determine whether any landslides in the area had slip surfaces at the top of or in the Jurassic strata. In addition, we measured the orientation and spacing of bedding and joint sets in several locations (Table 1; Plate 1, Sheet 1).

Hylland and Lowe (1995), Ashland and Hylland (1997), Biek and others (2003), and a Wasatch County map (unpublished information) previously identified several landslides in Timber Lakes. We mapped previously studied landslides in detail and identified previously unmapped landslides on aerial photographs. The primary photos used were a 1:7,920 scale set flown in the spring of 1999 by Wasatch County. We also used a two-foot contour map of Timber Lakes provided by Wasatch County to identify landslides,

Table 1. Orientation and spacing of bedding and joint sets.

Site	Formation	Location (UTM)	Strike & Dip; Spacing (in)			
			Bedding	Joint set	Joint set	Joint set
A	Twin Creek Limestone	0474575, 4482287	097, 20; 6-12	213, 75; 12-18	137, 90	
B	Twin Creek Limestone	0474516, 4482126	108, 13; 2-12	289, 75; 4-12	244, 81	
C	Nugget Sandstone	0474905, 4482471	084, 25; 2-40	216, 64; 12-18	340, 82; 4-12	142, 90; 72
D	Nugget Sandstone	0475276, 4482589	097, 23; 2-40	128, 90; 12-36	159, 90; 12	
E	Nugget Sandstone	0477027, 4482960	125, 22; 2-40	112, 84; 2-24	010, 82; 18-36	039, 56; 4-10
F	Twin Creek Limestone	0474631, 4481961	098, 17; 2-12			
G	Nugget Sandstone	0474782, 4482820	123, 39; 2-40			
H	Keetley Volcanics	0479862, 4480698	285, 20; 1-36	005, 76		

especially in heavily timbered areas where it was more difficult to see topography on the air photos.

We distinguished landslides primarily on the basis of morphology. Locations with hummocky topography, scarps, ground cracks, evacuated areas, transverse ridges, or contour lines that changed from concave to convex were investigated in the field. Scarps, ground cracks, and evacuated areas are geomorphic features unique to landslide processes (where tectonic origins can be ruled out). We also investigated areas with leaning or curved trees, springs, ponds, or phreatophytes; however, these occurrences are not alone indicative of landslide processes. Leaning and curved trees may result from snowpack creep or localized shallow soil creep. Springs, ponds, and phreatophytes may be purely hydrologic phenomena. Additionally, ponding is common in heterogeneous glacial tills. For the purposes of this report, we define the term 'phreatophyte' (a plant that grows in shallow groundwater conditions) loosely to include quaking aspen and thick grass.

We mapped the northern part of Timber Lakes on the above-mentioned 1:7,920 scale aerial photographs. Because the Pine Ridge landslide has been studied in some detail (Ashland and Hylland, 1997), we mapped only the outline of the slide and the prominent internal scarps caused by recent partial reactivation. We mapped the southern part of Timber Lakes on a 1:4,800 scale topographic map from the above-mentioned two-foot contour data because the area is heavily forested, precluding aerial photograph mapping. The field maps were digitized using ArcInfo™ and then finalized in ArcView® to facilitate measurement, modeling, viewing, and planning use.

We gave each landslide an index number and a name based on a nearby road name or geographic feature (Table 2a). The index numbers appear on or near each landslide on the map (Plate 1) and in parentheses following the mention of a landslide in the text. For each landslide, the classification, mode of sliding, failed lithology, area, and aspect were tabulated (Table 2a). Features indicative of past slope failure, recent movement, and shallow groundwater were also compiled for each landslide (Table 2b). The landslide classification and mode of sliding were determined in the field according to Cruden and Varnes (1996). The failed lithology for each landslide was estimated from field observation and by the use of the map of Biek and others (2003). In some areas, open percolation test pits or other shallow excavations provided information about subsurface materials. The area and aspect of each landslide were determined using ArcView®. We tabulated the morphological and hydrologic features discussed above according to whether they indicate past slope failure, recent slope movement, or shallow groundwater.

Table 2a. Characteristics of Timber Lakes landslides.

Index #	Name	Classification	Mode of Sliding	Failed Lithology	Area of Landslide Deposit		Aspect
					sq. meters	acres	
1	Westview	Rock slide-Earth flow	Rotational-flow	Keetley Volcanics (Volcanic Breccia of Coyote Canyon)	218910	54.09	W
2	Beaver Bench	Rock slide	Rotational	Keetley Volcanics (Tuffaceous Unit)	82600	20.41	NE
3	Cottonwood	Rock slide-Earth flow	Rotational-flow	Keetley Volcanics (Volcanic Breccia of Coyote Canyon)	152089	37.58	N
4	Cedar Bark	Earth slide-Earth flow	Rotational-flow	glacial till	48577	12.00	W
5	Clyde Lake	Earth slide	Rotational	glacial till, Keetley Volcanics?	97327	24.05	N
6	Pine Ridge	Earth slide	Rotational	glacial till, Keetley Volcanics?	599225	148.07	N
7	Witts Lake	Earth slide	Rotational	glacial till, Keetley Volcanics?	79957	19.76	NE
8	Ridgeline	Earth slide	Rotational	Keetley-derived residual soil (Volcanic Breccia of Coyote Canyon)	14020	3.46	NE
9	Valley View	Earth slide	Rotational	Keetley-derived residual soil (Volcanic Breccia of Coyote Canyon)	13636	3.37	SW
10	Acorn	Earth slide	Rotational	glacial till	6410	1.58	W
11	Aspen	Earth slide	Rotational	glacial till - colluvium	6245	1.54	E
12	Lake Creek	Debris slide	Translational	glacial till - colluvium	n/a	n/a	E
13	Lake Creek	Debris slide	Translational	glacial till - colluvium	n/a	n/a	E
14	Lake Creek	Debris slide	Translational	glacial till - colluvium	n/a	n/a	E
15	Blazing Star	Rock-earth slide	Rotational	Keetley Volcanics, glacial till	144716	35.76	E
16	Birch	Rock-earth slide	Rotational	Keetley Volcanics, glacial till	74931	18.52	N
17	Tanglewood	Rock-earth slide	Rotational	Keetley Volcanics, glacial till	129127	31.91	N
18	Blue Spruce	Rock-earth slide	Rotational	Keetley Volcanics, glacial till	68317	16.88	NW
18a	Blue Spruce	Debris flow	Flow	Keetley Volcanics, glacial till, colluvium	*4299	*1.06	SW
19	Horseshoe	Earth slide-Debris flow	Rotational-flow	glacial till	18677	4.62	N
20	Quakie Grove	Earth slide	Rotational	Keetley-derived residual soil (Volcanic Breccia of Coyote Canyon)	2917	0.72	NE
	Total				1757681	434.33	

* Area included in Blue Spruce landslide deposit.

Table 2b. Morphologic and hydrologic features of Timber Lakes landslides.

Index #	Name	Features Indicative of:		
		Past Slope Failure	Recent Movement	Shallow Groundwater
1	Westview	MS, FS, MiS, TR, HT	S, GC, LT	Sp, Ph
2	Beaver Bench	MS, MiS, HT		P
3	Cottonwood	MS, MiS, HT, EA		Ph
4	Cedar Bark	MS, MiS, HT		
5	Clyde Lake	MS, MiS, HT		
6	Pine Ridge	MS, MiS, HT	S, DS, GC	Sp, Ph
7	Witts Lake	MS, MiS, HT, EA	LT	Sp, Ph
8	Ridgeline	MS, HT		
9	Valley View	MS, MiS, HT		
10	Acorn	MS, HT		
11	Aspen	MS, FS, MiS, HT	S, GC, LT	Ph
12	Lake Creek	MS, HT, EA		Ph
13	Lake Creek	MS, HT, EA	S, DS	Sp, Ph
14	Lake Creek	MS, MiS, EA	S, DS	
15	Blazing Star	MS, MiS, HT, TP	LT, DS	P, Ph
16	Birch	MS, MiS, HT, TP	LT	P, Ph
17	Tanglewood	MS, MiS, HT, EA	DS, LT	Sp, Ph
18	Blue Spruce	MS, MiS, HT, EA, TP		Sp, P, Ph
18a	Blue Spruce	MS, HT, EA		Ph
19	Horseshoe	MS, MiS, EA		Ph
20	Quakie Grove	MS, HT		Ph

Features Index

MS: Main Scarp*
FS: Flank Scarp*
MiS: Minor Scarps*
TR: Transverse Ridges
HT: Hummocky Topography
EA: Evacuated Areas
TP: Trapped Ponds

*Scarps are vegetated and rounded

Features Index

S: Fresh Scarps[1]
DS: Recent Debris Sliding
GC: Ground Cracks
LT: Leaning/Curved Trees[2]

[1]Scarps are mostly not vegetated and not rounded
[2]Not necessarily related to landsliding

Features Index

Sp: Springs
P: Ponds
Ph: Phreatophytes

4.0 OBSERVATIONS AND INTERPRETATIONS

4.1 Lithology

We found no evidence that the Nugget Sandstone or Twin Creek Limestone are involved in landsliding. Landslides in the northwest corner of Timber Lakes initiated in the Keetley Volcanics or in the residual soils overlying the Keetley Volcanics (Table 2a). Based on the map of Biek and others (2003) and field observations, the Beaver Bench slide (2) originated in the Tuffaceous Unit of the Keetley Volcanics (Table 2a). We observed white-gray, fine-grained tuff on the ridge directly west of the Beaver Bench slide (2)(Plate 1, Sheet 1). The Westview (1), Valley View (9), Ridgeline (8), Quakie Grove (20), and Cottonwood (3) slides are derived from the Volcanic Breccia of Coyote Canyon Member of the Keetley Volcanics as determined from the map of Biek and others (2003) and field observations (Table 2a). We observed volcanic breccia in a small slope cut on lot 1375 near the Westview slide (1)(Plate 1, Sheet 1). Additionally, white-gray tuff breccia crops out in roadcuts along Ridgeline Drive in the scarp zone of the Westview slide (1)(Plate 1, Sheet 1).

In the northeast portion of Timber Lakes, Keetley Volcanics are exposed in the walls of a steep gully on lot 803 (Plate 1, Sheet 2). However, the outcrop is rather inaccessible, and, thus, we were unable to make detailed lithologic observations or determine if the Keetley Volcanics is in place at this location. Field observations confirm that the dominant surface lithology of northeast Timber Lakes is unconsolidated, poorly sorted glacial till containing clay- through boulder-sized clasts as discussed and shown by Biek and others (2003). The Cedar Bark (4), Clyde Lake (5), Pine Ridge (6), Witts Lake (7), Horseshoe (19), and Acorn (10) slides originated in the glacial till (Table 2a). However, the depth to the Keetley Volcanics in the northeast part of the study area is unknown: it is possible that the deeper-seated Clyde Lake (5), Pine Ridge (6), and Witts Lake (7) landslides involve the underlying Keetley Volcanics (Ashland and Hylland, 1997).

In the southeastern half of Timber Lakes, we observed several exposures of the Keetley Volcanics. Because the area was not mapped by Biek and others (2003), we are uncertain which subdivision of the Keetley Volcanics underlies southeastern Timber Lakes Estates. A percolation test pit and a shallow excavation at lots 52 and 537, respectively (Plate 1, Sheet 3), exposed Keetley Volcanics at depths of 5–7 ft below the land surface. The material is poorly to moderately consolidated and is characterized by a light gray, fine-grained matrix containing hornblende, biotite, and pebble- to cobble-sized volcanic and lithic fragments. Overlying the Keetley Volcanics at these locations is a brown, heterogeneous, poorly sorted, unconsolidated material interpreted to be glacial till. We observed an excellent exposure of the Keetley Volcanics, labeled as 'H' on Plate 1, Sheet 3, in a Lake Creek streamcut on the east side of the creek near lot 658. Thick, north-dipping (Table 1) beds display similar lithologic characteristics to the localities described above. At location 'H', soft, damp, fine-grained material with Keetley Volcanics lithology can be found between bedding planes, probably indicating a zone of alteration by groundwater flow. The contact between the Keetley Volcanics and overlying till is approximately 7 ft above stream level. Taking into account the above observations, the shallow landslides in southeastern Timber Lakes are derived from glacial till and colluvial hillslope deposits (Table 2a). The deeper-seated slides (Blazing Star (15), Birch (16), Tanglewood (17), and Blue Spruce (18) slides) are probably failing in the Keetley Volcanics (Table 2a), although the possibility of failure in the glacial till cannot be ruled out, especially if locally thick till deposits exist.

4.2 Landslide Morphology

On Plate 1, landslide scarps are the zones between the scarp line symbol (with hachures pointing downhill) and the uphill edge of the shaded landslide deposit. With the exception of the Pine Ridge (6), Westview (1), and Aspen (11) landslides and the recent shallow debris slides, landslide scarps in Timber Lakes have been rounded by erosion and vegetated, although the topographic relief produced by the scarps usually remains significant. Minor scarps are common features of landslides in Timber Lakes (Table 2b; Plate 1). Minor scarps represent differential movement within a landslide or secondary landslides within a larger, host landslide. Secondary landslides within host landslides are more easily saturated by water, require smaller driving forces to cause movement, and have a greater frequency of movement than the host landslide (Cronin, 1992). Minor scarps in the Westview (1), Beaver Bench (2), Clyde Lake (5), Pine Ridge (6), Witts Lake (7), Horseshoe (19), and Blue Spruce (18) slides represent local reactivation of these landslides (Plate 1). However, only scarps in the Westview (1) and Pine Ridge (6) slides are fresh enough to conclusively indicate recent local reactivation. It is uncertain whether other minor scarps in landslides in Timber Lakes occurred during original movement or subsequent reactivation.

A feature we interpret to be a transverse ridge is present on the Westview landslide (1) (Plate 1, Sheet 1; Table 2b). Transverse ridges are small ridges on the foot of a landslide that trend perpendicular to the direction of movement. Transverse ridges are caused by compressional stresses in the accumulation zone of the landslide.

Excluding the Pine Ridge (6), Westview (1), and possibly the Cottonwood slides (3), the hummocky topography of landslides in the northwestern half of Timber Lakes has been muted. With the possible exception of the Blue Spruce slide (18), the landslides in the southeastern portion of the subdivision generally have sharp, well-defined hummocky topography. Evacuated areas are present in some landslides in Timber Lakes (Table 2b; Plate 1). Evacuated areas, trough-like features where material has been removed by landsliding or debris sliding, range in scale from a few meters across and tens of meters long to tens of meters across and hundreds of meters long.

The Blazing Star (15), Birch (16), and Blue Spruce (18) slides, all located in southeastern Timber Lakes, display back-tilted surfaces at the base of the main scarps of the slides (Plate 1, Sheets 3 and 4). The back-tilted surfaces catch water to form ephemeral "trapped" ponds (Table 2b). An additional notable feature on the Blue Spruce slide (18) is a possible debris flow deposit (18a), visible as a small lobe in the northwestern part of the slide area (Plate 1, Sheet 4). Field observations reveal that the lobe is poorly sorted, but contains approximately 40% boulders.

The Horseshoe slide (19) initiated as a rotational slump in the glacial till (Table 2a). Below a moderately steep internal scarp, slide material has apparently been removed, probably by repeated debris flow events (Plate 1, Sheet 2). A small mass of material at the northern end of the scarp area, deflecting Lake Creek to the north, is most likely a debris flow deposit (Plate 1, Sheet 2).

The Westview (1) and Cottonwood (3) landslides are classified as rock slide-earth flows under the Cruden and Varnes (1996) classification (Table 2a). The slides probably initiated as rotational rock slumps in the Keetley Volcanics, hence the first descriptor. The Cedar Bark slide (4) is classified as an earth slide-earth flow; it initiated as a rotational slump in the glacial till. Because the three slides now exhibit internally deformed, lobate, fan-like morphology, and have traveled a significant distance from their source area, the slides are best classified as earth flows. Earth flows are common in weathered clay-bearing rocks on moderate slopes with adequate moisture (Cruden and Varnes, 1996), all of which are present where the Westview (1) and Cottonwood (3) landslides are located. Clay-bearing materials are prone to slope failure because clays have low internal friction values. Internal friction is a measure of the resistance to sliding forces within a mass of material. Additionally, the strength of clays is lowered by the presence of water, creating additional instability. The presence of phreatophytes and small streams on both slides and springs on the Westview slide (1) indicate the presence of shallow groundwater (Plate 1, Sheet 1; Table 2b).

The Westview landslide (1) locally exhibits signs of recent movement (Table 2b). Features that suggest activity can be found in the narrow, upper portion of the slide (Plate 1, Sheet 1). Fresh scarplets, ground cracks, and hummocky topography are present on a small slope along a southern lateral scarp (Plate 1, Sheet 1; Table 2b). The lateral scarp is about 300 ft long. Ground cracks perpendicular to the lateral scarp are located approximately 200 ft west of the disturbed slope although the cracks may be manmade features. At the toe of the landslide, a grove of quaking aspen contains leaning and dead trees (Plate 1, Sheet 1). Brief examinations of structures built on the Westview slide (1) revealed no signs of foundation cracking or other strain.

Other landslides in Timber Lakes show signs of recent movement. The Pine Ridge slide (6) exhibits numerous fresh scarps and ground cracks in the reactivated portion of the slide (Plate 1, Sheet 2)(Ashland and Hylland, 1997). The Aspen slide (11), a small rotational earth slide above Lake Creek (Plate 1, Sheet 3), was apparently triggered historically when the slope was cut for development (Kohler, personal communication, 2000). The Aspen slide (11) has fresh ground cracks, main, lateral, and minor scarps in the southeastern portion of the slide where a significant portion of the slide material has moved down slope (Plate 1, Sheet 3; Table 2b). Beyond this zone, the main scarp of the Aspen slide (11) continues another 160 ft to the northwest where it dies out and small, lateral, *en echelon* ground cracks and scarplets extend downhill to the end of Aspen Road, trending perpendicular to the main scarp (Plate1, Sheet 3). In addition, fresh, shallow debris slides (12, 13, 14) are very common on the steep slopes above Lake Creek (Plate 1). The debris slides often display fresh main scarps and leave behind evacuated areas and paths of hummocky, coarse debris and broken trees. Shallow debris slides are also common on the feet of deep-seated landslides above Lake Creek, such as the Tanglewood slide (17) (Plate 1, Sheet 3) and Pine Ridge slide (6)(Ashland and Hylland, 1997). At least one debris slide occurred where drainage has been diverted onto a steep slope above Lake Creek. Due to the high number of debris slides in Timber Lakes, mapping all debris slides was beyond the scope of this study. It is also possible that there are other landslides or landslide-related features in Timber Lakes that escaped our notice.

4.3 Hydrologic and Vegetation Features

Shallow groundwater contributes to the instability of a landslide by increasing the pressure of water (pore pressure) contained within the voids of the slide mass. With increasing pore pressure, the grains of the slide mass approach a state of buoyancy by the pore water, reducing the amount of resistance the grains offer to shear forces that drive landslide movement. Springs, streams, ponds, and lakes are usually proof of shallow groundwater. The locations of springs and ponds on or near landslides have been mapped (Plate 1) and tabulated (Table 2b). Ponds and small lakes are common throughout Timber Lakes; some small lakes have been dammed to form reservoirs (Plate 1). The Clyde Lake (5), Pine Ridge (6), and Witts Lake (7) slides are located on slopes below reservoirs (Plate 1, Sheets 1 and 2).

Evidence from field observations indicates that shallow groundwater is abundant in the Westview (1) landslide. Two springs are located in the landslide (Plate 1, Sheet 1; Table 2b). Both springs flowed steadily from the time of first observation in mid-July to the most recent observation at the end of October (normally the driest part of the year), suggesting that groundwater flow through the slide is persistent. Additionally, unusual amounts of vegetation are present on the slide mass for its aspect and elevation, indicating near-surface groundwater. Dense groves of quaking aspen occupy a major portion of the west-facing landslide. Thick, tall grass can be found in the vicinity of the disturbed slope mentioned above.

The Timber Lakes subdivision is drained and bounded on the northeast by Lake Creek. Streams add to the instability of a landslide when they erode the toe of a slide, decreasing the forces that resist movement of the slide mass. Lake Creek is currently undercutting the Clyde Lake (5), Pine Ridge (6), Witts Lake (7), Tanglewood (17), Blazing Star (18), and Aspen (11) landslides (Plate 1). Additionally, small perennial streams are cutting the toes of the Westview (1), Beaver Bench (2), Cottonwood (3), Acorn (10), and Blue Spruce (18) slides (Plate 1, Sheets 1 and 4).

Vegetation is important to consider in landslide studies because changes in vegetation occur where the soil is disturbed by downslope creep or sliding, and in areas of shallow groundwater. Roots add strength to the soil, and may act to stabilize the slopes. Sage and oak brush grow on slopes at lower elevations in the study area, except where stands of aspen, willows, and grass grow in areas of shallow groundwater. An aspen and conifer forest is developed at higher elevations in the southeastern part of the subdivision, and along the north-facing banks of Lake Creek. Tree roots help to stabilize the soil in these areas, particularly on the steep slopes above Lake Creek (e.g. – Ashland and Hylland, 1997).

Leaning and curved trees are common in Timber Lakes and have been mapped (Plate 1) and tabulated when on a landslide (Table 2b). Just below the main scarp of the Aspen slide (11), a 60 ft tall aspen tree is leaning uphill, probably due to rotational soil movement on that landslide (Plate 1, Sheet 3). A grove of quaking aspens 30–40 ft tall is leaning downhill below a minor scarp in the Witts Lake landslide (7), indicating possible recent movement of that small secondary slump (Plate 1, Sheet 2). In the southeastern portion of the subdivision, pine trees 60–70 ft tall and 2–3 ft in diameter with shallow to deep bends in the trunks are common. A grove of cottonwoods with trees around 100 ft tall and 2–3 ft in diameter is present on the toe of the westernmost portion of the Tanglewood slide (17) (Plate 1, Sheet 3). The grove contains several trees that are bent and/or leaning. When located in a landslide area, leaning or curved trees are usually found on the main scarp or on the toe of a slide. The Aspen (11), Blazing Star (15) and Tanglewood (17) slides have leaning and/or curved trees growing on the main scarps, while the Westview (1), Birch (16), and Tanglewood (17) slides have leaning and/or curved trees in the toe areas (Plate 1, Sheets 1 and 3; Table 2b). Leaning or curved trees in the scarp area of a landslide may indicate shallow slope failure of the scarp material. Leaning or curved trees in the toe area of a landslide may result from shallow or deep-seated movement of the toe. However, we observed no other conclusive evidence for deep-seated movement on the Westview (1), Birch (16), or Tanglewood (17) slides. As mentioned above, localized shallow soil creep or snowpack creep may cause leaning and curved trees. Thus, the presence of leaning or curved trees does not necessarily indicate deep-seated slope failure.

5.0 SLOPE STABILITY ANALYSIS

5.1 Description of Selected Landslides

The Cedar Bark, Beaver Bench, and Blazing Star slides were the three landslides selected for preliminary slope stability analysis (Fig. 1). We selected the Cedar Bark slide to investigate the frictional properties of the glacial till because we are confident that the slide occurred in the glacial deposits. Likewise, we selected the Beaver Bench slide to constrain the frictional properties of the Keetley Volcanics because we are confident that the slide occurred in the volcanic deposits. Additionally, the Beaver Bench slide displays the most ideal rotational slump geometry of the landslides in the Keetley Volcanics. We chose the Blazing Star slide for study because, like several other landslides in Timber Lakes, the toe of the slide is being modified by Lake Creek.

5.1.1 Cedar Bark Slide

The Cedar Bark slide, located in northern Timber Lakes (Fig. 1, Fig. 2), initiated as a rotational earth slide in glacial till and changed into an earth flow down slope. The landslide has a west aspect and an area of 12 acres. The distance between the main scarp and the most distal tip is approximately 1,340 ft (Fig. 2). The width of the landslide deposit ranges from approximately 1,000 ft at the foot of the slide to about 150 ft near the head (Fig. 2).

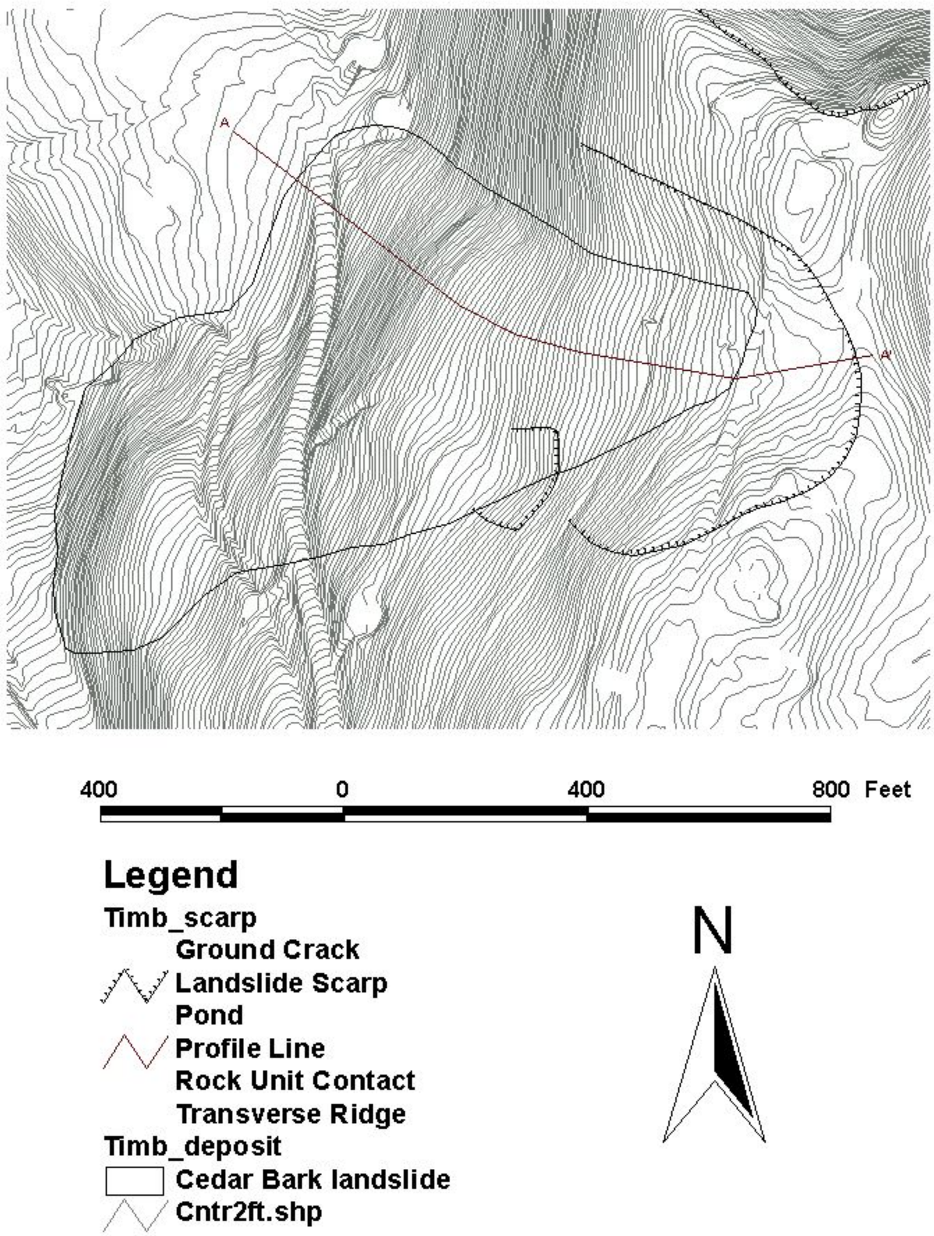
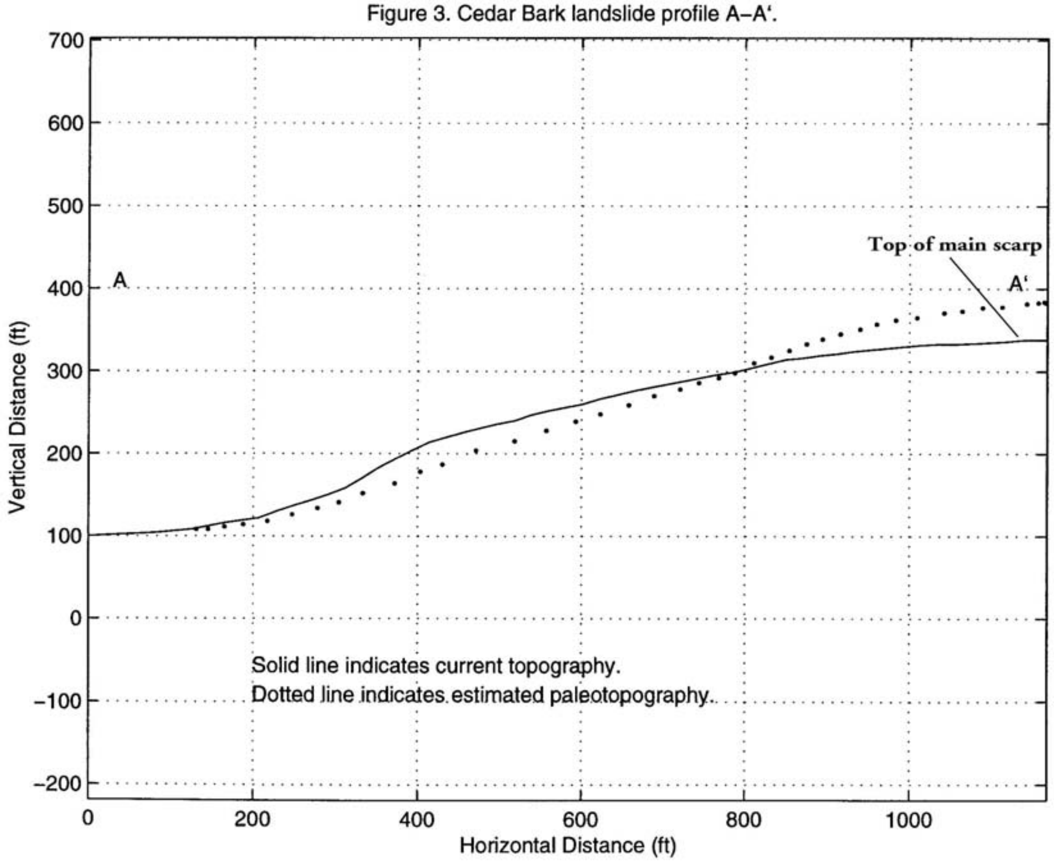


Figure 2. Map of Cedar Bark landslide.

The Cedar Bark slide displays a very subdued horseshoe-shaped main scarp east of the slide deposit (Fig. 2). The landslide also contains a subtle, bowl-shaped minor scarp on the left flank of the slide deposit (Fig. 2). About midway through the slide, an abrupt change in slope occurs (Fig. 2). This ridge, trending perpendicular to the direction of movement, is interpreted to be directly above the toe of the initial rupture surface. Down slope from this point, the slide apparently behaved as an earth flow. The profile A-A' (Fig. 2) used for modeling of the Cedar Bark slide is shown in Figure 3. The average slope along A-A', from the head of the landslide deposit to the toe is 15 degrees (Table 3).

Figure 3. Cedar Bark landslide profile A–A'.



5.1.2 Beaver Bench Slide

The Beaver Bench slide, located in northwestern Timber Lakes (Fig. 1, Fig. 4), is a rotational rock slide in the Tuffaceous Unit of the Keetley Volcanics (Biek and others, 2003). The landslide has a northeast aspect with an area of approximately 20 acres. The distance between the main scarp and the most distal tip is approximately 1,220 ft (Fig. 4). The greatest width of the landslide deposit is about 1,390 ft (Fig. 4).

The Beaver Bench slide has a prominent bowl-shaped main scarp immediately southwest of the landslide deposit (Fig. 4). The landslide also contains a minor scarp and secondary slide deposits at the northern edge of the landslide (Fig. 4). A small perennial stream runs along the toe of the Beaver Bench slide. The profile B-B' (Fig. 4) used for modeling of the Beaver Bench slide is shown in Figure 5. The average slope along B-B', from the head of the landslide deposit to the toe is 8 degrees (Table 3).

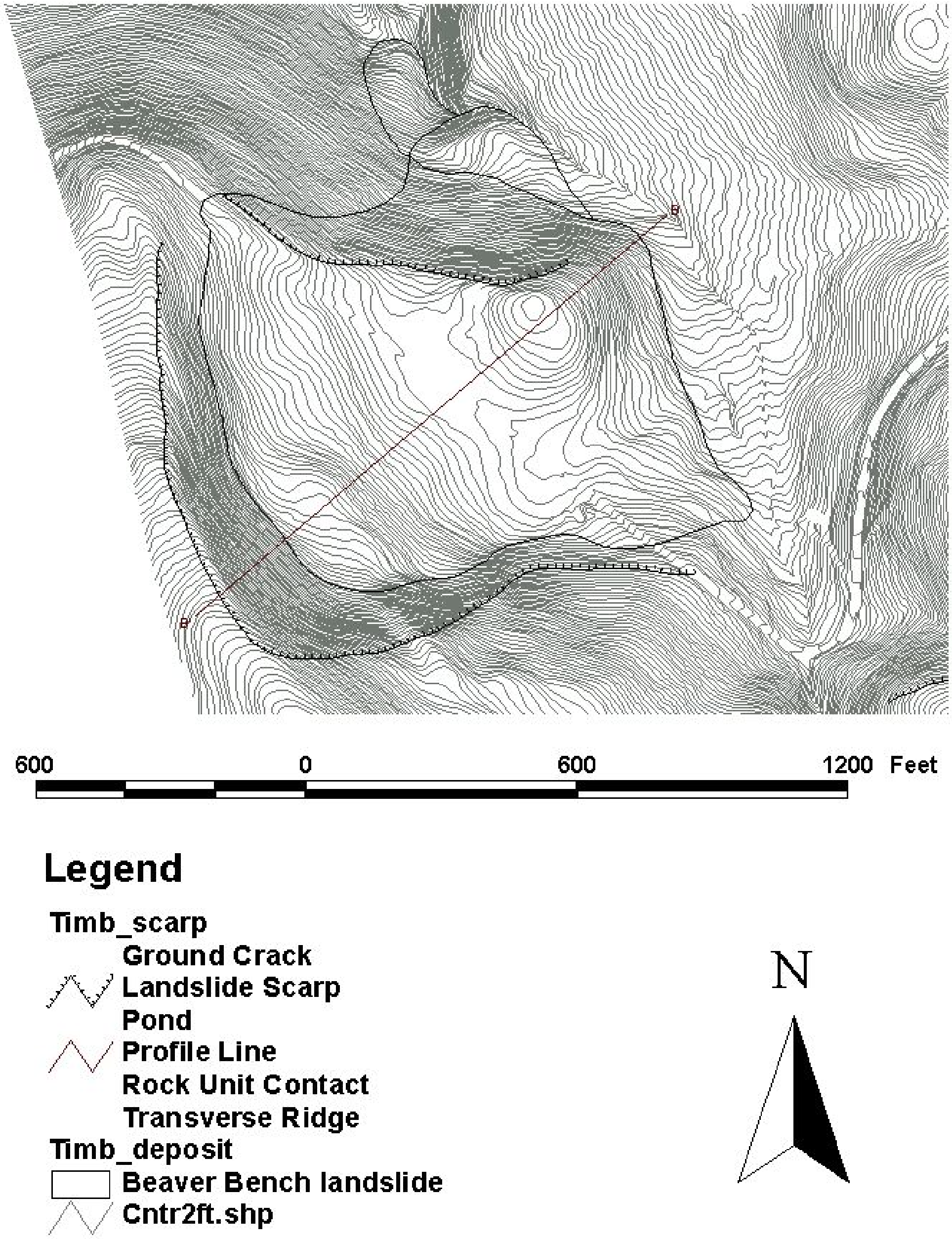
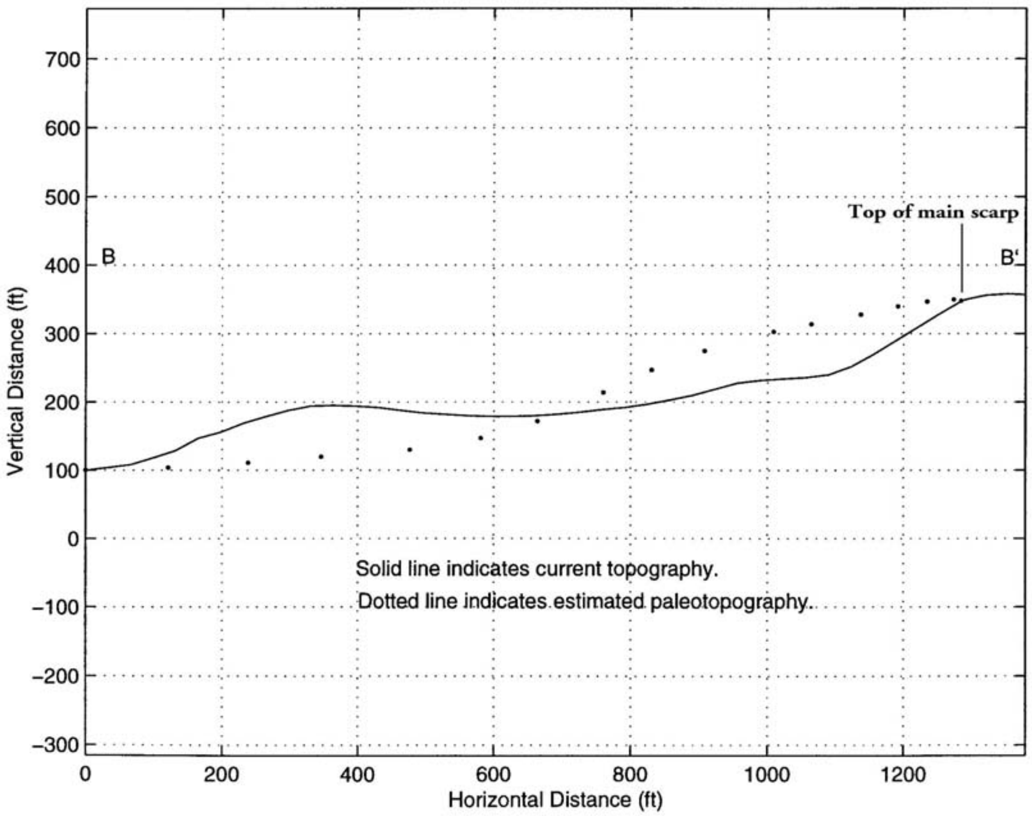


Figure 4. Map of Beaver Bench landslide.

Figure 5. Beaver Bench landslide profile B–B‘.



5.1.3 Blazing Star Slide

The Blazing Star slide, located in southeastern Timber Lakes (Fig.1, Fig. 6), is a rotational rock-earth slide, probably occurring in the Keetley Volcanics and incorporating overlying glacial till. The landslide faces east and incorporates an area of about 36 acres. The distance between the main scarp and the most distal tip is approximately 1,020 ft (Fig. 6). The landslide deposit is about 3,400 ft wide (Fig. 6).

The Blazing Star slide has a prominent, primarily linear main scarp immediately west of the landslide deposit for roughly the southern two-thirds of the landslide (Fig. 6). A prominent main scarp is absent for most of the northern one-third of the landslide (Fig. 6). About where the continuous main scarp dies out, a series of minor scarps radiate out to the southeast (Fig. 6). These features suggest scissor-type motion of the slide mass about a point located where displacement along the main scarp dies out. On the slopes directly above Lake Creek, where the creek is actively eroding the toe of the slide, there are numerous, steep, discontinuous escarpments that may be minor landslide scarps or debris slide scarps. The Aspen slide, which was initiated by a developer cutting a steep slope above Lake Creek, is adjacent to the southeastern boundary of the Blazing Star slide (Fig. 6). The profile C-C’ (Fig. 6) used for modeling of the Blazing Star slide is shown in Figure 7. The average slope along C-C’, from the head of the landslide deposit to the toe is 13 degrees (Table 3).

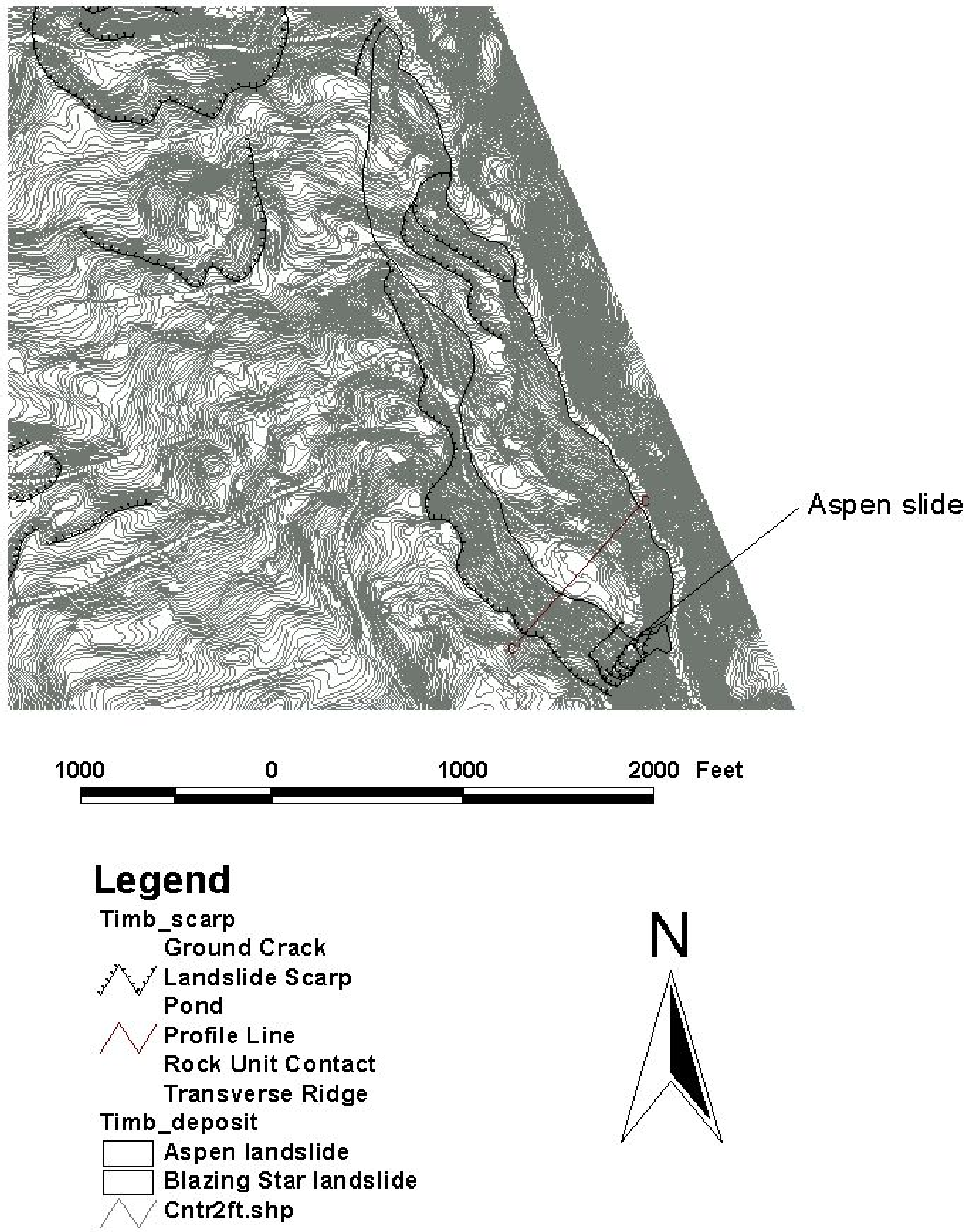
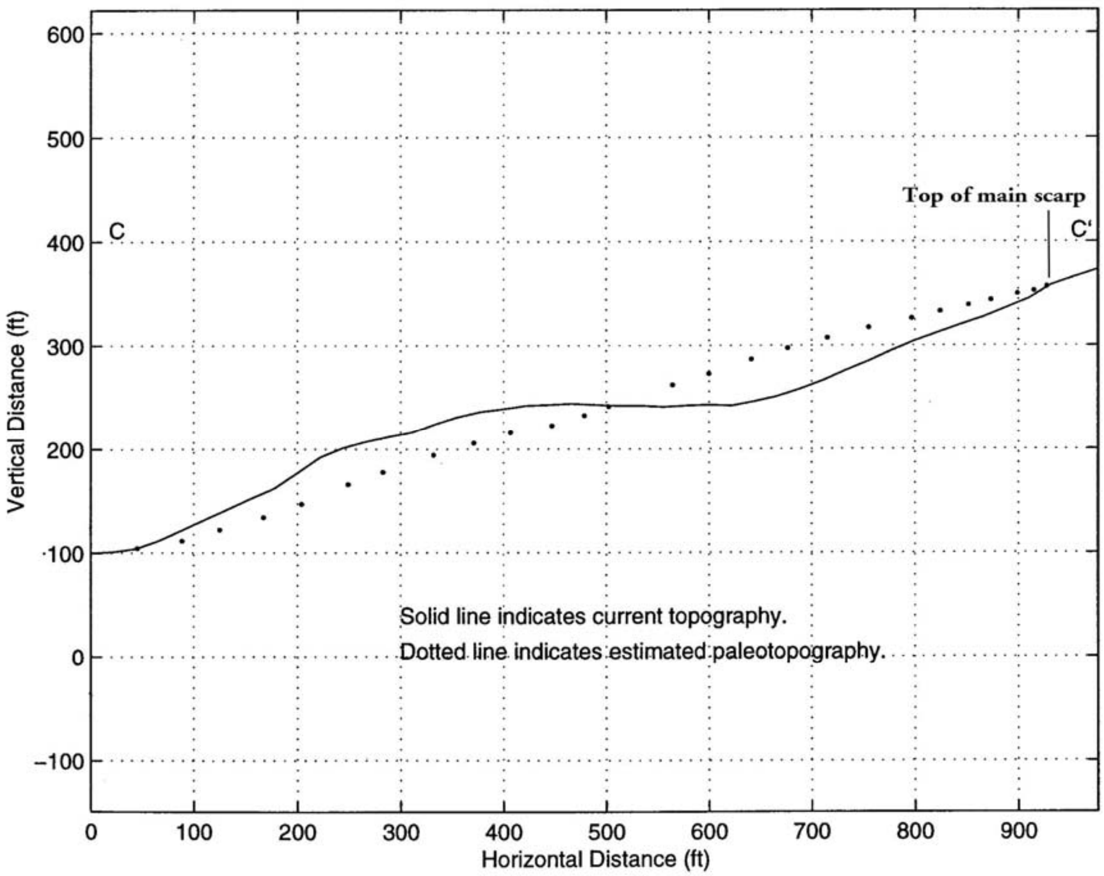


Figure 6. Map of Blazing Star landslide.

Figure 7. Blazing Star landslide profile C–C‘.



5.2 Scope and Method

The slope stability analyses were confined to two-dimensional sections of landslides with circular slip surfaces. We specified the unit weight of the soil as 121 lbs/ft^3 for moist soil and 136 lbs/ft^3 for saturated soil regardless of the type of material comprising the slide. These were the average in situ and saturated unit weights of glacial till measured in the Pine Ridge slide by Ashland and Hylland (1997). We varied the friction angle of the slide material from 15–40 degrees: Eyles and Sladen (1981) report minimum residual friction angles of 15 degrees for glacial till and most peak friction angle values for glacial till fall below 40 degrees (e.g., Eyles and Sladen, 1981; Bell, 2002; Müller and Schlüchter, 2001). We defined the cohesion of the slide material as zero. We varied the configuration of the groundwater table to simulate 1) dry conditions in the slide mass, 2) groundwater at approximately mid-level in the slide mass, and 3) total saturation of the slide mass with the groundwater table at the land surface.

The scope of this study is limited by a dearth of information as to the subsurface configuration of the slip surfaces and groundwater tables, and the lack of data for the mechanical properties and specific weights of the deposits. Given this situation, a constant specific weight and no cohesive strength were assigned to all of the deposits. Setting the cohesion to zero implies that the frictional strength is large compared to the cohesive strength. Some outcrops of the Keetley Volcanics are more consolidated than others, and those rocks may have greater cohesive strength than the unconsolidated till and colluvium. If the cohesive strength is significant, then the true peak and residual friction angles may be lower than estimated by stability modeling. The shape of the circular failure surface is not dependent on the friction angle of the deposit when there is no cohesion. Additionally, when residual shear strength is attained, the failure plane will have little or no cohesion (e.g., Bell, 2002).

We modeled slope stability with the program PC-STABL5M, using a modified Bishop method (Federal Highway Administration, 1988). PC-STABL5M calculates the factor of safety of a slide mass under conditions of either static, or pseudo-static loading. Only static equilibrium was used in this study; we did not implement the pseudo-static solution, which is designed to incorporate the effects of ground acceleration created by an earthquake. Input data for PC-STABL5M modeling includes the geometry of the land surface, the physical parameters of the soil mass, and the configuration of the water table. The position at which the slip surface intersects the land surface is constrained by field observations where applicable. Several hundred trial slip surfaces are then calculated automatically; the ten surfaces with the lowest factors of safety are reported and plotted.

Parameters and features investigated included 1) peak and residual friction angles, and 2) identifying segments of the slide mass that are least stable under present conditions. Soil friction angle is the arctangent of the coefficient of friction of the slide material. This coefficient is usually greater in undisturbed deposits than in the sheared material located along the slip surface at the base of the slide mass. Estimates of peak friction angle require restoration of the slide mass to the original configuration of the hillside prior to failure (e.g. – Ashland and Hylland, 1997). Residual friction angle is constrained by modeling the slide mass in its present configuration. However, the present topography of a landslide may not be representative of the topography of the landslide at the time of last movement. Hence, our estimates for residual friction angles represent lower bound values at each specified groundwater level for the model configuration. Residual friction angle is then the arctangent of the coefficient of friction along the slip surface at the base of the slide. We also calculated the average slope for each landslide deposit from the head of the slide mass to the toe by dividing the change in elevation between head and toe by the horizontal distance between head and toe, as determined from the landslide map (Plate 1, Table 3).

Restoration of the slide mass to the original configuration of the hillside is open to subjective error. We applied three types of constraints to the problem; 1) the original slope profile is a continuation of the ground surface above the crown and below the toe of the slide, 2) the profile must be concave upward to mimic natural slopes in the area, and 3) area balancing. The area balancing constraint is derived from the observation that two polygons are created when the original slope profile is superimposed upon that of the slide. One polygon is located below the point of intersection of the two profiles, and the other is upslope from that point (Fig. 3, 5, 7). The top and base of the lower polygon are the post-slide and pre-slide profile lines, respectively. Conversely, the top and base of the upper polygon are the pre-slide and post-slide profile lines, respectively. This configuration arises because the upper part of the slide mass moved downward relative to the original ground surface during rotational slumping and sliding, while the lower part of the slide moved upward. The areas of these two polygons must therefore be equal for any acceptable configuration of the pre-slide ground surface, assuming that there is no mass transport normal to the plane of the profiles.

We wrote a computer program to partly automate generation of acceptable pre-slide ground surface profiles. The topography along the present day ground surface was entered and displayed on the computer screen. The operator then sketched a concave upward profile of a candidate pre-slide ground surface using the computer cursor. The areas of the two polygons bounded by the pre-slide and present day profile lines were then calculated. If the areas did not balance, then a new pre-slide profile was sketched. This process was repeated until the areas of the upper and lower polygons were equal. The resulting pre-slide profile was not unique, but at least it satisfied the three constraints we imposed for acceptable surface profiles.

5.3 Simulation Strategy

We studied each landslide to estimate the following parameters or features:

- Case 1: Peak friction angle.
- Case 2: Lower bound residual friction angle and stability of the slide in its present configuration.
- Case 3: Location of the most critical, or least stable, segment of the landslide.

We found peak and residual friction angles by performing several simulations in which the groundwater level and friction angle were varied between specified limits. The preferred estimate of friction angle was that angle at which the calculated factor of safety was 1.0 for a specified groundwater level. We found this preferred value by interpolating the factor of safety - friction angle curve. Peak friction angles were determined using the constraints outlined below for Case 1 simulations and residual friction angles were estimated using Case 2 simulations. Positions of the main scarps and toes were either fixed based on field observations, or allowed to vary within a specified lateral distance. The toe of the Cedar Bark slide was located in the vicinity of an abrupt change in slope in the lower part of the slide. This slide apparently transitioned into an earth flow in its lower reaches, and the toe of the slip surface was buried by debris. The toes of the Beaver Bench and Blazing Star slides were located in the creek beds at the base of the slides. The positions of the main scarps were well constrained from mapping of all three of the slides.

The distribution of groundwater within a slide mass is a critical feature for modeling slope stability. Groundwater pressure decreases the effective normal stress across failure surfaces and therefore decreases the factor of safety. The configuration of the groundwater table is not known for slides in the Timber Lakes subdivision, neither at present nor in the past. Given the lack of constraining data, we modeled slides with no groundwater, groundwater level at approximately mid-level throughout the slide mass, and groundwater level at the surface. These three configurations can be used to crudely estimate the peak and residual friction angles required to cause instability over a wide range of hypothetical groundwater conditions. That is, by inspecting the results for the three cases, one can roughly 'estimate' predicted friction angles for other groundwater conditions within the slide mass. The dry conditions provide an absolute lower bound friction angle estimate that is theoretically possible, but probably unrealistically low. Engineering practice and experience suggest that groundwater is probably present within the slide mass at the time of failure; this contention is supported by the reactivation of the Pine Ridge slide (Ashland and Hylland, 1997) which occurred following unusually wet seasons in the early to middle 1980s. We suspect, but cannot prove at this time, that the friction angles predicted by the mid-level to saturated groundwater configurations are the most realistic values.

Partial reactivation of landslides because of changes in water content, loading, and surface geometry is an important consideration when planning and approving developments. The most critical part of a slide is defined here as that segment in which the model slip surfaces produce the lowest factor of safety. The modeling proceeded by a process of elimination; we distributed trial slip surfaces of various radii at random in different parts of the slide until those segments with the lowest factors of safety were isolated. The groundwater conditions and friction angles we used to evaluate slope stability during the trials are outlined below.

Case 1: Initial Topography

Geometrical constraint: Fixed main scarp and with position of toe scarp constrained to a specified interval.
Groundwater Level: None, mid-slide, land surface (saturated)
Friction Angles: 40, 30, 20, 15 degrees

Case 2: Present Topography

Stability of the entire slide mass with fixed main scarp and toe at distal end of mass.
Groundwater: None, mid-level, land surface (saturated)
Friction Angles: 40, 30, 20, 15 degrees

Case 3: Location of the most critical area of present-day slide mass

Groundwater: None, land surface (saturated)
Friction Angles: 40, 30, 20, 15 degrees

Table 3. Average slope of landslide deposits.

Slide #	Slide Name	dx (ft)	dy (ft)	Slope (%)	Slope (deg)	Lithology
1	Westview	2941	569	19	11	Keetley Volcanics
2	Beaver Bench	1038	137	13	8	Keetley Volcanics
3	Cottonwood	1353	254	19	11	Keetley Volcanics
9	Valley View	519	97	19	11	Keetley Volcanics
20	Quakie Grove	228	44	19	11	Keetley Volcanics
15	Blazing Star	616	141	23	13	Keetley Volcanics?
16	Birch	779	124	16	9	Keetley Volcanics?
17	Tanglewood	1481	286	19	11	Keetley Volcanics?
18	Blue Spruce	747	187	25	14	Keetley Volcanics?
8	Ridgeline	453	175	39	21	Keetley Volcanics[1]
Average				19	11	Keetley Volcanics
4	Cedar Bark	823	215	26	15	Glacial till
10	Acorn	315	94	30	17	Glacial till
19	Horseshoe	779	98	13	7	Glacial till
11	Aspen	401	171	43	23	Glacial till
5	Clyde Lake	962	173	18	10	Glacial till?
6	Pine Ridge	1699	335	20	11	Glacial till?
7	Witts Lake	650	121	19	11	Glacial till?
12	Lake Creek	422	184	44	24	Glacial till - colluvium[2]
13	Lake Creek	422	166	39	21	Glacial till - colluvium[2]
14	Lake Creek	152	110	72	36	Glacial till - colluvium[2]
Average				24	13	Glacial till

[1] Thin, lower part of slide deposit lies on slope of Jurassic Nugget Sandstone. Slope values not used in averages.
[2] Shallow debris slides not included in slope value averages.

6.0 RESULTS

Table 4. Stability analysis results for selected landslides.

	Cedar Bark Landslide						Beaver Bench Landslide						Blazing Star Landslide					
	Case 1		Case 2		Case 3		Case 1		Case 2		Case 3		Case 1		Case 2		Case 3	
Groundwater	φ[1]	**FS[2]**	φ	**FS**	φ	**FS**	φ	**FS**	φ	**FS**	φ	**FS**	φ	**FS**	φ	**FS**	φ	**FS**
dry	40	2.86	40	3.63	40	1.59	40	2.88	40	8.36	40	1.60	40	2.86	40	3.70	40	1.47
	30	1.97	30	2.50	30	1.09	30	1.98	30	5.75	30	1.10	30	1.97	30	2.55	30	1.01
	20	1.24	20	1.58	29	1.05	20	1.25	20	3.63	27	0.97	20	1.24	20	1.61	29	0.97
	17	1.04	15	1.16	28	1.01	16	0.98	15	2.67	20	0.69	16	0.98	15	1.18	20	0.64
	16	0.98			27	0.97	15	0.92			15	0.51	15	0.91			15	0.47
	15	0.91			20	0.69												
					15	0.51												
mid-level	40	2.04	40	2.88			40	2.21	40	6.58			40	1.93	40	3.03		
	30	1.41	30	1.98			30	1.52	30	4.53			30	1.33	30	2.08		
	22	0.98	20	1.25			21	1.01	20	2.85			23	0.98	20	1.31		
	20	0.89	16	0.99			20	0.96	15	2.10			22	0.93	16	1.03		
	15	0.65	15	0.92			15	0.71					20	0.84	15	0.97		
													15	0.62				
land surface	40	1.49	40	1.93	45	1.02	40	1.50	40	4.56	50	1.02	40	1.49	40	1.97	48	0.97
	30	1.02	30	1.33	44	0.99	30	1.03	30	3.14	49	0.98	30	1.02	30	1.36	45	0.87
	29	0.98	25	1.07	42	0.92	29	0.99	20	1.98	44	0.83	29	0.98	23	1.00	40	0.73
	20	0.64	24	1.02	40	0.86	20	0.65	15	1.46	40	0.72	20	0.65	22	0.95	30	0.50
	15	0.47	23	0.98	30	0.59	15	0.48			30	0.49	15	0.48	20	0.86	20	0.32
			20	0.84	20	0.37					20	0.31			15	0.63	15	0.23
			15	0.62	15	0.28					15	0.23						

[1]φ: friction angle (deg.)
[2]FS: factor of safety

6.1 Cedar Bark Slide

Peak Friction Angles (Case 1): We estimated peak friction angles of 16, 22 and 29 degrees under dry conditions, mid-level water table, and total saturation of the slide, respectively (Fig. 8, Table 4). Sample stability analyses are shown in Figure 9.

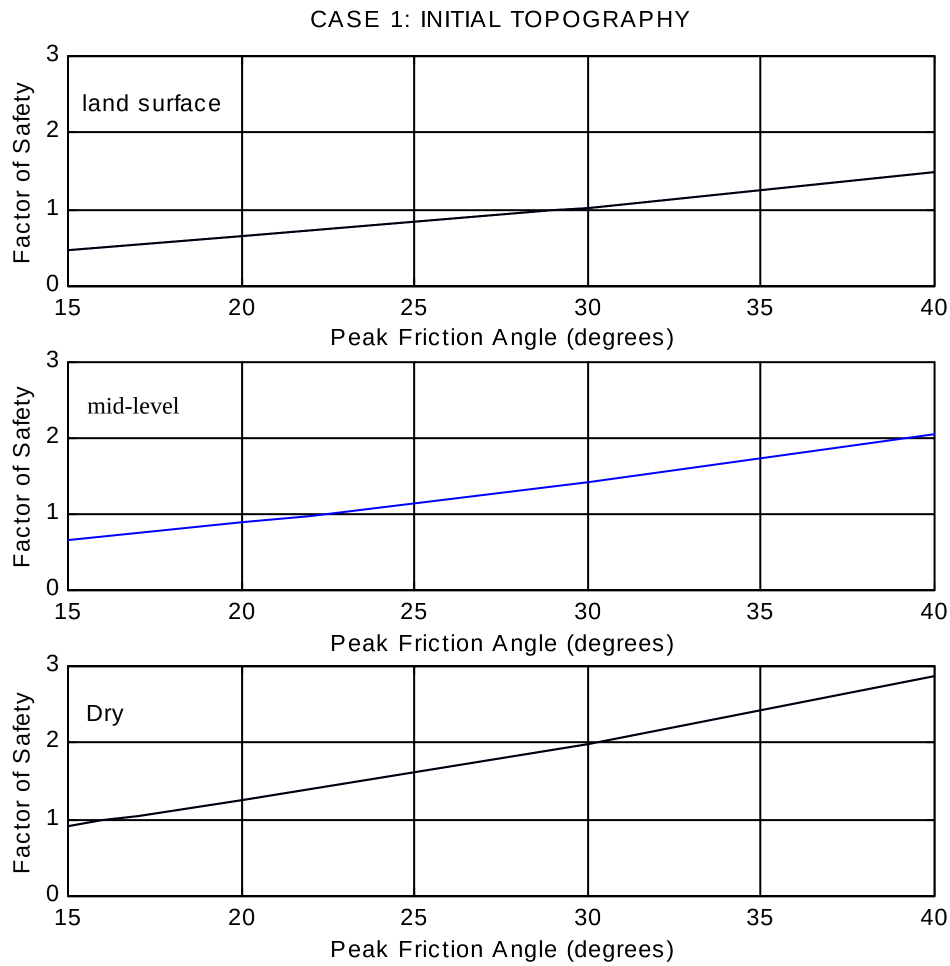
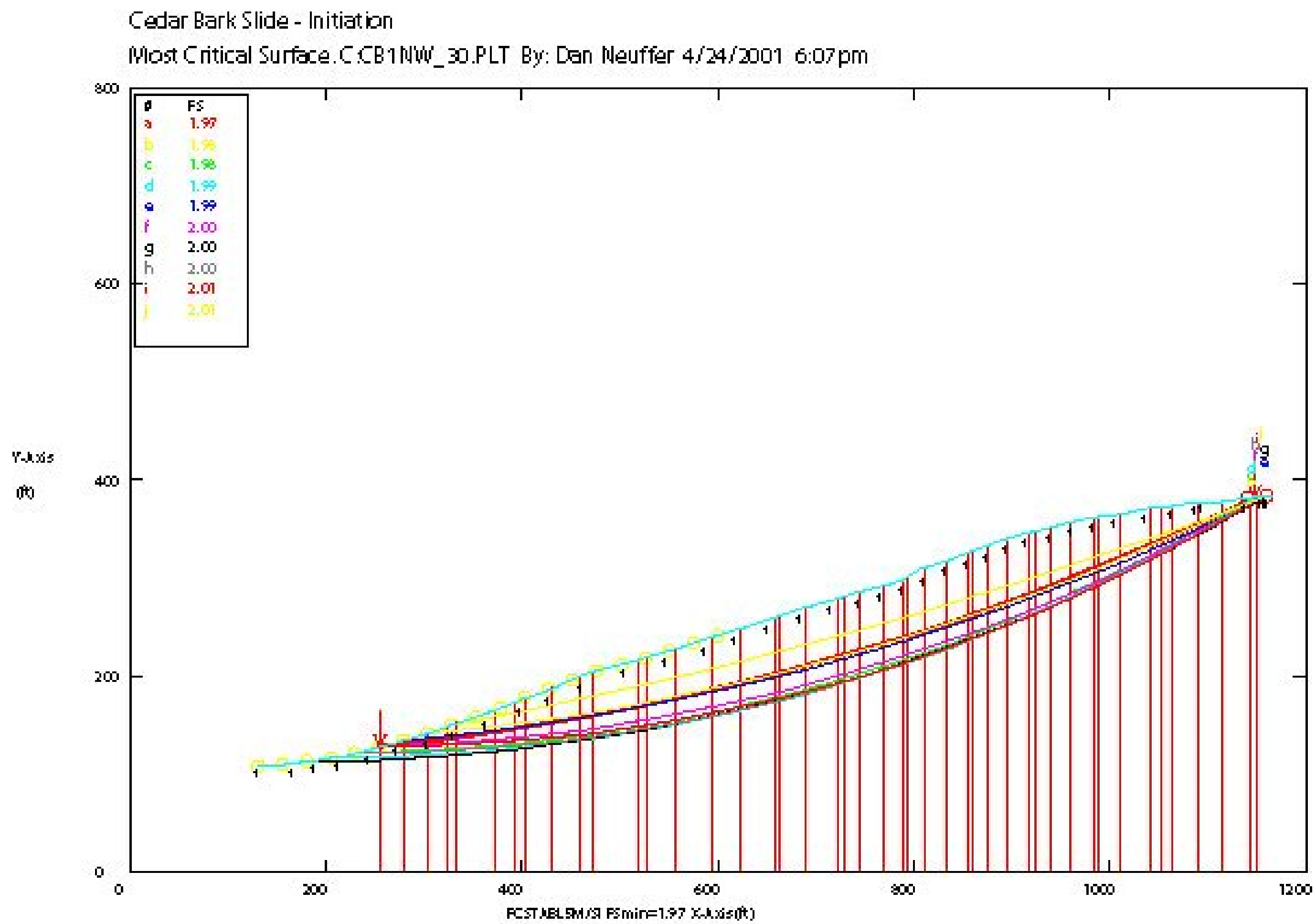
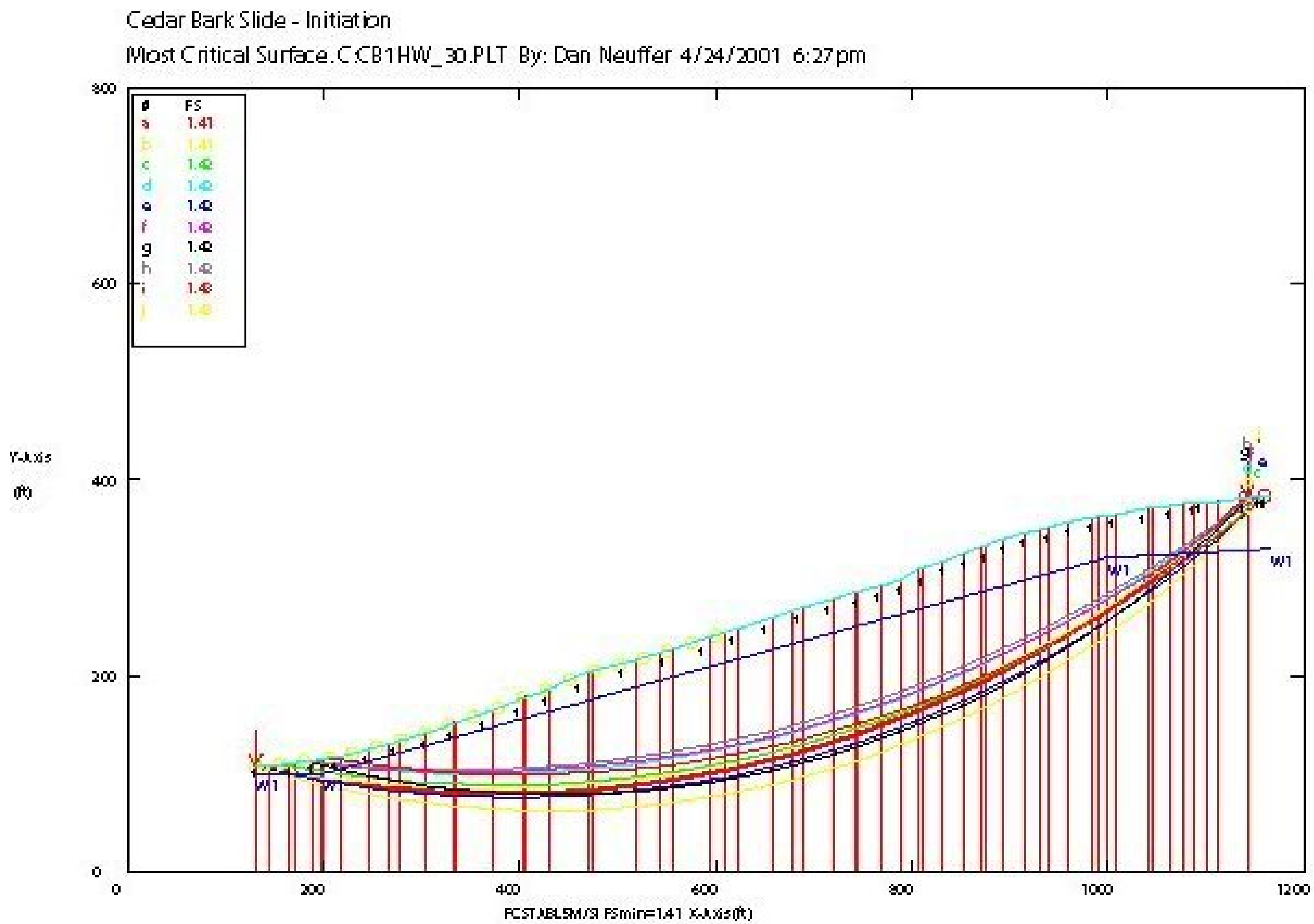


Figure 8: Factor of Safety as a function of Peak Friction Angle for the Cedar Bark landslide (Case 1 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.



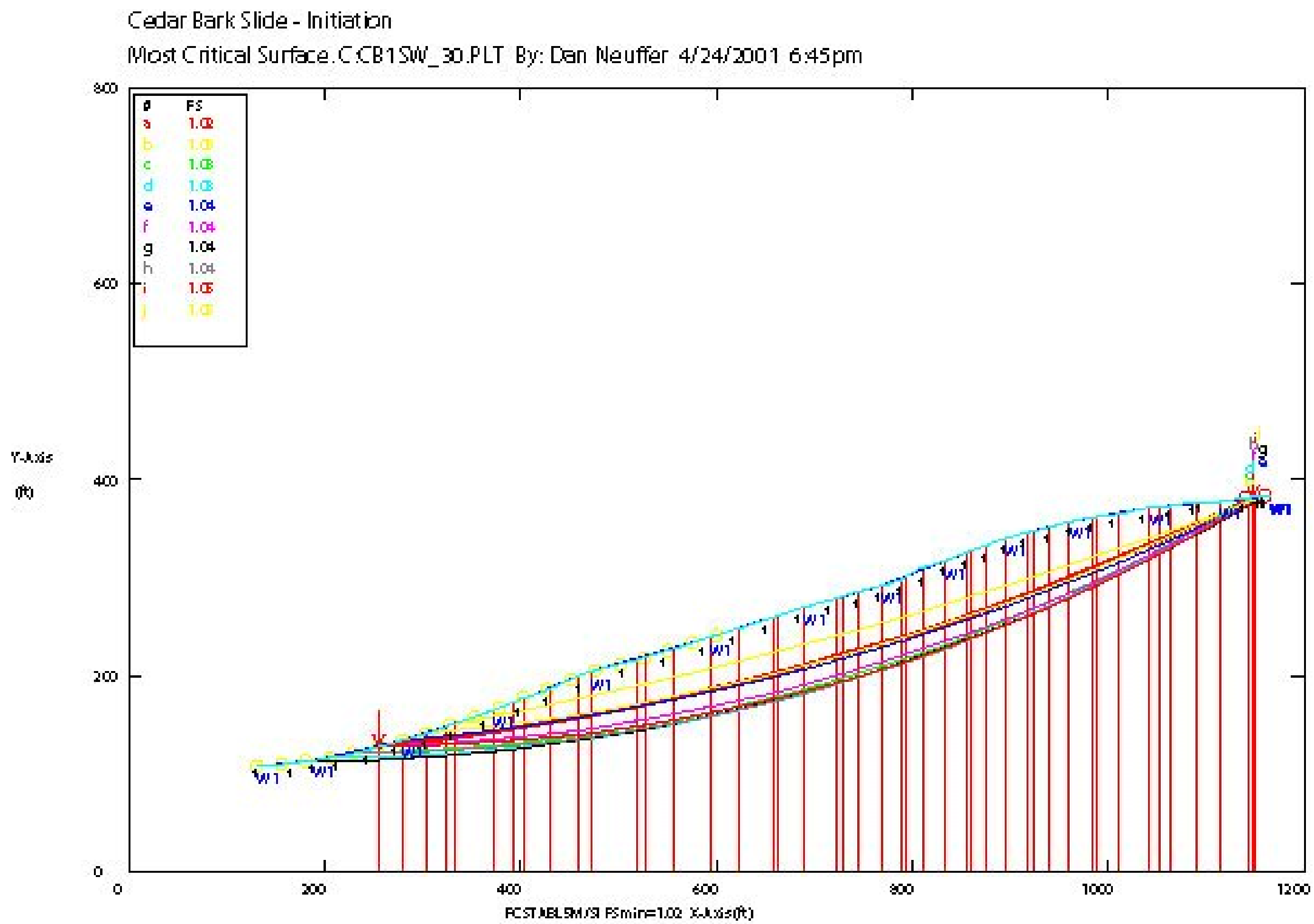
Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	till	121	136	0	30	0	0	

Figure 9a. Ten most critical slip surfaces of Cedar Bark landslide (Case 1 analysis) with no groundwater in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	till	121	136	0	30	0	0	W1

Figure 9b. Ten most critical slip surfaces of Cedar Bark landslide (Case 1 analysis) with groundwater mid-level in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	till	121	136	0	30	0	0	W1

Figure 9c. Ten most critical slip surfaces of Cedar Bark landslide (Case 1 analysis) with groundwater saturating the slide mass.

Residual Friction Angles (Case 2): The factor of safety was greater than 1.0 for residual friction angles as low as 15 degrees under dry conditions (Fig. 10, Table 4). The factor of safety was 1.0 at a lower bound residual friction angle of ~16 degrees and mid-level groundwater table. The lower bound residual friction angle was ~23 degrees under simulated conditions of groundwater saturation. Sample stability analyses are shown in Figure 11.

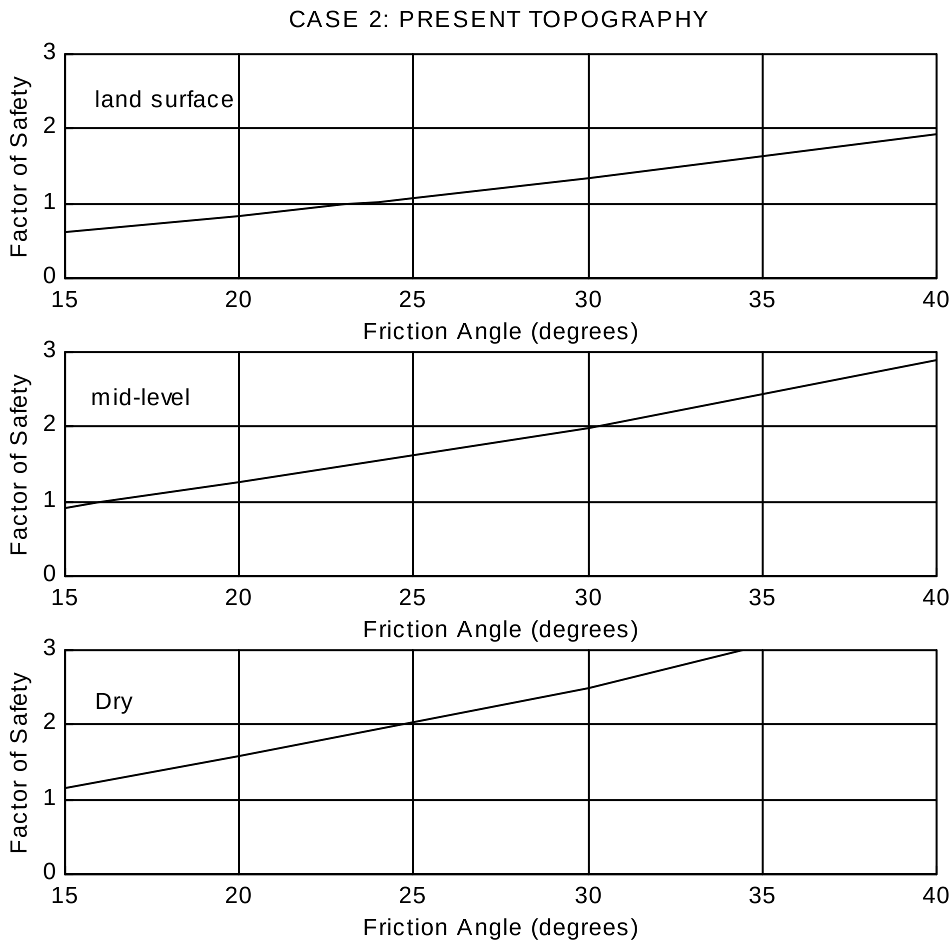
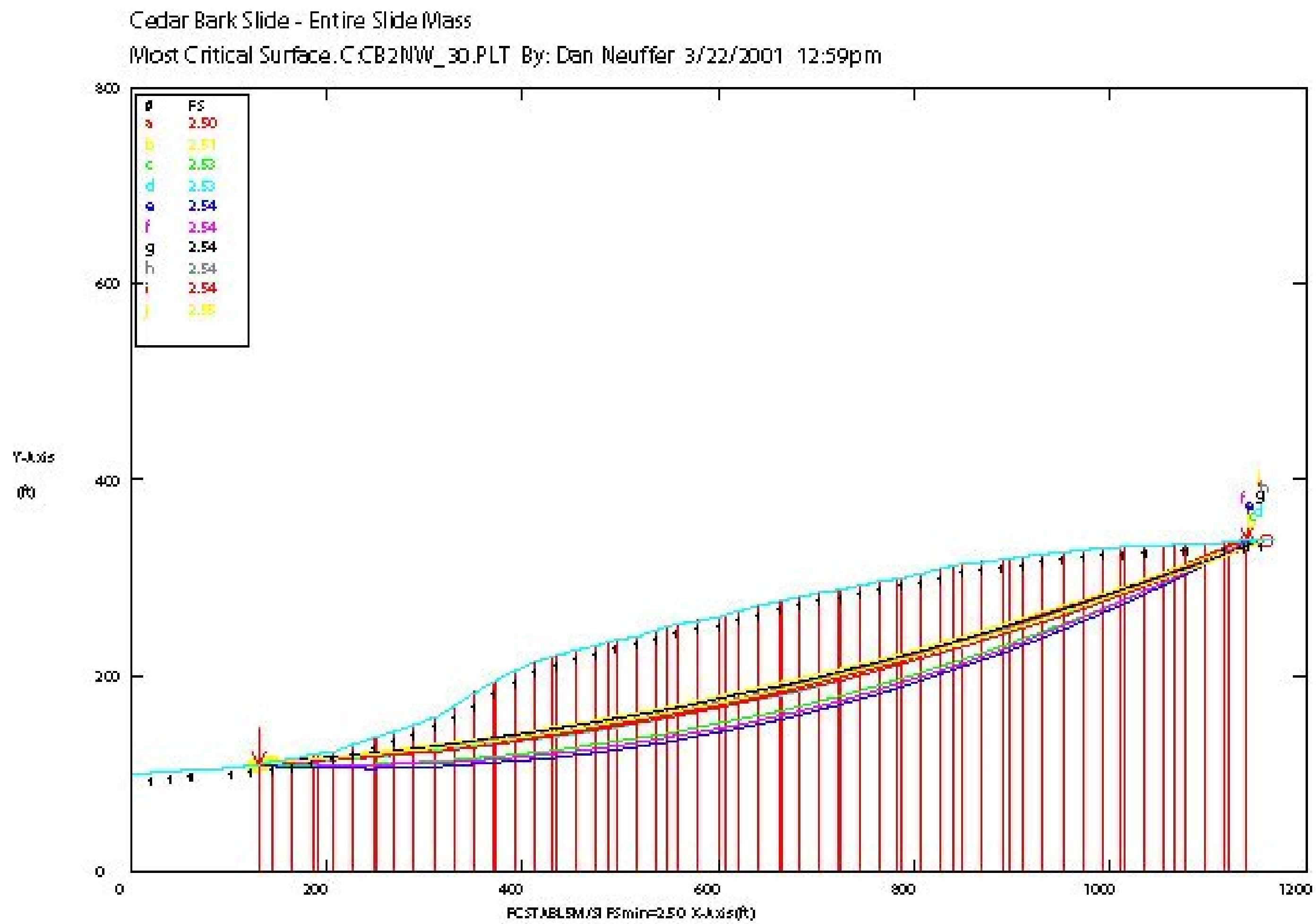
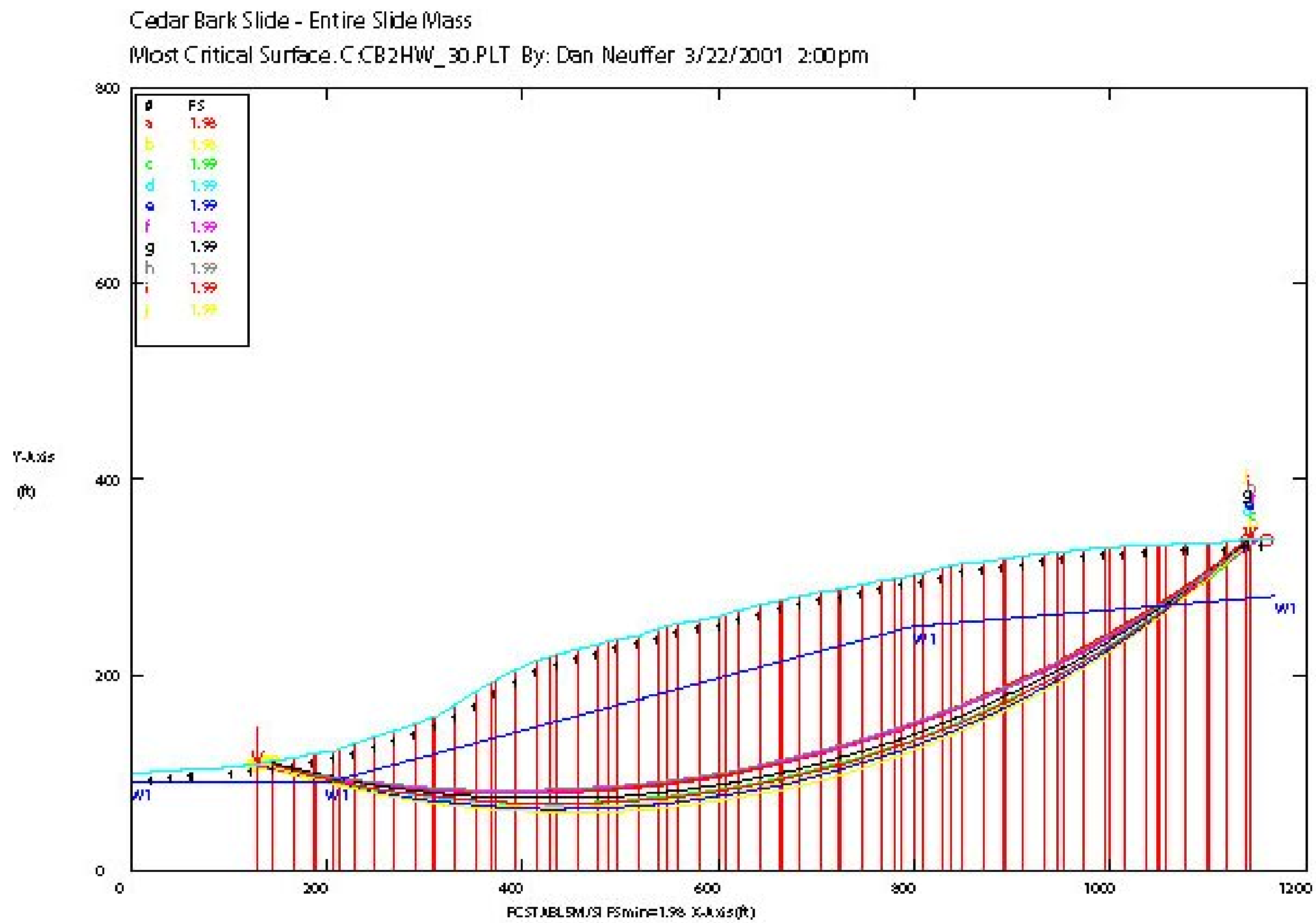


Figure 10: Factor of Safety as a function of Friction Angle for the Cedar Bark landslide (Case 2 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 till	121	136	0	30	0	0	

Figure 11a. Ten most critical slip surfaces of Cedar Bark landslide (Case 2 analysis) with no groundwater in the slide mass.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 till	121	136	0	30	0	0	W1

Figure 11b. Ten most critical slip surfaces of Cedar Bark landslide (Case 2 analysis) with groundwater mid-level in the slide mass.

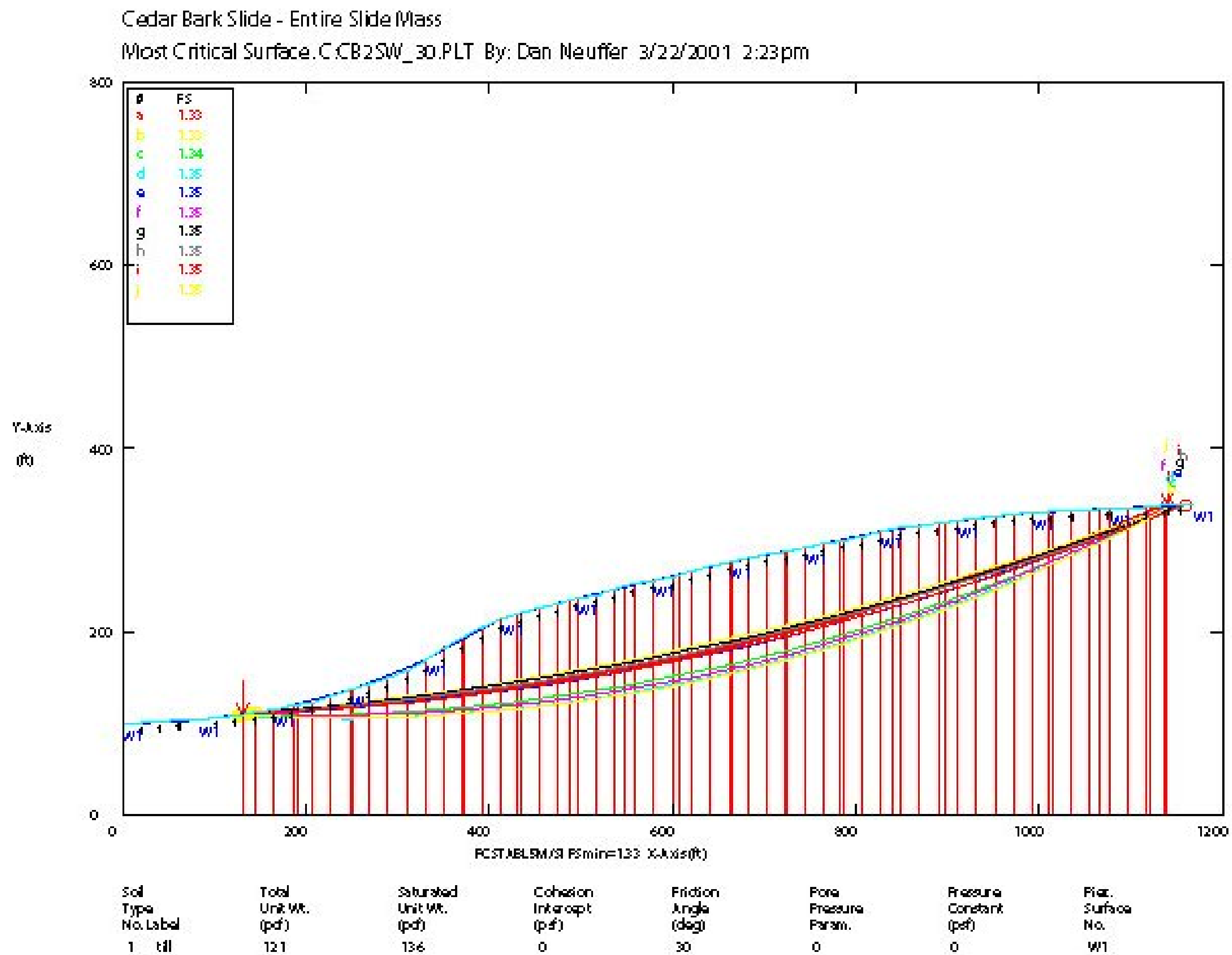


Figure 11c. Ten most critical slip surfaces of Cedar Bark landslide (Case 2 analysis) with groundwater saturating the slide mass.

Critical Segment (Case 3): The steep slope at the toe of the Cedar Bark slide is the most critical segment found by modeling (Fig. 12, Table 4). Debris slides and shallow slumps are probable under saturated conditions and possible under less than saturated conditions, given the projection of the friction angle curve between saturated and dry conditions for FS = 1 (Fig. 12; Table 4). Because the most critical segment has not yet failed, the peak friction angle for the glacial till must be greater than the minimum critical friction angle. Thus, the peak friction angle for the glacial till is greater than 27 degrees (Fig. 12; Table 4), provided cohesion is negligible and the materials that compose the most critical area are representative of materials at greater depth within the Cedar Bark slide. Sample stability analyses are shown in Figure 13.

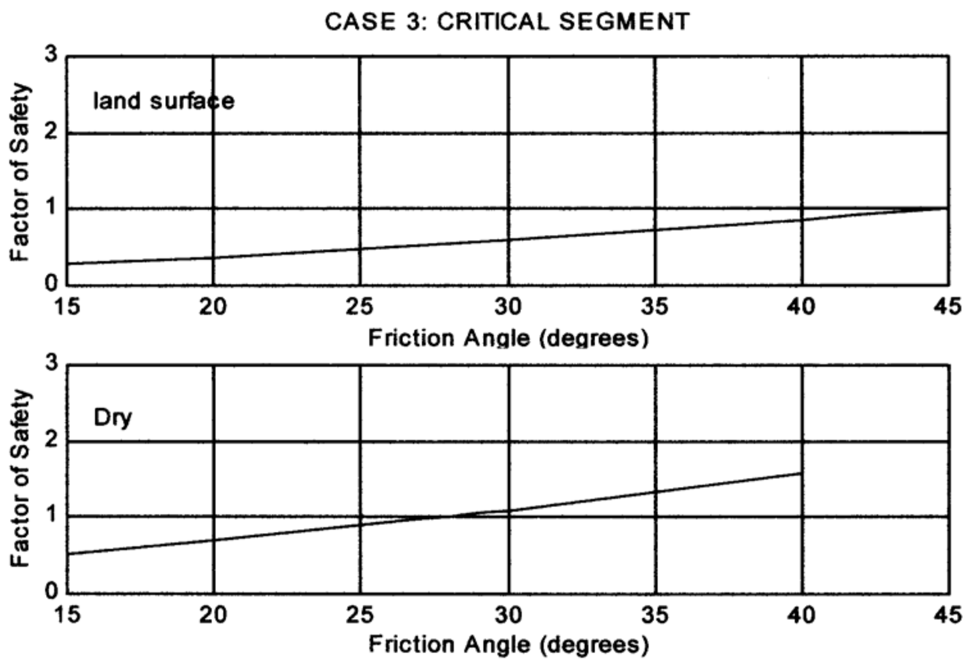
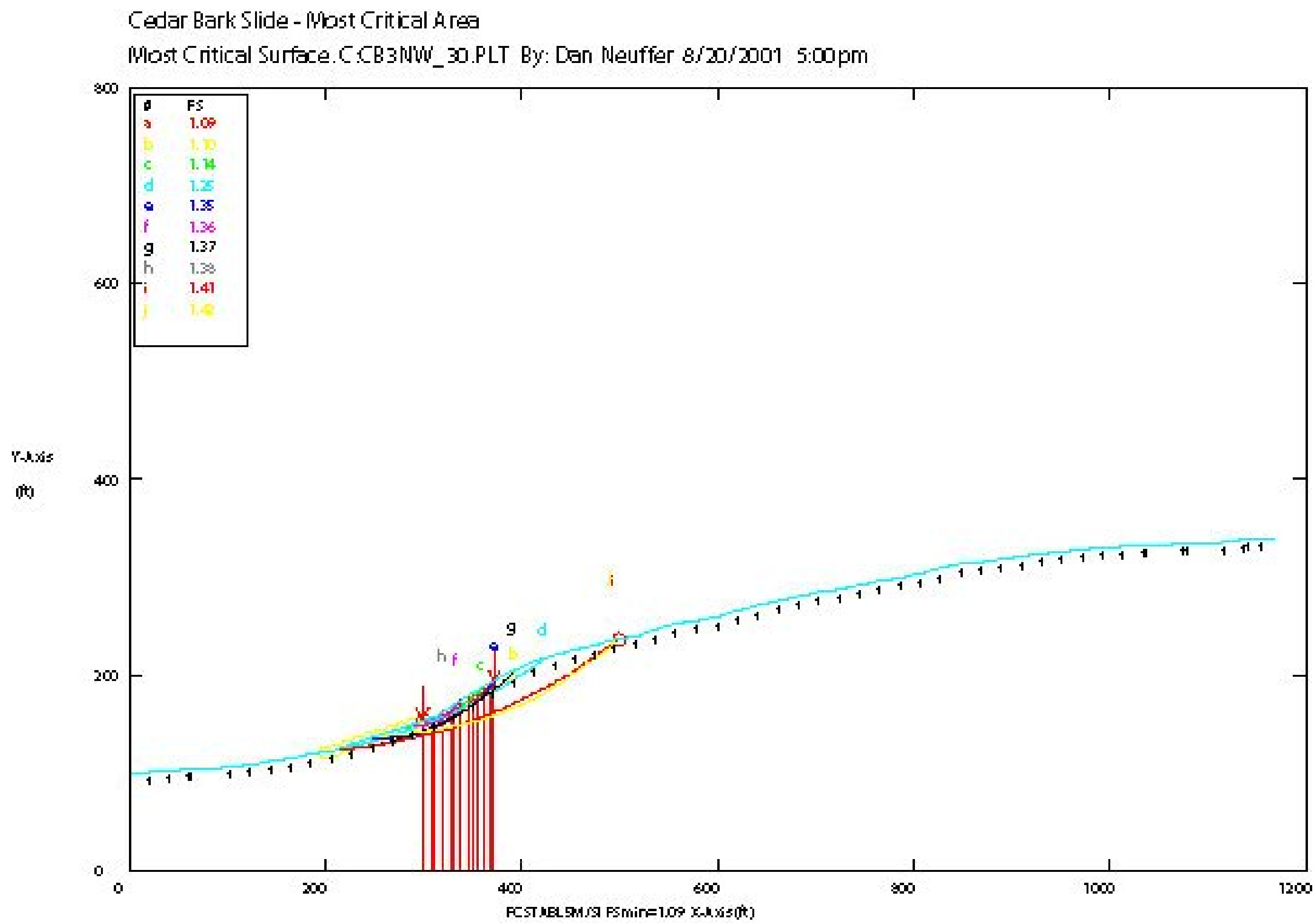
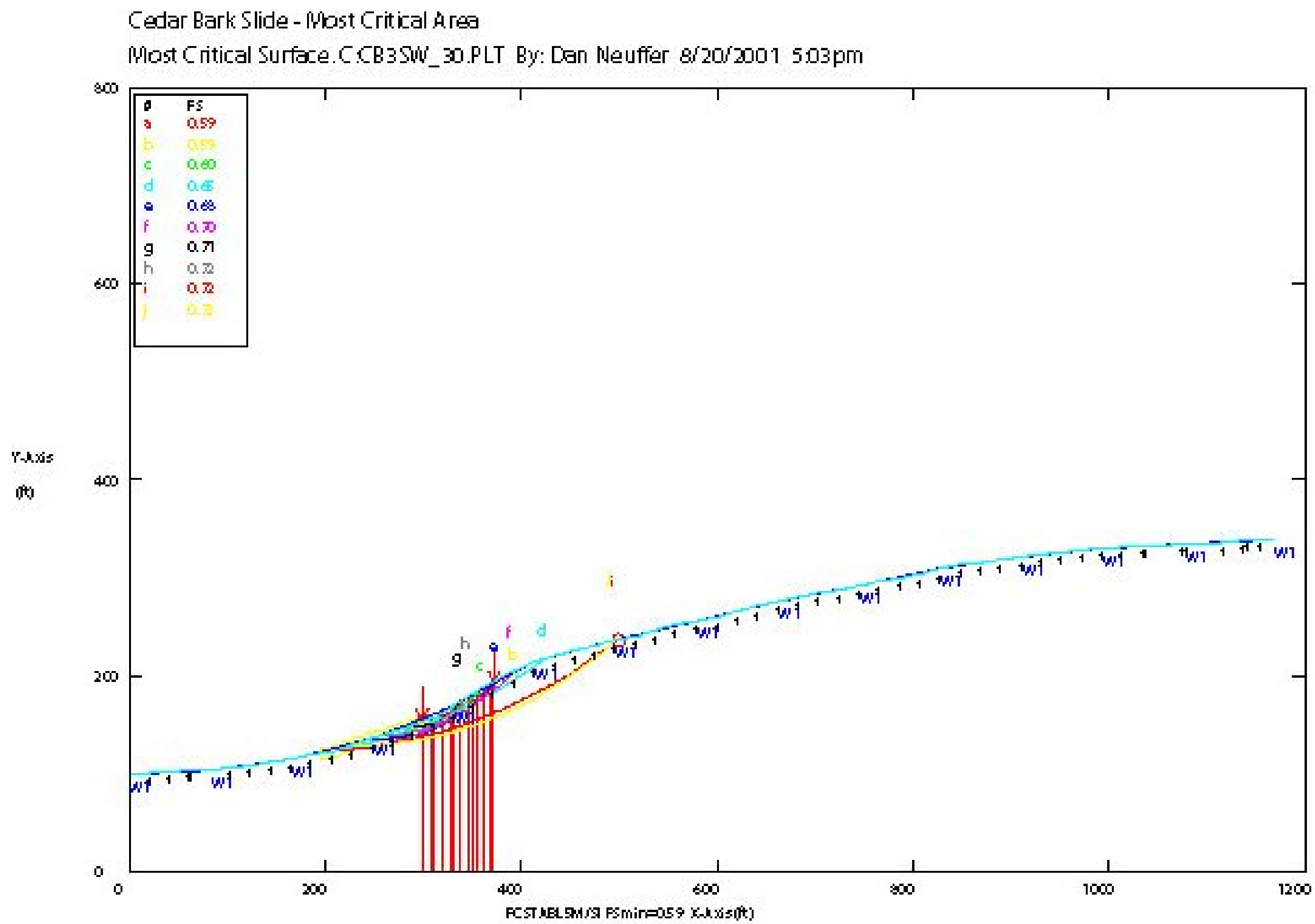


Figure 12: Factor of Safety as a function of Friction Angle for the Cedar Bark landslide (Case 3 Analysis). The height of the ground water within the slide mass varies from zero (dry) to the land surface when the slide is fully saturated.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	till	121	136	0	30	0	0	

Figure 13a. Ten most critical slip surfaces of Cedar Bark landslide (Case 3 analysis) with no groundwater in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	till	121	136	0	30	0	0	W1

Figure 13b. Ten most critical slip surfaces of Cedar Bark landslide (Case 3 analysis) with groundwater saturating the slide mass.

6.2 Beaver Bench Slide

Peak Friction Angles (Case 1): We estimated peak friction angles of 16, 20 and 29 degrees under dry conditions, mid-level water table, and total saturation of the slide, respectively (Fig. 14, Table 5). Sample stability analyses are shown in Figure 15.

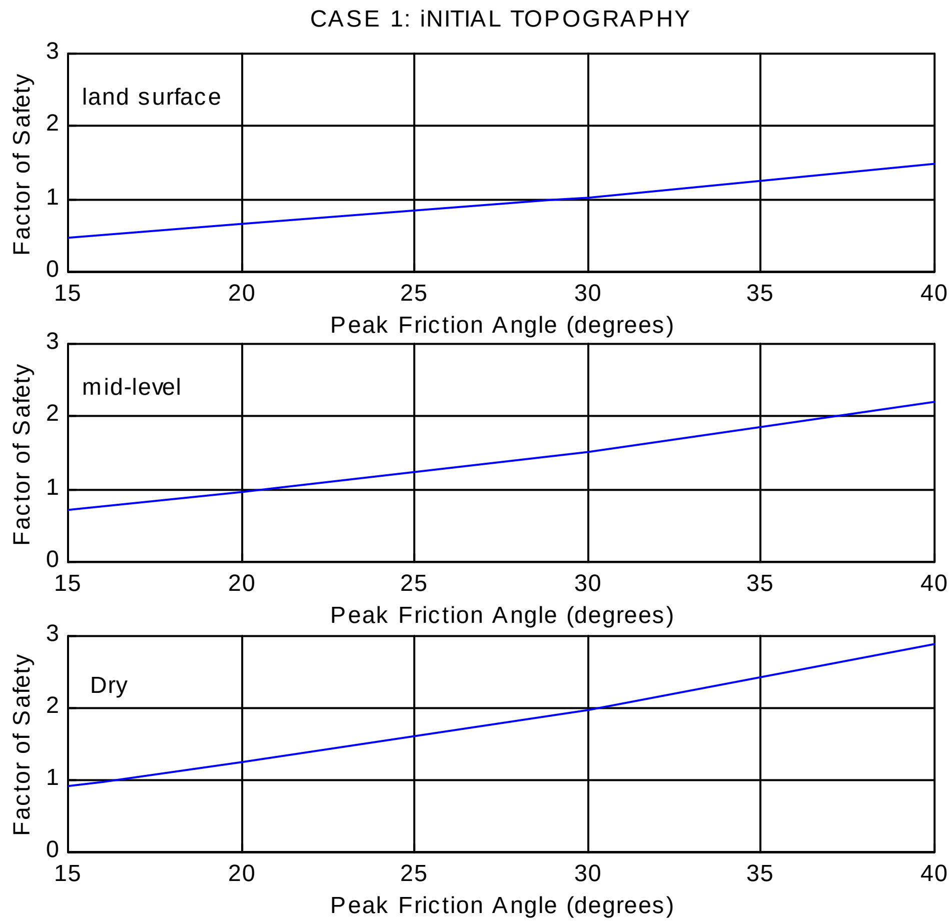
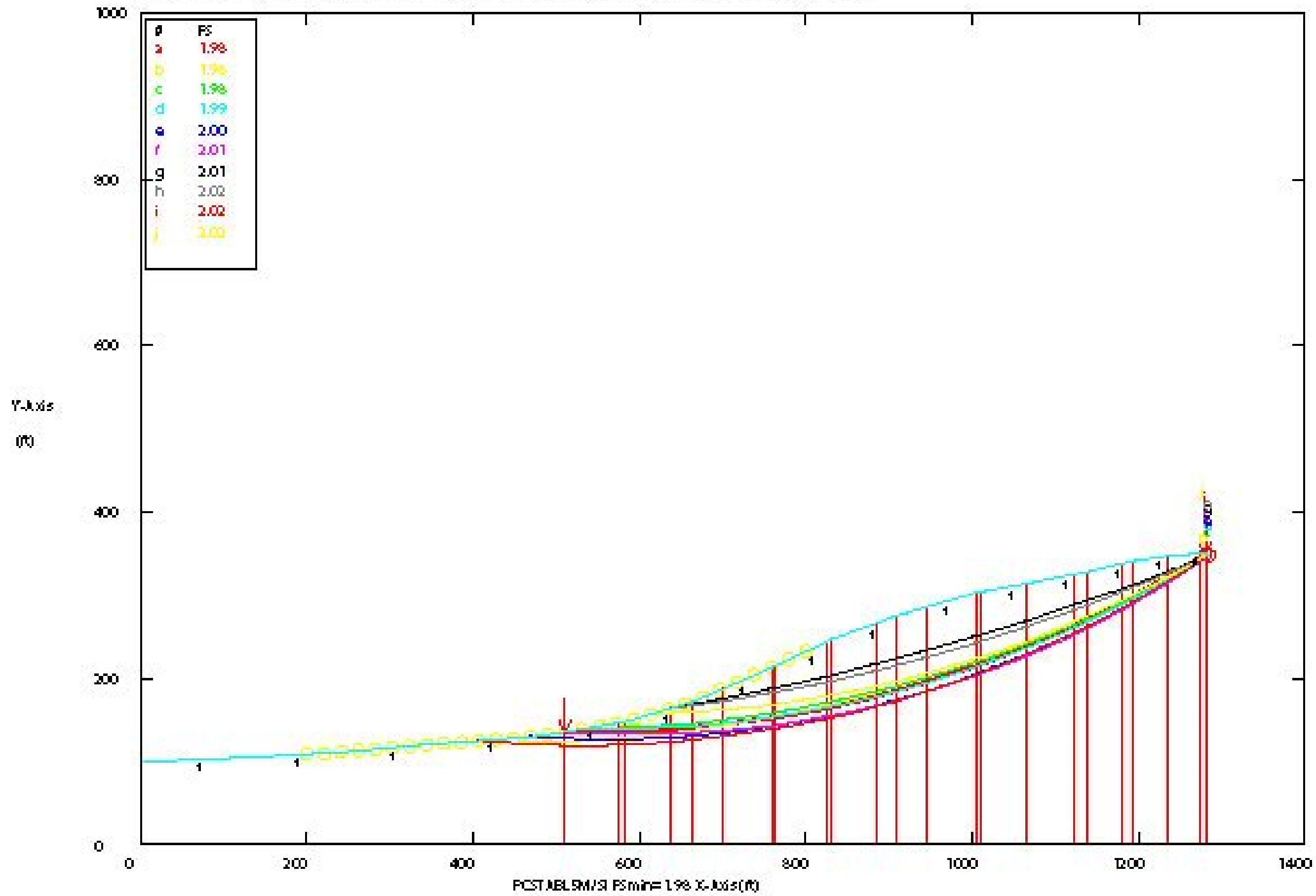


Figure 14: Factor of Safety as a function of Peak Friction Angle for the Beaver Bench landslide (Case 1 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.

Beaver Bench Slide - Initiation

Most Critical Surface. C:BB1NW_30.PLT By: Dan Neuffer 4/24/2001 7:31pm

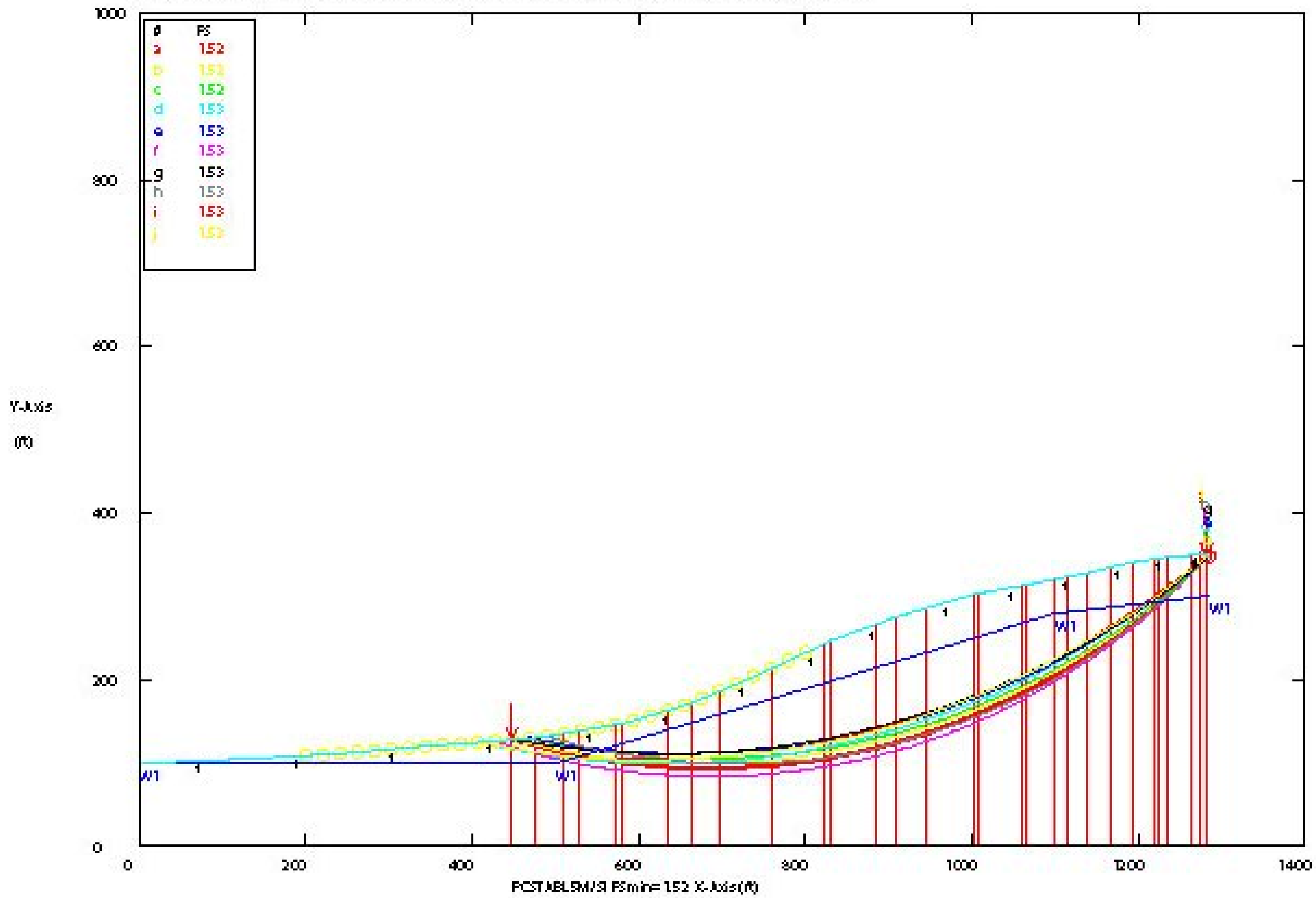


Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	volcanic	121	136	0	30	0	0	

Figure 15a. Ten most critical slip surfaces of Beaver Bench landslide (Case 1 analysis) with no groundwater in the slide mass.

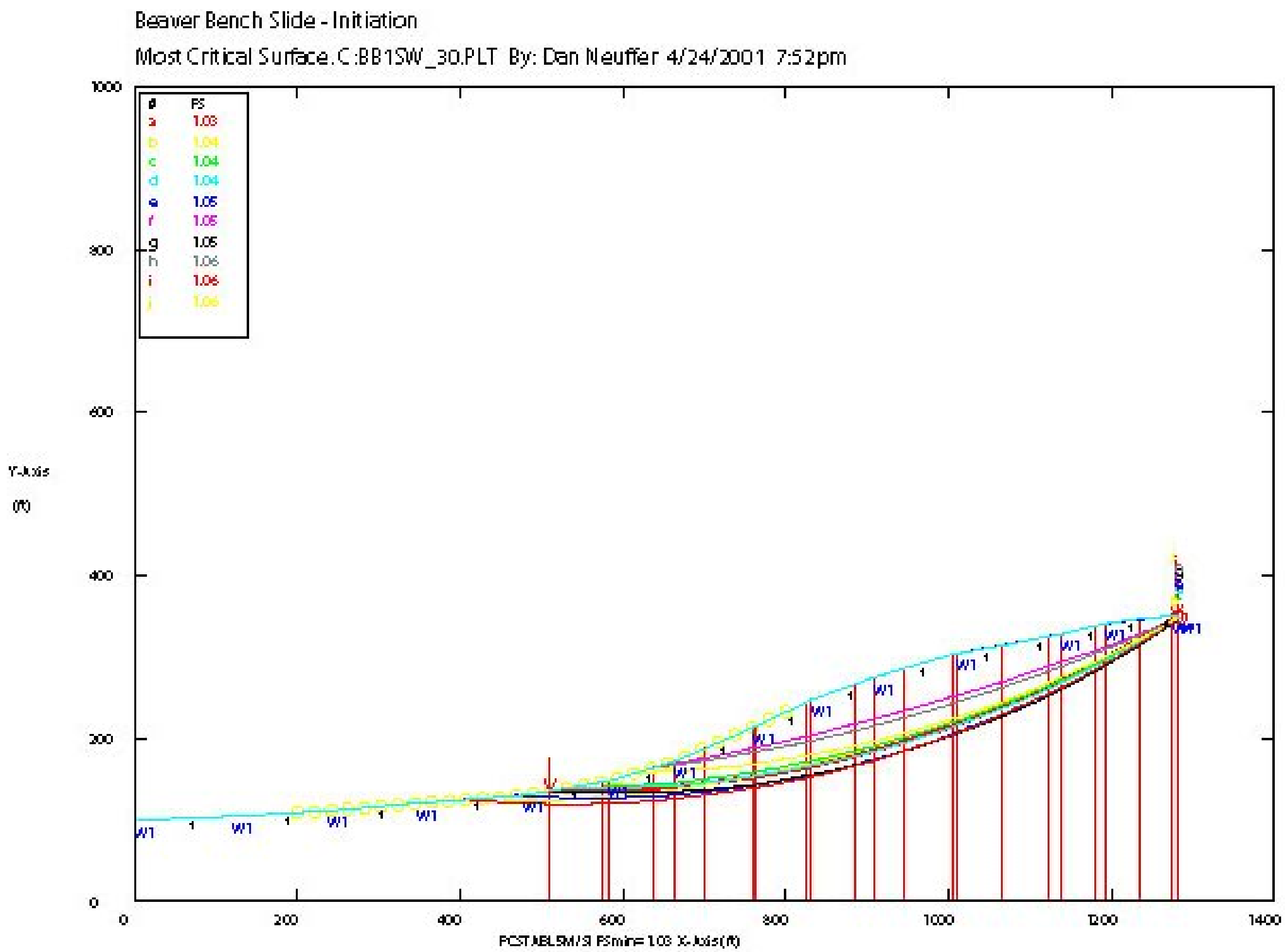
Beaver Bench Slide - Initiation

Most Critical Surface. C:BB1HW_30.PLT By: Dan Neuffer 4/24/2001 7:48pm



Soil Type No. Label		Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	volcanic	121	136	0	30	0	0	W1

Figure 15b. Ten most critical slip surfaces of Beaver Bench landslide (Case 1 analysis) with groundwater mid-level in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	volcanic	121	136	0	30	0	0	W1

Figure 15c. Ten most critical slip surfaces of Beaver Bench landslide (Case 1 analysis) with groundwater saturating the slide mass.

Residual Friction Angles (Case 2): The factor of safety is greater than 1.0 even for very low friction angles of 15 degrees and saturated groundwater conditions (Fig. 16, 17; Table 5). Extrapolating from Figure 16, the residual friction angle under fully saturated groundwater conditions is approximately 12 degrees. Sample stability analyses are shown in Figure 17.

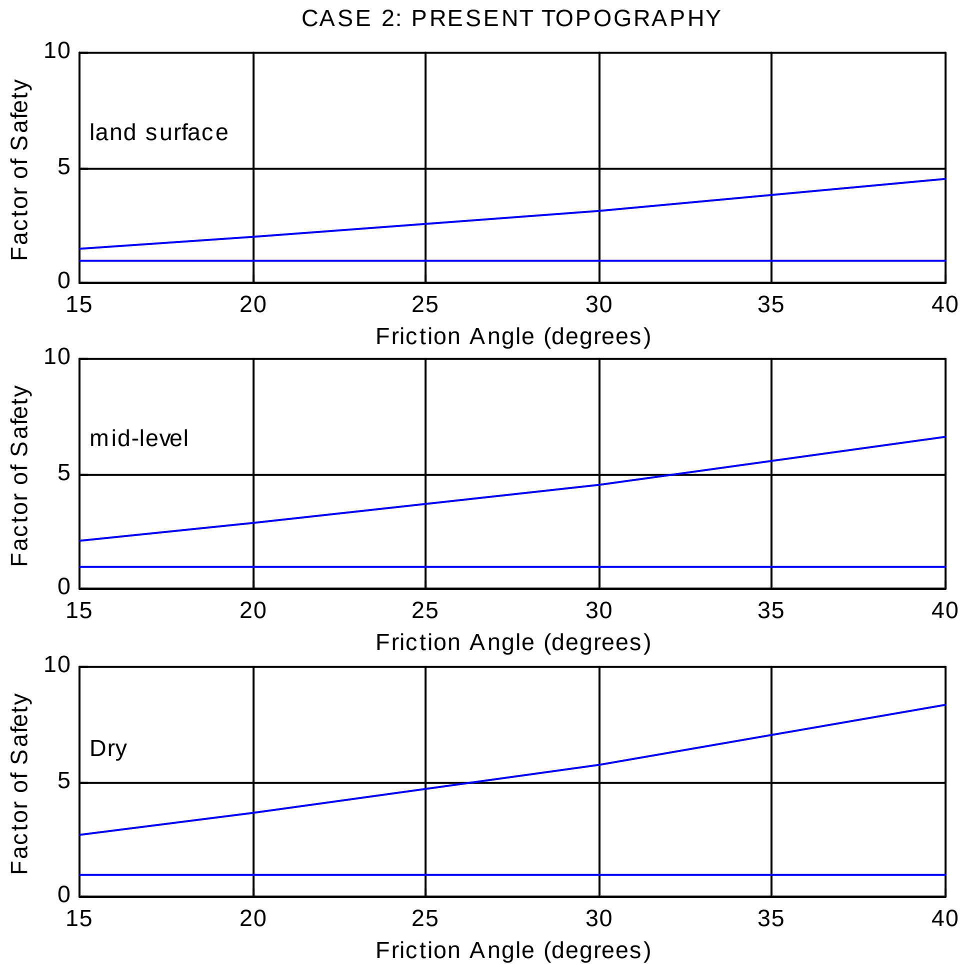
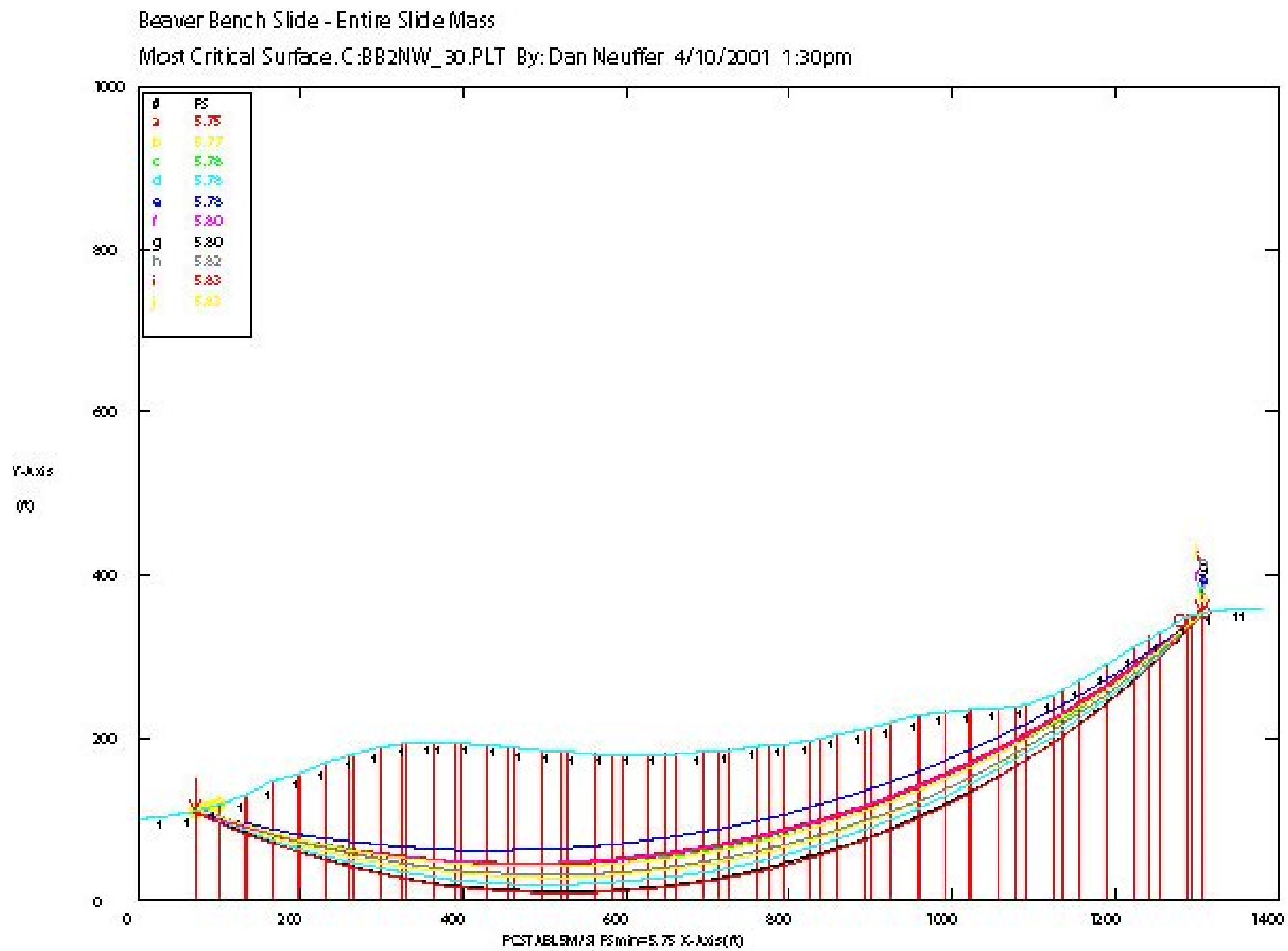
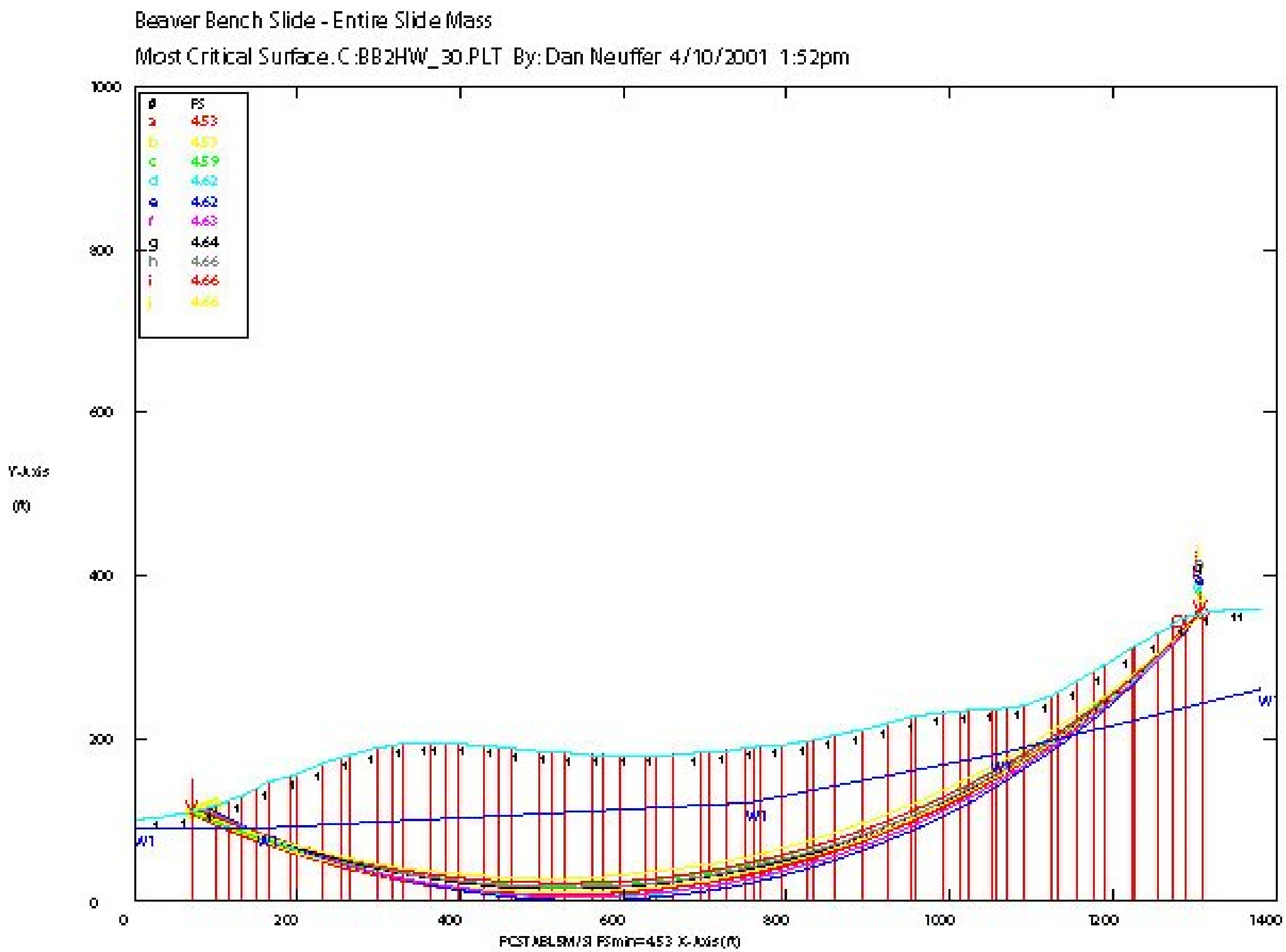


Figure 16: Factor of Safety as a function of Friction Angle for the Beaver Bench landslide (Case 2 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 volcanic	121	136	0	30	0	0	

Figure 17a. Ten most critical slip surfaces of Beaver Bench landslide (Case 2 analysis) with no groundwater in the slide mass.

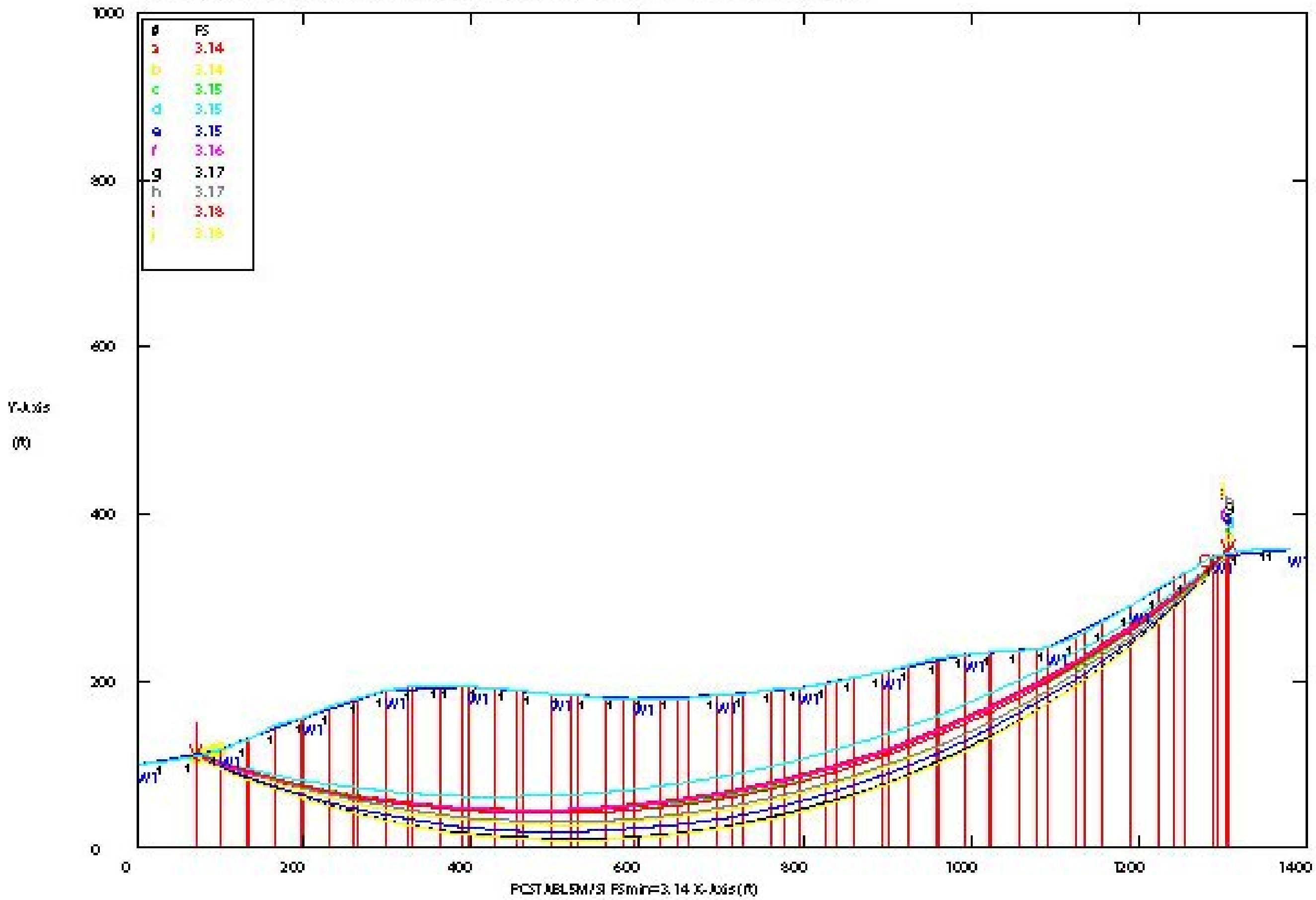


Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 volcanic	121	136	0	30	0	0	W1

Figure 17b. Ten most critical slip surfaces of Beaver Bench landslide (Case 2 analysis) with groundwater mid-level in the slide mass.

Beaver Bench Slide - Entire Slide Mass

Most Critical Surface. C:BB2SW_30.PLT By: Dan Neuffer 4/10/2001 2:00pm



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 volcanic	121	136	0	30	0	0	W1

Figure 17c. Ten most critical slip surfaces of Beaver Bench landslide (Case 2 analysis) with groundwater saturating the slide mass.

Critical Segment (Case 3): The steep slope formed by the main scarp is the most critical segment identified by stability modeling (Fig. 18, Table 5), although the steep toe of the slide is nearly as critical. Debris slides and shallow slumps are probable under saturated groundwater conditions and possible under less than saturated conditions, given the projection of the friction angle curve between saturated and dry conditions for FS = 1 (Fig. 18; Table 5). Because the most critical segment has not yet failed, the peak friction angle for the Keetley Volcanics must be greater than the minimum critical friction angle. Thus, the peak friction angle for the Keetley Volcanics is greater than 27 degrees (Fig. 18; Table 5), provided cohesion is negligible and the materials that compose the most critical area are representative of materials at greater depth within the Beaver Bench slide. Sample stability analyses are shown in Figure 19.

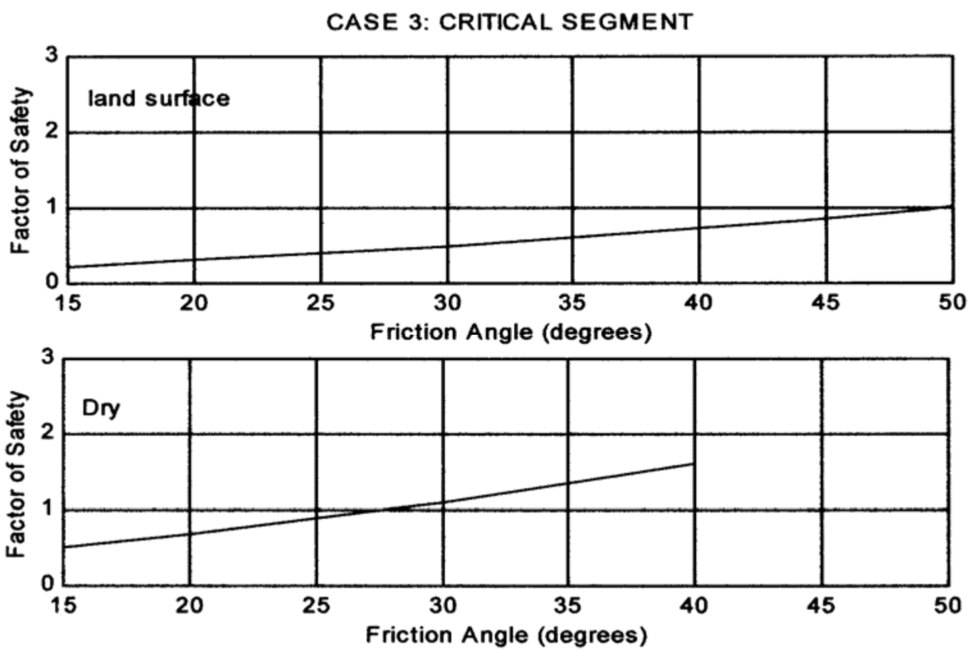
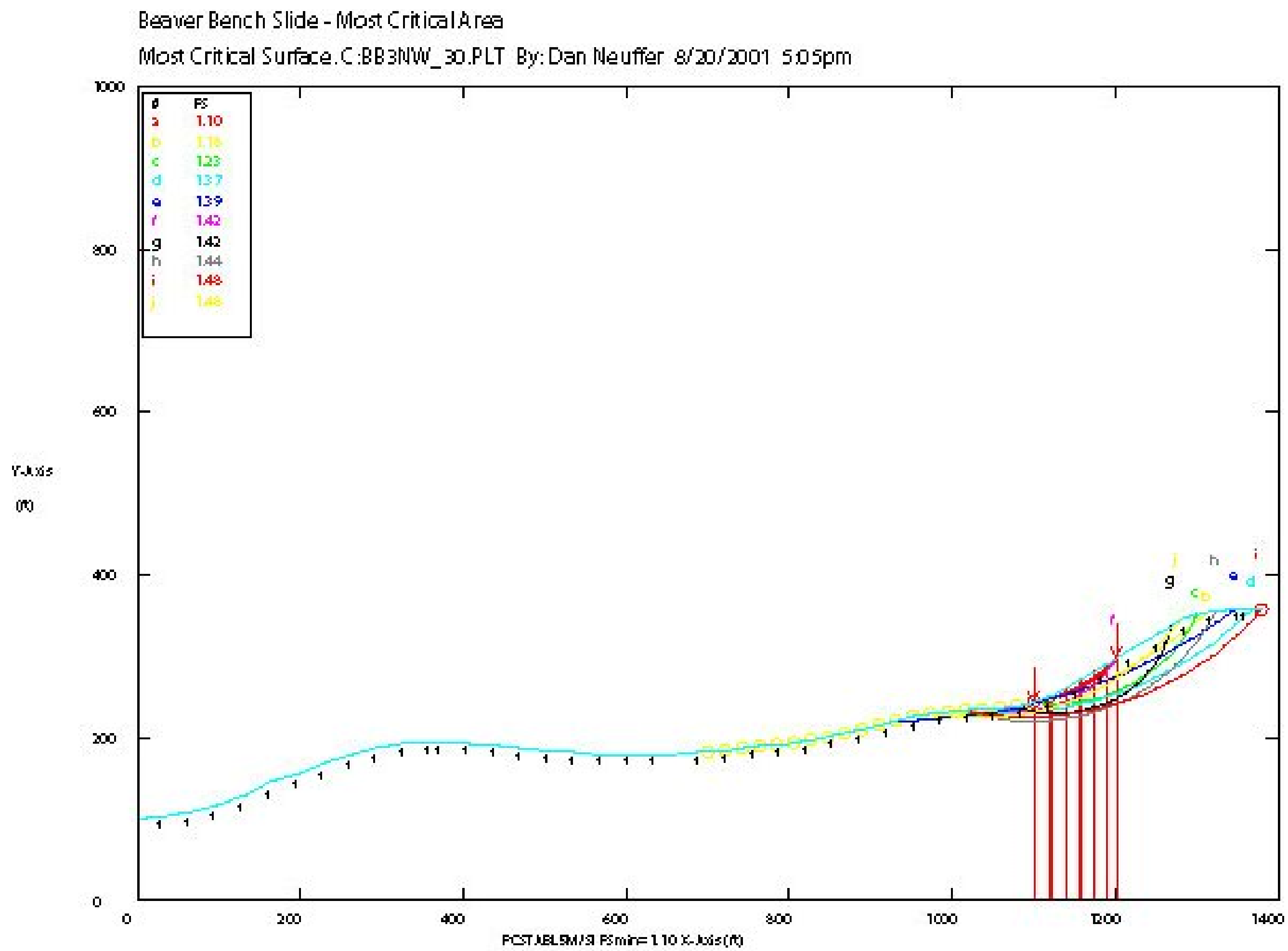
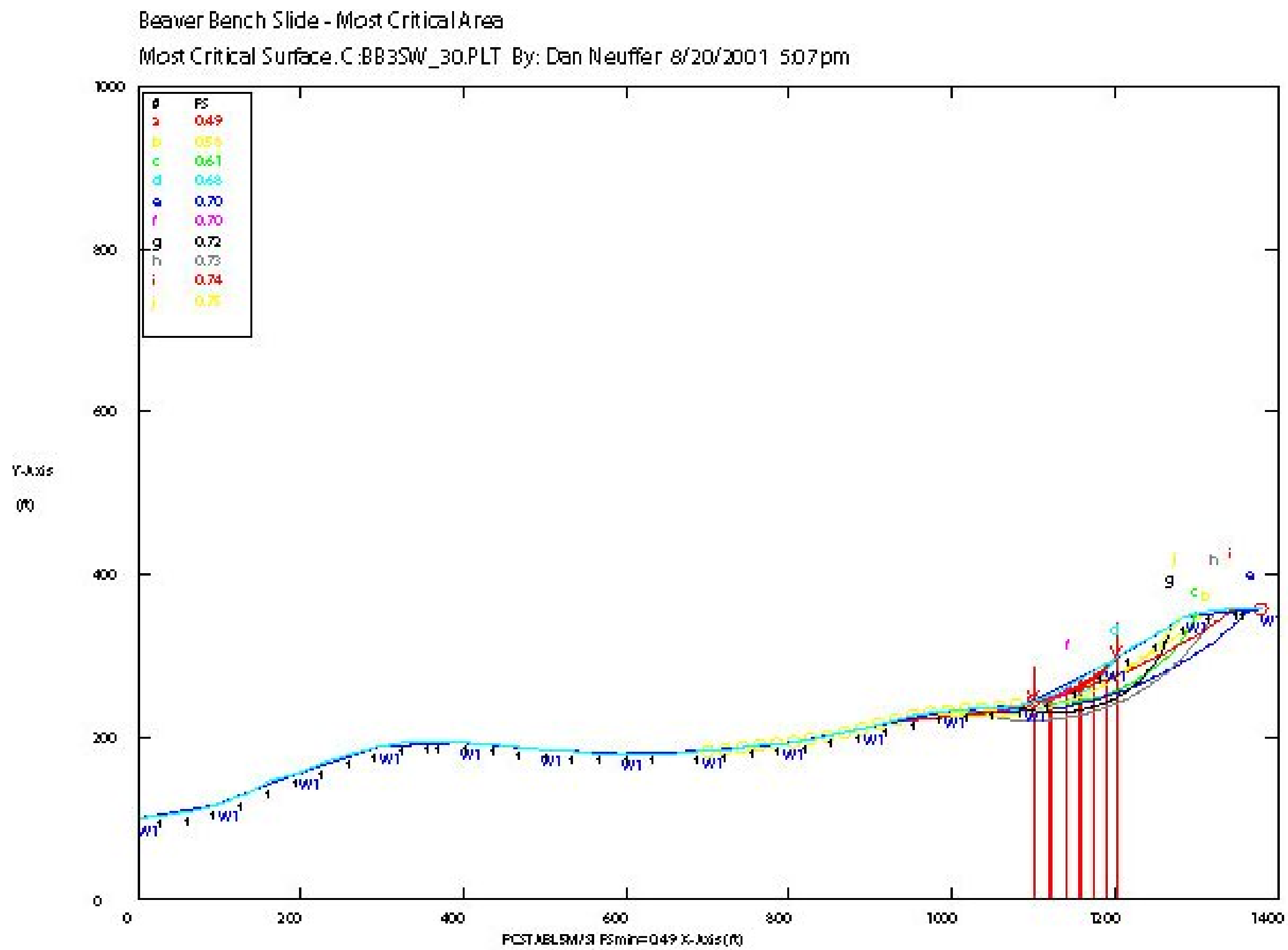


Figure 18: Factor of Safety as a function of Friction Angle for the Beaver Bench landslide (Case 3 Analysis). The height of the ground water within the slide mass varies from zero (dry) to the land surface when the slide is fully saturated.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 volcanic	121	136	0	30	0	0	

Figure 19a. Ten most critical slip surfaces of Beaver Bench landslide (Case 3 analysis) with no groundwater in the slide mass.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 volcanic	121	136	0	30	0	0	W1

Figure 19b. Ten most critical slip surfaces of Beaver Bench landslide (Case 3 analysis) with groundwater saturating the slide mass.

6.3 Blazing Star Slide

Peak Friction Angles (Case 1): We estimated peak friction angles of 16, 23 and 29 degrees under dry conditions, mid-level water table, and total saturation of the slide, respectively (Fig. 20, Table 6). Sample stability analyses are shown in Figure 21.

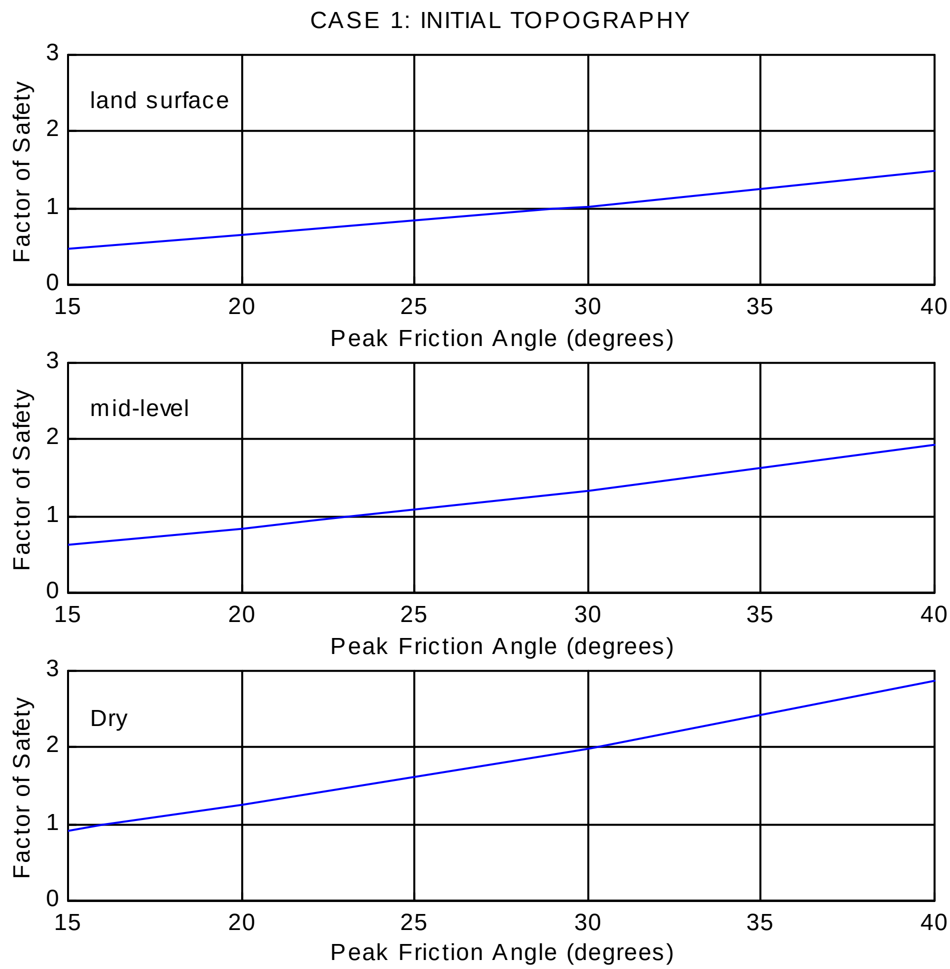
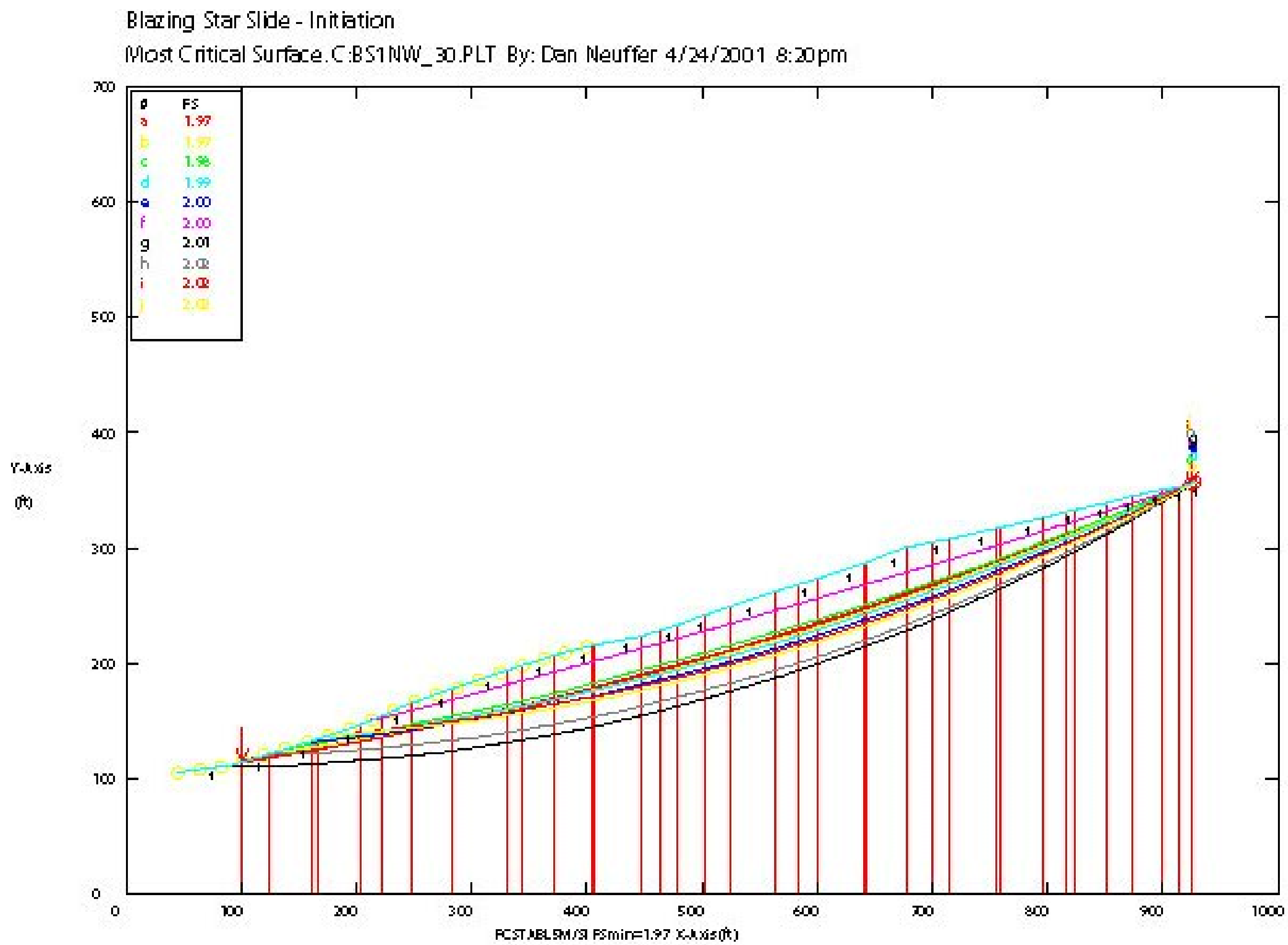
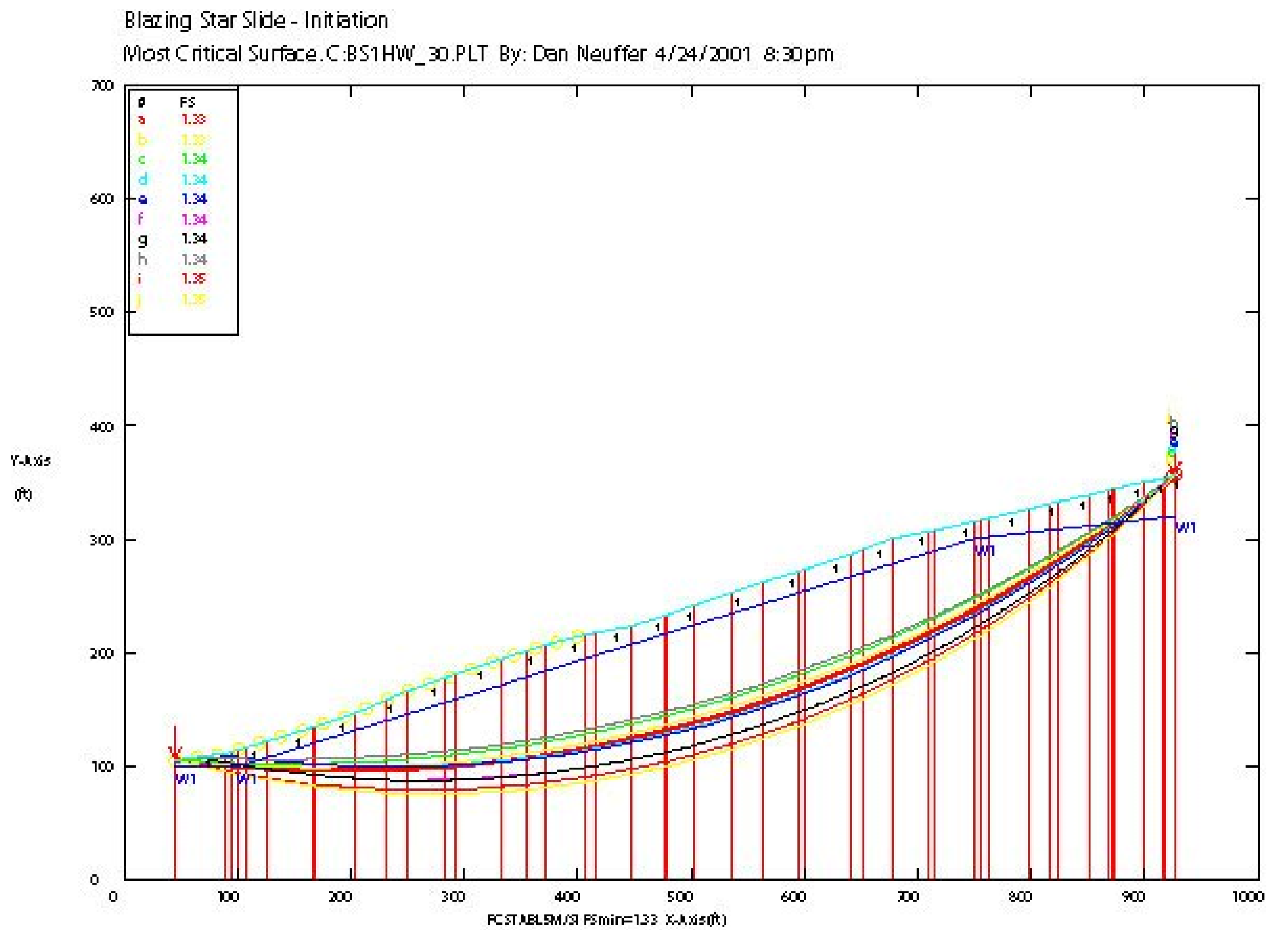


Figure 20: Factor of Safety as a function of Peak Friction Angle for the Blazing Star landslide (Case 1 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.



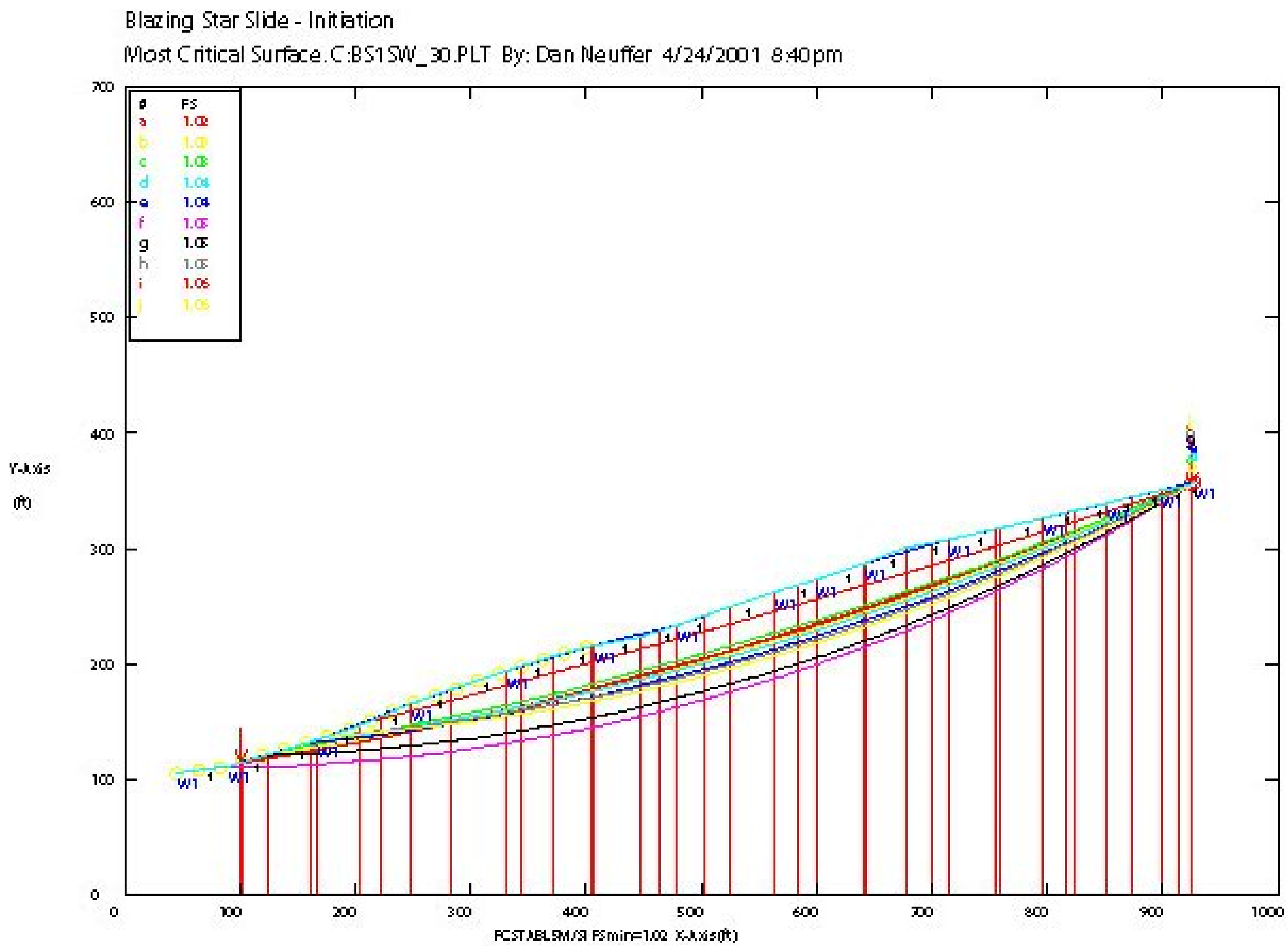
Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	vol-fill	121	136	0	30	0	0	

Figure 21a. Ten most critical slip surfaces of Blazing Star landslide (Case 1 analysis) with no groundwater in the slide mass.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 vol-fill	121	136	0	30	0	0	W1

Figure 21b. Ten most critical slip surfaces of Blazing Star landslide (Case 1 analysis) with groundwater mid-level in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	vol-fill	121	136	0	30	0	0	W1

Figure 21c. Ten most critical slip surfaces of Blazing Star landslide (Case 1 analysis) with groundwater saturating the slide mass.

Residual Friction Angles (Case 2): The factor of safety is greater than 1.0 under dry conditions for friction angles as low as 15 degrees. Lower bound residual friction angles of 15 and 23 degrees were estimated under mid-level and saturated groundwater conditions (Fig. 22, Table 6). Sample stability analyses are shown in Figure 23.

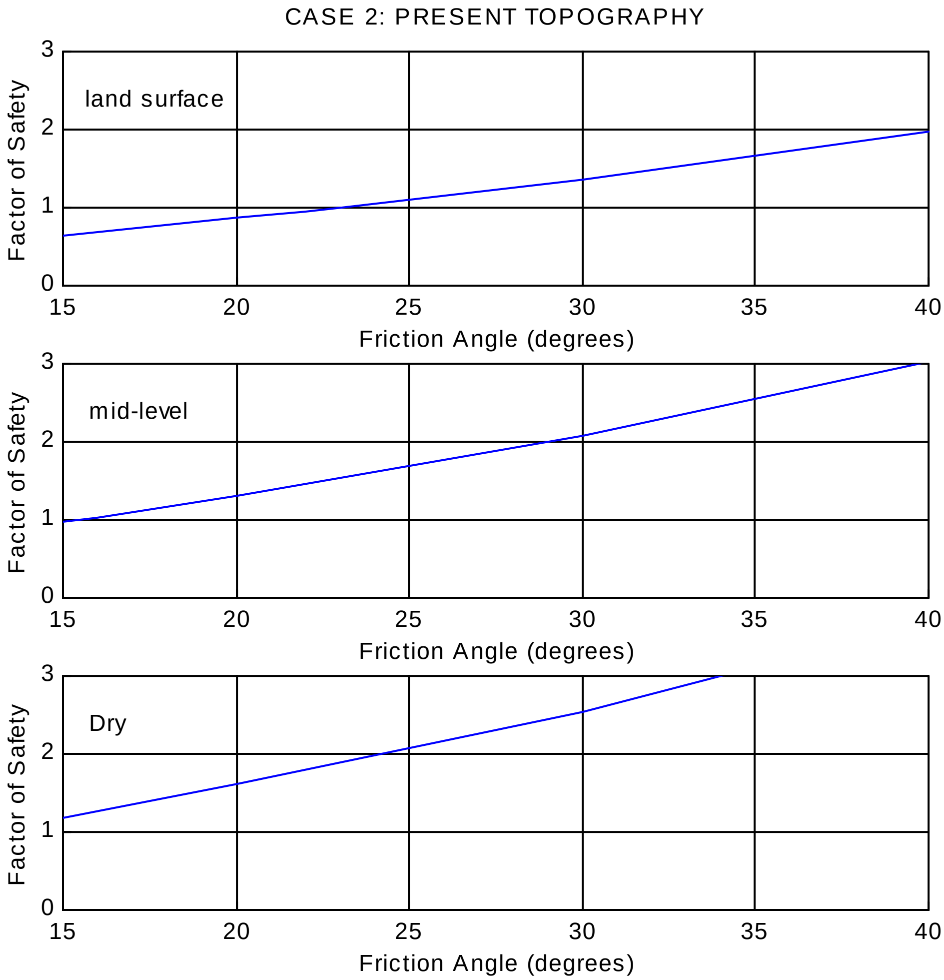
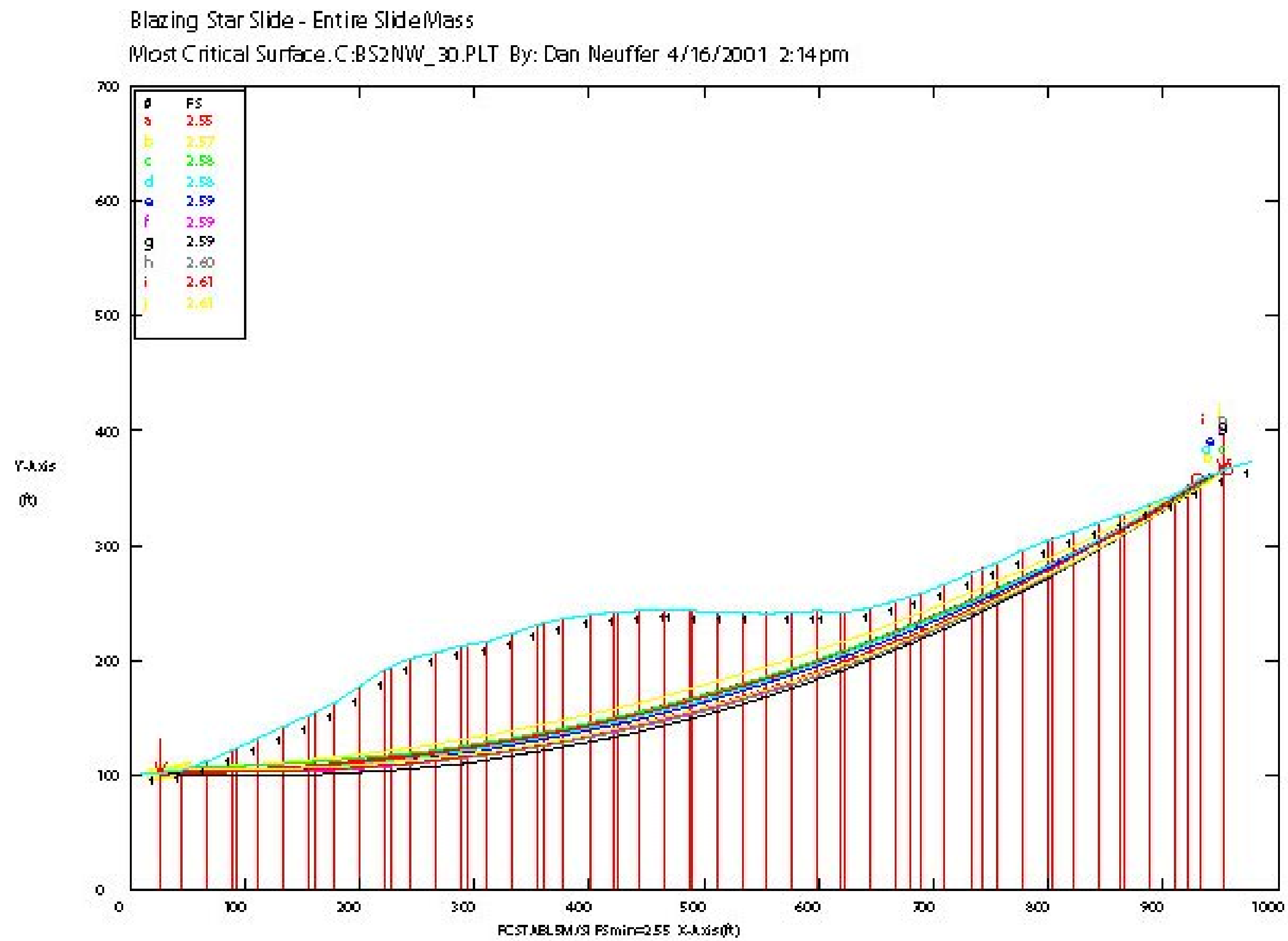
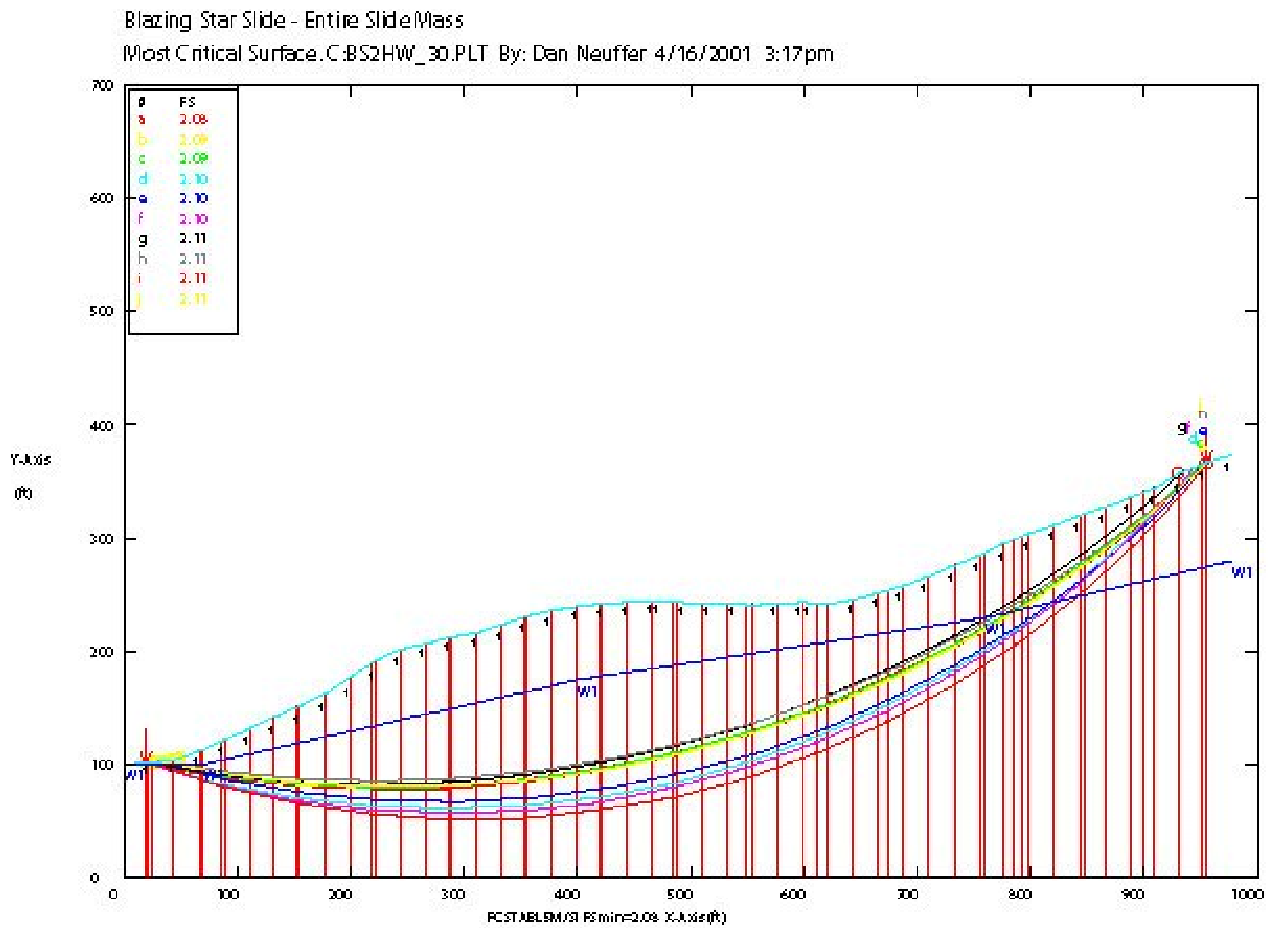


Figure 22: Factor of Safety as a function of Friction Angle for the Blazing Star landslide (Case 2 Analysis). The height of the ground water within the slide mass varies from zero (dry), to mid-level, to the land surface when the slide is fully saturated.



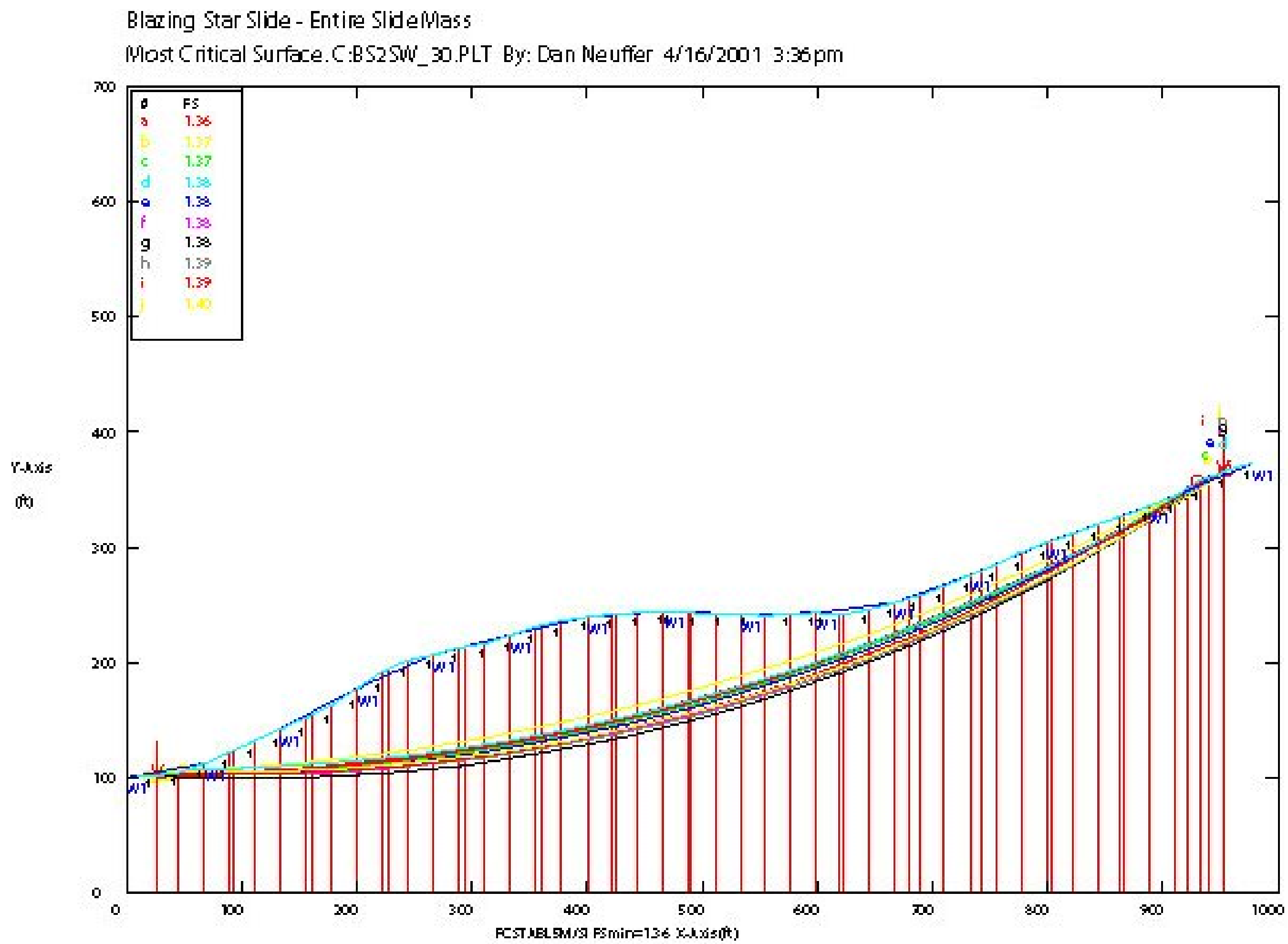
Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 vol-61	121	136	0	30	0	0	

Figure 23a. Ten most critical slip surfaces of Blazing Star landslide (Case 2 analysis) with no groundwater in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	vol-fill	121	136	0	30	0	0	W1

Figure 23b. Ten most critical slip surfaces of Blazing Star landslide (Case 2 analysis) with groundwater mid-level in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	vol-fill	121	136	0	30	0	0	W1

Figure 23c. Ten most critical slip surfaces of Blazing Star landslide (Case 2 analysis) with groundwater saturating the slide mass.

Critical Segment (Case 3): Debris slides and shallow slumps along the steep bank of Lake Creek are probable under saturated groundwater conditions and possible under less than saturated conditions, given the projection of the friction angle curve between saturated and dry conditions for FS = 1 (Fig. 24, Table 6). This result is substantiated by recent debris slides that were mapped in that area. One of these recent debris slides had a small spring at the base of the main debris slide scarp. The main scarp of the Blazing Star slide is nearly as steep as the toe, and, thus, is also prone to local instability. Sample stability analyses are shown in Figure 25.

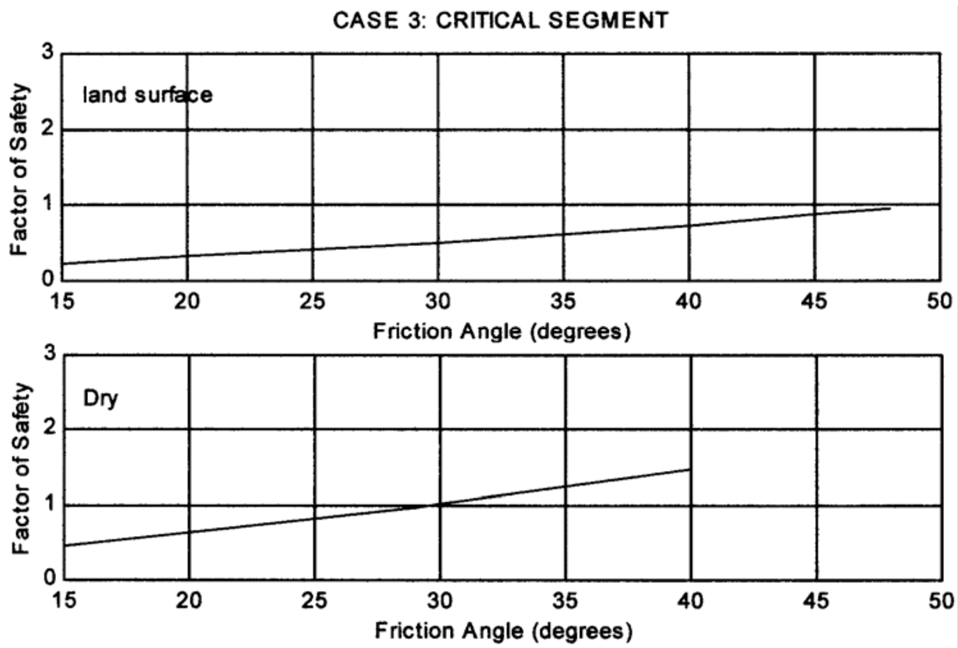
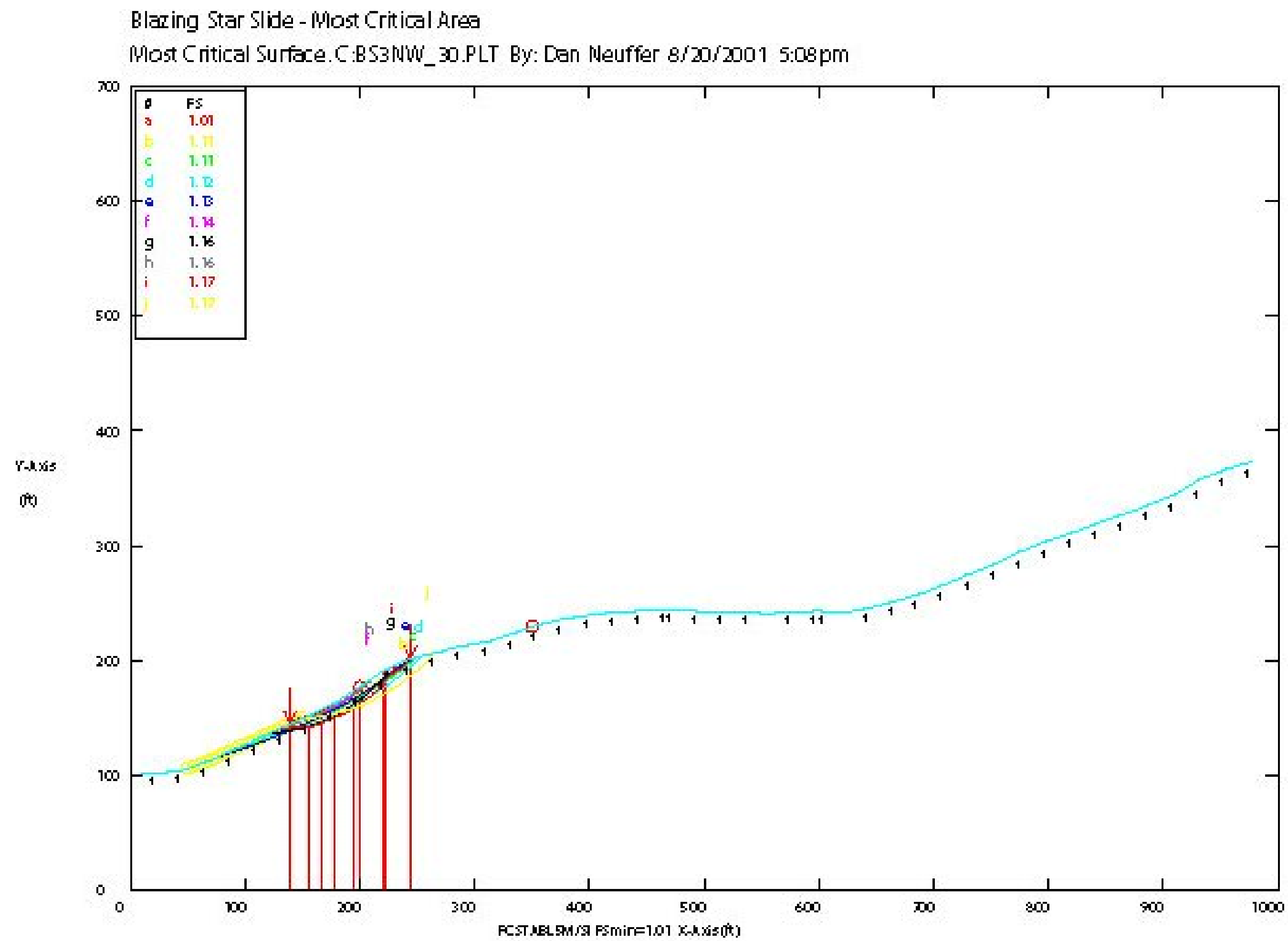
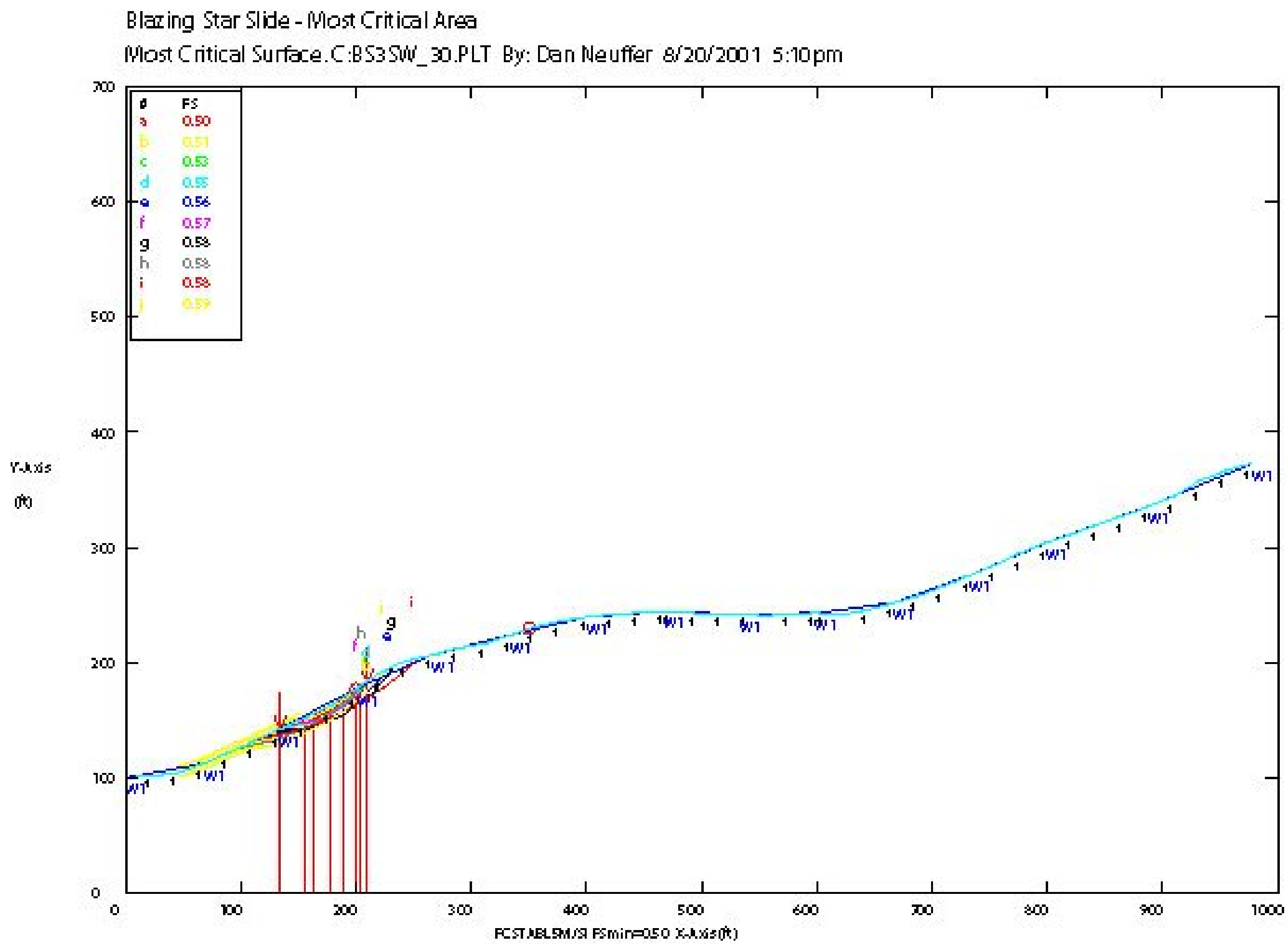


Figure 24: Factor of Safety as a function of Friction Angle for the Blazing Star landslide (Case 3 Analysis). The height of the ground water within the slide mass varies from zero (dry) to the land surface when the slide is fully saturated.



Soil Type No. Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1 vol-til	121	136	0	30	0	0	

Figure 25a. Ten most critical slip surfaces of Blazing Star landslide (Case 3 analysis) with no groundwater in the slide mass.



Soil Type No.	Label	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	vol-fill	121	136	0	30	0	0	W1

Figure 25b. Ten most critical slip surfaces of Blazing Star landslide (Case 3 analysis) with groundwater saturating the slide mass.

7.0 DISCUSSION

Several limitations of this study should be kept in mind when interpreting the results of the slope stability modeling, even though the results are reasonable based upon observations in the field, and by comparison to other landslide studies. The geometry of the slip surfaces and frictional parameters of the slide mass cannot be checked independently because there is little subsurface data and no measurements of the physical properties of the deposits, other than those reported by Ashland and Hylland (1997). We assumed the slip surfaces to be circular but other configurations are possible and could affect the estimates of frictional parameters. The configuration of the groundwater surface was also unconstrained because of the lack of subsurface data. We partly overcame this problem by simulating three different configurations of the groundwater table, but the fact remains that the configuration of the groundwater surface could be significantly different than in our models. There may also be local, or perched groundwater within the heterogeneous slide deposits, as well as artesian conditions that generate high pore water pressure.

These types of uncertainties lead the Utah Geological Survey (Hylland, 1996) to recommend the use of conservative parameters and a factor of safety of greater than or equal to 1.5 in preliminary analyses such as those reported here. At mid-level and saturated groundwater conditions, if friction angles are less than 23 and 32 degrees, respectively, the present configuration of the Cedar Bark slide has a factor of safety of less than 1.5 (Figs. 10, 11; Table 4). Likewise, at mid-level and saturated groundwater conditions, if friction angles are less than 22 and 31 degrees, respectively, the present configuration of the Blazing Star slide has a factor of safety of less than 1.5 (Figs. 22, 23; Table 6).

7.1 Friction Angles

We estimated peak friction angles of ϕ'_p = 16–29 degrees from the slope stability simulations of the Cedar Bark, Beaver Bench and Blazing Star slides; however, the range of ϕ'_p from 20–29 degrees probably reflects more realistic groundwater conditions. The friction angles represent composites of glacial till and Keetley Volcanics. Glacial till is the primary material involved in the Cedar Bark slide. The upper part of the Blazing Star slide is in glacial till, but the deeper part of the slide may be in Keetley Volcanics. The Beaver Bench slide is apparently confined to the Keetley Volcanics.

ϕ'_p of 16–29 degrees are generally below the range $29 < \phi'_p < 55$ degrees estimated by Ashland and Hylland (1997) for glacial till in the Pine Ridge slide, but 29 degrees is slightly greater than their preferred range of residual friction angle ϕ'_R = 21–27 degrees. Additionally, the ϕ'_p values derived by Ashland and Hylland (1997) are for shallow debris slides in glacial till, and may not be representative of materials involved in the deep-seated slides. Friction angles for glacial tills from various localities indicate $16 < \phi'p < 45$ degrees (Bell, 2002; Müller and Schlüchter, 2001; Lebourg et al., 2004; Kazi and Knill, 1969; Hammond et al., 1992). Eyles and Sladen (1981) gave both ϕ'_p and ϕ'_R for unweathered and weathered lodgement tills in Northumberland, England. ϕ'_p = 32–

37 degrees, and ϕ'_R = 30–32 degrees for the unweathered tills. ϕ'_p = 27–35 degrees and ϕ'_R = 15–32 degrees for moderately to highly weathered tills. Hence, the range of peak friction angles found in this study aligns well with previously reported values.

Frictional properties of the Keetley Volcanics have not been determined by either laboratory or in situ testing to our knowledge. ϕ'_p for Keetley Volcanics is constrained only by Case 1 simulations of slope stability for the Beaver Bench slide. This slide is developed in the Tuffaceous Unit of the Keetley Volcanics (Biek and others, 2003). ϕ'_p = 16–29 degrees (Fig. 14, 15; Table 5), the same range estimated for the Cedar Bark and Blazing Star slides. If there is a difference in ϕ'_p between till and volcanic material it is not resolved in this study.

Peak friction angles may be even larger than estimated if pore pressure was greater than hydrostatic (e.g. – artesian conditions) when slides initiated, or if failure was triggered by earthquake ground motion. The peak friction angles determined during this study may therefore be lower bound, or conservative estimates. The Case 3 analysis for the Cedar Bark and Beaver Bench slides produced $\phi'_p > 27$ degrees for both glacial till and Keetley Volcanics. This result is at the high end of the range of peak friction angles estimated by Case 1 analyses. The Case 1 ϕ'_p values may be too low for the above-mentioned reasons. Alternatively, the Case 3 ϕ'_p estimates may be too high because they reflect the frictional properties of surficial materials and not materials at depth within the landslides. As discussed above, soft, fine-grained material was observed between bedding planes in the Keetley Volcanics, indicating the possibility of weak zones at depth.

This study did not include a comprehensive pseudo-static analysis for estimating friction angles and landslide stability under seismic conditions. Preliminary calculations on the Cedar Bark slide indicate that a peak horizontal ground acceleration (PGA) of 0.15g would give ϕ'_p = 24–42 degrees and ϕ'_R = 21–37 degrees for glacial till, depending on groundwater conditions. A PGA of 0.3g would give ϕ'_p = 32–53 degrees and ϕ'_R = 29–48 degrees for glacial till, again depending on groundwater conditions. PGA values were obtained from the U.S. Geological Survey Earthquake Hazards Program National Hazard Map (U.S. Geological Survey). For the western Wasatch County area, 0.15g was the estimated PGA with 10% probability of exceedance in 50 years; 0.3g was the estimated PGA with 2% probability of exceedance in 50 years (U.S. Geological Survey).

We estimated residual friction angles for reactivation of the landslides ranging from less than 15 degrees up to 23 degrees. As discussed above, these estimates represent lower bound values for residual friction angles; nonetheless, the results are also comparable to those obtained in other studies. Ashland and Hylland (1997) estimated residual friction angles between 19 and 30 degrees, with an average range of 21–27 degrees, for the Pine Ridge landslide. Residual friction angles from glacial tills and other mixtures of gravel, sand, silt and clay vary between 12 and 35 degrees (Bell, 2002; Müller and Schlüchter, 2001; Eyles, 1983; Vaughan and Walbancke, 1978; Renteria, 1994). In general, friction angle decreases with increasing clay content.

7.2 Least Stable Segments

The least stable parts of the landslides are located on steep slopes bounded by abrupt change in topographic gradient (Fig. 13, 19, 25). There are several specific features worthy of comment. The toe of the Beaver Bench slide is almost as steep as the main scarp, which was identified as the least stable segment. The steep toe of the slide should also be treated with caution during development. Loading the toe from above by constructing buildings should be avoided. The toe could also be destabilized by erosion, but this would require unusually high and persistent flow in the small creek at the base of the Beaver Bench slide.

Additionally, the main scarp of the Blazing Star slide is almost as steep as the toe, which was identified as the least stable segment. Hence, the main scarp of the slide should be given due caution during development. The steep banks leading downward to Lake Creek contain a number of shallow and active debris slides, an observation that is reinforced by the stability modeling. The construction of roads, utilities, and buildings should be carefully planned to mitigate against instability generated by the weight of structures, the removal of material, and the addition of groundwater. This area is particularly susceptible to mass wasting where Lake Creek erodes the base of the hillside.

7.3 Strategy for Further Work

The slope stability analyses presented in this report are limited by the dearth of information about the subsurface geometry of the slide masses and groundwater table, as well as by the lack of geotechnical measurements. Given the extreme heterogeneity of glacial till and Keetley Volcanic rocks, conditions may vary widely within a slide mass, and the movement of groundwater may be convoluted and difficult to predict. Geometrical information on the subsurface location of the slip surfaces and the distribution of groundwater should be given first priority in future work. Subsurface information can be obtained by drilling boreholes in selected parts of the slides, although trenches and pits are useful for very shallow investigations. Borings will also be useful for determining the degree of weathering and alteration of the deposits, as well as information about the composition and textures of the deposits. The installation and monitoring of inclinometer casings in potentially active slides (such as the Westview, Aspen, and Pine Ridge slides) may yield information on slip surface locations and the distributions of displacement with depth. The installation of piezometers and a long-term monitoring program would be necessary to adequately characterize groundwater conditions in the area. Due to the large clast sizes and heterogeneity characteristic of slope materials in Timber Lakes, we recommend the use of large scale field or laboratory direct shear testing devices (e.g., Stormont and Farfan, 2005) for the estimation of shear strengths. Material testing in the field is preferred to laboratory testing of samples, although any information on the mechanical and physical parameters of the slide material is useful at this time. Further modeling of landslides with better constraints on material properties and groundwater conditions could involve delineating the more and less stable portions of slide masses.

Monitoring of several slides by repeated Global Positioning Satellite (GPS) surveys may be desirable. GPS surveys can be done quickly and at modest cost. Survey markers should be installed in the near future, before adverse climatic conditions like those of the early 1980s are repeated. Candidate slides to monitor include the Westview, Aspen, and Pine Ridge slides because they display evidence of recent activity. Monitoring may also be useful to assess the impact of increased development and irrigation on slide stability.

7.4 Guidelines for Landowners

A number of simple precautions can be implemented to mitigate the potential for adverse impacts by landslides.

- The Utah Geological Survey recommends that sites on potentially unstable slopes should not be developed until detailed slope stability analyses are performed. Potentially unstable slopes include the least stable segment(s) of a landslide, landslides that have a factor of safety less than 1.5 using conservative parameters (the Cedar Bark and Blazing Star slides), and landslides that have not been analyzed for slope stability.
- Development should be planned to minimize those activities that decrease the resisting forces, or increase the driving forces, for landslide motion. The most common mistakes are excavation of material at the base of steep slopes, creation of steep slopes within the interior of a slide mass, and adding surcharge load at the top of the slide, and at the tops of steep embankments within the slide. Surcharge loading includes buildings, large water storage tanks (if the combined load of the tank and water weighs more than the material removed), or deposits of excess material from excavations.
- Minimize activities that introduce water into the subsurface. Slope stability is strongly dependent on the distribution of pore water pressure in the slide masses. Water from irrigation of lawns, effluent from septic systems, reservoir seepage, concentration of runoff from impervious surfaces, and pipeline leaks may increase the flow and accumulation of groundwater in the subsurface. The heterogeneous nature of the deposits in Timber Lakes Estates may cause groundwater to move in a surprising and unpredictable manner through the subsurface. Landowners could be encouraged to landscape with plants that grow well in the natural climate, rather than introducing plants and grasses that require excessive irrigation. Landowners should also be made aware that activities on their land could impact slope stability in adjacent areas, even if their land is not on a slide mass.
- Natural vegetation adds strength to the soil by developing root systems, and vegetation also inhibits rapid infiltration of water into the subsurface. Maintaining natural vegetative cover is particularly important in areas susceptible to failure by debris sliding; the steep slopes above Lake Creek are a case in point. However, as mentioned above, plant species that require significant irrigation should not be introduced, as the extra water will have adverse effects on slope stability.

8.0 CONCLUSIONS

We produced a comprehensive, detailed landslide map of Timber Lakes Estates in Wasatch County, Utah. About 13% of the total acreage of Timber Lakes (about 3200 acres) consists of landslide deposits. We mapped twenty separate landslides scattered throughout Timber Lakes based on field investigation and aerial photograph and topographic map interpretation. Landslides involved the Tertiary Keetley Volcanics, Quaternary glacial till, and unconsolidated deposits derived from these units. Geologic mapping produced no evidence indicating that Jurassic strata of the Nugget Sandstone and Twin Creek Limestone were involved in landsliding in Timber Lakes Estates. Three of the landslides, the Pine Ridge, Westview, and Aspen slides, display fresh scarps or other signs of recent activity. In addition, active debris sliding commonly occurs on slopes above Lake Creek. Six landslides, the Clyde Lake, Pine Ridge, Witts Lake, Tanglewood, Blazing Star, and Aspen slides, are being undercut by Lake Creek. Landslide and pertinent lithologic and hydrologic data obtained through field observations, measurements and interpretations were tabulated.

Additionally, we performed preliminary slope stability analyses on three landslides in Timber Lakes Estates. Using PC-STABL5M, we statically modeled the Cedar Bark slide, an earth slide-earth flow in Quaternary glacial till, the Beaver Bench slide, a rock slide in Tertiary Keetley Volcanics, and the Blazing Star slide, a rock-earth slide in Keetley Volcanics and glacial till. We modeled each landslide under three different scenarios to estimate peak and residual friction angles of the material and to locate the least stable area of the landslide. We varied groundwater levels to simulate dry, mid-level, and saturated conditions. We estimated peak friction angles of 16–29 degrees and residual friction angles of <15–23 degrees for glacial till and Keetley Volcanics at differing groundwater conditions. The range of peak friction angles from 20–29 degrees probably represents more realistic groundwater conditions. This study did not reveal a difference in friction angles between Keetley Volcanics and glacial till. Peak friction angles were at or below published values for ϕ'_p of glacial till and similar natural aggregates, while residual friction angles fell within the range of published values for ϕ'_R of till and till-like materials. Estimated peak friction angles would be greater if pore pressures were greater than hydrostatic or if dynamic loading was induced by earthquake ground shaking; however, the possibility of weak zones at depth in the glacial till and Keetley Volcanics cannot be ruled out. The least stable segments within the landslides were on the steepest slopes within the slide, on either the main scarp or toe. For all three landslides, these segments would probably fail in saturated groundwater conditions and possibly fail in less than saturated conditions. Using conservative groundwater and material parameters, the factors of safety for the present configurations of the Cedar Bark and Blazing Star slides are less than 1.5, lower than the guidelines suggested by the Utah Geological Survey (Hylland, 1996).

The slope stability analyses were limited by a lack of information concerning material properties, groundwater conditions, and subsurface geometry of the landslides. Future studies involving boreholes, trenches, material testing, GPS surveys, and groundwater monitoring are necessary to resolve these issues. To reduce landslide hazard, developers and landowners should avoid loading the tops of landslides and steep slopes, cutting toes of slides and steep slopes, removing vegetation from steep slopes, and introducing water into landslides and steep slopes by irrigation, septic systems, reservoirs, or surface drainage. The Utah Geological Survey recommends that development should not occur on potentially unstable slopes until a detailed slope stability analysis is completed.

9.0 ACKNOWLEDGMENTS

Wasatch County and Timber Lakes Property Owners Association provided project funding. Barry Solomon, Francis Ashland, Mike Hylland, and Gary Christenson at the Utah Geological Survey participated in reviews and provided valuable insight. Charles Payton of AMEC participated in project and report reviews. We thank Craig Nelson, Dr. Danny Horns, and Dr. Paul Santi for helpful reviews. Anthony Kohler, formerly of Wasatch County, and Mike Camper of Timber Lakes Property Owner's Association provided a great deal of assistance. Ivan Spencer and Don Wood at Wasatch County contributed their GIS expertise to the mapping effort.

10.0 REFERENCES

Ashland, F.X., and Hylland, M.D., 1997, Preliminary geotechnical-engineering slope-stability investigation of the Pine Ridge landslide, Timber Lakes Estates, Wasatch County, Utah: Utah Geological Survey Report of Investigation 232, 29 p.

Bell, F.G., 2002, The geotechnical properties of some till deposits occurring along the coastal areas of eastern England: Engineering Geology, v. 63, p. 49–68.

Biek, R.F., Hylland, M.D., Welsh, J.E., and Lowe, Mike, 2003, Geologic map of the Center Creek quadrangle, Wasatch County, Utah: Utah Geological Survey Map 192, 25 p., 2 pl. 1:24,000.

Cronin, V.S., 1992, Compound landslides: Nature and hazard potential of secondary landslides within host landslides, *in* Slosson, J.E., Keene, A.G., and Johnson, J.A., eds., Landslides/Landslide Mitigation: Boulder, Colorado, Geological Society of America Reviews in Engineering Geology, v. IX, p. 1–9.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Schuster, R.L., Landslides: investigation and mitigation: Transportation Research Board National Research Council Special Report 247, p. 36–75.

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

Eyles, N., and Sladen, J.A., 1981, Stratigraphy and geotechnical properties of weathered lodgement till in Northumberland, England: Quarterly Journal of Engineering Geology, v. 14, p. 129–142.

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., ed., 1996, Guidelines for evaluating landslide hazards in Utah: Utah Geological Survey Circular 92, 16 p.

Hylland, M.D., compiler, 1995, Engineering geologic map folio, western Wasatch County, Utah: Utah Geological Survey Open-File Report 319, 12 sheets, scale 1:24,000.

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

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.

Lebourg, T., Riss, J., and Pirard, E., 2004, Influence of morphological characteristics of heterogeneous moraine formations on their mechanical behavior using image and statistical analysis: Engineering Geology, v. 73, p. 37–50.

Müller, B.U., and Schlüchter, C., 2001, Influence of the glacier bed lithology on the formation of a subglacial till sequence — ring-shear experiments as a tool for the classification of subglacial tills: Quaternary Science Reviews, v. 20, p.1113–1125.

Renteria, Rene, 1994, Strength and behavior of soil, *in* Hall, D.E., Long, M.T., and Remboldt, M.D., eds., 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.

Stormont, J.C., and Farfan, E., 2005, Stability evaluation of a mine waste pile: Environmental and Engineering Geoscience, v. 11, n. 1, p. 43–52.

U.S. Geological Survey Earthquake Hazards Program National Hazard Map, retrieved July 16, 2001, from http://geohazards.cr.usgs.gov/eq/html/natlmap.html

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.

Wasatch County
Timber Lakes Landslide Map

Timber Lakes Property Owners Association

Plate 1, Sheet 3 of 4

The lot lines shown here were digitized for the internal use of Wasatch County Government. They were based upon the section control provided by the Wasatch County Recorder's Office. These lines should be used for reference purposes only. Questions concerning exact lot location should be directed to a licensed land surveyor.

DIGITAL PHOTOGRAMMETRY ACCURACY DECLARATION

Digital map data contained in these files was collected by photogrammetric methods. Reasonable procedures have been adhered to with regard to photo scale, equipment, calibration and operator experience to achieve the accuracy required by the scope of work.

The accuracy of this data presumes that there is no discernable error in the ground control survey.

Aero-Graphics cannot be responsible or liable for the further manipulation and plotting of design maps by the user's software.

The data collection procedure is designed to meet or exceed the requirements of United States National Map Accuracy Standards.

1. Horizontal accuracy. For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general, what is well-defined will also be determined by what is plottable on the scale of the map within 1/100 inch. Thus, while the intersection of two roads or property lines meeting at right angles would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc.

2. Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.

3. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy.

4. Mapping areas obscured by vegetation or shadows may not meet U.S. National Map Accuracy Standards. If spot elevations have been requested in those areas they are approximate. If the resulting map plots are altered from the specified scale and contour interval either by digital or photo/mechanical means, there is no assurance of accuracy.

5. It is the responsibility of the map user not only to field verify the accuracy of map information derived from the data, but also to ascertain whether or not the map scale, contour interval and accuracy are satisfactory for whatever purpose the map is to be used.

Wasatch County
Timber Lakes Landslide Map

Timber Lakes Property Owners Association

Plate 1, Sheet 2 of 4

The lot lines shown here were digitized for the internal use of Wasatch County Government. They were based upon the section control provided by the Wasatch County Recorder's Office. These lines should be used for reference purposes only. Questions concerning exact lot location should be directed to a licensed land surveyor.

DIGITAL PHOTOGRAMMETRY ACCURACY DECLARATION

Digital map data contained in these files was collected by photogrammetric methods. Reasonable procedures have been adhered to with regard to photo scale, equipment, calibration and operator experience to achieve the accuracy required by the scope of work.

The accuracy of this data presumes that there is no discernable error in the ground control survey.

Aero-Graphics cannot be responsible or liable for the further manipulation and plotting of design maps by the user's software.

The data collection procedure is designed to meet or exceed the requirements of United States National Map Accuracy Standards.

1. Horizontal accuracy. For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general, what is well-defined will also be determined by what is plottable on the scale of the map within 1/100 inch. Thus, while the intersection of two roads or property lines meeting at right angles would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc.

2. Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.

3. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy.

4. Mapping areas obscured by vegetation or shadows may not meet U.S. National Map Accuracy Standards. If spot elevations have been requested in those areas they are approximate. If the resulting map plots are altered from the specified scale and contour interval either by digital or photo/mechanical means, there is no assurance of accuracy.

5. It is the responsibility of the map user not only to field verify the accuracy of map information derived from the data, but also to ascertain whether or not the map scale, contour interval and accuracy are satisfactory for whatever purpose the map is to be used.

Wasatch County
Timber Lakes Landslide Map

Timber Lakes Property Owners Association
Plate 1, Sheet 1 of 4

The lot lines shown here were digitized for the internal use of Wasatch County Government. They were based upon the section control provided by the Wasatch County Recorder's Office. These lines should be used for reference purposes only. Questions concerning exact lot location should be directed to a licensed land surveyor.

DIGITAL PHOTOGRAMMETRY ACCURACY DECLARATION

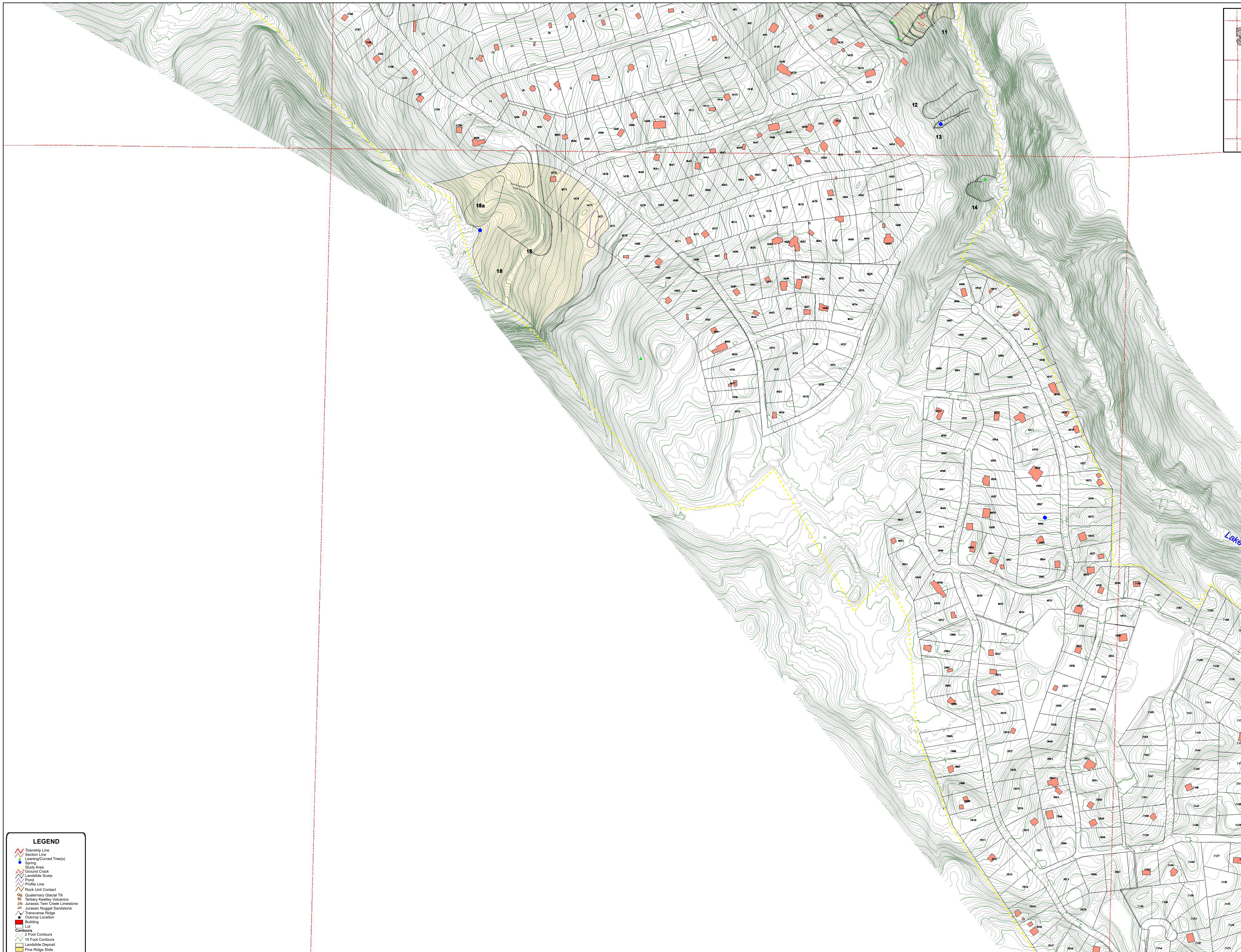
Digital map data contained in these files was collected by photogrammetric methods. Reasonable procedures have been adhered to with regard to photo scale, equipment, calibration and operator experience to achieve the accuracy required by the scope of work.

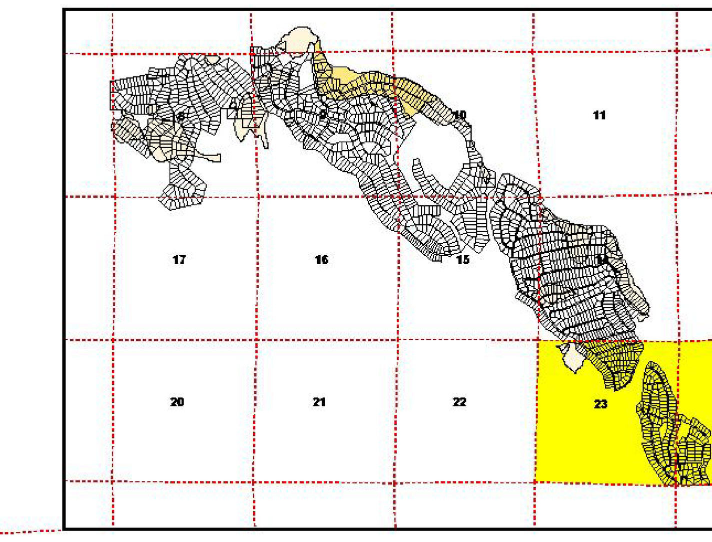
The accuracy of this data presumes that there is no discernable error in the ground control survey.

Aero-Graphics cannot be responsible or liable for the further manipulation and plotting of design maps by the user's software.

The data collection procedure is designed to meet or exceed the requirements of United States National Map Accuracy Standards.

1. Horizontal accuracy. For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general, what is well-defined will also be determined by what is plottable on the scale of the map within 1/100 inch. Thus, while the intersection of two roads or property lines meeting at right angles would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc.
2. Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.
3. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy.
4. Mapping areas obscured by vegetation or shadows may not meet U.S. National Map Accuracy Standards. If spot elevations have been requested in those areas they are approximate. If the resulting map plots are altered from the specified scale and contour interval either by digital or photo/mechanical means, there is no assurance of accuracy.
5. It is the responsibility of the map user not only to field verify the accuracy of map information derived from the data, but also to ascertain whether or not the map scale, contour interval and accuracy are satisfactory for whatever purpose the map is to be used.





DIGITAL PHOTOGRAMMETRY ACCURACY DECLARATION

Digital map data contained in these files was collected by photogrammetric methods. Reasonable procedures have been adhered to with regard to photo scale, equipment, calibration and operator experience to achieve the accuracy required by the scope of work.

The accuracy of this data presumes that there is no discernable error in the ground control survey.

Aero-Graphics cannot be responsible or liable for the further manipulation and plotting of design maps by the user's software.

The data collection procedure is designed to meet or exceed the requirements of United States National Map Accuracy Standards.

1. Horizontal accuracy. For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc. In general, what is well-defined will also be determined by what is plottable on the scale of the map within 1/100 inch. Thus, while the intersection of two roads or property lines meeting at right angles would come within a sensible interpretation, identification of the intersection of such lines meeting at an acute angle would obviously not be practicable within 1/100 inch. Similarly, features not identifiable upon the ground within close limits are not to be considered as test points within the limits quoted, even though their positions may be scaled closely upon the map. In this class would come timber lines, soil boundaries, etc.

2. Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.

3. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy.

4. Mapping areas obscured by vegetation or shadows may not meet U.S. National Map Accuracy Standards. If spot elevations have been requested in those areas they are approximate. If the resulting map plots are altered from the specified scale and contour interval either by digital or photo/mechanical means, there is no assurance of accuracy.

5. It is the responsibility of the map user not only to field verify the accuracy of map information derived from the data, but also to ascertain whether or not the map scale, contour interval and accuracy are satisfactory for whatever purpose the map is to be used.

Wasatch County
Timber Lakes Landslide Map

Timber Lakes Property Owners Association
Plate 1, Sheet 4 of 4

N W E S

200 0 200 400 600 800 1000 Feet

The lot lines shown here were digitized for the internal use of Wasatch County Government. They were based upon the section control provided by the Wasatch County Recorder's Office. These lines should be used for reference purposes only. Questions concerning exact lot location should be directed to a licensed land surveyor.