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Field Studies and Modeling Analysis of the Roan Creek Landslide, Garfield County, Colorado

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ABSTRACT

The Roan Creek landslide is located in the Roan Creek drainage basin in Garfield County, Colorado on the north-facing slope of Kimball Mountain. It initially failed on 24 April 1985 and currently is 4000 feet long, has an elevation differential of 650 feet between head scarps and toe, and ranges in width from 500 to 1500 feet. At the time of initial failure, the rapid movement and large size of the landslide caused concern that Roan Creek might be dammed. However, the slide stopped fifty feet from Roan Creek at its narrowest approach.

Field studies were initiated to determine the cause and mode of failure of the Roan Creek landslide. Field mapping was conducted utilizing a large-scale topographic base map produced with the aid of photogrammetric techniques. The areal extent of the slide, all primary structural features, surface water and seeps, and lithologic zones were mapped.

The Roan Creek landslide was classified as a slump-earthflow complex and occurred in both surficial and deposits in the pre-existing drainage and in Eocene-age bedrock comprising claystones, shales, siltstones and fine-grained sandstones. The head scarps cut horizontal beds of the Garden Gulch and Douglas Creek Members of the Green River Formation. Material from the Upper Shire Member of the underlying Wasatch Formation is also found in the slide mass. Most of the material present in the slide is highly fissile and friable.

Climatological data indicate that 1985 was the second wettest year during the period of record (1948 - present) in the Roan Creek basin. Precipitation was above normal in both March and April 1985, with 2.41 inches of rain falling during the seven days preceding failure of the landslide. Average discharge of Roan Creek was 74 percent above normal in March 1985 and 396 percent of normal in April 1985. The anomalously high discharges reflect rapid snowmelt in the uplands of the Roan Creek basin as well as above average precipitation. The combined effect of above normal precipitation and accelerated snowmelt on Kimball Mountain allowed high surface infiltration of water and saturation of material in the drainage which contributed to the slope failure.

Based on field notes and observations, air photo interpretation and published data, a three-stage failure model for the Roan Creek landslide was developed. Initial failure of the landslide occurred at the eastern head scarp. Material from the initial failure loaded the saturated soil and rock in the drainage bottom triggering a second phase of failure. Large volumes of rock and soil were removed by this second phase which resulted in the removal of lateral support in the western head scarp area. The failure of the western head scarp area was the third phase of the Roan Creek landslide. The proposed failure model was verified with PCSTABL4, a slope stability program.

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CONTENTS

APPENDICES

FIGURES

FIGURES CONTINUED

TABLES

PLATES

1.0 INTRODUCTION

1.1 Overview

The Roan Creek landslide is located in the Roan Creek drainage basin twenty miles northwest of DeBeque in Garfield County, Colorado (Figure 1) in T6S, R99W Section 28 and 33 on the north-facing slope of Kimball Mountain. It is approximately 4000 feet in length, has an elevation differential of 650 feet between the head scarps and the toe, and ranges in width from 500 to 1500 feet. Figure 2 is an overview of the slide taken from the opposite side of the valley.

Initial failure of the Roan Creek landslide occurred on 24 April 1985. Several state agencies, including the Colorado Department of Water Resources, rapidly became involved in formulating a hazard assessment of the landslide. Swift movement of the slide and its great volume necessitated a risk evaluation. The greatest concern was the potential of a landslide dam on Roan Creek, its probable failure and subsequent downstream flooding. Fortuitously, the landslide stopped 50 feet from Roan Creek (Figure 3) eliminating the immediate threat to the creek.

The Colorado Geological Survey (CGS) sent a geologist into the field to investigate the mass movement and submit an initial report (Turney, 1985). An aerial mission was flown by the CGS over the area in August of 1985 to procure aerial photographs at scales of 1:6000 and 1:18,000 (Figure 4). A more detailed analysis of the slide was desired which would include detailed surficial mapping of the Roan Creek landslide, a study of the primary stuctural features and a more definitive hazard evaluation.

1.2 Objectives

This engineering report has the following objectives:

1) To compile a field map detailing the areal extent, primary structures and other geologic features of the Roan Creek landslide.

2) Collection of climatological and hydrologic data and information on areal geology and soil properties.

3) Evaluation and analysis of field observations and data, including failure mode and mechanism, groundwater conditions and primary structures.

4) Soil property analysis from laboratory work and literature review.

5) Development of a failure mode model.

6) Modeling of the landslide utilizing PCSTABL4--a slope stability analysis program.

7) Draw appropriate conclusions on slide failure mechanisms and modeling efforts.

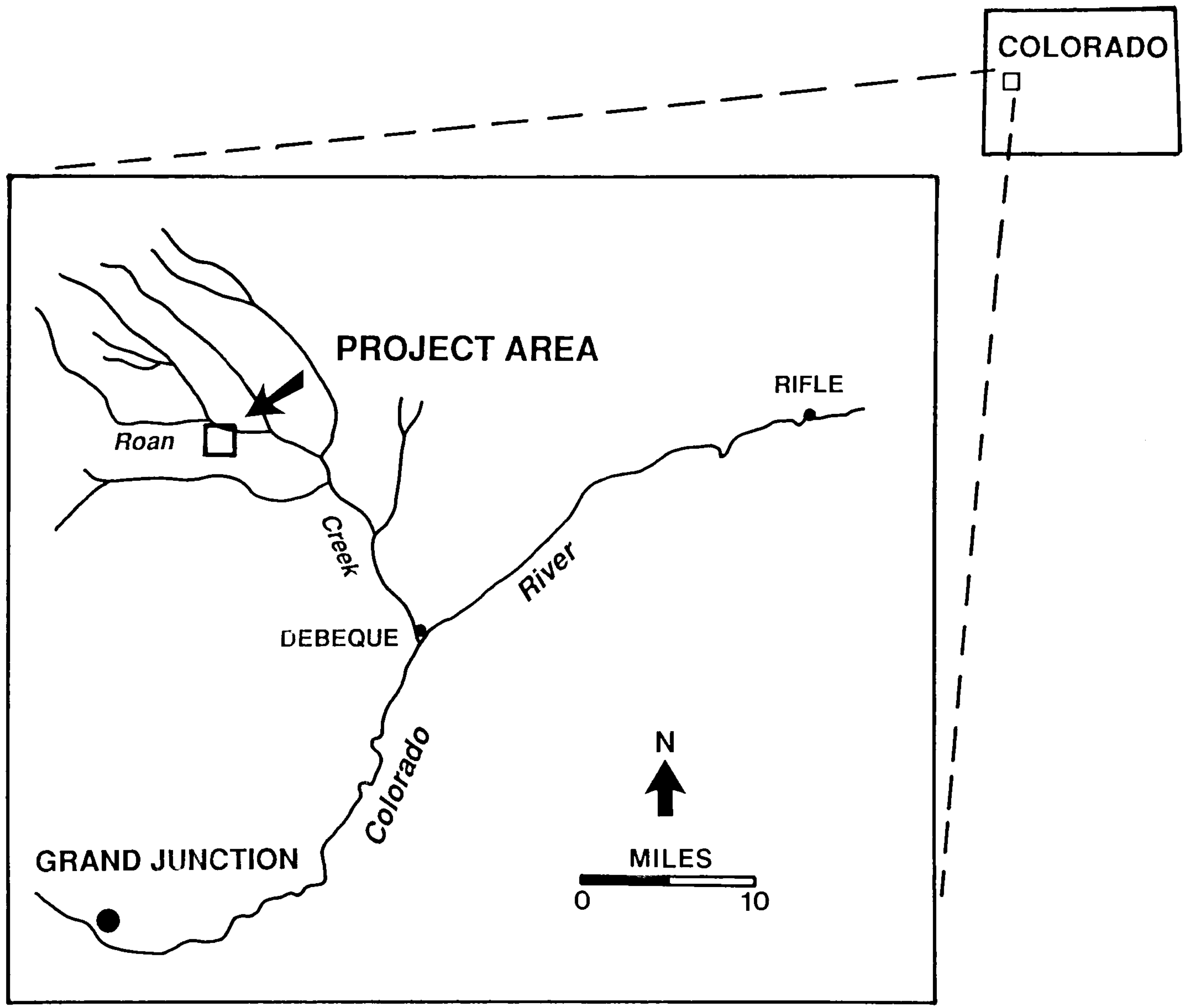


Figure 1. Location map of report area.

Figure 2. A view of the Roan Creek landslide looking south across Roan Creek valley.

Figure 3. The Roan Creek landslide halted 50 feet from Roan Creek. The height of the cliff bank in foreground is approximately 15 feet.

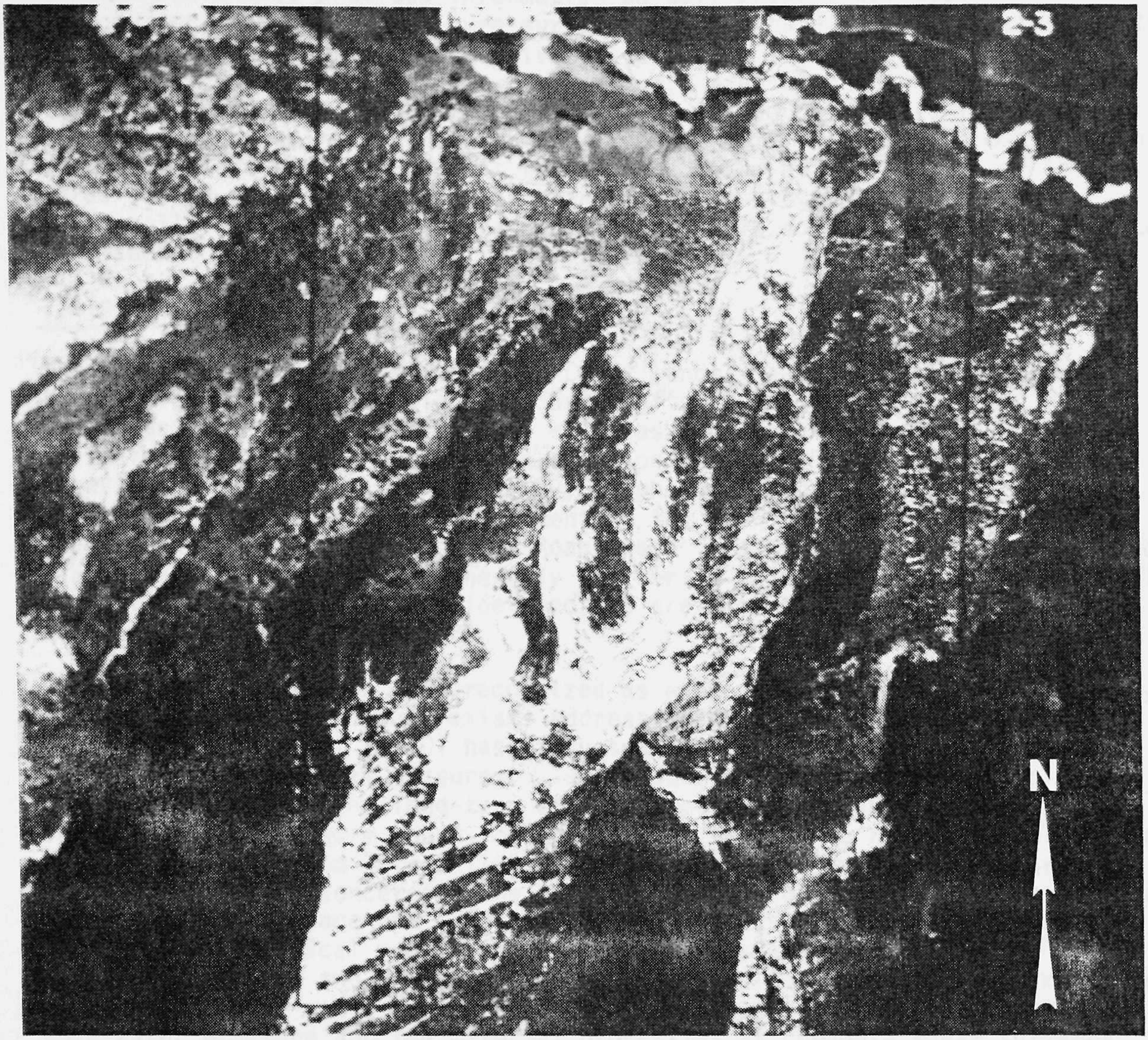


Figure 4. An aerial view of the Roan Creek landslide.

1.3 Methods of Study

Three weeks were spent in the field mapping the Roan Creek and Phantom landslides during the summer of 1986. Large-scale topographic base maps (scale 1:2400) compiled for the Colorado Geological Survey using photogrammetric techniques were utilized in conjunction with aerial photographs for the majority of the field mapping. Primary structural features (including scarps and tension cracks) as well as seeps, standing water and lithologic zonations were noted and logged.

This information was then used as a basis for planning a subsurface exploration program. In October 1986, the assistance of two Colorado School of Mines senior-level classes, Engineering Geophysics and Engineering Geology, was enlisted to pursue this program. Geophysics students conducted a variety of geophysical surveys utilizing resistivity profiling, shallow seismic (both reflection and refraction), and microgravity methods. Optimistically, these surveys would have provided information on soil properties, depth to groundwater and depth to failure surface. Unfortunately the conditions on the landslide surface were not conducive to good data collection and the geophysical data was of only marginal value. A gasoline-powered hand-auger was procured to drill some exploratory holes in the slide to collect soil samples and determine groundwater conditions. This program also met with only limited success as the auger was refused at depths of eleven feet or less below ground surface due to an abundance of rock fragments aligned sub-parallel to the ground surface at depth. Bulk soil samples were collected for laboratory analysis.

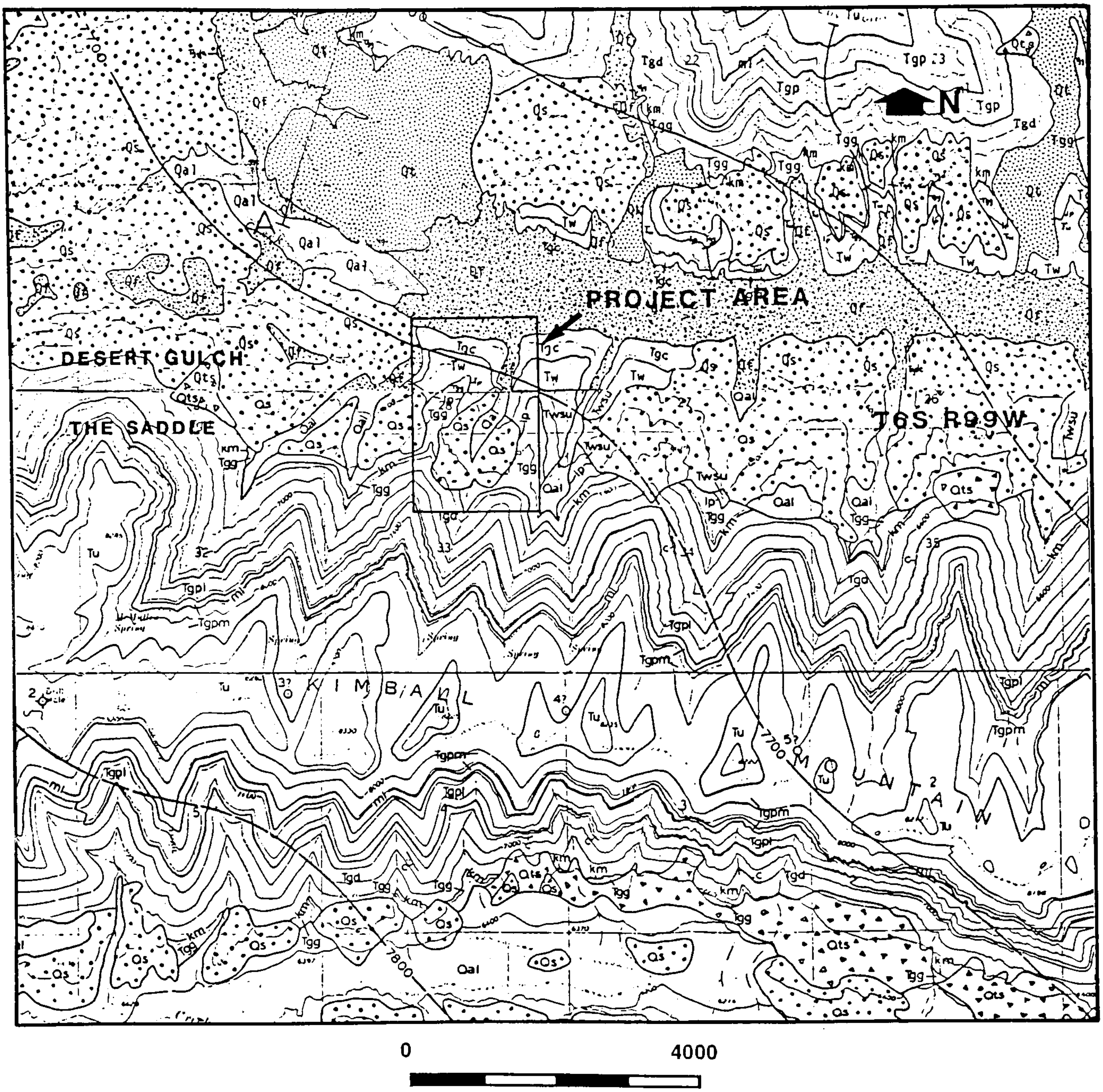
1.4 Previous Work

The first documentation of the Roan Creek landslide was compiled by Turney (1985) of the Colorado Geological Survey after an abbreviated field investigation. She classified the slide as a slump-earthflow complex and estimated its size and volume. In addition, Olson (1974) conducted an overview of landslide risk and valley morphology in the Roan and Parachute Creek drainage basins. His assessment of the Roan Creek basin included the identification and mapping of the Roan Creek landslide head scarps. The head scarps present in 1974 are generally smaller in magnitude than those currently present and associated landslide deposits are much less extensive than those existing today.

Because landslides have been recognized as exogenetic hazards since the early 1900's, abundant literature exists addressing hillslope stability and landslides. Terzaghi (1950) has discussed causes and dynamics of landslides and subsequent remedial measures. Ter-Stepanian (1963) used a mechanics approach to address the long-term stability of slopes. Rainfall and ancient landslide deposits were found to significantly influence recent landslides in a study by Nilsen and Turner (1975). The Transportation Research Board has published a report concerning analysis and control of landslides (Schuster and Krizek, 1978). Savage and Chleborad (1982) and Savage and Smith (1986) have developed mathematical models to determine stress and velocity fields within a landslide. Keefer and Johnson (1983) found earthflows are generally mobilized by increased pore-water pressure and that their velocities are a function of pore-water pressure and the material properties at boundary shear surfaces. A series of computer programs for slope stability analysis, titled STABL with increasing number suffices indicating revised versions, was created by Purdue University's Department of Civil Engineering (Lovell and others, 1985 and Carpenter, 1985). Iverson (1985, 1986) has derived a constitutive equation for mass movement behavior and postulated a theory for time-dependent behavior to explain the dynamics of slow landslides.

2.0 REGIONAL GEOLOGY

The Roan Creek basin is located in the Colorado Plateau physiographic province of the United States which is characterized by broad mesas deeply incised by river valleys, and lies in the western margin of the Piceance structural basin, a large asymmetric downward. The geology of the basin has been mapped in a series of U.S. Geological Survey quadrangles with the area immediately surrounding the Roan Creek landslide mapped by Johnson (1977, 1981). Figure 5 shows the geology of the study area.



Contour Interval = 200 ft

Figure 5. Geologic map of the study area, from Johnson 1977, 1981.

Figure 5. Continued.

EXPLANATION

Qal **Alluvial Deposits (Holocene)**—Found on flood plains of major streams

Qf **Alluvial Fan Deposits (Holocene)**—Dominant type of alluvium. Most of valley bottoms of major streams covered with coalescing fan deposits from distributary gulleys and channels

Qts **Talus and Slopewash Deposits (Holocene and Pleistocene)**— On steep slopes; grades laterally into aluvial fan deposits

Qs **Slump and Landslide Deposits (Holocene and Pleistocene)**—Common at base of steep canyon walls; some slumps partially buried by Pleistocene terrace deposits

Qt **Uinta Formation (Eocene)**— Mostly brown and gray, poorly bedded to massive, noncalcareous to moderately calcareous sandstone, siltstone, and mudstone, with thin layers composed of typical Parachute Creek Member Lithologies such as marlstone and silty marlstone, amd minor oil shale. Intertongues with Green River Formation

Ts **Slump Deposit (Eocene)**— Found only on Brush Mountain; highly contorted Uinta Formation and tongues of Green River Formation; contorting took place before sediments lithified

Green River Formation (Eocene)

Tgsk **Marlstone Tongue at Skinner Ridge**—Mostly buff-weathering, well-laminated marlstone; usually contains one 7-5 cm thick, rich oil-shale bed 6-9 m from top. Locally includes zones of massive mudstone typical of the Uinta Formation. Unit is silty, not well laminated on Brush Mountain. Grades into Unita Formation on northwest part of Brush Mountain. Joines Parachute Creek Member in southeastern part of quadrangle. From 4-20 m thick, thickens irregularly to southeast

Tgal **Marlstone Tongue at Sleepy Ridge**—Mostly marlstone and lean to moderately rich oil shale in southeastern part of quadrangle; grades to northwest into marlstone interbedded with massive gray and brown mudstone typical of Uinta Formation. Joins Parachute Creek Member in central part of quadrangle. Lower part of marlstone at Sleepy Ridge mapped as marlstone at Bull Fork in Figure Four Spring quadrangle to north. From 15-35 m thick, thickens irregularly to northwest

Tgp **Parachute Creek Member**—From base of Mahogany ledge to top of member, mostly lean to rich oil shale. Below Mahogany ledge, oil shale is interbedded marlstone and silty marlstone. Oil shale varies from well laminated to brecciated. Brecciated oil shale contains clasts of marlstone and siltstone and typically shows signs of soft-sediment deformation; includes numerous thin analcitized tuff beds. Thin-gray, massive siltstone beds present between top of R-5 rich oil-shale zone and base of R-6 rich oil-shale zone. Distinguished from underlying Douglas Creek Member by a much greater number of oil-shale beds and lack of stromatolites. Base of Parachute Creek Member is approximate base of R-4 rich oil-shale zone. About 280-370 m thick, thickens generally to north

ml **Mahogany ledge (Mahogany zone in subsurface)**—Richest oil-shale unit in Parachute Creek Member. Line on map shows top of ledge. About 18-28 m thick, thickens to northeast

Tgd **Douglas Creek Member**—Mostly olive-gray calcareous mudstone and gray sandstone and siltstone with some ostracodal, oolitic and algal limestones, and a few, thin oil-shale beds. Oil-shale beds typically brecciated and in many cases occur draped over top of thin stromatolite layers. Sandstones and siltstones typically 1 m thick or less; however, one sandstone as much as 10 m thick occurs about 45 m above base of member along south side of Brush Mountain. Bedding features observed in this sandstone include parallel-horizontal to low-angle cross laminae, troughs as high as 1 m, and symmetrical ripple laminae. Base of member is tuff bed at Kimball Mountain, which is approximately the top of clay-rich oil shales of Garden Gulch Member below. About 185-230 m thick, thickens to north

km **Tuff bed at Kimball Mountain**—Even-bedded tuff as much a 5 cm thick; consists of analcime which is partially replaced by spotty calcite crystals. Purple and gray on fresh surface, and rust-brown where weathered; locally discontinuous

Tgg **Garden Gulch Member**—Mostly papery fissile, laminated dark-gray to black, kerogen-rich clay shale with minor marlstone and silty marlstone. Two thin zones shown on measured section yielded 29 and 37.5 gallons of oil per ton with Fischer assay. About 60 m thick

lp **Marker bed at Long Point**—A widespread transgressive unit found throughout southwest Piceance Creek Basin. In Desert Gulch quadrangle, bed is an ostracodal limestone about 10-40 cm thick which locally contains **Goniobasis** and **Viviparus** gastropods

Tgc **Member at Cow Ridge**—Mostly dark gray clay shale, dark-brown carbonaceous clay shale, and thin coal beds with a few thin sandstone and siltstone beds. Coal beds usually less than 10 cm thick. Gastropods and pelecypods locally abundant. Only upper part of tonque is exposed along Roan Creek in southern part of quadrangle

Tw **Tongue of Wasatch Formation (Eocene)**— Mostly purple, maroon, and gray, massive mudstone with a few lenticular sandstone units. Sandstones are fine to medium grained, trough crossbedded, and as much as 10 m thick. About 70 m thick where exposed in southern part of quadrangle

From Johnson (1981)

2.1 Topography

In the vicinity of the Roan Creek landslide, topography ranges from 5800 feet above mean sea level on the valley floor of Roan Creek to elevations of 8330 feet on Kimball Mountain to the south and 8265 feet on Brush Mountain to the north (Figure 6).

2.2 General Stratigraphy

Several Eocene-age stratigraphic units outcrop on Kimball Mountain. The oldest is the Upper Shire Member of the Wasatch Formation which is overlain conformably by the Garden Gulch Member of the Green River Formation. Above the Garden Gulch lies the Douglas Creek Member of the Green River Formation which in turn underlies the Parachute Creek Member of the Green River Formation. All of these units are essentially horizontal with dips of less than 1 degree to the east. The relationship of these units is displayed in a generalized stratigraphic column in Figure 7.

The Upper Shire Member of the Wasatch Formation and the Garden Gulch Member of the Green River Formation are of particular interest as the Roan Creek landslide failed in these units. Parts of the Douglas Creek Member of the Green River Formation were also incorporated into the landslide through retrogressive failure at the head scarps.

The Upper Shire Member is composed of predominantly gray and maroon variegated mudstone, some shale and lenses of sandstone. Depositional environment has been interpreted as fluvial and mudflat in origin. Thickness of the unit in the mapping area is approximately 300 feet, but outcrop exposures are much thinner. Clay minerals present include kaolinite, illite, and montmorillonite (Hosterman and Dyni, 1972).

The Garden Gulch Member of mid-Eocene age and lacustrine origin consists of fissile kerogen-rich shale, calcareous sandstone, siltstone and mudstone and is approximately 200 feet in thickness in the study area. Clay composition of the member is similar to that of the Upper Shire Member.

The Douglas Creek Member in the Kimball Mountain area is composed primarily of siltstone, with some claystone and sandstone. Unit thickness is 400 feet.

While in the field, the author observed that the rocks of these units were generally fissile and friable, air slaked rapidly and readily failed when compressive or tensile stress was applied by hand.

2.3 Geomorphology

Roan Creek is a third order drainage which flows perennially and feeds into the Colorado River at DeBeque, twenty miles downstream of the slide area. Johnson (1977, 1981) has mapped extensive landslide deposits along both flanks of the Roan Creek valley. The deposits generally cover a larger areal extent on the north-facing slopes of the valley as these slopes retain greater quantities of water, producing a microclimate more conducive to slope failure. However, many slides are present on southern exposures as well, including a landslide, tentatively named the Phantom landslide, which failed within a week of the Roan Creek landslide directly across the valley (refer to Figure 6 for location). The Phantom landslide incorporated surficial deposit

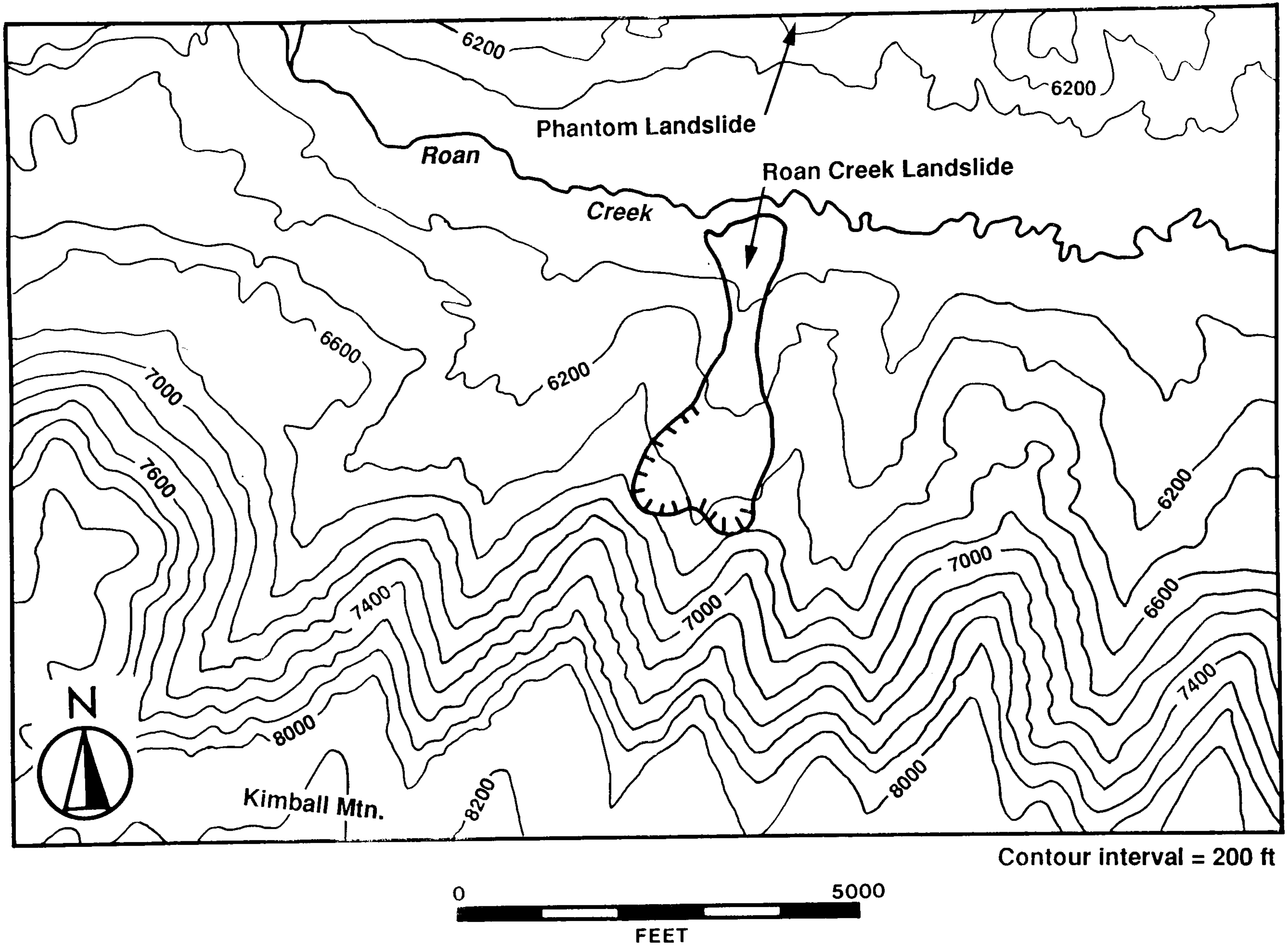


Figure 6. Topographic map of Roan Creek Landslide and immediate vicinity (from USGS 7.5' topographic quadrangles The Saddle and Desert Gulch).

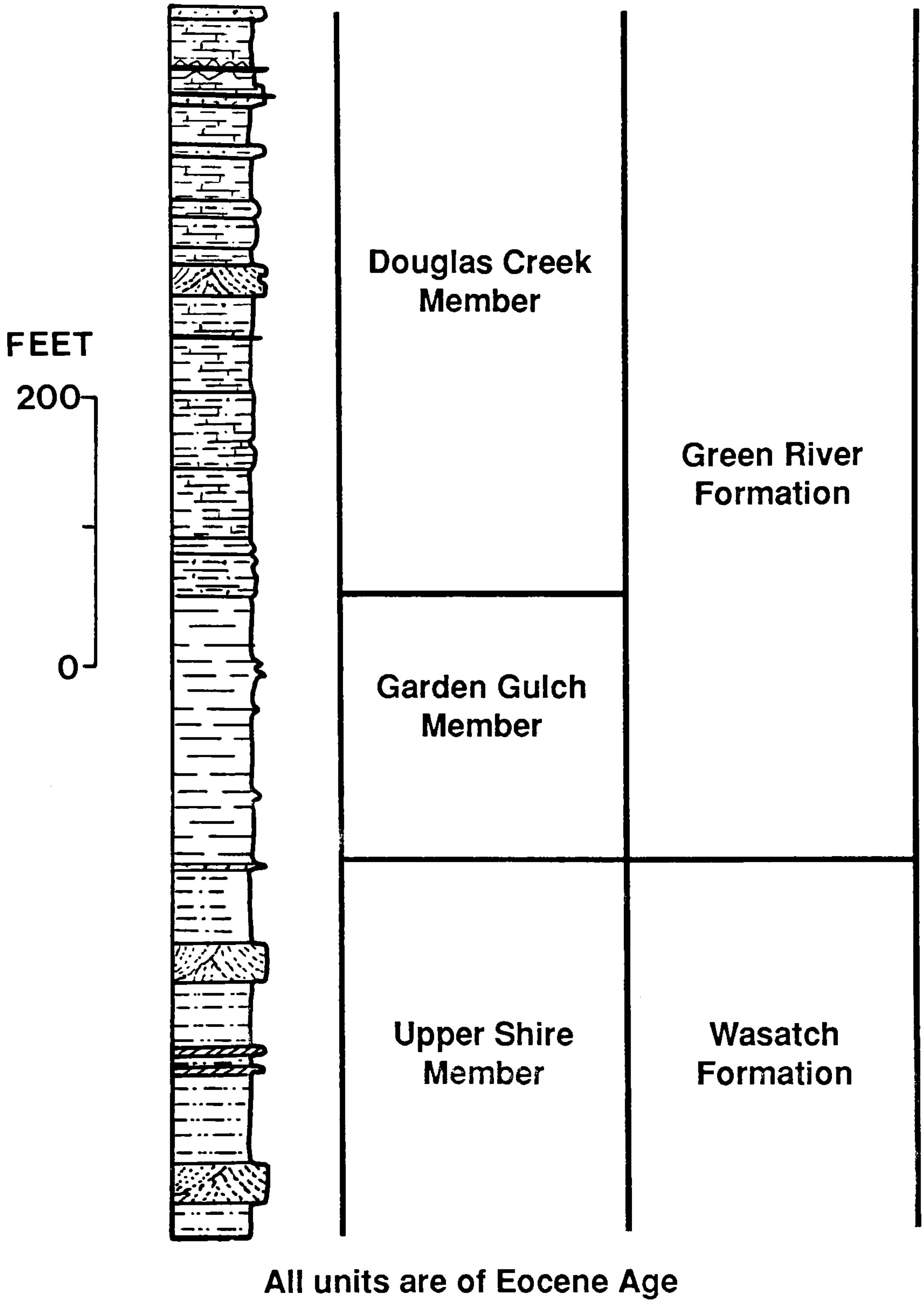


Figure 7. Generalized stratigraphic column (after Johnson, 1981).

materials, as well as bedrock from the Upper Shire Member of the Wasatch Formation and the Garden Gulch Member of the Green River Formation. Comparison of field observations indicates the Phantom landslide had a lower moisture content and higher viscosity than the Roan Creek landslide. This is not particularly surprising as southern exposures in the northern hemisphere tend to retain less water than northern exposures due to increased exposure to solar energy on south-facing slopes.

3.0 CLIMATOLOGY, HYDROLOGY, AND EARTHQUAKE SEISMOLOGY

3.1 Climatology

Climatological data collected from Altenbern, Colorado, five miles southeast of the Roan Creek landslide has been analyzed to determine the effect of precipitation on the failure of the slide. Mean annual precipitation at Altenbern between 1948 and 1985 is 15.31 inches. Annual precipitation records are displayed in Figure 8. The 24.18 inches, 158 percent of mean annual precipitation, that accumulated during the year of 1985 was the second highest total on record. Rainfall was 1.49 inches above normal in March 1985 and 1.58 inches above normal in April 1985. The Roan Creek landslide failed on 24 April 1985. In the seven days preceding failure, 2.41 inches of rain fell. This precipitation most likely contributed large volumes of water to the slide mass increasing pore water pressure and subsequently reducing the stability of the slide mass.

Nilsen and Turner (1975) studied the influence of rainfall and ancient landslide deposits on recent landslides in urban areas of northern California. They concluded smaller amounts of rain are required to generate landslides in spring than in other seasons of the year due to generally higher antecedent moisture contents. They also found that continuous rainfall caused more landslides than single, short-duration storm events separated by dry periods. The circumstances surrounding failure of the Roan Creek landslide correlate well with their study results, i.e., fairly continuous precipitation in the seven days prior to failure of the slide during the spring season.

3.2 Hydrology

Stream gage records compiled for Getty Oil exist for the water years 1971 to the present in the Roan Creek basin. Data from a gage 3 miles downstream of the landslide on Roan Creek were analyzed. Hydrographs depicting the average flow rates for the months of March and April for the period of record are presented as Figures 9 and 10. Mean average discharge for March is 20.4 cubic feet per second (cfs) and for April is 71.4 cfs. Average discharge in March 1985 was 35.4 cfs, 74 percent above average mean discharge. Average discharge in April 1985 was 282.7 cfs, 396 percent of mean average discharge for the month of April. The maximum discharge recorded in April prior to the failure of the Roan Creek landslide was 462 cfs on April 18th and 19th. Roan Creek discharge averaged 433 cfs with a maximum of 450 cfs and minimum of 425 cfs on 24 April, 1985 -- the date of initial failure of the Roan Creek landslide.

Figure 11 shows the relationships of temperature, Roan Creek discharge and precipitation during the first 25 days of April 1985. As temperature increased through the month, discharge also increased rapidly from 11 April to 19 April when discharge rose from 132 cfs to 443 cfs. The sudden drop in temperature on 17 April was accompanied by an increase in precipitation lasting seven days and a leveling off of discharge to a value of about 425 cfs.

The increased average discharge in these two months implies heavy snowmelt upstream of the gaging station. Some of the increased discharge can be attributed to above normal precipitation; however, this does not account for the extraordinary discharge anomaly in April 1985. The majority of this excess runoff is thought to be due to accelerated melting of the snowpack.

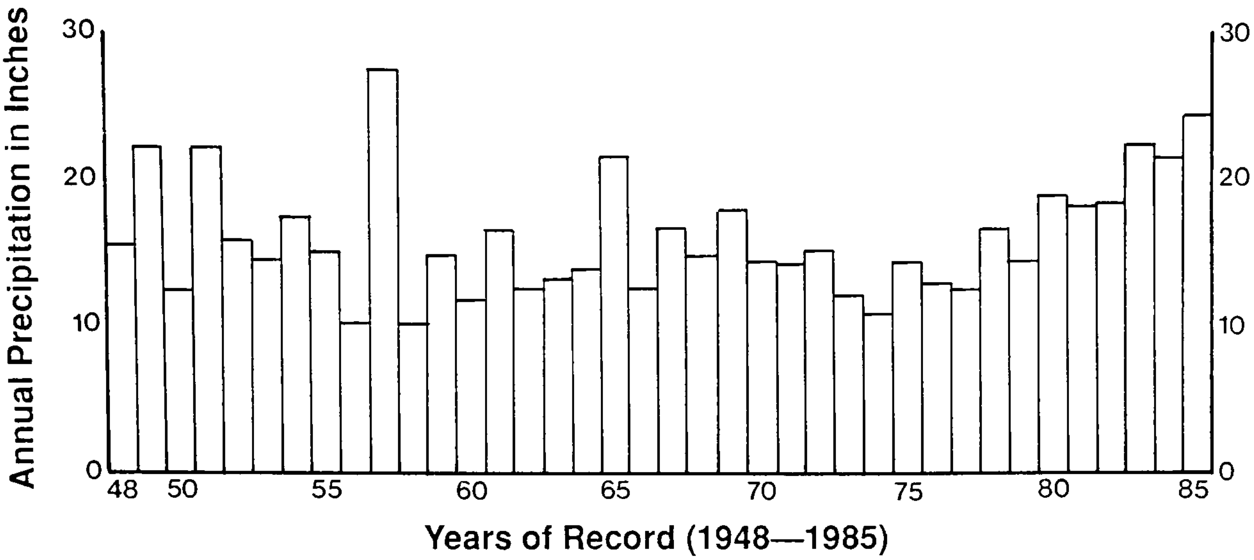


Figure 8. Annual precipitation at Altenbern, Colorado (1948-1985).

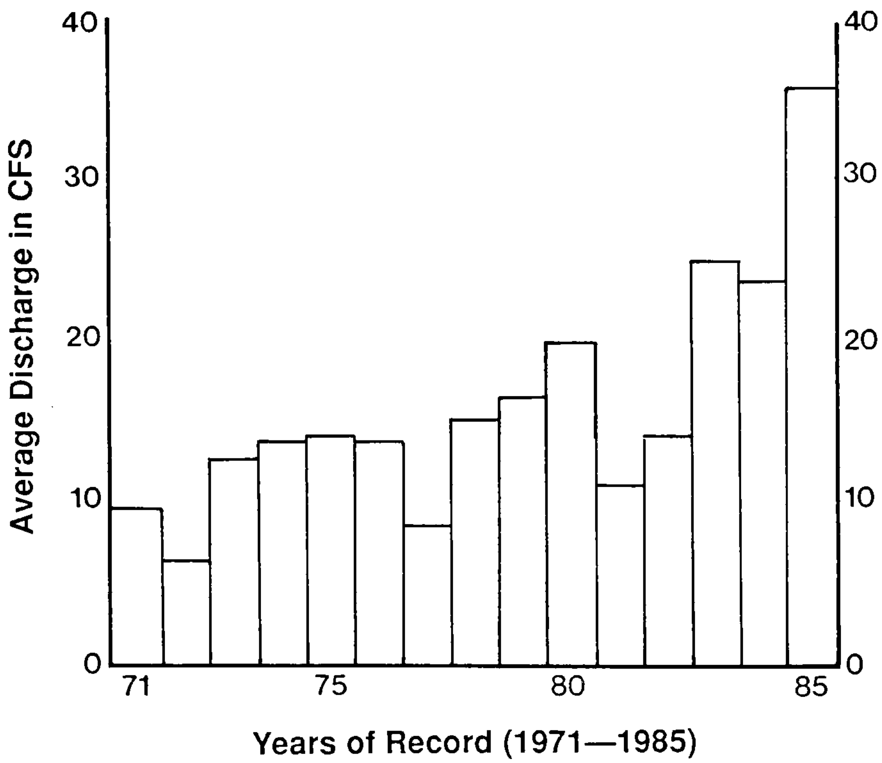


Figure 9. Average discharge of Roan Creek in March.

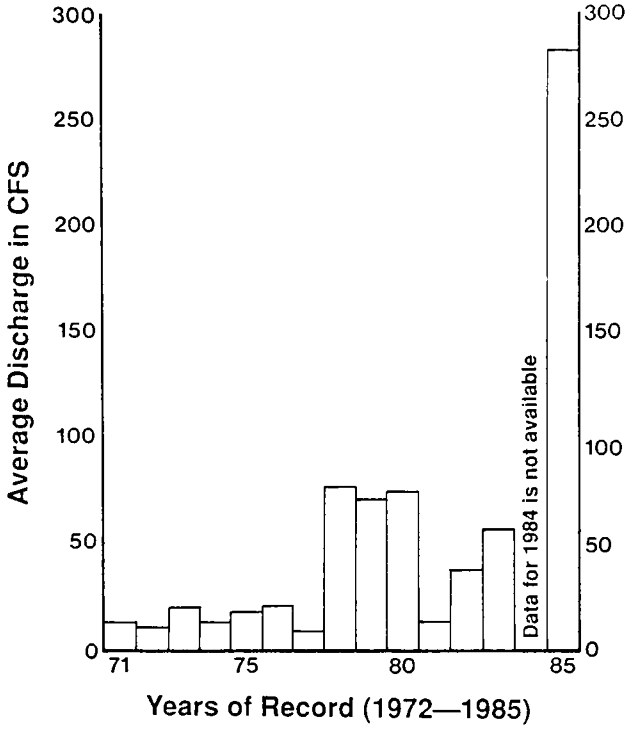


Figure 10. Average discharge of Roan Creek in April.

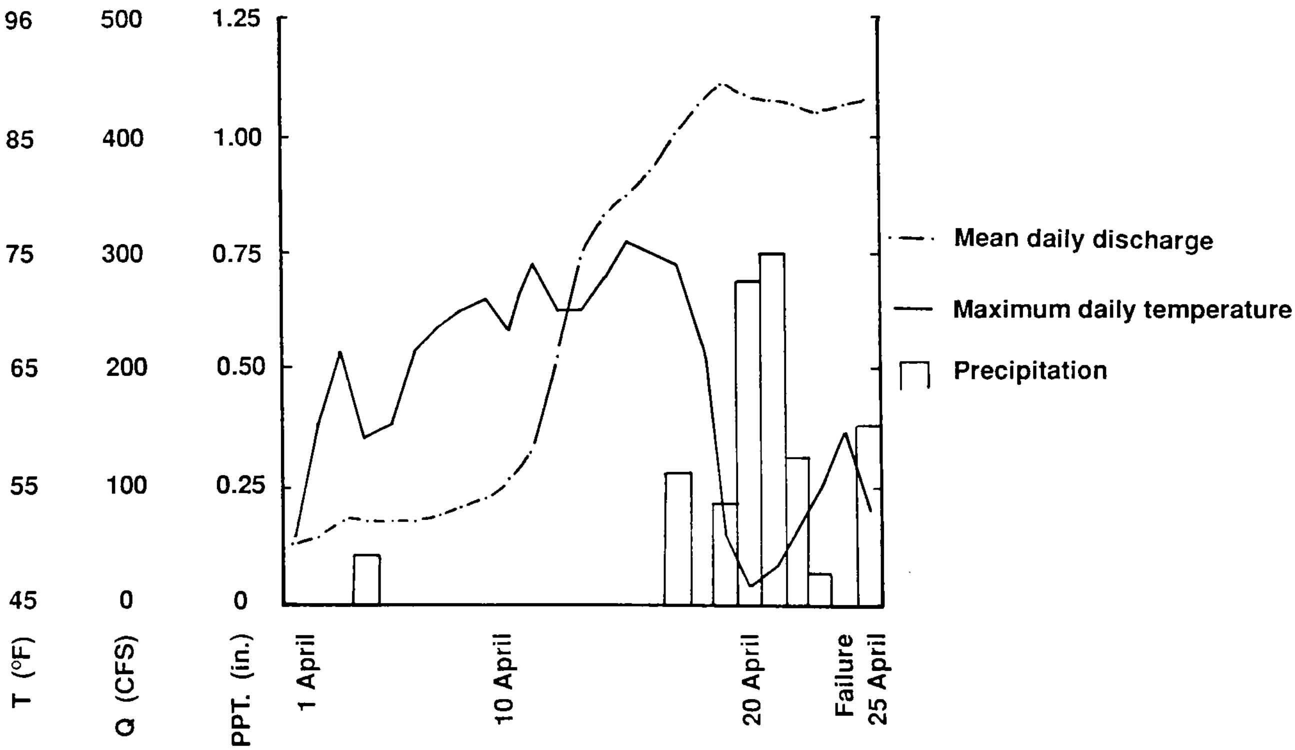


Figure 11. Maximum daily temperature, daily precipitation and mean daily discharge of Roan Creek in the first 25 days of April 1985.

The increase in discharge is significant and implies snowmelt in March and April was considerably above average in 1985. This also strongly suggests that snowmelt on the northern slopes of Kimball Mountain supplied additional water to the slide material as did the previously mentioned precipitation preceding the failure of the landslide. The combined effect of this excess water raised pore water pressure in the slide mass and decreased stability.

3.3 Earthquake Seismology

A computer search was conducted at the National Earthquake Information Center to determine if any seismic events occurred simultaneously with the failure of the landslide within a 300 kilometer radius. No seismic events are documented immediately preceding initial movement of the Roan Creek landslide; therefore, it is highly unlikely that active seismicity contributed to the failure of the landslide.

4.0 DESCRIPTION OF SLOPE MOVEMENTS

Varnes (1978) has sub-divided slope failures into six categories based on type of movement and type of material. Figure 12 shows his classification system of slope movements including falls, topples, slides, lateral spreads, flows, and complexes. The use of the term landslide in this paper constitutes slope movement in a generic sense only. The Roan Creek landslide is classified a slump-earthflow complex with some rock fall at the headscarp according to Varnes' criteria. Figure 13 is a representative diagram of a slump-earthflow.

Hunt (1984) more precisely defines a slump-earthflow as a "relatively slow movement of soil, rock or soil-rock mixture moving along some well-defined arc-shaped failure surface as a viscous fluid or slurry, usually terminating far beyond the failure zone." Field evidence for slumps include blocks rotated back into the slope and concentric surface cracks concave toward direction of movement.

4.1 Factors Affecting Slope Stability

Table 1 lists factors which contribute to reduced slope stability by increasing shear stresses acting on a slope or by decreasing shear strength of the slope material. Both increased shear stress and decreased shear strength are believed to be responsible for failure of the Roan Creek landslide. Of the factors listed in Table 1, high pore water pressures, surcharge weight of water within the slide mass and removal of lateral support appear to have increased shear stresses acting upon the slide. The two greatest factors leading to low shear strengths in the landslide apparently were the inherent weakness of the slide material and the effects of pore water decreasing intergranular contact. Evidence supporting the importance of these factors in the failure of the Roan Creek landslide is presented in subsequent sections. A number of additional factors from Table 1 may also have played a role in the failure of the slide, but are considered to be negligible in comparison to those discussed above.

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
		MANY UNITS	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow	Debris flow	Earth flow
			(deep creep)	(soil creep)	
COMPLEX			Combination of two of more principle types of movement		

Figure 12. Abbreviated classification of slope movements (from Varnes, 1978).

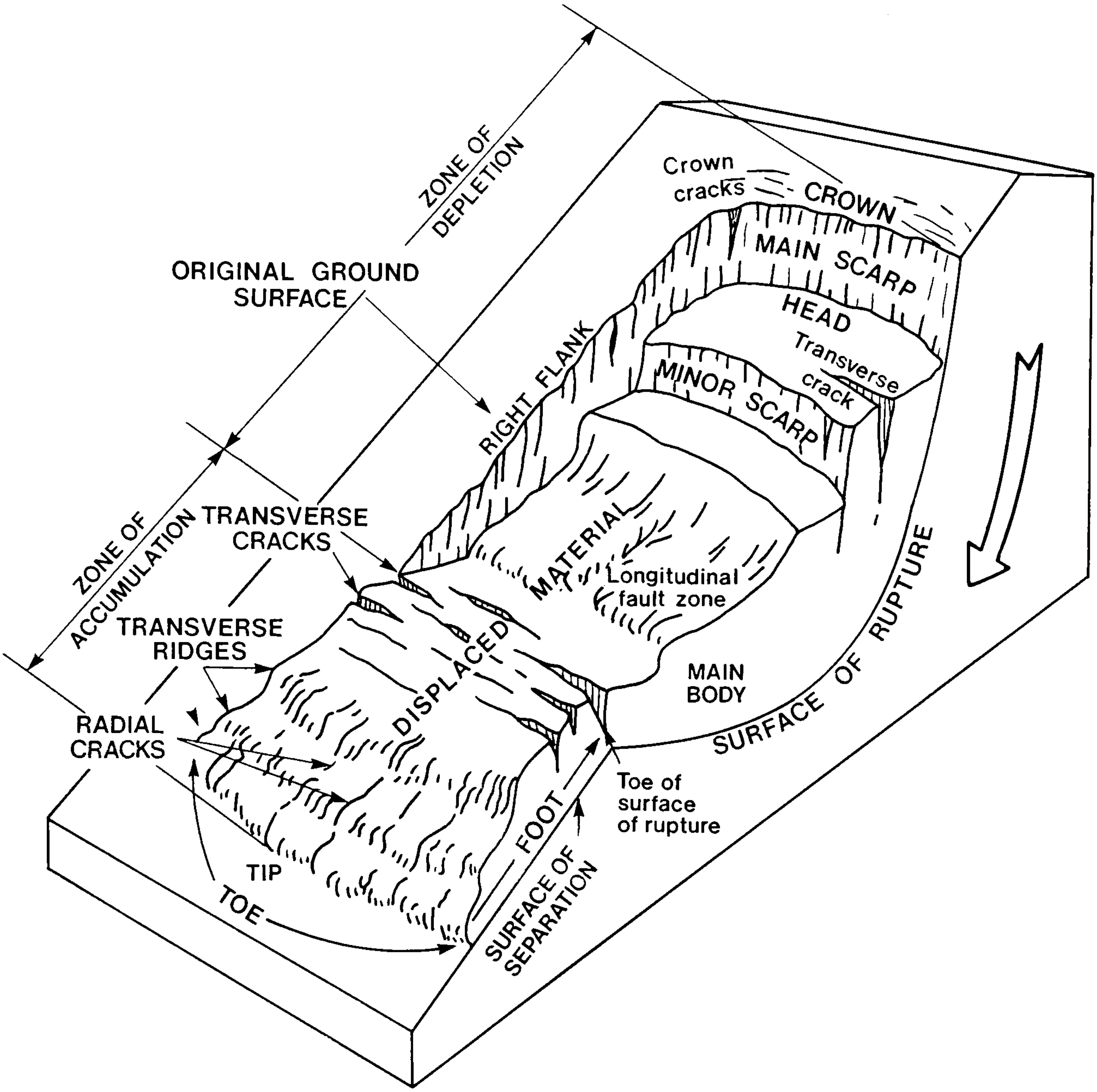


Figure 13. Diagram of a slump-earthflow (modified from Varnes, 1978).

Table 1. Factors contributing to reduced slope stability.

I. Factors leading to high shear stresses

A. Removal of lateral support
1. Erosion by streams
2. Creation of a new slope by previous landslides
3. Excavation by man

B. Surcharge or loading
1. Weight of rain, snow or water from springs
2. Accumulation of talus near the top of slopes or at the head of old landslides
3. Construction of earth fills
4. Weight of building or other structures

C. Transitory earth stresses
1. Earthquake action
2. Vibrations from blasting

D. Removal of underlying support
1. Undercutting of banks by running water
2. Subaerial weathering, wetting and drying and frost action

E. Increase in lateral pressure due to:
1. Water in cracks
2. Freezing of water in cracks
3. Swelling of clays

II. Factors leading to low shear strengths

A. Materials with low initial strength
1. Inherently weak materials or materials that weaken when disturbed
2. Texture
   a. Loose or poorly consolidated structures
   b. Soil particles with low intergranular friction
3. Geologic strcture/stratigraphy
   a. Discontinuities, joints, faults and bedding planes
   b. Strong materials overlying weak materials

B. Changes due to weathering and other physiochemical reactions
1. Physical disintegration
2. Hydration of clay minerals
3. Drying of clay minerals
4. Removal of cement by solution

C. Change in intergranular forces due to pore water
1. Buoyancy decreasing intergranular forces
2. Loss of intergranular pressure due to capillarity
3. Seepage pressure from groundwater

D. Changes in structure
1. Fissuring due to overconsolidation
2. Changes upon remolding

after Snyder (1977)

5.0 FIELD INVESTIGATIONS

5.1 Field mapping

5.1.1 Mapping In the summer of 1986, the author spent three weeks in the field mapping the Roan Creek landslide. A topographic base map of scale 1:2400 was prepared from aerial photographs using photogrammetric techniques. All visible primary structural features, lithologic zones within the slide mass, standing water and seeps, and the areal extent of the slide were mapped on this base map (Plate 1).

5.1.2 Primary structural features Primary structural features present at the Roan Creek landslide include head scarps, additional scarps within the slide mass due to retrogressive and progressive failure, tension cracks within and outside the slide boundaries, and lateral deposition levees. In this paper, the use of retrogressive failure denotes failure propagating upslope, while progressive failure refers to development of failure downslope. No longitudinal shear fractures were observed as erosion of the slide has been rapid and obscured any traces of these features. All mapped structural features are presented on Plate 1.

5.1.2.1 Head scarps The head scarps are present continuously around the perimeter of the slide mass in the upper third of the slide. To the west and east of the drainage are large cliff scarps (Figures 14 and 15) which are not visible on USGS topographic maps printed in 1968. Seepage in the center of the scarp face should be noted in Figure 15. Groundwater flow appears to be along horizontal bedding planes near the contact of the Garden Gulch and Douglas Creek Members of the Green River Formation as evidenced by seeps in the western cliff scarp. Olson (1974) mapped both cliff scarps in his field work, but at a lesser magnitude with less extensive associated landslide deposits. This would indicate initial failure of the slopes occurred sometime between the aerial missions flown to collect data for the topographic maps and 1974, or that the scarps were small enough to be masked when preparing a small-scale topographic base map without adequate field checking.

These cliff scarps do appear on aerial photographs flown for the United States Bureau of Land Management (BLM) in 1978. Figure 16 shows head scarp location and associated landslide deposits in 1978 with reference to scarp development and deposits currently observed. Comparing these aerial photographs with 1985 images shows that the cliff faces are larger and more pronounced after the most recent failure of the Roan Creek landslide. Currently the cliff scarps are approximately 150 feet high to the east of the drainage and 200 feet high west of the drainage. The cliff scarps dominate the upper reaches of the slide, but the head scarp is continuous along the upper perimeter of the slide reaching heights of 75 feet along the western margin (Figure 17). All scarps are presented on Figure 18 and Plate 1.

5.1.2.2 Additional scarps Scarps due to progressive failure are present within the western slide mass. The largest strikes roughly N10W, is 1300 feet in length and ranges in height from a few feet to 100 feet. A scarp and series of tension cracks also oriented N10W lie below this scarp and collectively are 500 feet long. The scarp ranges from 20 to 50 feet in height and the tension cracks vary in depth between four and six feet and in width from 1 to 6 feet. Tension crack spacing is approximately 10 feet.

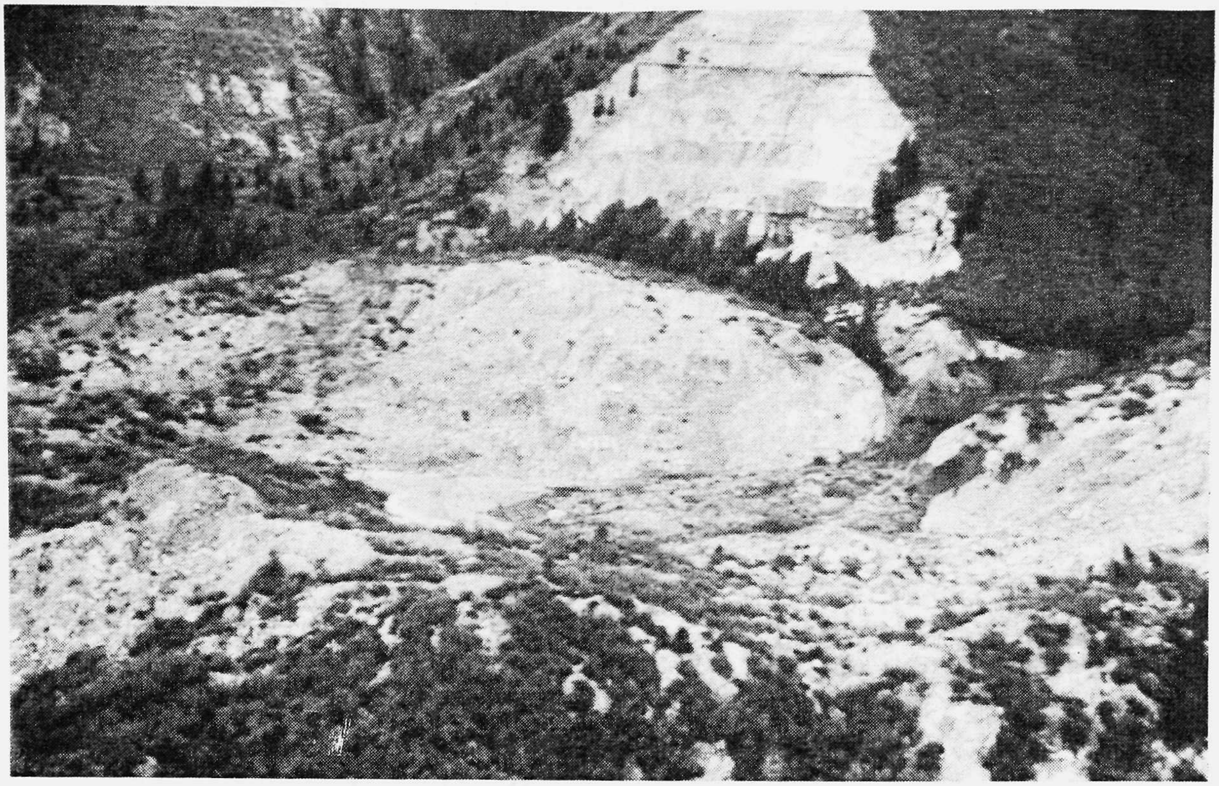


Figure 14. A view of the eastern head scarp which is approximately 150 feet high. Refer to Figure 16 for location.

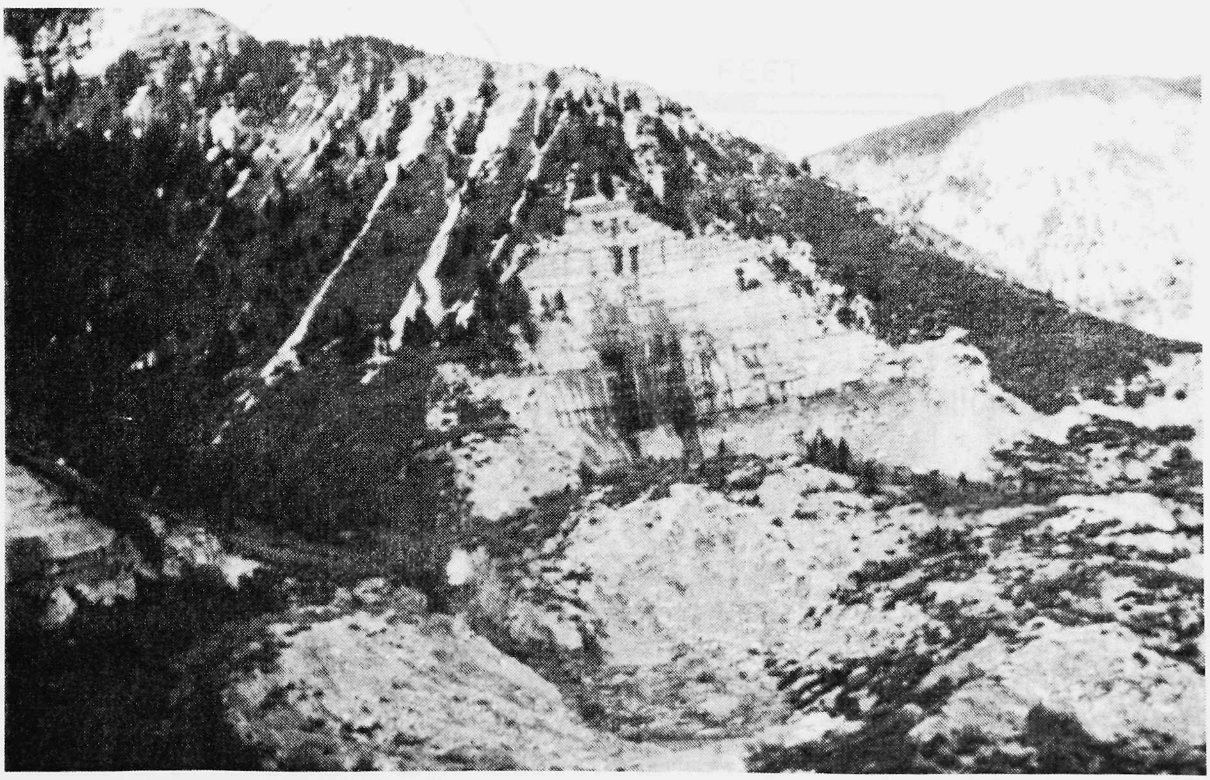


Figure 15. The western head scarp is approximately 200 feet high. Refer to Figure 16 for location.

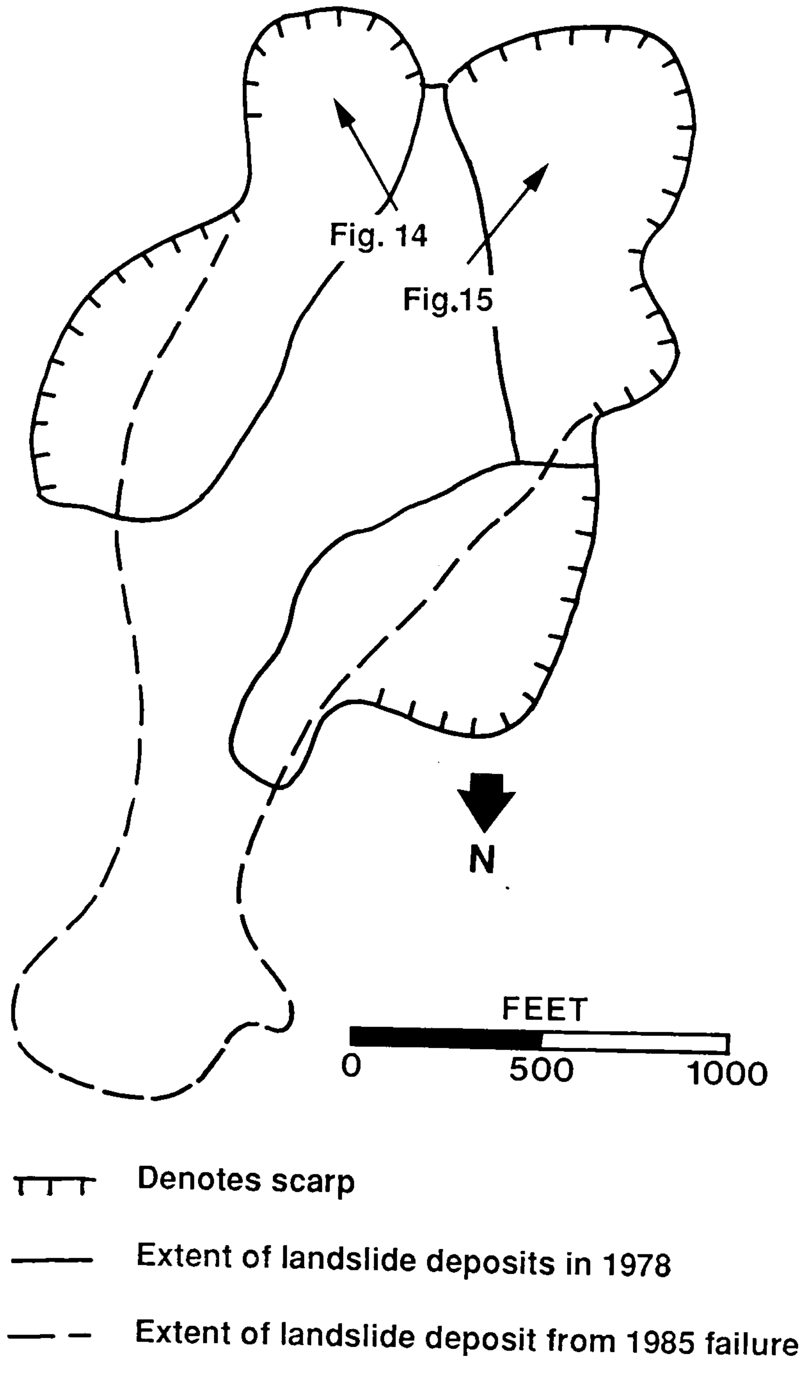


Figure 16. Scarp development and associated landslide deposits in 1978.

Figure 17. Scarp along western margin of Roan Creek landslide. Refer to Figure 18 for location.

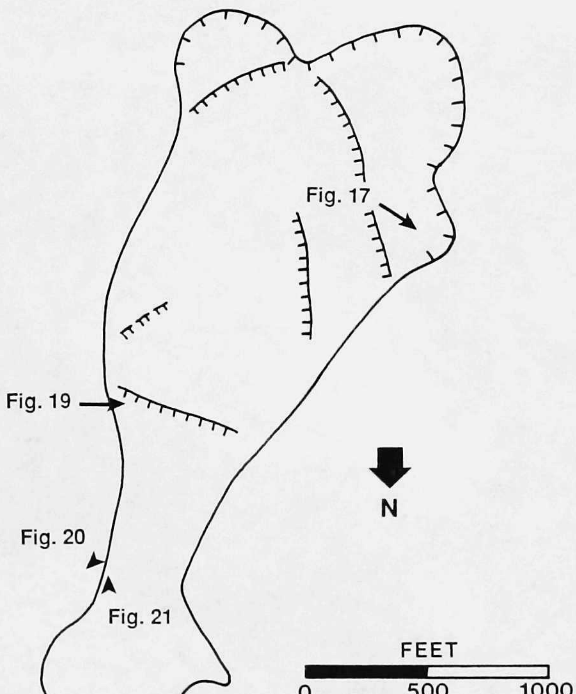


Figure 18. Scarp map of the Roan Creek Landslide.

Another distinct scarp (Figure 19) within the slide mass is located at 6175 feet in elevation and extends across the slide above its narrowest juncture (see Figure 18). It varies in height from 6 to 25 feet, but generally is 20 feet high.

5.1.2.3 Tension cracks Tension cracks are found both on and off the slide mass. Abundant cracks are found below the head scarps, but no distinct orientation of the features can be discerned. However, in the center of the slide, a series of tension cracks above the scarp at 6175 feet were mapped oriented N25W with lengths of 100 feet, depths of 2 to 6 feet, widths of 1 to 4 feet, and with approximate spacings of 15 feet. Tension cracks are also present beyond the slide mass to the east and west and are interpreted to have resulted from increased tensile stress acting on the surrounding slopes due to removal of lateral support. Figure 20 shows tension cracks mapped east of the slide mass which were interpreted to have formed in 1986, one year after failure of the main slide mass. Primary evidence for this interpretation was the fresh nature of the cracks which exhibited very little infilling during field investigations in 1986. The tension cracks off the slide mass imply potential retrogressive failure of the slopes surrounding the slide in the future.

5.1.2.4 Lateral levee A lateral deposition levee is present on the eastern flank of the slide with a length of 1200 feet (Figure 21). The height of the levee varies from 4 feet in its lower reaches to 15 feet in its upper reaches. Width also is variable decreasing from 15 feet to 6 feet towards the

Figure 19. Scarp exhibiting about 20 feet of vertical displacement crosscuts the slide mass approximately one third of the distance up the slide from the toe. Refer to Figure 18 for location.

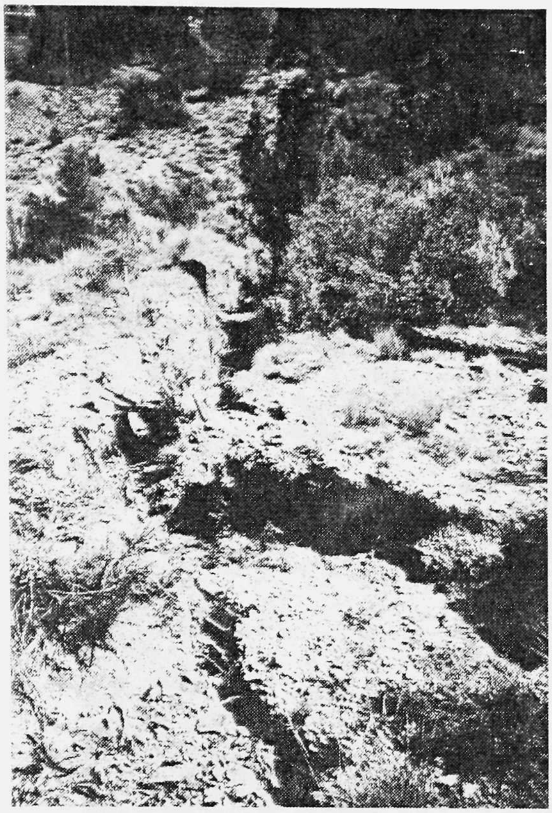


Figure 20. Tension cracks east of the slide mass. Refer to Figure 18 for location.

Figure 21. Twelve hundred foot long depositional levee along the eastern margin of the landslide. Refer to Figure 18 for location.

toe of the slide. Depositional levees are common landforms in earthflow deposits as the velocity of the flow is slower at its edges than in its center due to increased shearing stresses along the margins. Therefore, as the flow material on the sides stops, it is at the same height as the remainder of the flow material. However, flow continues in the center and the center areal mass is depleted as the soil flows onward. The difference in elevation between the center and lateral areas of the flow deposit results in what appears to be a levee.

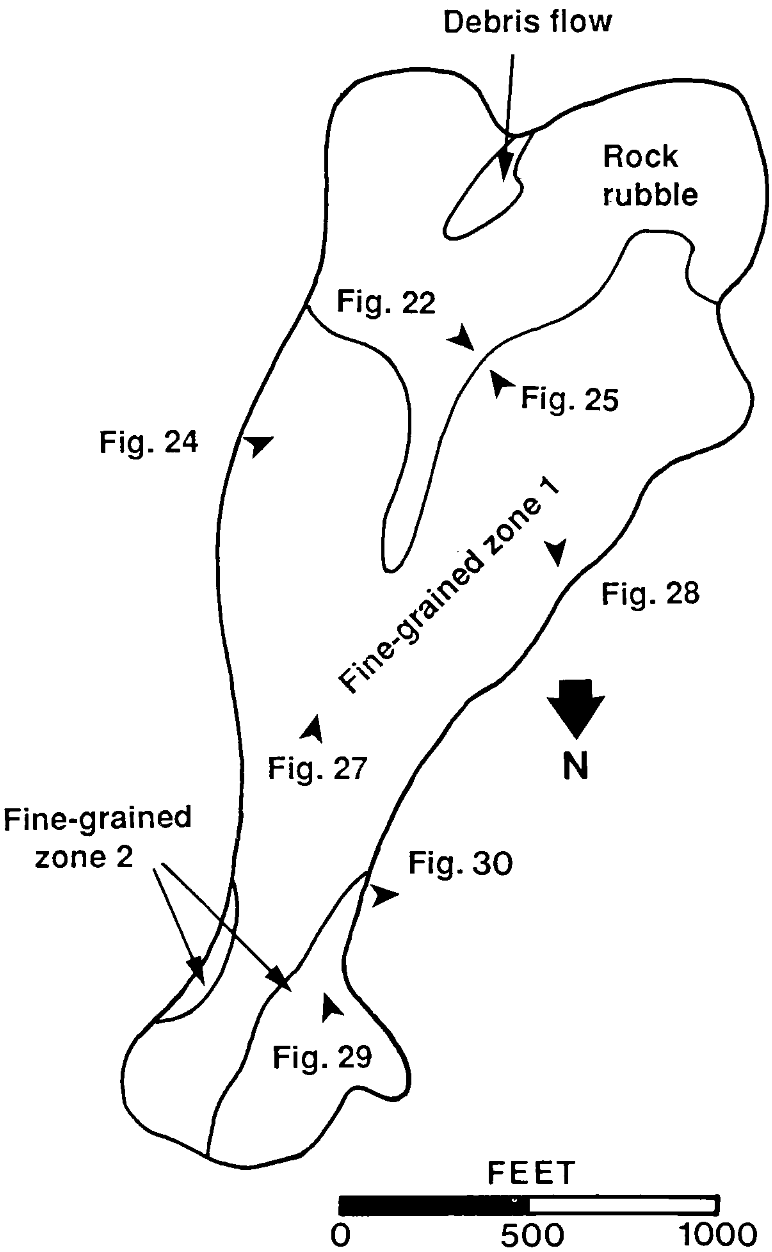
5.1.2.5 Depressions Several topographic depressions were mapped on the slide deposits, some of which form ponds. In the upper reaches of the slide are large depressions dominated by blocks of bedrock. The largest of these has dimensions of 200 feet in length, 100 feet in width and 40 feet in depth (Figure 22). It was noted that after a torrential rain, no standing water was present in any of these depressions. Numerous open cracks and holes allow infiltration of surface water into the slide mass. These depressions are interpreted to have formed when a large slab of rock present in the rock flows emanating from the western cliff scarp region broke apart due to tensile stresses.

Figure 22. Forty foot deep depression in upper reaches of slide. Person for scale in right center of photo. See Figure 23 for location.

5.1.3 Material zones

Distinct material zones exist within the slide (Figure 23). In the upper third of the slide, the predominant material present is bedrock rubble (Figures 24 and 25). Due to the heterogeneity of the material and the distance it has traveled, particle size ranges from silt to large blocks. Note the blocks of rock in Figure 25 are generally larger than those observed in Figure 24 due to closer proximity to the source area in the head scarp region. More friable and fissile material has been physically reduced to silt-size particles while stronger rock, such as sandstone, is present in large blocks with dimensions up to 8 feet by 8 feet by 8 feet. The rock rubble was derived from siltstones, fine-grained sandstones, claystones and shale of the Douglas Creek and Garden Gulch Members of the Green River Formation and of the Upper Shire Member of the Wasatch Formation.

The lower two thirds of the slide is predominantly fine-grained with an abundance of smaller rock fragments suspended within the clay-size matrix (Figure 26). In this zone, abundant blocks of vegetation and "A" soil horizon appear to have rafted on top of the slide mass as it moved downhill (Figure 27). The root structures of the vegetation have kept the blocks intact. On the flanks of the toe of the slide, another zone of predominantly fine-grained material is present, denoted as fine-grained zone 2 on Figure 23. It has a different texture and color from the primary fine-grained zone 1 and correlates to the hillslopes adjacent to the slide. The material was most probably incorporated into the slide mass as the slide moved into the drainage bottleneck before spreading onto an alluvial fan. A small debris flow deposit (see Figure 23) is present at the head of the slide below the juncture where the head scarp intersects the drainage from the upper elevations of Kimball Mountain.



EXPLANATION

UNIT	DESCRIPTION
Rock rubble	Size ranges from silt to blocks 8' X 8' X 8'; comprised of sandstones, siltstones, shales and claystones; derived from cliff scarp area
Fine-grained zone 1	Rock fragments of sand to gravel size suspended in clay-size matrix; abundant rafts of vegetation and "A" soil horizon present throughout this zone; most standing water found in this zone; generally dark brown in color
Fine-grained zone 2	Silty clay; derived from colluvium of surrounding slopes; reddish-brown color due to presence of limonite
Debris flow	Silt to clay matrix; coarser materials suspended in matrix including sand, cobbles and some very widely scattered boulders; derived from slopes of drainage on Kimball Mountain just above the headscarp of the slide

Figure 23. Materials zone map of the Roan Creek Landslide.

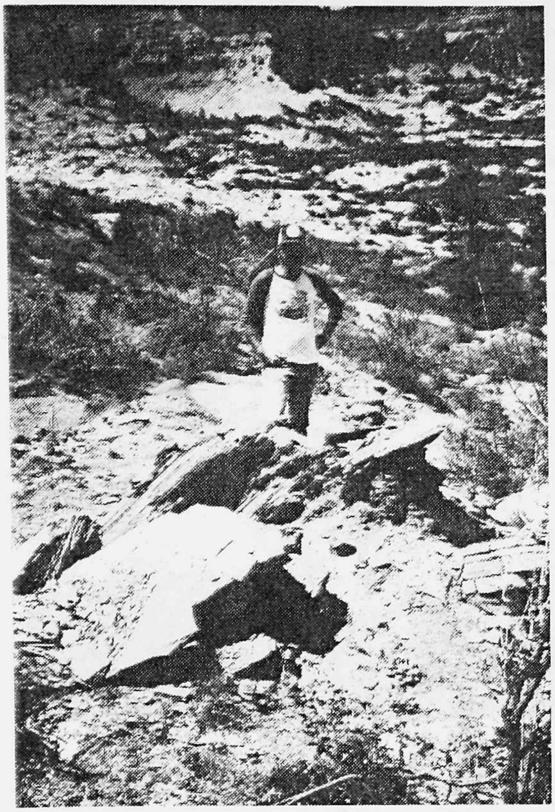


Figure 24. Highly fissile blocks of rock comprise the upper reaches of the landslide. Refer to Figure 23 for location.

5.1.4 Surface water and groundwater An abundance of surface water and groundwater was observed on the slide in July, August and October of 1986. The nature of water occurrence during these typically dry months suggests the water table and antecedent moisture content could be much higher and greater, respectively, during the wet months of spring. Three large ponds were mapped with dimensions of 100, 120 and 200 feet in length, 5 to 50 feet in width and depths of 1 foot to 10 feet. The pond in the west-central part of the landslide with approximate dimensions of 120 feet, 30 feet and 5-10 feet for length, width and depth, respectively is presented in Figure 28. In addition, several ponds of smaller dimensions were mapped. All standing surface water is shown on Plate 1. No surface water flow from the drainage above the headcscarp onto the slide was observed during field investigations. However, continuous flow of water off the toe of the slide (Figure 29) was observed indicating the slide has a considerable volume of water stored in it.

Groundwater recharge to the slide material most probably is the source of the water flowing off the slide. Several seeps were noted and mapped (Plate 1). Seeps are highly concentrated along the western flank in the lower one half of the slide (Figure 30), but also occur in other locations on the slide. The whiter areas on the photo are areas of calcite and gypsum mineralization. Study of the 1978 and 1985 aerial photographs indicates a well-defined drainage was overridden and infilled by the Roan Creek landslide along the western margin in the lower one half of the slide in 1985. This infilled, pre-existing drainage may act as a conduit for groundwater flow due to a differential permeability with the surrounding subsurface material and explain the high concentration of seeps along the western flank of the landslide. Abundant crystals of calcite, aragonite and gypsum are present on the surface throughout the lower one half of the slide suggesting groundwater was present at or very near the surface at some time, quite possibly at the time of failure and immediately after subsequent movement of the slide. The surface water and groundwater observations are important as water played an important role in the failure of the Roan Creek landslide.

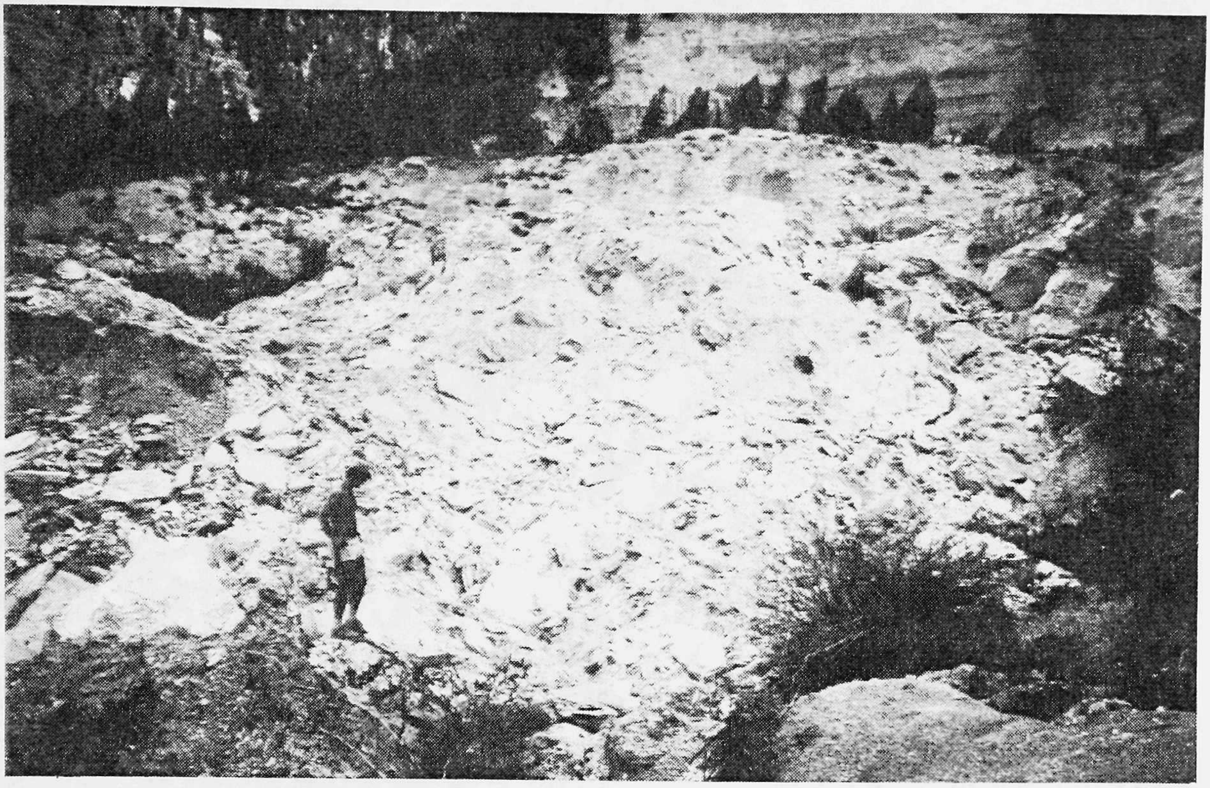


Figure 25. Texture of the upper reaches of the landslide where rock rubble dominates lithology. Refer to Figure 23 for location.

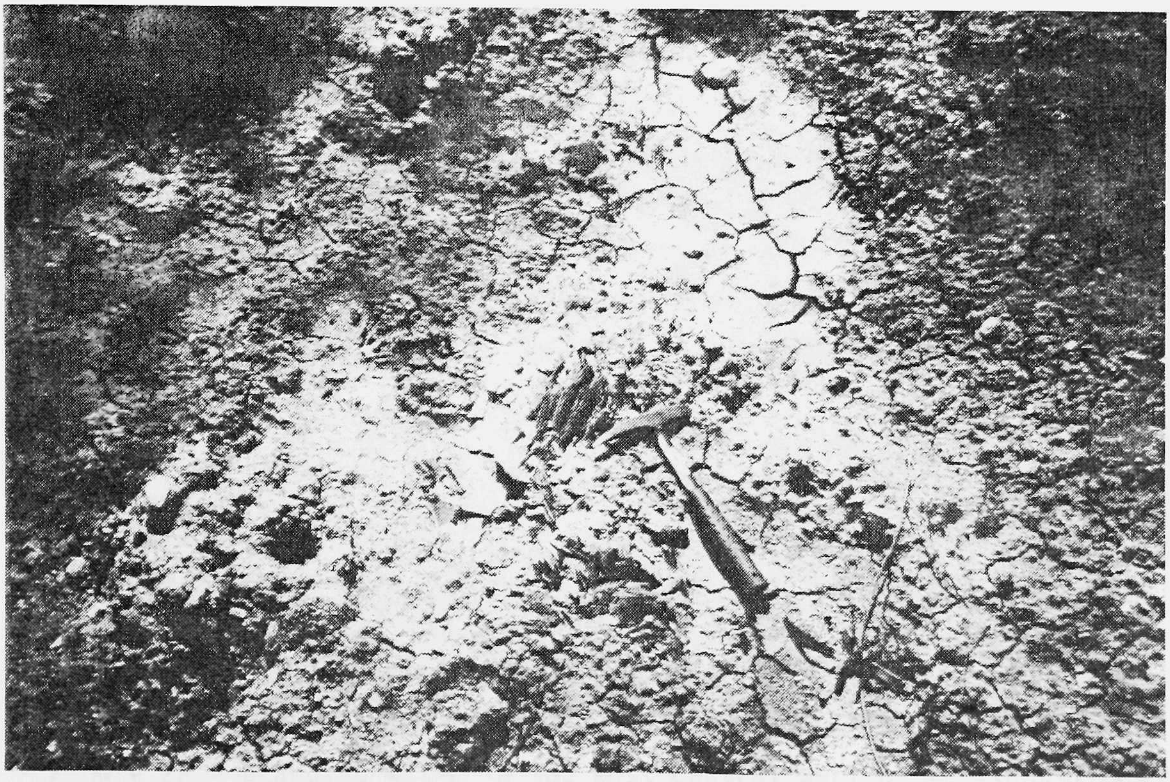


Figure 26. Fine-grained materials dominate the lower reaches of the landslide.

Figure 27. Vegetation and A-horizon "rafts" found in the central portion of the landslide. Refer to Figure 23 for location.

Figure 28. Standing water in the west central part of the landslide. Refer to Figure 23 for location.

5.2 Drilling program A drilling program was attempted in October 1986 to install piezometers to monitor groundwater fluctuations in the slide and to collect soil samples for laboratory analysis. A gasoline-powered auger was utilized with limited success as the auger was refused at depths of 11 feet or less below ground surface due to an abundance of rock fragments oriented sub-parallel to the ground surface. No information pertaining to depth to failure surface was obtained. In the areas drilled, the potentiometric surface was below the depth of refusal. Soil samples were collected for analysis of natural moisture contents, liquid limits, plastic indices and for soil classification.

Figure 29. Stream flowing on toe of slide (Figure 23 for location).

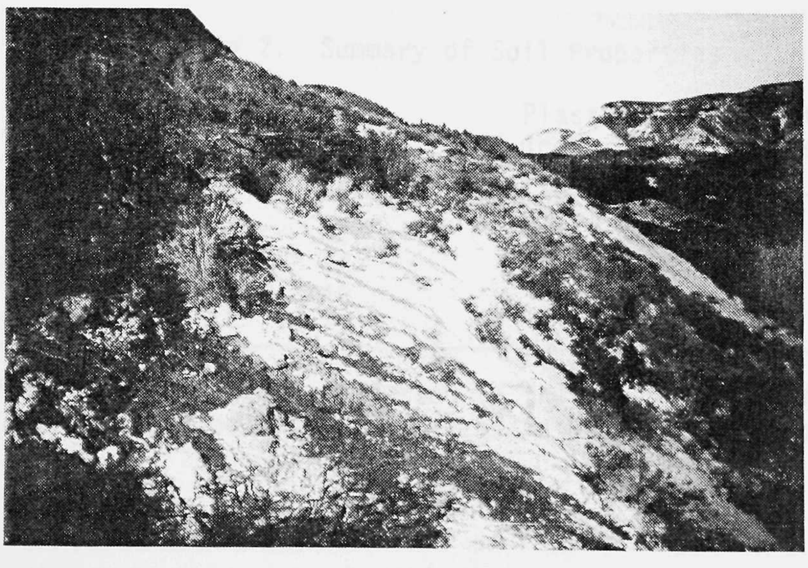


Figure 30. Seeps and associated calcite and gypsum mineralization along the central western margin of the landslide (Figure 23 for location).

6.0 SOIL ANALYSIS AND CLASSIFICATION

Soil samples were collected in the field in October of 1986. Three holes were logged and sampled in the drilling program described in section 5.2. Figure 31 is a sample location map. Due to bit refusal above the potentiometric surface, all samples were taken above the saturated zone. The samples were assumed to be representative of the lower regions of the slide where fine-grained materials dominate, however, these sample data cannot be confidently assumed to represent bedrock material properties in the upper reaches of the slide.

Moisture contents and Atterberg limits were determined for three samples, one from each respective hole. Moisture contents ranged from 17.7 to 29.4 percent. It should be noted that these moisture contents are indicative of soil conditions in October and not in the wet months of spring when the Roan Creek landslide failed. The liquid limits ranged from 41 to 48 and the plastic indices ranged from 13 to 25 for the soils tested. Explanations of procedures used in determining Atterberg limits and raw data used for calculations are presented in Appendix A-A'. According to U.S. Department of Agriculture (USDA) data (unpublished) moist bulk densities of the soil present in the drainage prior to failure ranged from 85 to 91 pounds per cubic foot.

Sieve analyses were run on the three samples to determine grain size distribution and to classify the soils. The results of the sieve analyses, including grain size distribution curves are presented in Appendix A-2. These soils classify as SM and SC soils (Unified Soil Classification System). ASTM (1986) defines SC soils as clayey sands and SM soils as silty sands. These samples appear to be derived from the siltstones and claystones of the Green River and Wasatch formations. USDA data (unpublished) classify the soils found in the vicinity of the landslide prior to failure as silty gravels (GM), clayey gravels (GC), or silty, clayey gravels (GM-GC). The discrepancy between USDA and this study's classification can be attributed to the physical degradation of gravel clasts in the landslide to sand and silt size particles due to the weak nature of the clast lithology. A summary of soil properties can be found in Table 2.

Table 2. Summary of Soil Properties

Sample Number	Moisture Content (%)	Liquid Limit (%)	Plastic Index (%)	Unified Soil Classification
1	20.5	41	13	SM
2	29.4	46	23	SC
3	17.7	48	25	SC

A series of torvane tests were conducted in the field around the perimeter of the landslide and throughout the slide mass in May 1987 to ascertain undrained

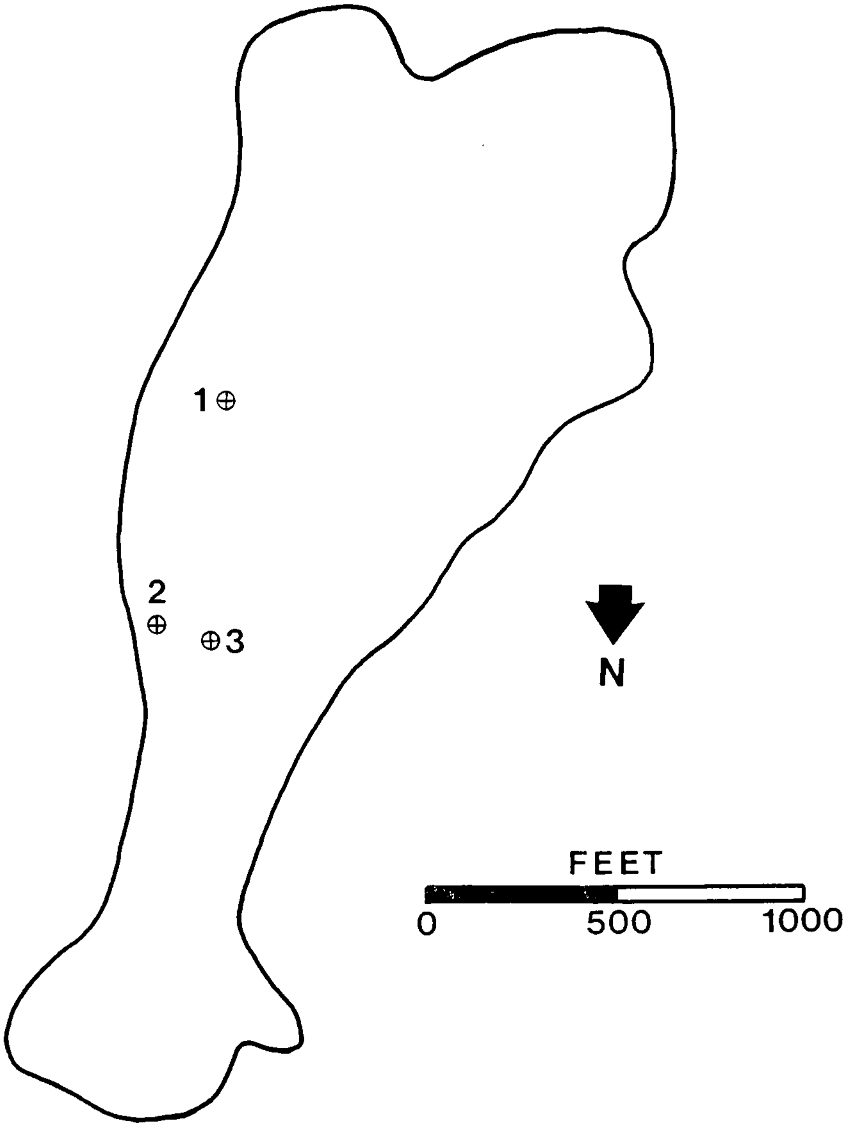


Figure 31. Soil sample location map. Numbers coincide with sample numbers in Table 2 and Appendix A-2.

residual shear strength. The torvane is a modified vane-shear apparatus which can be utilized in the field or laboratory to quickly determine values of undrained shear strength. The torvane data yielded values of residual undrained shear strength ranging from 120 to 520 pounds per square foot (psf). The mean value of shear strength was 270 psf. It should be noted that these results are from materials tested in the fine-grained zones in the lower reaches of the slide mass and subsequently are shear strengths of the soil in a remolded state. The wide range in values can be attributed to varying degrees of deformation dependent on distance transported from source area during failure of the landslide and original parent material (i.e. siltstone vs. sandstone vs. claystone).

Original shear strength of the soil prior to failure of the landslide may have been much greater than the values calculated using the torvane data.

7.0 FAILURE TO MODE

7.1 Eyewitness Accounts

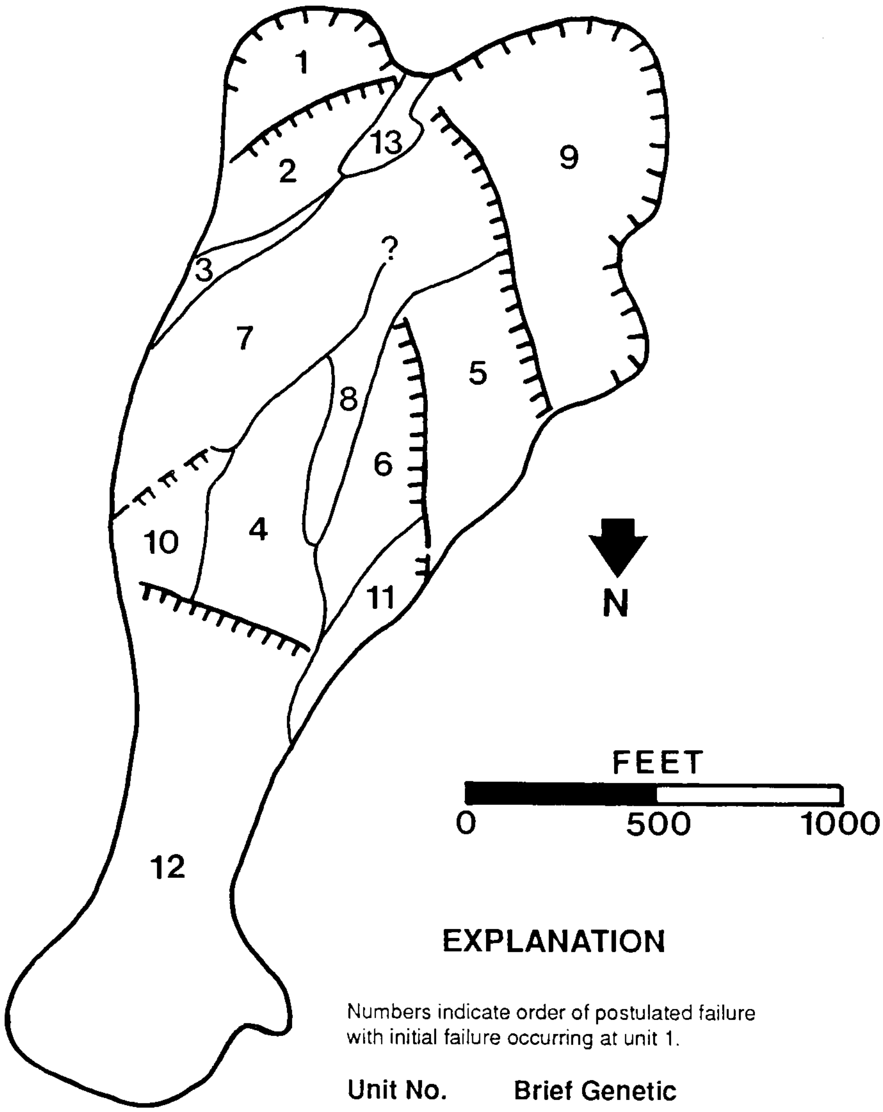
The Roan Creek landslide failed the night of 24 April 1985. Todd and Tracy Brackett, the ranchers who live below the landslide, stated that on the morning of 25 April 1985, they woke up to find the landslide approximately 200 feet high in the drainage to the south of their ranch. The slide was about 300 feet uphill of Roan Creek at the time. The rancher paced the distance from the creek to the landslide toe and calculated the velocity of the slide to be 40 feet per day. Kistner (1986) of the Colorado Department of Disaster Assistance stated the slide was moving at one foot per hour at the time he arrived at the site on 26 April 1985. Videotape footage shown on Denver television stations in late April 1985 indicated that the slide was still advancing as sage in the path of the earthflow was heard cracking. However, visible movement was not perceptible. The slide had slowed to just "inches" per day by 11 May 1985 (Turney, 1985). The earthflow stopped approximately 50 feet from Roan Creek at its closest approach.

7.2 Air Photo Interpretation and Comparison

Aerial photographs, flown for the United States Bureau of Land Management (BLM) on 30 September 1978, show two cliff scarps, arcuate head scarps on the east and west sides of the drainage and associated landslide deposits at the failure site (Figure 16). Some, but not all, of the previous slide material in the drainage was incorporated into the failure of April 1985. The eastern arcuate scarp and the lowermost western scarp were undisturbed in he most recent failure. However, additional movement was noted at all other pre-existing head scarps. New rockfall from the two cliff scarps and associated talus deposits were noted in the field in the summer of 1986 and on aerial photographs flown for the Colorado Geological Survey on 8 August 1985. New rockfall along the upper western margin scarp is noticeable, but a new failure of large magnitude was not observed.

A surficial geology map (Figure 32) is a summary of information presented on Plate 1 and has been compiled from an extensive examination of the 1985 aerial photographs and field notes. Figure 32A is an explanation sheet for the surficial deposits map. All major scarps have been noted, rotation blocks identified and individual flow deposits delineated. The numbers assigned to each unit indicate prostulated order of failure with initial failure occurring in unit 1. Units 1, 2 and 9 are rotational blocks below the head cliff scarps while units 5 and 6 are slump blocks below secondary scarps. Units 3, 4, 7, 8, 10, 11 and 12 are flow deposits originating from scarps and failure surfaces uphill. The debris flow deposit post-dating the slide was labeled unit 13. All of these units are also presented on Plate 1.

Initial failure of the 1985 Roan Creek landslide most probably occurred in the upper reaches of the slide at the cliff scarps along preferential, pre-existing failure surfaces. The slump block below the eastern cliff scarp was rotated approximately 45 degrees back into the slope by the 1985 failure as evidenced by tree rotation. The 1978 photos indicate that trees were vertical at that time. In addition, the large scarp downslope from the eastern cliff scarp (upper boundary of unit 2 in Figure 32/Plate 1) developed



EXPLANATION

Numbers indicate order of postulated failure with initial failure occurring at unit 1.

Unit No.	Brief Genetic Description
1	rotational block
2	rotational block
3	flow deposit
4	flow deposit
5	secondary slump block
6	secondary slump block
7	flow deposit
8	flow deposit
9	rotational block
10	flow deposit
11	flow deposit
12	flow deposit
13	debris flow deposit

Figure 32. Surficial deposits map of the Roan Creek Landslide.

in 1985 due to progressive, downslope, failure in the pre-existing transverse ridge, which had formed in response to rotational movement in an earlier (pre-1985) failure.

The scarp above the western margin (the northern one-half of the upper boundary of unit 9 in Figure 32/Plate 1) is largely unchanged from 1978 imagery, but movement of the material below the scarp has been drastic and highly pronounced. The topography of the failure block below the western cliff scarp (Figure 32/Plate 1, unit 9) has radically changed position since 1978, and much of the overlying earthflow deposits further down the drainage (Figure 32/Plate 1, units 7 and 8).

7.3 Failure Mode

The Roan Creek landslide is very complex; however, after extensive field observations and mapping, compilation of a detailed surficial deposits map, construction of transverse and longitudinal cross-sections, and aerial photo comparison and interpretation, a model can be suggested. Figures 33 and 34 are longitudinal and transverse cross-sections, along A-A' and D-D', respectively, of the slide and were compiled from Plate 1 and field observation notes.

Field observations and photogrammetric studies indicate three distinct phases of failure occurred during the Roan Creek landslide movement (Figures 35, 39 and 40). The first phase of the model (Figure 35) supposes the eastern cliff scarp failed first. One piece of dominant evidence suggests failure along B-B' occurred first. Mass wasting deposits below the eastern cliff scarp are overlain by flow deposits (Figure 32/Plate 1, units 7 and 8) interpreted to have originated from the scarp area below the western cliff scarp (upper boundary of units 7 and 8 in Figure 32/Plate 1) indicating the mass wasting material from the eastern cliff scarp was deposited prior to failure of the western cliff scarp region. Figure 36 is a cross-section along B-B', the proposed area of initial failure.

Figure 37 is a two-stage, diagrammatic representation of how failure is believed to have occurred along B-B'. Movement along the pre-existing failure surface daylighting at the eastern cliff scarp initiated failure of the Roan Creek landslide. As the slump block below the cliff scarp rotated back into the slope, secondary failure occurred along a new failure surface on the downslope side of the pre-existing transverse ridge. The postulated failure model then suggests that movement of waste material from this secondary scarp down the drainage generated a surcharge load on the surficial material in the drainage (Figure 38) subsequently reducing the stability of that zone and causing the second phase of failure (Figure 39). Unit 3 on Figure 32/Plate 1 is the last exposed remnant of the surcharge load material.

Concentric topographic contours on Plate 1 suggest the failure shown in cross-section along A-A' (Figure 38). One major scarp is present at the failure head with an additional scarp present downhill due to progressive, or downhill, failure. Failure most probably occurred due to surcharge loading by the rock debris from the eastern cliff scarp on soil previously saturated by high precipitation and accelerated snowmelt. The sudden loading also most probably generated excess pore water pressures within the soil mass. A zone

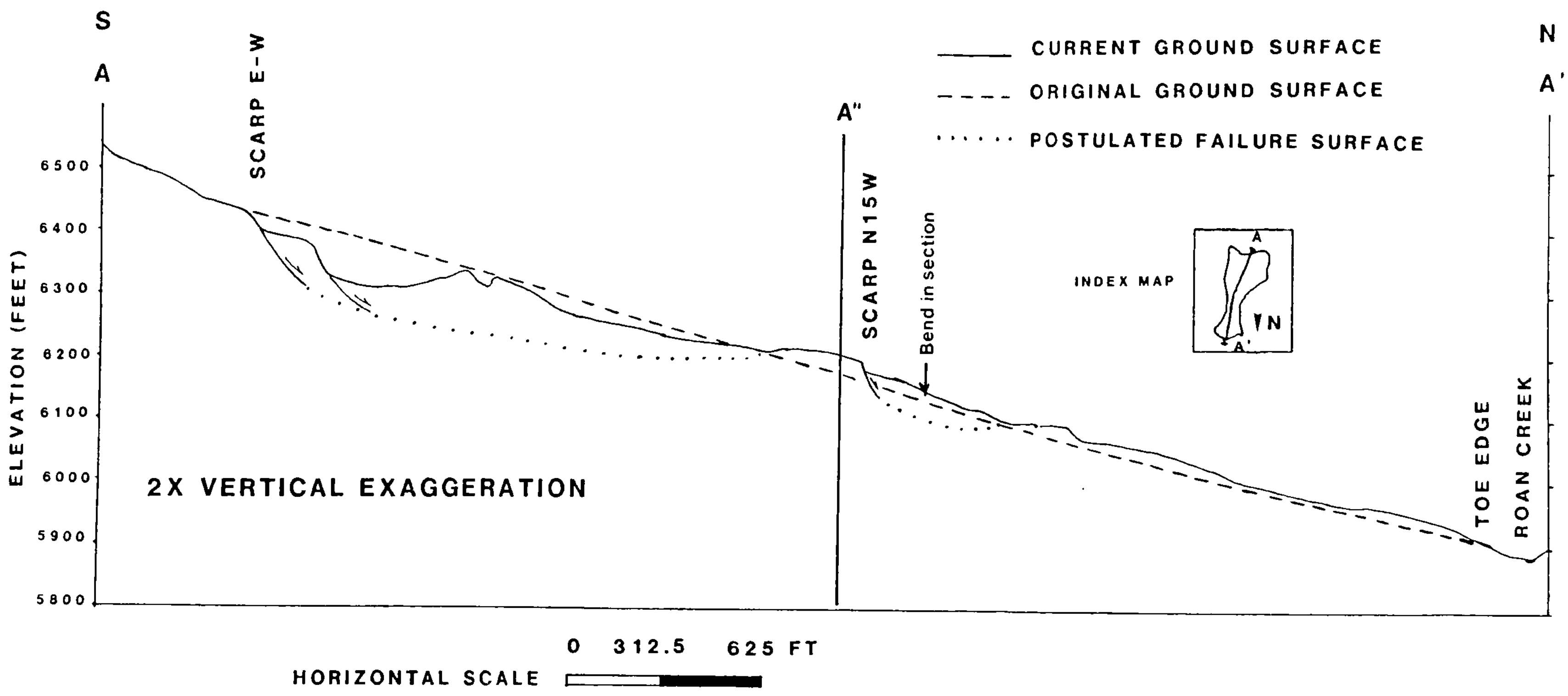


Figure 33. Cross-section along A-A'.

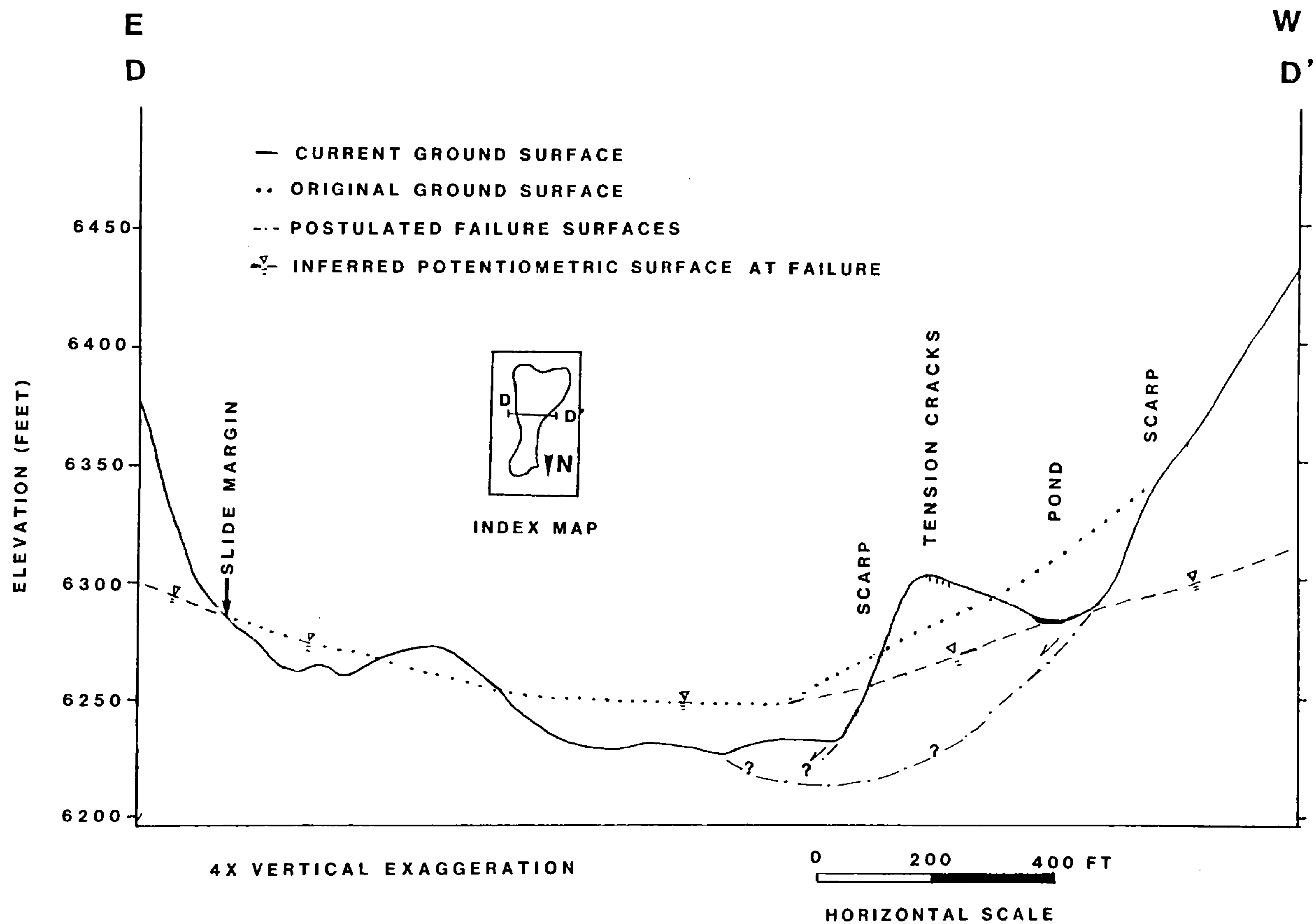


Figure 34. Cross-section along D-D'.

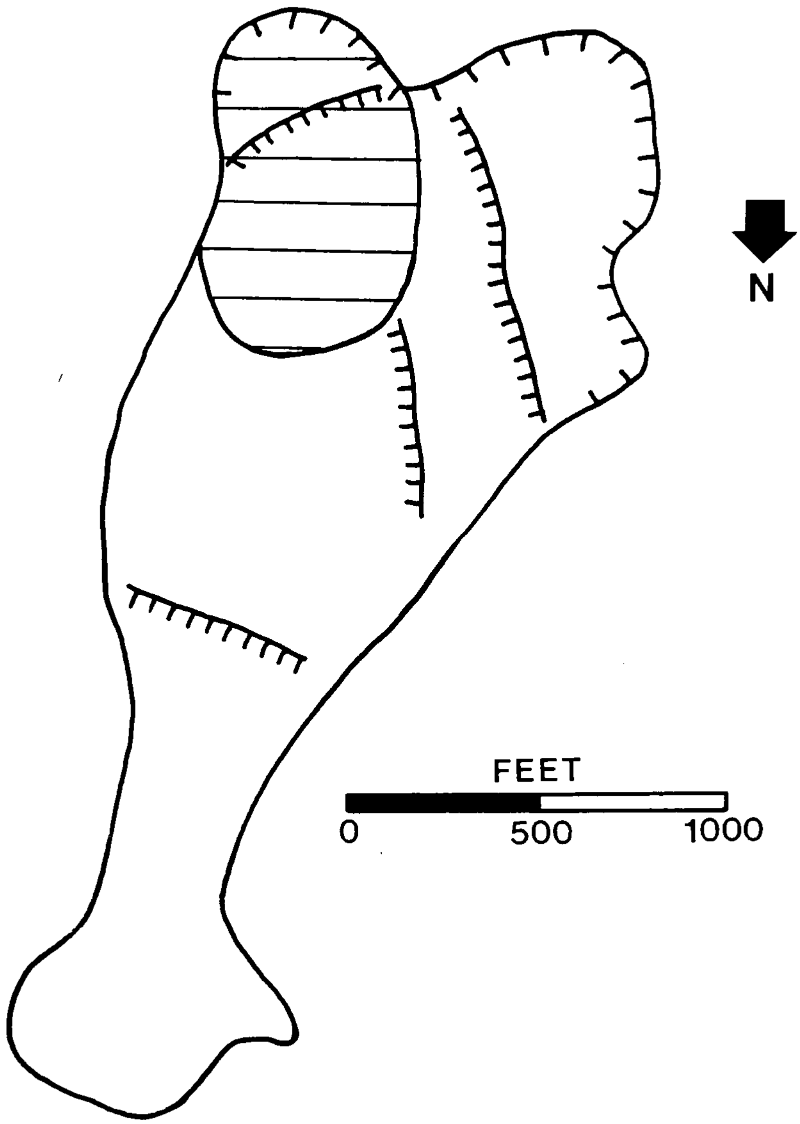


Figure 35. Phase 1 Movement of the Roan Creek landslide.

of depletion, approximately 1900 feet in length along A-A', existed during this second phase of failure. A 2500 foot long zone of accumulation extends from the boundary with the zone of depletion to the toe of the landslide. It should be noted hat no rock rubble was visible in the field immediately below the boundary between the zones of depletion and accumulation (note: this boundary is coincident with point A'). This suggests the failure surface long A-A' did not penetrate the underlying bedrock of the Wasatch Formation and crosscuts only surficial deposits. Differences in elevation between the current ground surface and the pre-failure ground surface prior to surcharge loading, reconstructed from aerial photographs, in the zone of depletion are up to 90 feet. This implies the failure surface in this section of the slide is at least 90 feet below the original ground surface. Unit 4 on Figure 32/Plate 1 represents deposits correlating to failure along A-A'.

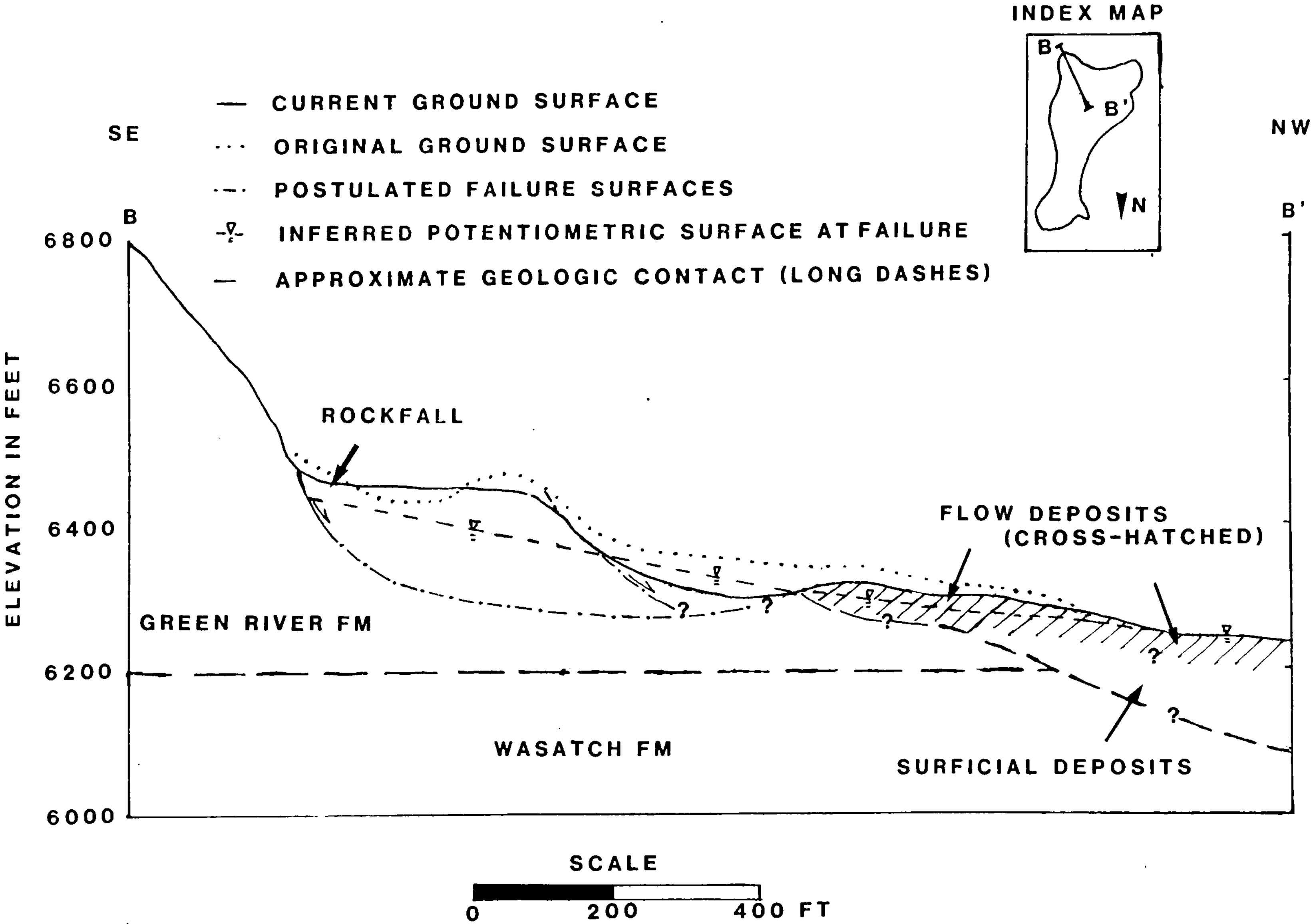


Figure 36. Cross-section along B-B'.

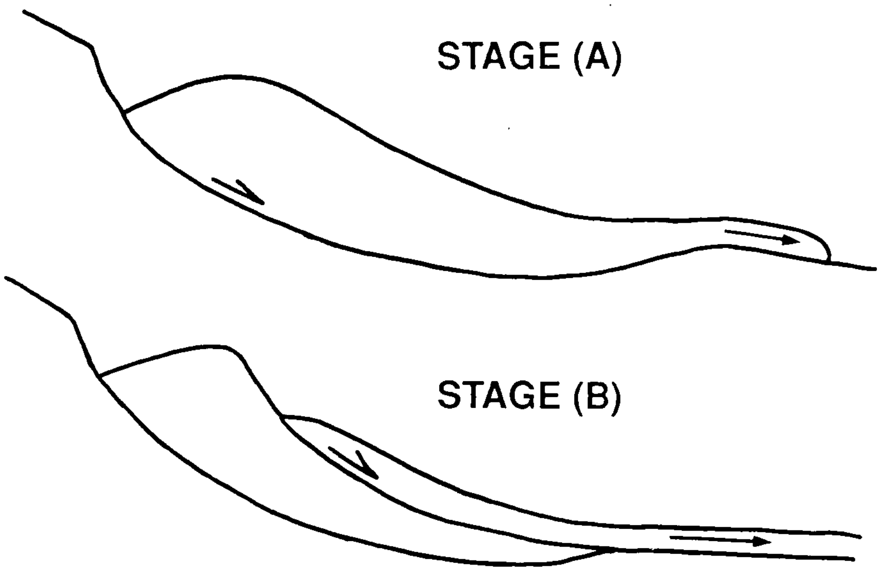


Figure 37. Diagrammatic representation of proposed failure sequence along cross-section B-B'. (Not to scale.)

Removal of material in the zone of wasting in the second stage of failure resulted in a significant reduction of lateral confining pressures acting on the rotational block below the western cliff scarp and on the slopes to the west of the drainage. This lead to the third phase of failure (Figure 40) which included renewed failure along the western cliff scarp and progressive, downward-migrating, mass wasting of the slopes to the west as evidenced in the field by a series of scarps and tension cracks oriented semi-parallel to the drainage.

A diagrammatic sketch of the proposed mode of failure along the western section of D-D' (see Figure 34) is presented in Figure 41. Examination of Figure 34 shows that failure must have originated upslope due to current topography higher than that prior to failure in the central portion of D-D'. With this point in mind, it is most improbable that failure initiated at the drainage bottom and retrogressed, or migrated uphill. Upon failure along the western margin slopes, a single slump block broke up into two separate units labeled 5 and 6 on Figure 32/Plate 1. It should be noted that only slight movement has occurred upslope of the scarp defining the upper boundary of unit 5 on Figure 32/Plate 1. Therefore, the failure of units 5 and 6 had little effect on the stability of the northern section of unit 9.

Figure 42 is a cross-section along C-C' through the western cliff scarp and rotation block area. The failure model postulates that removal of material along A-A' reduced the lateral confining pressures acting on the slopes below the western cliff scarp, subsequently causing retrogressive failure of these slopes. A five-stage, diagrammatic representation of failure along C-C' is shown in Figure 43. Stage (a) shows the pre-existing topography and failure

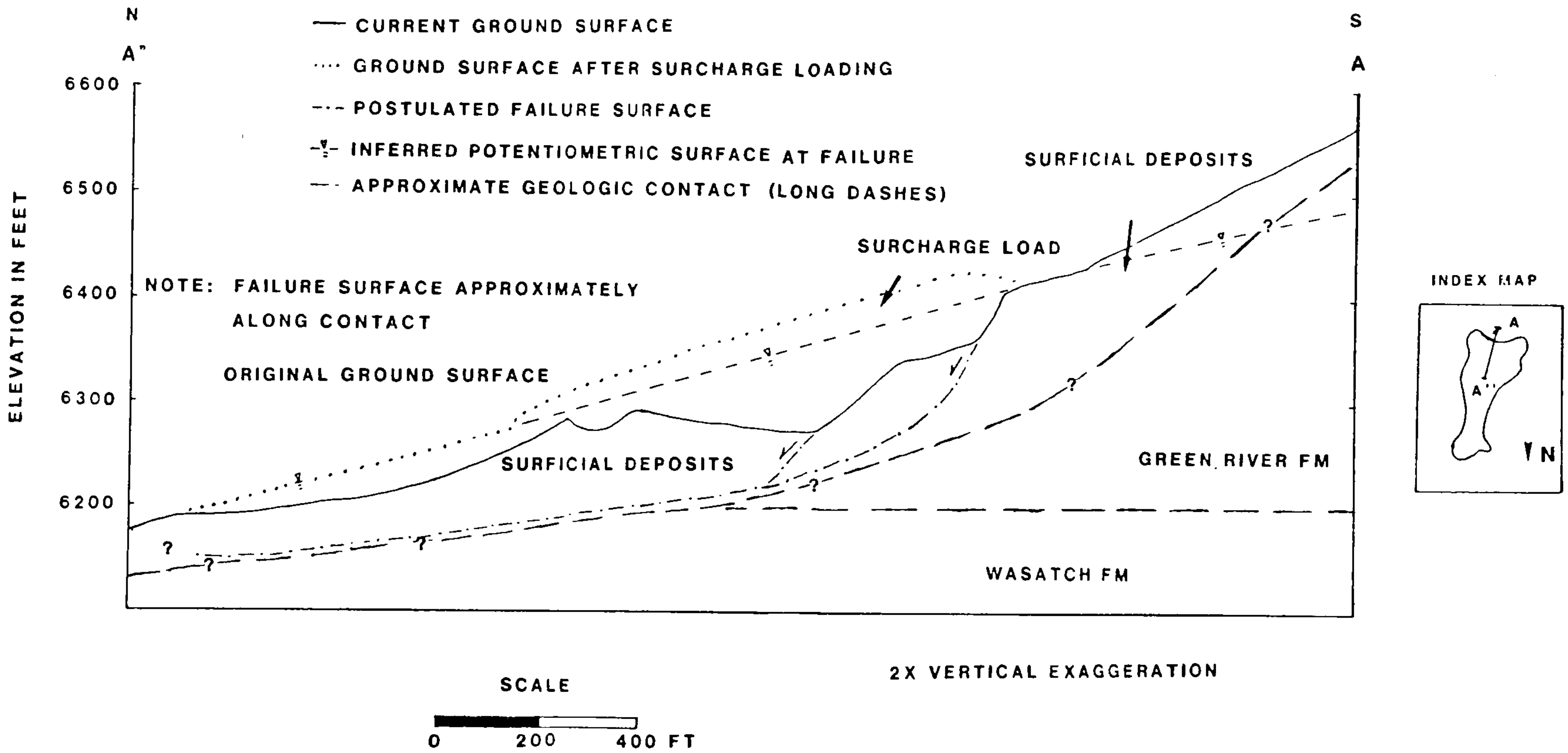


Figure 38. Cross-section along A-A' after surcharge loading.

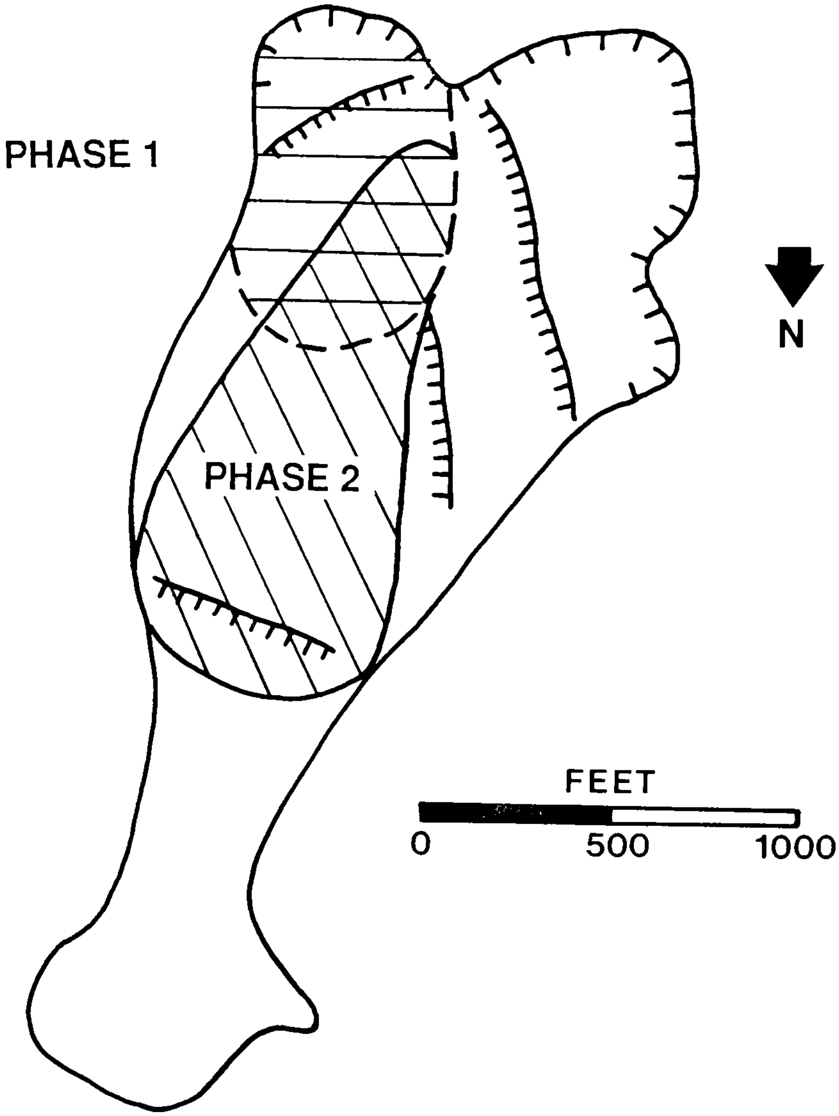


Figure 39. Phase 2 movement of the Roan Creek landslide.

plane daylighting at the cliff scarp. The failure along A-A' and subsequent removal of lateral support is represented in stage (b). Failure due to removal of lateral support by failure along A-A' is shown in stage (c). The head scarp of this failure surface is coincident with that representing the upper boundary of unit 5 in Figure 32. Stage (d) shows the vertical displacement at the head scarp in (c) immediately after failure which resulted in reduced lateral support of the failure plane daylighting at the cliff scarp. Failure along the pre-existing failure plane is shown in stage (e).

Two large flows, with large amounts of rock rubble (Figure 32/Plate 1, units 7 and 8), emanating from the scarp defining the lower boundary of unit 9, overlie the majority of surficial material in the upper reaches of the slide (see Figures 23 and 32). This suggests that failure in the western cliff scarp area was the last to occur in the upper reaches of the slide.

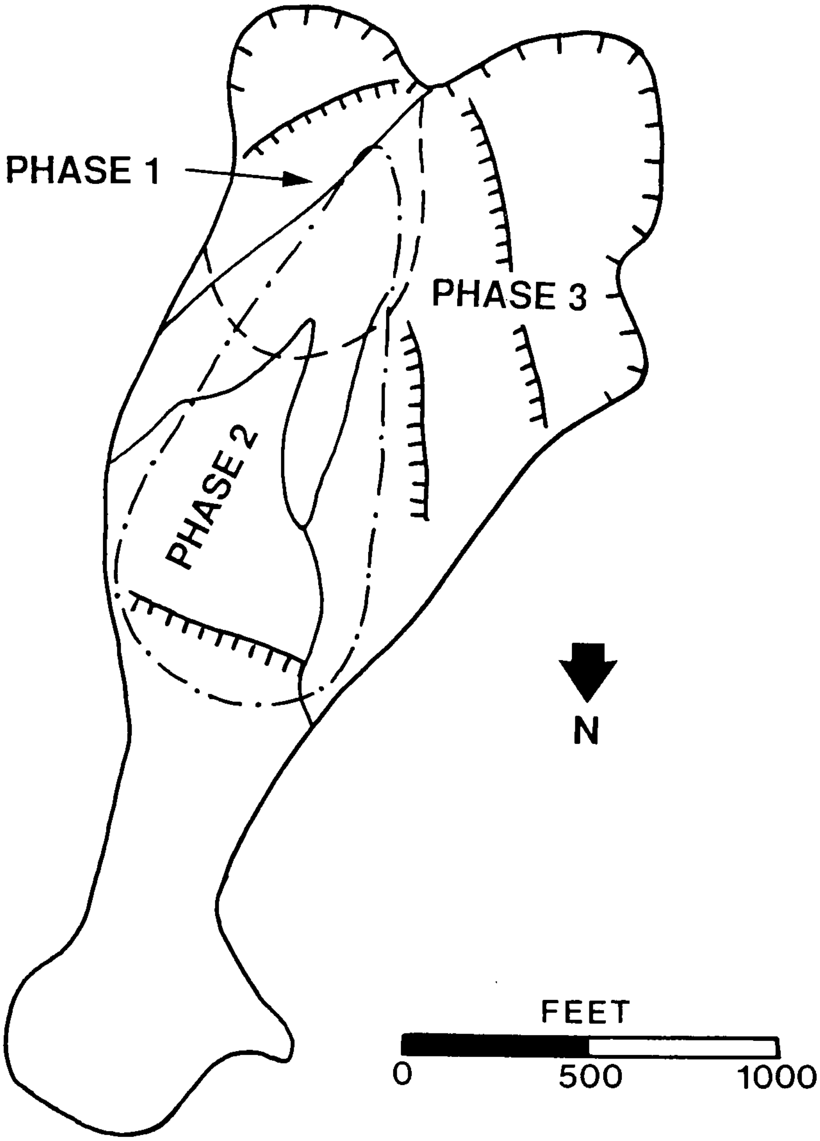


Figure 40. Phase 3 movement of the Roan Creek landslide.

Failure along the scarp oriented N15W (Figures 18 and 33) occurred entirely in the zone of accumulation and is postulated to have occurred after the failure in the upper reaches of the slide. This failure can probably be attributed to high pore water pressures as well as low material shear strength present in the upper region of the zone of accumulation.

A debris flow mapped below the intersection of the drainage with the head scarp postdates failure of the slide. Field evidence and photographs taken in April 1985 suggest the debris flow occurred shortly after failure of the Roan Creek landslide. The most probable causes of debris flow initiation were undercutting of lateral support of the material along the slopes of the drainage immediately uphill of the major head scarp of failure along A-A' and high soil moisture contents.

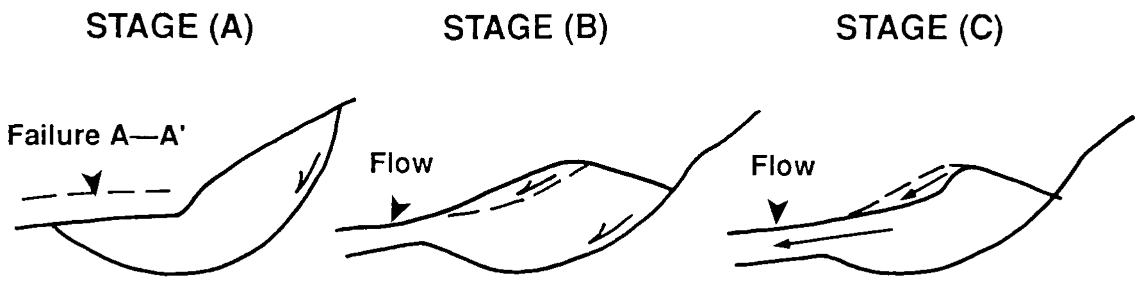


Figure 41. Diagrammatic representation of proposed failure sequence along cross-section D-D'.

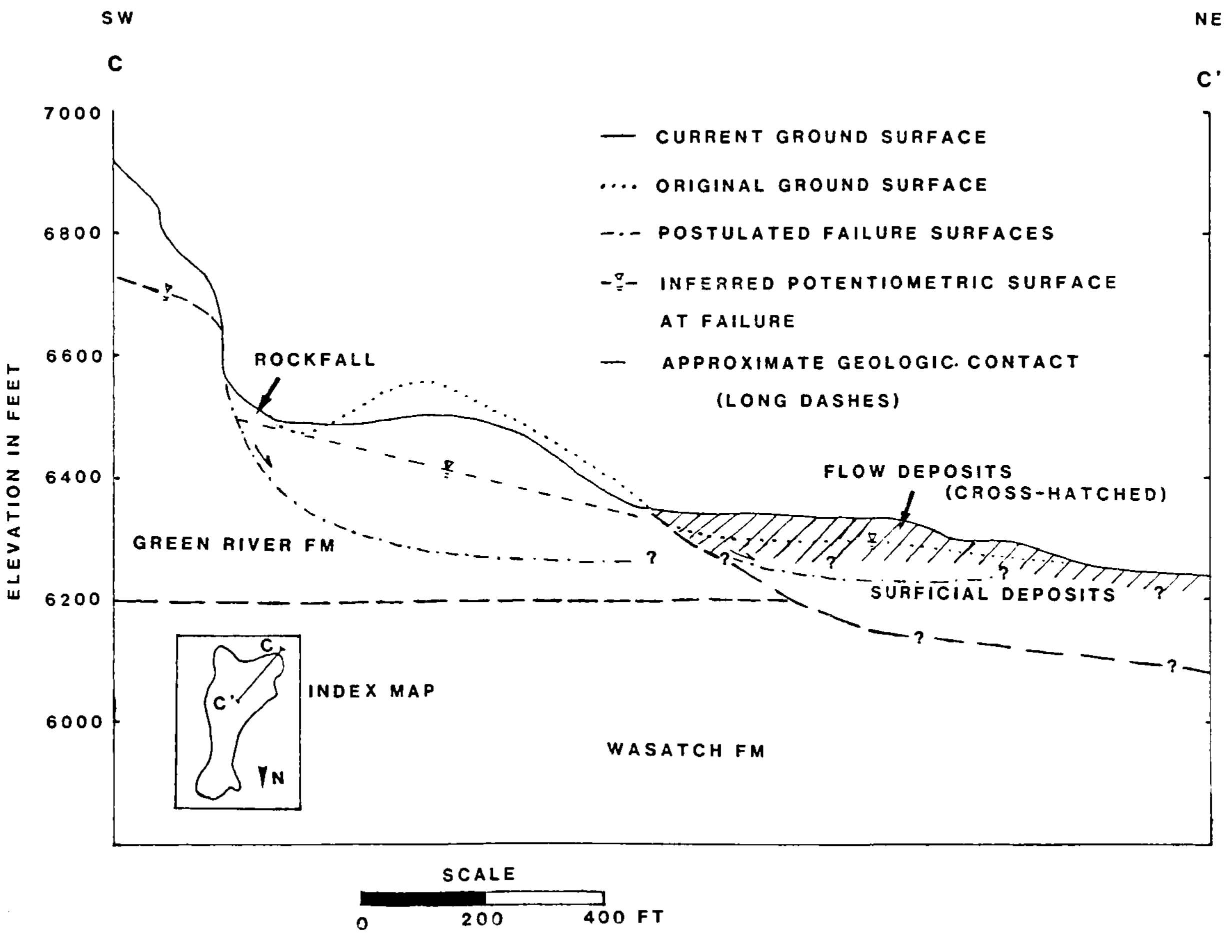


Figure 42. Cross-section along C-C'.

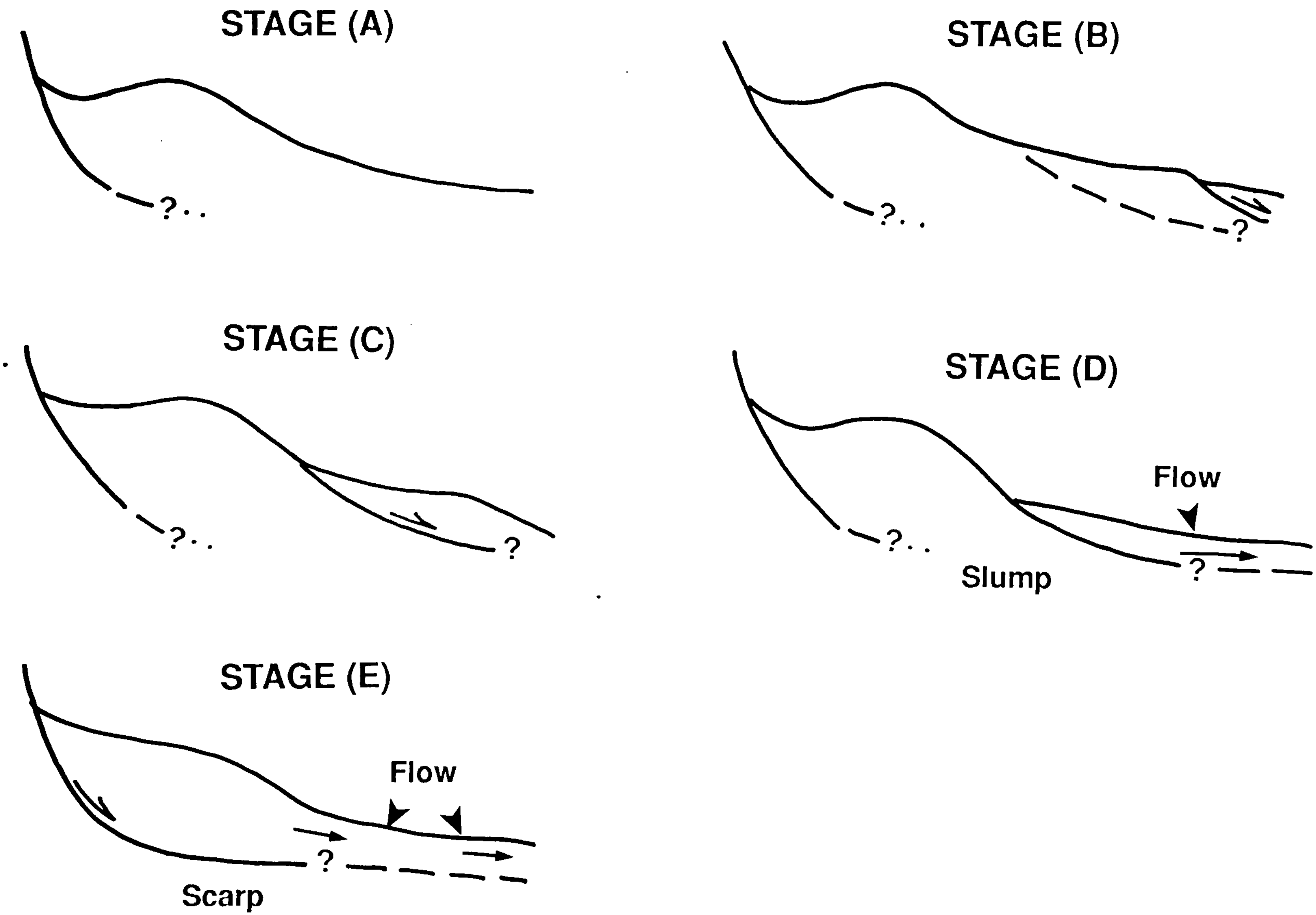


Figure 43. Diagrammatic representation of proposed failure sequence along cross-section C-C'.

8.0 MODELING AND ANALYSIS

In order to corroborate the failure model of the Roan Creek landslide developed from geologic observations and described in Section 7.4, the postulated mode of failure was modeled with PCSTABL4. PCSTABL4 is a computer program developed at Purdue University (Lovell and others, 1985 and Carpenter, 1985) for slope stability analysis. Each of the three phases of failure was analyzed with the model. Soil properties, pre-failure topography and groundwater conditions were all estimated and utilized to generate failure surfaces approximating those observed in the field in the field and their respective factors of safety with PCSTABL4. It should be noted that uncertainties in assessing shear strength properties of the Roan Creek slide material necessitated a degree of argumentative circularity in the slope stability analyses.

8.1 Background

PCSTABL4 is the IBM-PC version of STABL4, the fourth in a series of computer programs written in FORTRAN IV source language for the general solution of slope stability problems utilizing a two-dimensional limiting equilibrium method. Factors of safety calculated by PCSTABL4 are generated using either the simplified Janbu or modified Bishop methods of slices. The simplified Janbu method is applicable to non-circular failure surfaces while the modified Bishop method is used for circular failure surfaces.

Up to one hundred random trial failure surfaces can be generated for a specific slope geometry in a single run of PCSTABL4 with the ten most critical failure surfaces and their respective factors of safety recorded. Conversely, a known failure surface can be analyzed and soil properties and geometric configurations back calculated. A combination of these variables must be input in order to run PCSTABL4: topographic (surface boundaries, subsurface stratigraphy, potentiometric surface configuration, and soil properties -- including moist and saturated unit weights, cohesion and angle of internal friction. Limits must be placed on the initiation and termination positions of the trial failure surfaces and the desired method of analysis must be specified.

8.2 Analysis

8.2.1 Geometric and soil parameters A preliminary geometric model was established for the Roan Creek landslide to assess input parameters based on Figure 38. Analysis along profile A-A' was chosen as the spatial limits of the failure surface and minimum depth to failure surface were well-defined. The head scarp along the profile was mapped in the field and the toe of the failure was delineated where flow and accumulation of the slide material are evident. No bedrock-derived material was evident in the field beyond the defined toe; therefore, failure along A-A' was thought to be restricted exclusively to surficial deposits. A differential of 90 feet in topography from pre-failure to currently observed topography places a minimum depth of the failure surface at least 90 feet below the original ground surface in the upper reaches along the profile. Data presented in Sections 3.1 and 3.2

suggest the potentiometric surface was at or very close to the original ground surface prior to surcharge loading.

The volume of surcharge material present along profile A-A' was determined graphically by estimating the difference in topography prior to and after failure of unit 2 (Figure 32/Plate 1) along B-B' and assuming conservation of mass downslope. Areal distribution of the surcharge load was assumed to be nearly uniform with a depth of 20 to 25 feet over the upper reaches along A-A'. The postulated failure surface fo Figure 38 was defined geometrically for utilization in the PCSTABL4 analysis. Moist and saturated unit weights of the surficial material were estimated to be 90 pounds per cubic foot (pcf) and 100 pcf, respectively. These values were considered to be representative as USDA values (unpublished) for the moist unit weights of the material at the landslide site ranged from 85 to 91 pcf.

According to the failure model proposed in Section 7.4, failure of the Roan Creek landslide occurred in both bedrock and surficial materials. Bedrock shear strength properties are documented in other engineering geology studies conducted in the Roan Creek basin in these particular units (West and Associates, 1984). Shear strengths presented in these studies were calculated from the results of consolidated undrained triaxial shear tests on siltstone-claystone bedrock core samples. Values thought to be representative of the units involved in the Roan Creek landslide failure were utilized in the modeling analysis and are presented in Table 3. The Garden Gulch Member of the Green River Formation was assigned strength properties of 110 pcf moist unit weight, 115 pcf saturated unit weight, cohesion of 500 psf and an angle of internal friction of 15 degrees. The Upper Shire Member of the Wasatch Formation was assumed to have a moist unit weigh of 100 pcf, a saturated unit weight of 105 pcf, cohesion of 500 psf and a phi angle of 15 degrees.

Table 3. Rock properties used in slope stability analysis

MATERIAL	UNIT WEIGHT (PCF) MOIST	SATURATED	COHESION (PSF)	PHI (DEG.)
Garden Gulch Mbr.	110	115	500	15
Wasatch Fm.	100	105	500	15

However, surficial deposit strength parameters were not defined in these studies. Therefore, a determination of appropriate soil shear strength properties was required. Due to the assumption of the model proposed in section 7.4 that a surcharge load was placed on the upper reaches of profile A-A', a total stress analyses should be used in evaluating short-term stability and when sudden loading conditions are encountered. A total stress analysis using undrained shear strength, C(u), and the phi = 0 concept was conducted.

8.2.2 Modeling of failure along profile A-A' Wasatch and Green River formation bedrock along A-A' was assumed to have the properties described in Table 3. However, these properties had no effect on the stability analysis as it was assumed that failure occurred entirely within surficial deposits. The surcharge load material derived fro the Garden Gulch in the eastern head scarp region was assumed to have equivalent properties to the surficial material. The surficial soil deposits in the drainage were assumed to be homogeneous. Field observations indicate the assumption of homogeneity is relatively valid as all the soil found in the drainage is derived from the same parent material and is not very far removed from its source on Kimball Mountain. Slight local variations in soil properties can be attributed to different genetic origins (i.e. colluvium vs. alluvium vs. landslide deposits).

Values of undrained shear strength ranging from 300 to 1500 psf were utilized, in conjunction with the unit weights and groundwater conditions described above for the failure plane defined in Figure 38, to determine what shear strength yielded a factor of safety of 1.0 using the Janbu method of slices. Figure 44 is a plot of factor of safety versus undrained shear strength compiled from PCSTABL4 results.

An undrained shear strength of 1350 psf generated a factor of safety of 1.0. Undrained shear strength was then assigned this value for the remainder of stability analyses involving surficial materials. This shear strength value is considerably higher than those calculated using torvane data in Section 6, but as stated in that section, shear strength at failure could have been much greater than the values determined with the torvane in the flow deposits. However, this value for undrained shear strength should be considered only approximate.

In order to assess the impact of the surcharge load, slope stability prior to surcharge loading along A-A' was also addressed using PCSTABL4. Input parameters were essentially the same as described above with the difference being the removal of surcharge load and utilization of an undrained shear strength of 1350 psf. This analysis yielded a factor of safety of 1.23. The greater factor of safety of 1.23. The greater factor of safety prior to surcharge loading appears to suggest that the additional load of material derived from failure along B-B' was enough to cause failure along A-A'. The input data and output results of this analysis are presented in Appendix B-1.

8.2.3 Comparison of results with other methods The PCSTABL4 results along A-A', discussed in the above paragraphs, were checked using hand calculations. Hand Calculations using the Fellinius method of slices yielded factors of safety of 1.43 and 1.08 for the postulated failure surface in Figure 38 prior to and after surcharge loading, respectively. The hand solution is presented in Appendix C. In general, a lower factor of safety is calculated using the Fellinius method of slices versus the Bishop or Janbu methods of slices (McCarthy, 1982). However, this is only true for slope stability analyses under effective stress conditions. When a total stress analysis is conducted (i.e. phi=0), all three methods reduce to the same relationship and, therefore, the factors of safety calculated by each method should be equal regardless of what method is specified. The discrepancy in values of factor of safety of 5 and 14 percent between hand and computer-aided solutions for surcharge and pre-surcharge loading conditions, respectively, can be attributed to the degree of precision available in each of the two

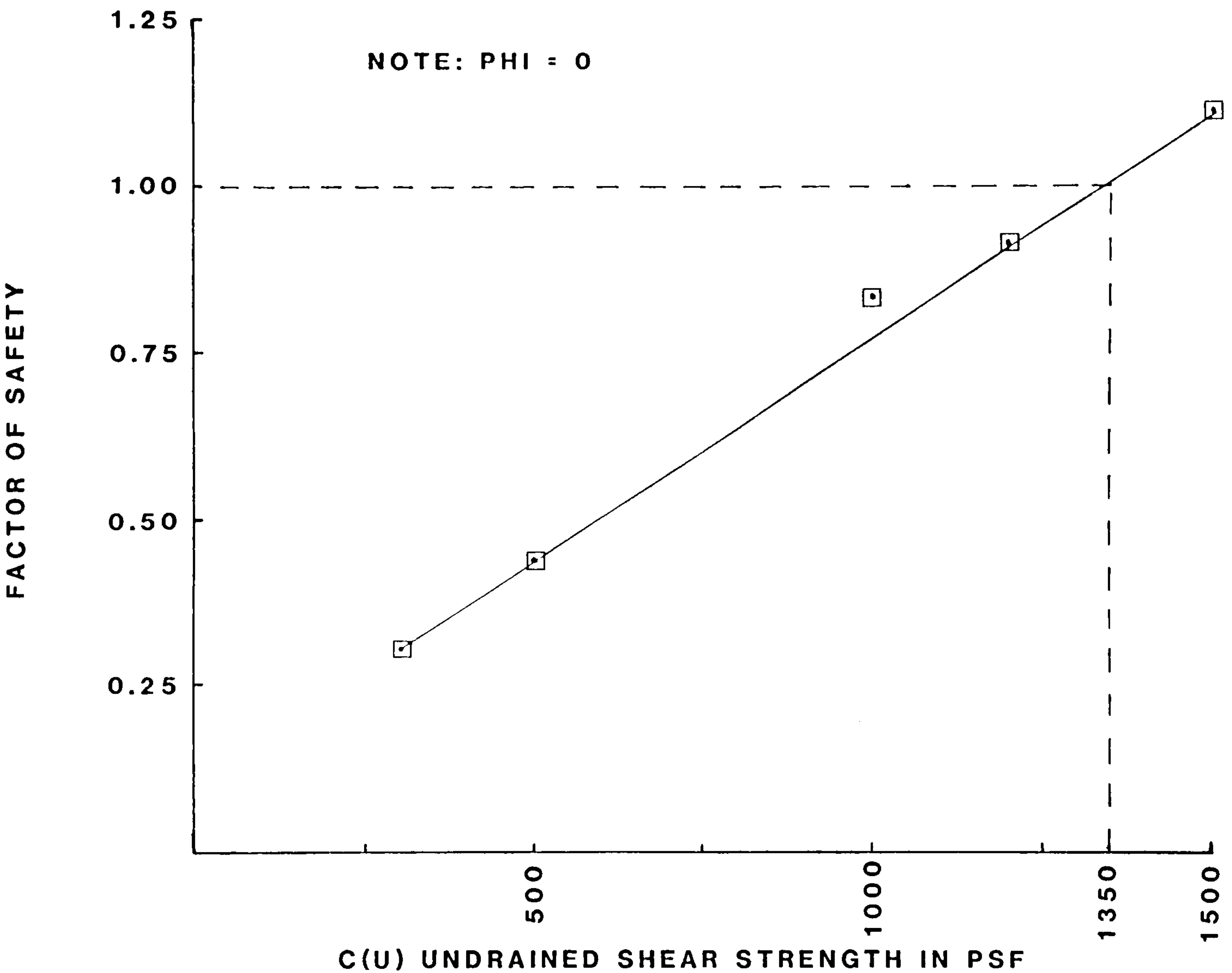


Figure 44. Determination of undrained shear strength.

methods. Analyzing stability with the computer allows a much higher degree of precision in comparison to hand calculations. Smaller slices generated by the computer allow for a more precise definition of slice area, the angle of inclination of each slice, as well as the arc length of the lower boundary of the slice. Subsequently, the driving and resisting moments are more precisely defined and the calculated factor of safety is more exact. Therefore, the hand solution factors of safety should only be considered rough estimates of actual slope stability conditions when used in comparison to those calculated with the aid of the computer when total stress analyses are used.

The PCSTAB4 results were also checked against results computed by STABL3, a mainframe computer version in the STABL series, on the VAX 8600 using the same input file. The STABL3 results were essentially identical to those of PCSTABL4 with variance of only a few thousandths in values of factors of safety which can be attributed to different random number generators utilized by the VAX 8600 and the IBM-PC computers.

8.2.4 Modeling of failure along profile B-B' According to the failure model proposed in Section 7.4, initial failure of the Roan Creek landslide occurred in the eastern head region along the eastern cliff scarp. A PCSTABL4 analysis along B-B' (see Figure 36) was conducted to define the failure plane configuration and its respective factor of safety. Failure in the head region was well-defined by a cliff scarp (see Figure 14). Failure was assumed to have occurred exclusively in bedrock material as it is the predominant material type present in this section of the slide. Therefore, the bedrock strength parameters presented in Table III were utilized in the analysis. The potentiometric surface along B-B' was assumed to be at the surface near the drainage valley center, but to significantly fall below the previous ground surface towards the eastern cliff scarp (see Figure 36) due to an increase in topographic gradient. Appendix B-2 contains the PCSTABL4 data input file for the analysis along B-B'.

The PCSTABL4 output file generated with the input file of Appendix B-2 is presented in Appendix B-3. Utilizing the Janbu option, analysis of the B-B' profile yielded a factor of safety of 0.995 for the specified conditions. This indicated that failure would have occurred under the given criteria, and therefore, seems to suggest that the first phase of the postulated failure model is justifiable.

8.2.5 Modeling of failure along profile D-D' The proposed model suggests the third phase of failure occurred along the western margin slopes and in the western cliff scarp region due to reduction of lateral confining pressure after failure along A-A'. According to Figure 32/Plate 1, unit 5 was the first to fail along the western margin. Therefore, PCSTABL4 was utilized to analyze stability along profile D-D' (see Figure 34) prior to and after failure along A-A'. A total stress analysis was conducted with the original topographic conditions outlined on Figure 34 assuming the potentiometric surface to be at the ground surface in the valley bottom and to fall significantly below the ground surface as the slope increased gradient. An undrained cohesion of 1350 psf was specified. This analysis yielded a critical factor of safety of 1.20 for the given conditions suggesting that the slope was stable prior to failure along A-A'. Appendix B-4 contains the input and output for this analysis.

An additional total stress analysis was run with PCSTABL4 after failure along A-A' to assess any change in slope stability. Failure along A-A' was assumed to have lowered the topographic surface by about 20 feet in the cross-section along D-D' with a subsequent reduction in the water table. Introducing the new topographic boundaries and groundwater conditions, a factor of safety of 0.98 was calculated appearing to suggest failure along A-A' and subsequent removal of lateral support along the base of the western margin resulted in failure of these slopes. The appropriate data and output files for this run are presented in Appendix B-5.

<u>8.2.6 Modeling of failure along profile C-C'</u> Failure along A-A' was also proposed to have removed lateral support of the slopes immediately below the western cliff scarp along profile C-C'(see Figure 42). The postulated failure mode suggested retrogressive, or upward-migrating, failure of two scarps along the profile with terminal failure occurring at the western cliff scarp (see Figure 43).

Three lithologic units were identified and defined a long the cross-section, including surficial deposits, the Garden Gulch Member of the Green River Formation, and the Upper Shire Member of the Wasatch Formation. Each unit was assigned strength parameters and unit weights previously discussed. Groundwater was inferred to be at the ground surface in the drainage bottom and to increase in depth below the surface towards the western cliff scarp (see Figure 42) due to increased topographic gradient. Large seeps in the cliff scarp face observed during and after failure of the Roan Creek landslide were represented in the model by defining a second potentiometric surface daylighting halfway up the cliff face.

Initial failure was hypothesized to have occurred at the scarp defining the upper boundary of units 7 and 8 (Figure 32/Plate 1). Therefore, slope stability was first analyzed prior to failure along A-A' with boundary constraints representing the observed scarp. The calculated factor of safety was 1.19 suggesting stable slopes prior to failure along A-A'. Appropriate data and output files are presented in Appendix B-6.

Stability of the slope after failure along A-A' was modeled by removing 20 feet of surficial material along the lower reaches of profile C-C'. The factor of safety was subsequently reduced to 0.97 appearing to support the proposition that failure along A-A' precipitated retrogressive failure uphill. Appendix B-7 contains the data and output files for this analysis.

Vertical displacement of the scarp bounding units 7 and 8 (Figure 32/Plate 1) was then proposed to reduce the factor of safety of the scarp daylighting at the western cliff face. In order to assess this supposition, two analyses were conducted. Firstly, a factor of safety was determined for the cliff scarp prior to failure of the lower scarp noted above. Using the initial topographic, groundwater and strength parameters described earlier, a calculated factor of safety of 1.12 was generated by PCSTABL4. Secondly, an analysis was performed assuming 20 feet of vertical displacement along the lower scarp had occurred when it failed. Field observation indicates that 20 feet of displacement is a reasonable assumption. PCSTABL4 generated a factor of safety of 0.995 for these conditions. The reduced factor of safety upon removal of lateral support seems to suggest that failure along C-C'was indeed retrogressive in nature. The data input and output files for these two analyses are presented in Appendices B-8 and B-9, respectively.

One additional analysis was conducted to assess the validity of the retrogressive failure model along C-C'. Failure along C-C'could possibly have been along a single failure plane; so the issue was addressed. A single, long failure surface closely approximating the two individual failure surfaces generated by PCSTABL4 with factors of safety of less than 1.0 was defined and evaluated. The failure surface initiated in the drainage bottom and terminated at the western cliff scarp. Utilizing the strength, groundwater and topographic conditions used in the analysis along profile C-C'immediately after failure along A-A', a factor of safety of 1.11 was calculated. This also seems to suggest the probable mode of failure along C-C'was of a retrogressive nature. However, considering the number of assumptions and the degree of uncertainty with respect to strength properties, failure could conceivably have occurred in either mode. The appropriate input and output files for this run are found in Appendix B-10.

8.2.7 Effect of lowering potentiometric surface on factor of safety After analyses were conducted along the four profiles, the effect of the position of the inferred potentiometric surfaces on factors of safety was addressed. The potentiometric surfaces on factors of safety was addressed. The potentiometric surface was lowered from the position used in the analyses (see previous discussion and Appendix B data input files) by 5, 10 and 20 feet under the most critical failure conditions along profiles A-A', B-B' and C-C' It should be noted that only the effect on the terminal failure condition along profile C-C'was analyzed. The results are plotted on Figure 45.

A lowering of the potentiometric surface of 20 feet along A-A' increased the factor of safety from 1.0 to 1.05. A reduction of total head by 20 feet along profiles B-B' and C-C'increased the factors of safety from 1.00 to 1.09 and from 1.00 to 1.06, respectively. The small increases in factor of safety suggest that these slopes are not highly sensitive to location of the potentiometric surface.

8.3 Conclusions

PCSTABL4 was utilized in order to assess the validity of the hypothesized failure model proposed in Section 7.4. Initial failure was postulated to have occurred entirely in bedrock material along profile B-B'. The modeling results corroborate this postulation as a factor of safety of 0.995 was calculated for the scarp daylighting at the eastern cliff scarp indicating failure would indeed have occurred with the assigned conditions. Material from failure along B-B' was assumed to have generated a surcharge load on the upper reaches of profile A-A'. Shear strength properties of the surficial materials were determined by back calculation along profile A-A' under surcharge conditions assuming that failure was imminent (i.e. the factor of safety was equal to 1.0) and that undrained conditions existed.

Back calculation using a total stress analysis yielded an undrained shear strength of 1350 psf. Analysis along profile A-A' prior to surcharge loading generated a factor of safety of 1.23 suggests that failure was caused due to surcharge loading.

The third phase of postulated failure occurred along the western margin and western cliff scarp area of the slide due to removal of lateral support after failure along A-A'. Analysis of slope stability along profile D-D' indicated

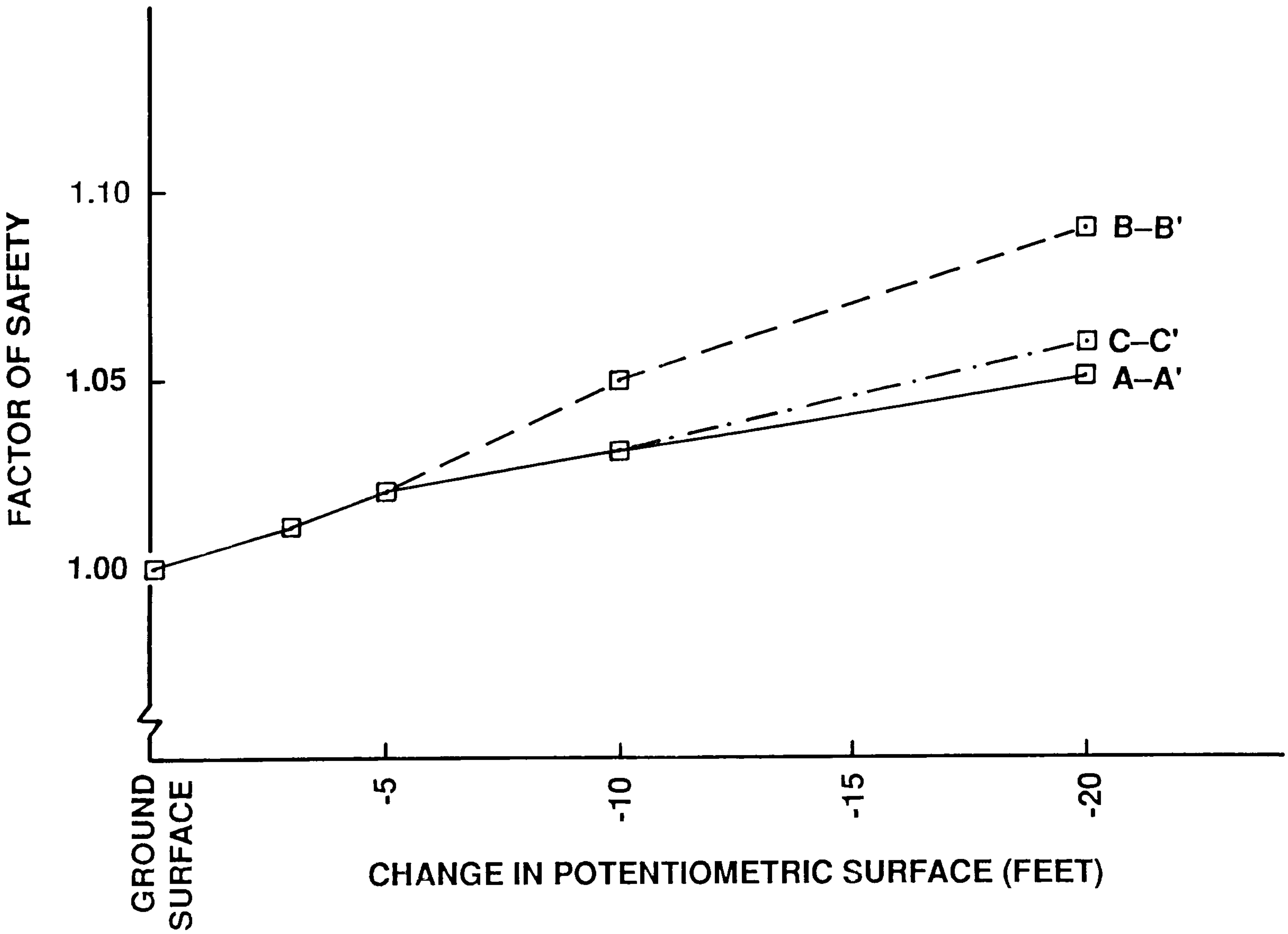


Figure 45. Effect of lowering potentiometric surface on factor of safety.

that removal of lateral support would lower the factor of safety from 1.20 to 0.98 suggesting failure of the western margin slopes. Failure along profile C-C' was hypothesized to be retrogressive in nature and was seemingly supported by modeling results. Factors of safety of the lower and upper failure surface along C-C'were reduced from 1.19 to 0.97 and from 1.12 to 0.995, respectively, after removal of material from their respective toe areas. Analysis of a single, long failure surface along C-C' yielded a factor of safety of 1.11 also suggesting failure was retrogressive. The effect of lowering the potentiometric surface on the factor of safety was analyzed as well. Results indicate that a reduced total head of 20 feet increases factors of safety by 5 to 9 percent depending on the geometry and stratigraphic units present along an individual profile.

The preceding stability analyses support the proposed sequence of failure events.

9.0 SUMMARY AND CONCLUSIONS

9.1 Summary and Conclusions

The Roan Creek landslide is located in a first order drainage on the north side of Kimball Mountain in the Roan Creek basin and has been classified as a slump-earthflow complex. It failed in late April 1985 in bedrock of the Garden Gulch Member of the Green River Formation and the Upper Shire Member of the Wasatch Formation as well as in the surficial materials present in the drainage.

The second greatest annual precipitation on record, 158 percent of mean annual precipitation, fell during the year of 1985. In the seven days preceding failure of the landslide, 2.41 inches of rain were recorded. The average discharge of Roan Creek in april 1985 was 282.7 cubic feet per second (cfs), 396 percent of mean average discharge for April. Maximum discharge reached 462 cfs shortly prior to failure of the landslide. The anomalously high Roan Creek discharge strongly suggests rapid snowmelt in the highlands, including Kimball Mountain, surrounding the Roan Creek basin. The combined effect of high precipitation and accelerated snowmelt generated soil conditions at or near saturation and high groundwater levels. The excess water present on the north flank of Kimball Mountain generated high pore water pressure which in association with the inherently weak shear strength of the materials present reduced slope stability ad caused failure of the Roan Creek landslide.

All visible primary structures (including scarps and tension cracks), seeps, standing water and surficial deposit variation within the Roan Creek landslide were mapped. Soil samples collected in a field drilling program were analyzed for natural moisture contents, liquid limits and plastic indices and classified according to the Unified Soil Classification with grain size analyses data. Moisture contents ranged from 17.7 to 29.4 percent for samples collected in the month of october, liquid limits ranged from 41 to 48, and plastic indices ranged from 13 to 25. Utilizing grain size analysis results, the samples were classified as silty sands and clayey sands, with clay percentage increasing with distance away from the head region of the landslide.

Using field notes and observations, calculated soil properties, extensive air photo interpretation of images flown in 1978 and 1985 (pre-and post-failure, respectively) and a surficial geologic map, a failure model explaining the sequence of events in the Roan Creek landslide was developed. Three distinct phases of failure were identified. Initial failure of the landslide occurred at the eastern cliff scarp in the upper region of the slide mass. This was supported by stratigraphic interpretation of surficial deposits below the scarps along the drainage bottom. The material from the initial failure created a sufficiently large surcharge on the existing saturated surficial material in the drainage reducing slope stability and causing the second phase of failure. The second phase of failure involved a failure surface and subsequent flow of material beyond the toe of the failure surface. Large volumes of material removed from the zone of wasting during the second stage of failure resulted in reduced lateral confining pressure acting on the western margin of the slide and on the rotation block beneath the western cliff scarp. The subsequently reduced slope stability along the western margin and at the western head scarp resulted in failure of the third phase of the Roan Creek landslide.

PCSTABL4 was utilized to test the validity of the postulated failure model. After identifying geometry, soil properties and groundwater configuration for each of the three successive phases of failure, each phase was independently analyzed. The factor of safety calculated for the most critical failure, was 0.995. The surcharge load applied to the upper regional along profile A-A' reduced the calculated factor of safety of the slope from 1.23 to 1.00, most probably causing the second stage of failure. Mass wasting associated with failure along A-A' reduced the lateral confining pressures acting on the toes of the slopes along D-D' and C-C' reducing calculated factors of safety from 1.20 to 0.98 and from 1.19 o 0.97, respectively. This resulted in the third phase of failure. Failure along C-C' appears to have been retrogressive, with failure of the lower slopes reducing the calculated factor of safety of the upper regional along the profile from 1.12 to 0.995.

9.2 Future Stability

A survey control network has not been installed at the Roan Creek landslide to monitor subsequent movement of the slide mass since its initial failure in April of 1985. Field observations indicate that movement of the existing slide mass has been negligible to non-existent in the springs of 1986 and 1987. Retrogressive failure of adjacent slopes to the landslide was noted in 1986 and 1987 in the form of tension cracks and small-scale scarps and suggests that danger of future failure does exist. However, it is highly unlikely these features will result in mass moment on the scale of the Roan Creek landslide. The landslide mass does contain a large volume of groundwater as evidenced by the absence of a surface stream in the upper reaches of the slide and the presence of a stream flowing off the toe of the landslide, as well as the standing ponds of water and seeps present throughout the slide mass. Any future slope stability studies of the landslide would necessitate a more complete survey and understanding of the groundwater conditions and material properties and their effect on slope stability.

If another year, or series of years, of exceedingly high precipitation and accelerated snowmelt occur in conjunction, it is possible the Roan Creek landslide could be remobilized. As evidenced by abundant landslide deposits up and down the Roan Creek valley from Brush Creek to Carr Creek, earthflows are recurrent exogenetic hazards in the Roan Creek basin. A cursory geomorphic examination indicates that the majority of landslides originating from the northern slopes of Kimball Mountain have not adversely affected the flows of Roan Creek. However, the danger posed to Roan Creek and its valley is not analyzed in detail in this engineering report.

No remedial measures to stabilize the Roan Creek landslide are currently suggested as the slide appears to presently be stable and poses no immediate threat of damming the creek. However, the event studied has left potential unstable, steep slopes in the head scarp area which could lead to reactivation and lateral advance of the earthflow in the future.

10.0 REFERENCES CITED

American Society for Testing and Materials, 1986, Annual book of ASTM standards, V.04.08, soil and rock; building stones, 1078p.

Carpenter, J.R., 1985, PCSTABL4 user manual: School of Civil Engineering, Purdue University, West Lafayette, Indiana, 77p.

Hosterman, J.W. and Dyni, J.R., 1972, Clay mineralogy of the Green River Formation, Piceance Creek Basin, Colorado -- a preliminary study: U.S. Geological Survey Professional Paper 800-D, p. D159-D163.

Hunt, R.E., 1984, Geotechnical engineering investigation manual, McGraw-Hill, New York. 983p.

Iverson, R.M., 1985, A constitutive equation for mass-movement behavior: Journal of Geology, V. 93, p. 143-160.

Iverson, R.M., 1986, Dynamics of slow landslides: a theory for time-dependent behavior, in, A.D. Abrahams, Editor, Hillslope Processes, Allen & Unwin, Boston, p. 297-317.

Jex-Piland Engineers and Geologists, 1970-1985, Roan Creek Getty Station gaging records, prepared for Getty Oil.

Johnson, R.C., 1977, Preliminary geologic map and cross section of the Saddle Quadrangle, Garfield County, Colorado: U.S. Geological Survey Map MF-829.

Johnson, R.C., 1981, Preliminary geologic map of Desert Gulch quadrangle, Garfield County, Colorado: U.S. Geological Survey Map MF-1328.

Keefer, D.K. and Johnson, A.M., 1983, Earthflows: morphology, mobilization and movement: U.S. Geological Survey Professional Paper 1264, 56p.

Lovell, C.W., Sharma, S. and Carpenter, J.R., 1985, Introduction to slope stability analysis with STABL4: School of Civil Engineering, Purdue University, West Lafayette, Indiana, 124p.

McCarthy, D.F., 1982, Essentials of soil mechanics and foundations, second edition, basic geotechnics: Reston Publishing Company, Reston, Virginia, 632 p.

Nilsen, T.H. and Turner, B.L., 1975, Influence of rainfall and ancient landslide deposits on recent landslides (1950-71) in urban areas of Contra Costa County, California: U.S. Geological Survey Bulletin 1388, 18p.

National Oceanic and Atmospheric Administration, 1940-1985, Climatological Data Annual Summaries for Colorado.

Olson, R.W., 1974, Valley morphology and landslides, Roan Creek and Parachute Creek basins, western Colorado: unpublished Masters thesis, Colorado State University, 102p.

Savage, W.Z. and Chleboarad, A.F., 1982, A model for creeping flow in landslides: Bulletin of the Association of Engineering Geologists, V.XIX, No. 4, p. 333-38.

Savage, W.Z. and Smith, W.K., 1986, A model for the plastic flow of landslides: U.S. Geological Survey Professional Paper 1385, 32p.

Schuster, R.L. and Krizek, R.J., editors, 1978, Landslides: Analysis and control, Transportation Research Board Special Report 176, 234p.

Snyder, L.E., 1977, Report on the Rolling Hills Country Club landslide and nearby slopes, South Table Mountain, Jefferson County, Colorado: unpublished Master of Engineering Report, Colorado School of Mines, ER-1956, 137p.

Ter-Stepanian, G., 1963, On the long-term stability of slopes: Norwegian Geotechnical Institute Publication Number 52, p. 1-14.

Terzaghi, K., 1950, Mechanism of landslides, in, Application of geology to engineering practice: Geological Society of America, p. 83-123.

Turney, J., 1985, Roan Creek earthflows T6S, R99W, Section 28, 33: Colorado Geological Survey Internal Memorandum, 7p.

Turney, J., 1985, Roan Creek valley slump-earthflow history T6S, R99W, Sec. 20-29, 32-36: Colorado Geological Survey Internal Memorandum, 6p.

U.S. Department of Agriculture, unpublished, Preliminary soil survey of Garfield County, Colorado.

U.S. Geological Survey, 1968, 7.5 minute topographic quadrangle, The Saddle, Garfield County, Colorado.

U.S. Geological Survey, 1987, 7.5 minute topographic quadrangle, Desert Gulch, Garfield County, Colorado.

Varnes, D.J., 1978, Slope movement types and processes, in, Schuster and Krizek (editors), Landslides: Analysis and control, Transportation Research Board Special Report 176, p. 11-33.

West, M.W. and Associates, Inc., 1984, proprietary unpublished consultants report.

APPENDIX A-1

ATTERBERG LIMITS

Both the liquid and plastic limits and subsequently plastic indices were determined for three samples utilizing ASTM (1986) procedures.

The liquid limit was determined using the one-point liquid limit procedure. Essentially, this method calculates the liquid limit using the relationship:

$$L.L. = K * W(n),$$

where,
L.L. = the liquid limit,
W(n) = the moisture content,
and K = a factor for obtaining the liquid limit from water content and number of blows causing closure of the groove.

Two trials were conducted for each sample. The average of the two liquid limits was then defined to be the liquid limit. Applicable data is presented in Table A-1'A.

Plastic limit tests were conducted according to ASTM (1986) standards. Plastic limits and indices are presented in Table A-1'B.

Table A-1A.

Sample No.	N	W(n)	K	L.L. (%)
1	22	.42	0.985	41
1	28	.41	1.010	41
				41
2	25	.46	1.000	46
2	24	.46	0.995	46
				46
3	23	.48	0.990	48
3	24	.48	0.995	48
				48

Table A-1B.

Sample No.	P.L. (%)	P.I. (%)
1	28	13
2	23	23
3	23	25

APPENDIX A-2

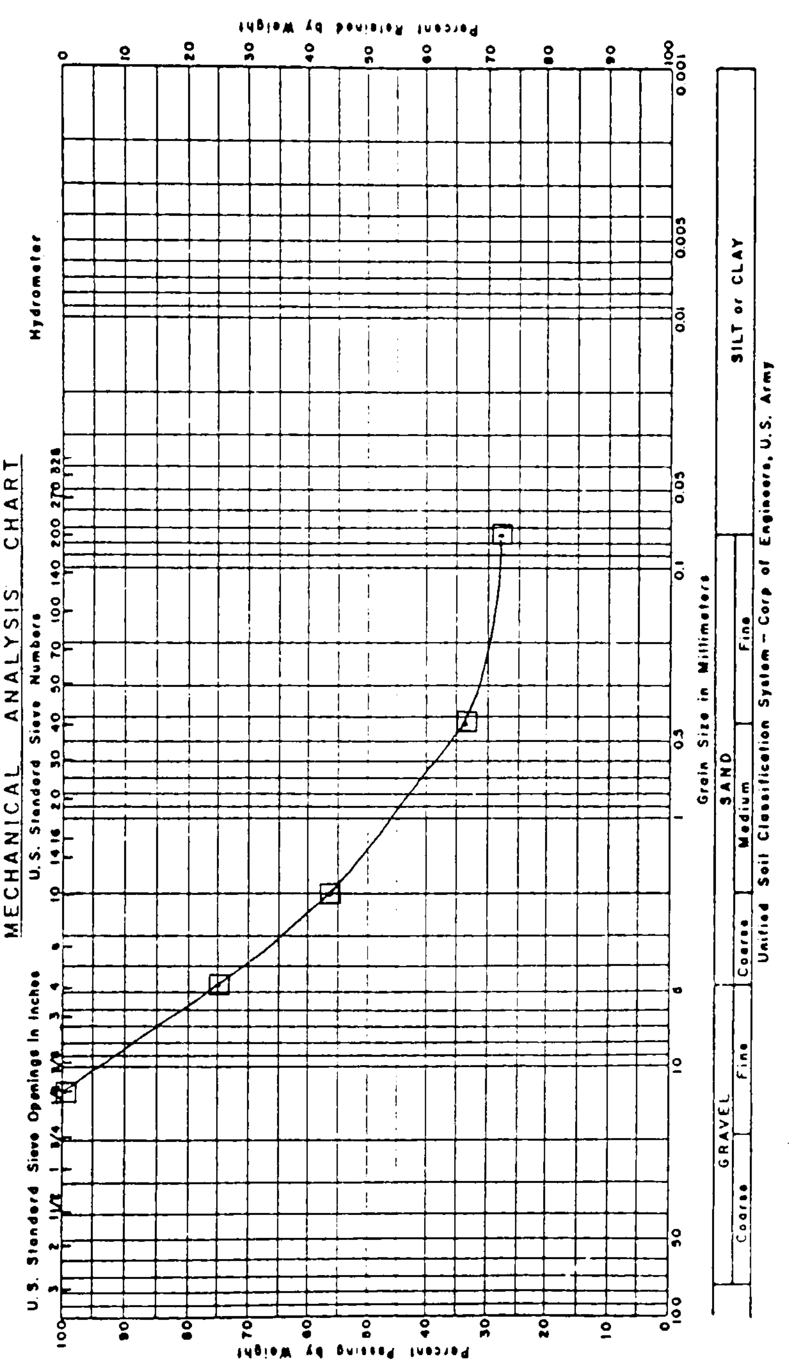
GRAIN SIZE DISTRIBUTION DATA

Table A-2 Grain Size Distribution

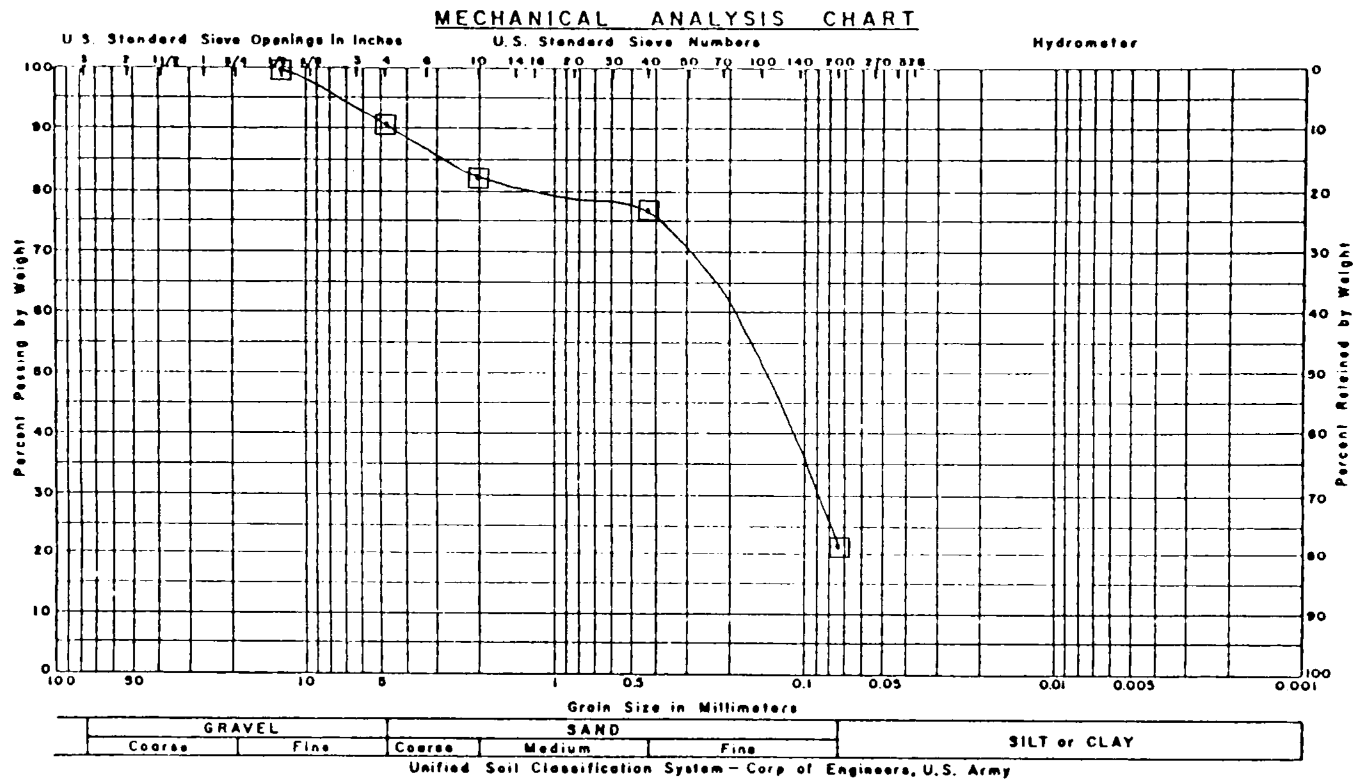
	Percent Retained				
	Sieve #4	#10	#40	#200	pan
SAMPLE 1	25.0	18.9	22.5	5.5	28.1
SAMPLE 2	9.5	7.6	6.1	55.7	21.1
SAMPLE 3	15.5	20.7	19.8	15.9	28.1

Grain size distribution curves for each of the samples are presented on the following pages.

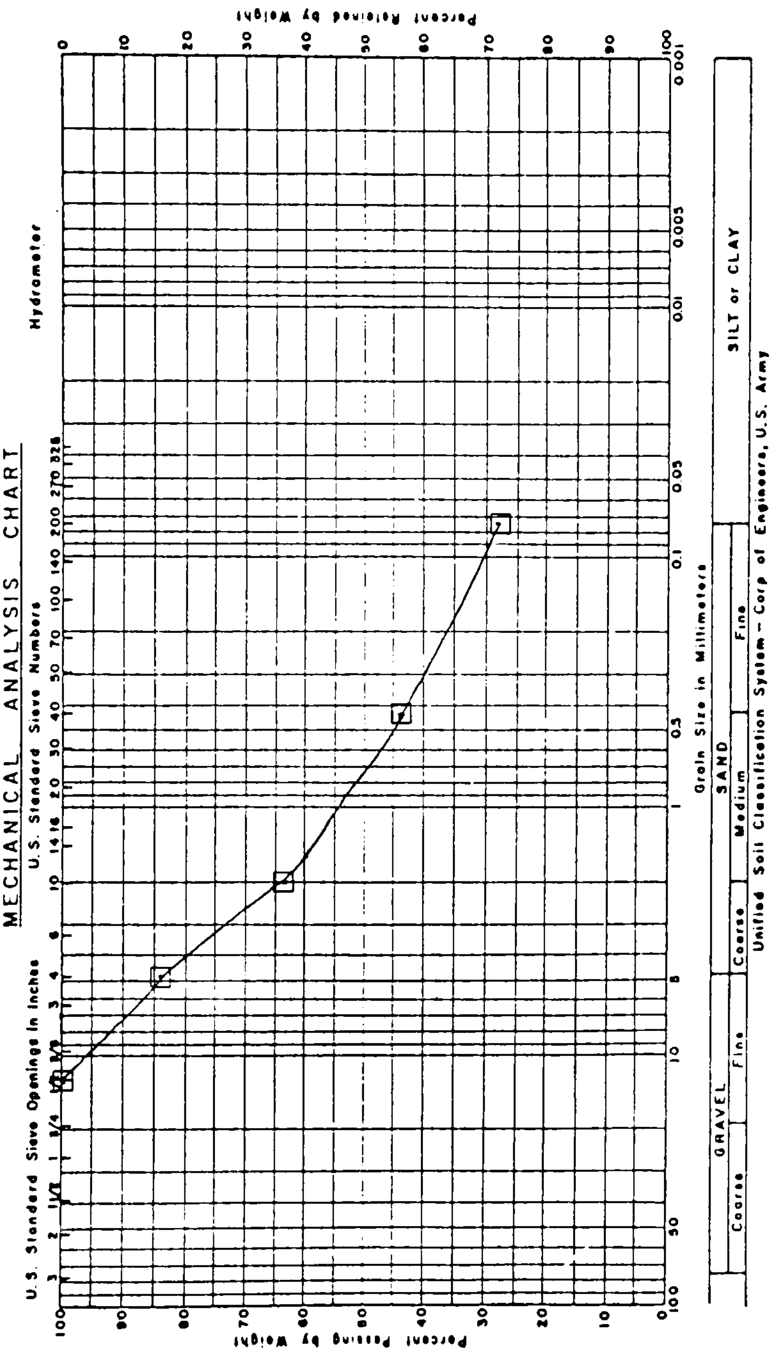
SAMPLE 1


MECHANICAL ANALYSIS CHART
U.S. Standard Sieve Openings in Inches
U.S. Standard Sieve Numbers
Hydrometer
3 2 1 1/2 1 3/4 1/2 3/8 3 4 6 10 14 16 20 30 40 50 70 100 140 200 270 325
Percent Passing by Weight
Percent Retained by Weight
100 90 80 70 60 50 40 30 20 10 0
0 10 20 30 40 50 60 70 80 90 100
100 50 10 5 1 0.5 0.1 0.05 0.01 0.005 0.001
Grain Size in Millimeters
GRAVEL
Coarse
Fine
SAND
Coarse
Medium
Fine
SILT or CLAY
Unified Soil Classification System – Corp of Engineers, U.S. Army

SAMPLE 2


MECHANICAL ANALYSIS CHART
U.S. Standard Sieve Openings in Inches
U.S. Standard Sieve Numbers
Hydrometer
Percent Passing by Weight
Percent Retained by Weight
Grain Size in Millimeters
GRAVEL
Coarse
Fine
SAND
Coarse
Medium
Fine
SILT or CLAY
Unified Soil Classification System — Corp of Engineers, U.S. Army

SAMPLE 3



MECHANICAL ANALYSIS CHART
U.S. Standard Sieve Openings in Inches
U.S. Standard Sieve Numbers
Hydrometer
Percent Passing by Weight
Percent Retained by Weight
Grain Size in Millimeters
GRAVEL
Coarse
Fine
SAND
Coarse
Medium
Fine
SILT or CLAY
Unified Soil Classification System - Corp of Engineers, U.S. Army

APPENDIX B-1

INPUT AND OUTPUT FILES
FOR ANALYSIS ALONG PROFILE A-A'
PRIOR TO SURCHARGE LOADING

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE A-A'

4 2
0. 50. 2050. 325. 1
2050. 325. 2600. 458. 1
0. 20. 1200. 90. 2
1200. 90. 2600. 90. 2
SOIL
2
90. 100. 1350. 0. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
WATER
1 62.4
3
0. 50.
2050. 325.
2600. 400.
SURFACE
10
200. 75.
400. 50.
600. 50.
800. 70.
1000. 80.
1200. 100.
1400. 115.
1600. 145.
1800. 195.
1900. 315.
EXECUT
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

```
Run Date:              9 March 1988
Time of Run:           11:28
Run By:                D. Umstot
Input Data Filename:   abef.dat
Output Filename:       abef.out
```

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE A-A'

BOUNDARY COORDINATES

2 Top Boundaries
4 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	50.00	2050.00	325.00	1
2	2050.00	325.00	2600.00	458.00	1
3	.00	20.00	1200.00	90.00	2
4	1200.00	90.00	2600.00	90.00	2

ISOTROPIC SOIL PARAMETERS

2 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	90.0	100.0	1350.0	.0	.00	.0	1
2	100.0	105.0	500.0	15.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

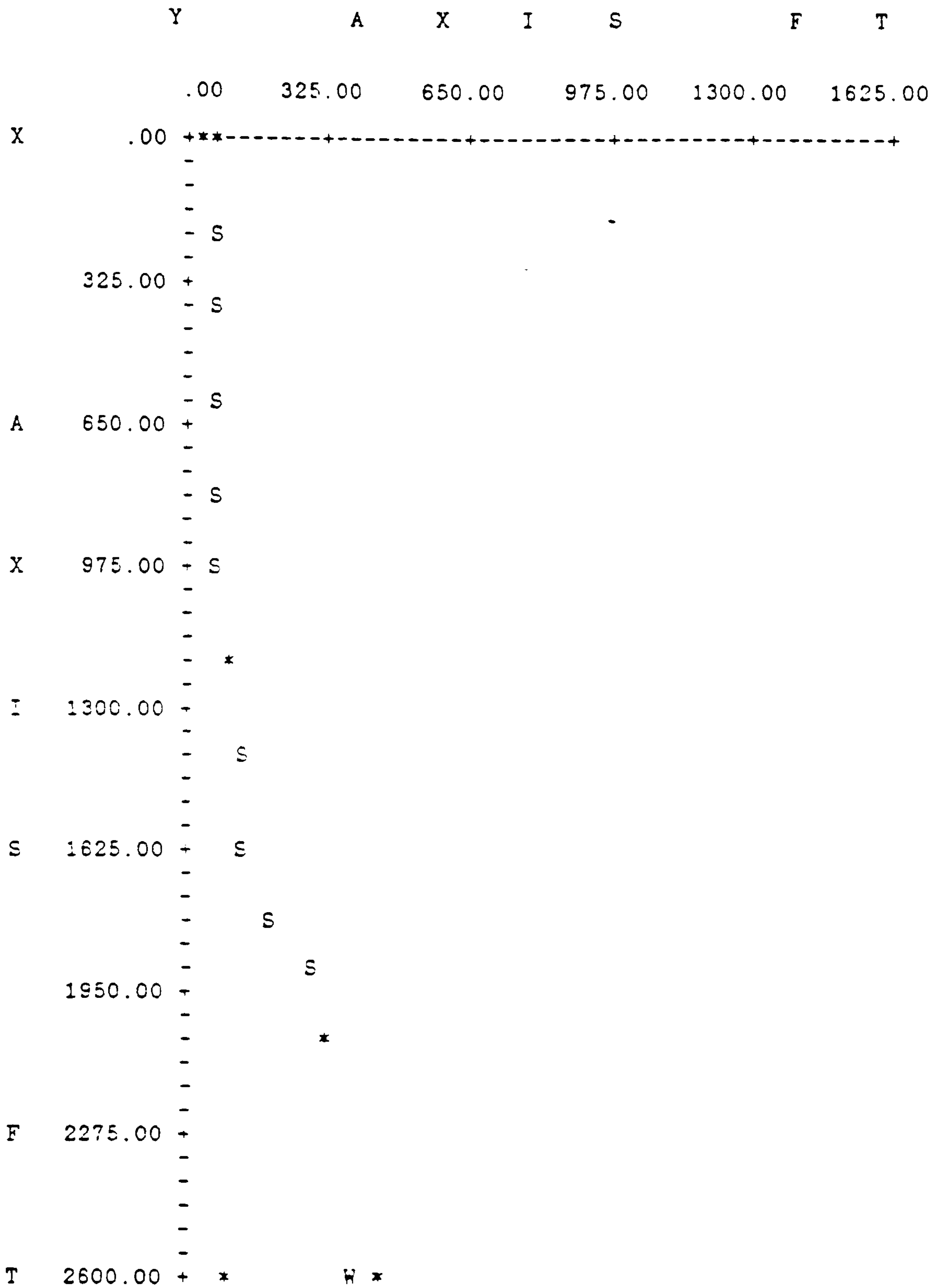
Piezometric Surface No. 1 Specified by 3 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	50.00
2	2050.00	325.00
3	2600.00	400.00

Trail Failure Surface Specified By 10 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	76.83
2	400.00	50.00
3	600.00	50.00
4	800.00	70.00
5	1000.00	80.00
6	1200.00	100.00
7	1400.00	115.00
8	1600.00	145.00
9	1800.00	195.00
10	1900.00	304.88

Factor Of Safety For the Preceding Specified Surface = 1.230


Y AXIS FT
.00
325.00
650.00
975.00
1300.00
1625.00
X AXIS FT
.00
325.00
650.00
975.00
1300.00
1625.00
1950.00
2275.00
2600.00
S
W

Sample Input Data File for PCSTABL4 along B-B'

```
PROFILE                              Line 1
ROAN CREEK LANDSLIDE B-B'                 2
8 6                                       3
0. 240. 920. 378. 1                       4
920. 378. 1080. 470. 1                    5
1080. 470. 1170. 435. 1                   6
1170. 435. 1240. 435. 1                   7
1240. 435. 1380. 500. 1                   8
1380. 500. 1600. 800. 1                   9
0. 80. 300. 200. 2                       10
300. 200. 1600. 200. 2                   11
SOIL                                     12
2                                        13
110. 115. 500. 15. 0. 0. 1               14
100. 105. 500. 15. 0. 0. 1               15
WATER                                    16
1 62.4                                   17
3                                        18
0. 240.                                  19
900. 350.                                20
1320. 450.                               21
LIMITS                                   22
1 1                                      23
0. 0.                                    24
1600. 0.                                 25
CIRCLE                                   26
10 10                                    27
200. 400. 1360. 1380.                    28
0. 50. 0. 0.                             29
```

Explanation of input file.

Line 3	total number of boundaries; number of surface boundaries
Lines 4-11	coordinates of boundaries; soil type beneath boundary
Line 13	number of soil types
Lines 14-15	soil properties: moist unit weight; saturated unit weight; cohesion; phi angle; pore pressure parameters; pressure constant; potentiometric surface in unit
Line 17	number of potentiometric surfaces
Line 18	number of points defining potentiometric surface
Lines 19-21	coordinates for line 18
Line 23	lower limit of generated failure surfaces
Lines 24-25	coordinates of lower limit
Line 27	10 trial failure surfaces generated from each of ten points equally spaced between initiation limits defined in line 28
Line 28	trial failure surfaces to initiate between first two numbers and terminate between last two numbers
Line 29	minimum elevation failure surface may extend;line segment length; restrictions placed on angle of initiation of failure

APPENDIX B-3

SAMPLE OUTPUT FILE GENERATED BY PCSTABL4
WITH INPUT FILE FROM APPENDIX B-2

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 24 NOVEMBER 1987
Time of Run: 12:35
Run By: D. UMSTOT
Input Data Filename: STABLA.DAT
Output Filename: STABLA.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE B-B"

BOUNDARY COORDINATES

6 Top Boundaries
8 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	240.00	920.00	378.00	1
2	920.00	378.00	1080.00	470.00	1
3	1080.00	470.00	1170.00	435.00	1
4	1170.00	435.00	1240.00	435.00	1
5	1240.00	435.00	1380.00	500.00	1
6	1380.00	500.00	1600.00	800.00	1
7	.00	80.00	300.00	200.00	2
8	300.00	200.00	1600.00	200.00	2

ISOTROPIC SOIL PARAMETERS

2 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1
2	110.0	105.0	500.0	15.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 3 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	240.00
2	900.00	350.00
3	1320.00	450.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1600.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 200.00 ft.
and X = 400.00 ft.

Each Surface Terminates Between X = 1360.00 ft.
and X = 1380.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 29 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)	Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00	12	706.02	88.18
2	239.05	238.77	13	755.98	88.32
3	280.05	218.16	14	805.69	93.72
4	322.83	184.28	15	854.94	102.34
5	367.21	161.24	16	903.52	114.15
6	412.99	141.14	17	951.23	129.11
7	459.99	124.07	18	997.87	147.14
8	507.99	110.10	19	1043.23	165.17
9	556.81	99.28	20	1087.12	192.11
10	606.23	91.67	21	1129.36	218.57
11	656.04	87.30	22	1169.77	248.32

Point No.	X-Surf (ft)	Y-Surf (ft)	Point No.	X-Surf (ft)	Y-Surf (ft)
23	1208.17	280.34	27	1338.60	431.26
24	1244.41	314.79	28	1364.72	473.89
25	1278.32	351.54	29	1377.97	499.06
26	1309.76	390.41			

*** .995 ***

Failure Surface Specified By 30 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	236.82	236.18
3	275.88	204.96
4	316.98	176.49
5	359.94	150.91
6	404.56	128.33
7	450.61	108.87
8	495.83	89.30
9	546.18	79.62
10	595.24	69.98
11	644.85	63.73
12	694.77	60.89
13	744.76	61.48
14	794.60	65.50
15	844.05	72.93
16	892.87	83.73
17	940.83	97.85
18	987.72	115.22
19	1033.30	135.77
20	1077.36	159.40
21	1119.71	185.99
22	1160.13	215.42
23	1193.40	247.56
24	1234.44	282.24
25	1267.99	319.32
26	1298.92	358.60
27	1327.08	399.92
28	1352.35	443.07
29	1374.59	487.85
30	1379.54	499.78

*** .996 ***

Failure Surface Specified By 30 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	236.90	236.26
3	276.03	205.13
4	317.20	176.76
5	380.22	151.28
6	404.89	128.81
7	450.99	109.46
8	498.31	93.31
9	546.63	80.46
10	595.72	70.94
11	645.34	64.82
12	695.27	62.12
13	745.26	62.85
14	795.09	67.00
15	844.51	74.57
16	89.30	85.51
17	941.22	99.77
18	988.06	117.28
19	1033.58	137.97
20	1077.57	161.73
21	1119.83	188.45
22	1160.16	218.01
23	1198.36	250.27
24	1234.26	285.07
25	1267.69	322.25
26	1298.49	361.64
27	1326.51	403.05
28	1351.63	446.28
29	1373.72	491.14
30	1376.73	498.48

*** .997 ***

Failure Surface Specified By 30 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	236.37	235.69
3	275.03	203.99
4	315.80	175.03
5	358.47	148.97
6	402.84	125.92
7	448.70	106.00
8	495.83	89.30
9	544.00	75.90
10	642.54	59.25
11	642.54	59.25
12	692.44	56.08
13	742.44	56.37
14	792.30	60.12
15	841.78	67.32
16	89.64	77.92
17	938.85	91.88
18	985.58	109.12
19	1031.21	129.58
20	1075.31	153.14
21	1117.67	179.70
22	1158.09	209.13
23	1196.38	241.29
24	1232.35	276.02
25	1265.83	313.15
26	1296.66	352.51
27	1324.69	393.92
28	1349.79	437.16
29	1371.84	482.04
30	1378.97	499.52

*** .998 ***

Failure Surface Specified By 29 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	240.86	241.18
3	283.42	214.94
4	327.52	191.38
5	373.00	170.60
6	419.68	152.68
7	467.37	137.68
8	515.91	125.66
9	565.09	116.66
10	614.74	110.73
11	664.66	107.88
12	714.66	108.12
13	764.54	111.46
14	814.13	117.88
15	863.22	127.36
16	911.64	139.86
17	959.18	155.33
18	1005.68	173.71
19	1050.95	194.94
20	1094.82	218.92
21	1137.13	245.58
22	1177.70	274.80
23	1216.38	306.48
24	1253.03	340.49
25	1287.51	376.70
26	1319.66	414.98
27	1349.41	455.18
28	1376.61	497.14
29	1377.59	498.88

*** 1.000 ***

Failure Surface Specified By 29 Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)	Point No.	X-Surf (ft)	Y-Surf (ft)
1	222.22	273.33	13	768.10	69.68
2	259.07	239.54	14	817.86	74.58
3	298.20	208.41	15	867.15	82.94
4	339.40	180.09	16	915.74	94.73
5	382.49	154.72	17	963.39	109.89
6	427.25	132.43	18	1009.86	128.35
7	473.45	113.32	19	1054.92	150.01
8	520.88	97.49	20	1098.36	174.78
9	569.30	85.02	21	1139.96	202.52
10	618.47	75.97	22	1179.51	233.10
11	668.16	70.38	23	1216.83	266.37
12	718.12	68.28	24	1251.73	302.18

Failure Surface Specified By 29
Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
25	1284.04	340.34
26	1313.60	380.66
27	1340.27	422.96
28	1363.91	467.02
29	1378.41	499.26

*** 1.000 ***

Failure Surface Specified By 29
Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	222.22	273.33
2	258.67	239.11
3	297.45	207.54
4	338.36	178.79
5	381.19	153.00
6	425.74	130.30
7	471.78	110.80
8	519.09	94.60
9	567.42	81.79
10	616.53	72.41
11	666.18	66.53
12	716.13	64.17
13	766.11	65.34
14	815.89	70.04
15	865.21	78.24
16	913.83	89.91
17	961.51	104.98
18	1008.00	123.37
19	1053.08	145.01
20	1096.52	169.77
21	1188.10	197.54
22	1177.61	228.17
23	1214.87	261.52
24	1249.67	297.42
25	1281.86	335.68
26	1311.28	376.13
27	1337.73	418.54
28	1361.14	402.72
29	1377.03	498.62

*** 1.002 ***

Failure Surface Specified By 28
Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	244.44	276.67
2	282.33	244.03
3	322.40	214.12
4	364.46	187.09
5	408.31	163.08
6	453.73	142.16
7	500.50	124.48
8	546.39	110.12
9	597.17	99.14
10	646.60	91.59
11	696.43	87.52
12	746.43	86.94
13	796.34	89.86
14	845.93	96.26
15	894.95	106.11
16	943.16	119.36
17	990.33	135.95
18	1036.22	155.80
19	1060.61	178.80
20	1123.29	204.85
21	1164.04	233.83
22	1202.67	265.58
23	1238.98	299.95
24	1272.80	336.77
25	1303.96	375.87
26	1332.32	417.06
27	1357.73	460.12
28	1376.92	498.57

*** 1.004 ***

Failure Surface Specified By 29
Coordinate Points

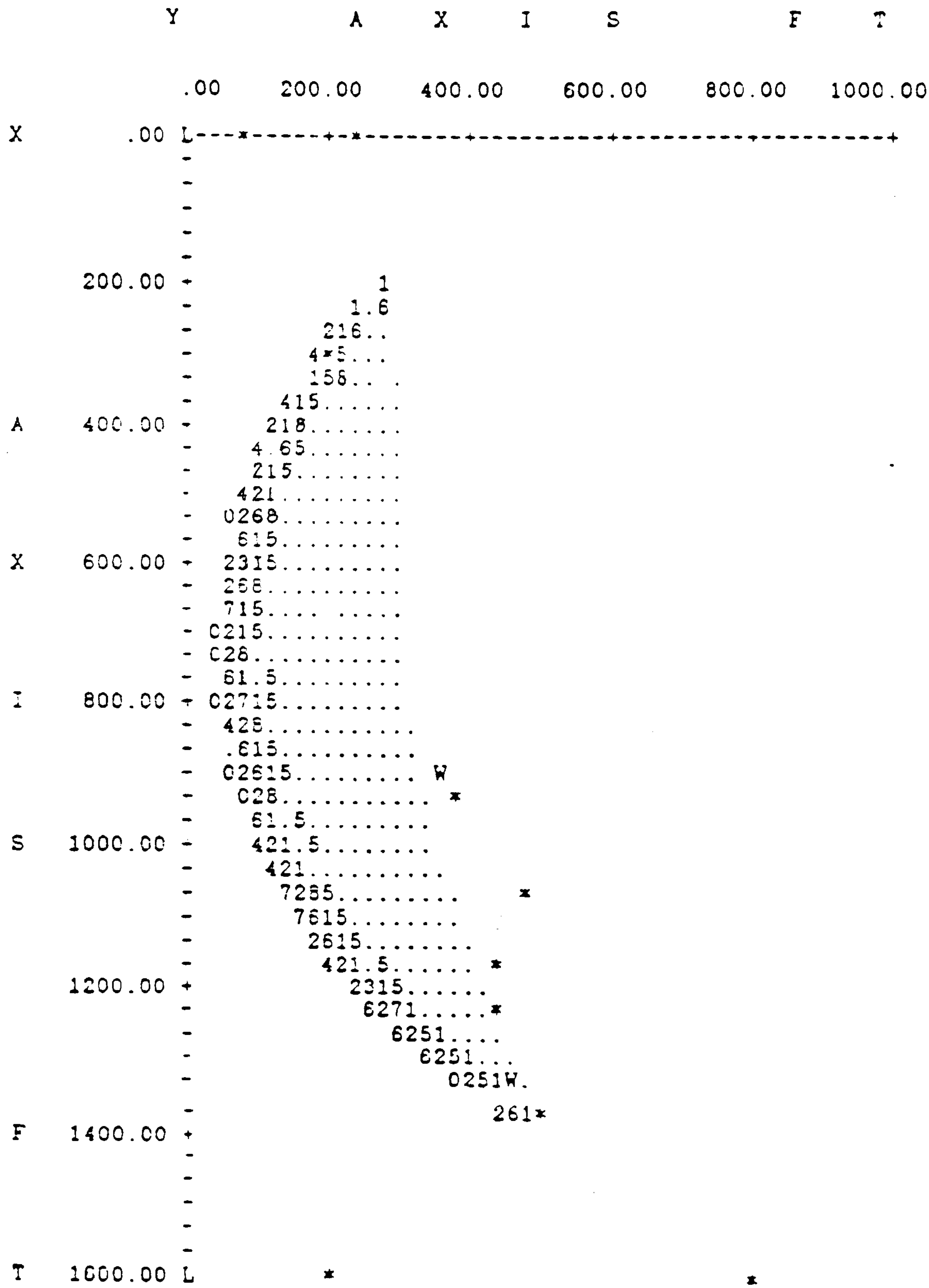
Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	238.13	237.66
3	278.30	207.97
4	320.50	181.06
5	364.36	157.05
6	409.74	136.06
7	456.43	118.17
8	504.23	103.48
9	552.90	92.04
10	602.24	83.92
11	652.01	79.14
12	701.99	77.73
13	751.95	79.69
14	801.66	85.02
15	850.91	93.70
16	899.45	105.67
17	947.08	120.89
18	993.57	139.30
19	1038.71	160.79
20	1082.30	185.28
21	1124.14	212.66
22	1164.04	242.80
23	1201.81	275.56
24	1237.29	310.79
25	1270.31	348.34
26	1300.72	388.03
27	1328.38	429.68
28	1353.17	473.10
29	1362.20	491.74

*** 1.004 ***

Failure Surface Specified By 30
Coordinate Points

Point No.	X-Surf (ft)	Y-Surf (ft)
1	200.00	270.00
2	235.36	234.65
3	273.13	201.89
4	313.14	171.90
5	355.17	144.82
6	399.02	120.79
7	444.46	99.94
8	491.27	82.36
9	539.21	68.15
10	588.04	57.38
11	637.50	50.10
12	687.36	46.35
13	737.36	46.15
14	787.25	49.49
15	836.77	56.37
16	885.69	66.75
17	933.74	80.57
18	980.69	97.76
19	1026.30	118.25
20	1070.34	141.92
21	1112.59	168.65
22	1152.84	198.32
23	1190.88	230.77
24	1226.52	265.84
25	1259.58	303.34
26	1289.90	343.10
27	1317.32	384.92
28	1341.70	428.57
29	1362.93	473.84
30	1371.47	496.04

*** 1.005 ***


Y AXIS FT
.00
200.00
400.00
600.00
800.00
1000.00
X AXIS FT
.00
200.00
400.00
600.00
800.00
1000.00
1200.00
1400.00
1600.00

APPENDIX B-4

INPUT AND PARTIAL OUTPUT FILES
FOR ANALYSIS ALONG PROFILE D-D'
PRIOR TO FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE D-D'
3 3
0. 150. 180. 150. 1
180. 150. 580. 190. 1
580. 190. 1000. 330. 1
SOIL
1
90. 100. 1350. 0. 0. 0. 1
WATER
1 62.4
4
0. 150.
180. 150.
580. 170.
1000. 260.
LIMITS
1 1
0. 0.
1000. 0.
CIRCLE
10 10
0. 100. 700. 800.
0. 50. 0. 0.
```

```
                         ** PCSTABL4 **

                               by
                        Purdue University

                  --Slope Stability Analysis--
               Simplified Janbu Method of Slices
                 or Simplified Bishop Method

Run Date:                       4 MARCH 1988
Time of Run:                    16:25
Run By:                         D. UMSTOT
Input Data Filename:            D1.DAT
Output Filename:                D1.OUT

PROBLEM DESCRIPTION  ROAN CREEK LANDSLIDE FAILURE D-D'

BOUNDARY COORDINATES

               3 Top    Boundaries
               3 Total  Boundaries
```

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	150.00	180.00	150.00	1
2	180.00	150.00	580.00	190.00	1
3	580.00	190.00	1000.00	330.00	1

ISOTROPIC SOIL PARAMETERS

1 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	90.0	100.0	1350.0	.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 4 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	150.00
2	180.00	150.00
3	580.00	170.00
4	1000.00	260.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1000.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = .00 ft.
and X = 100.00 ft.

Each Surface Terminates Between X = 700.00 ft.
and X = 800.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

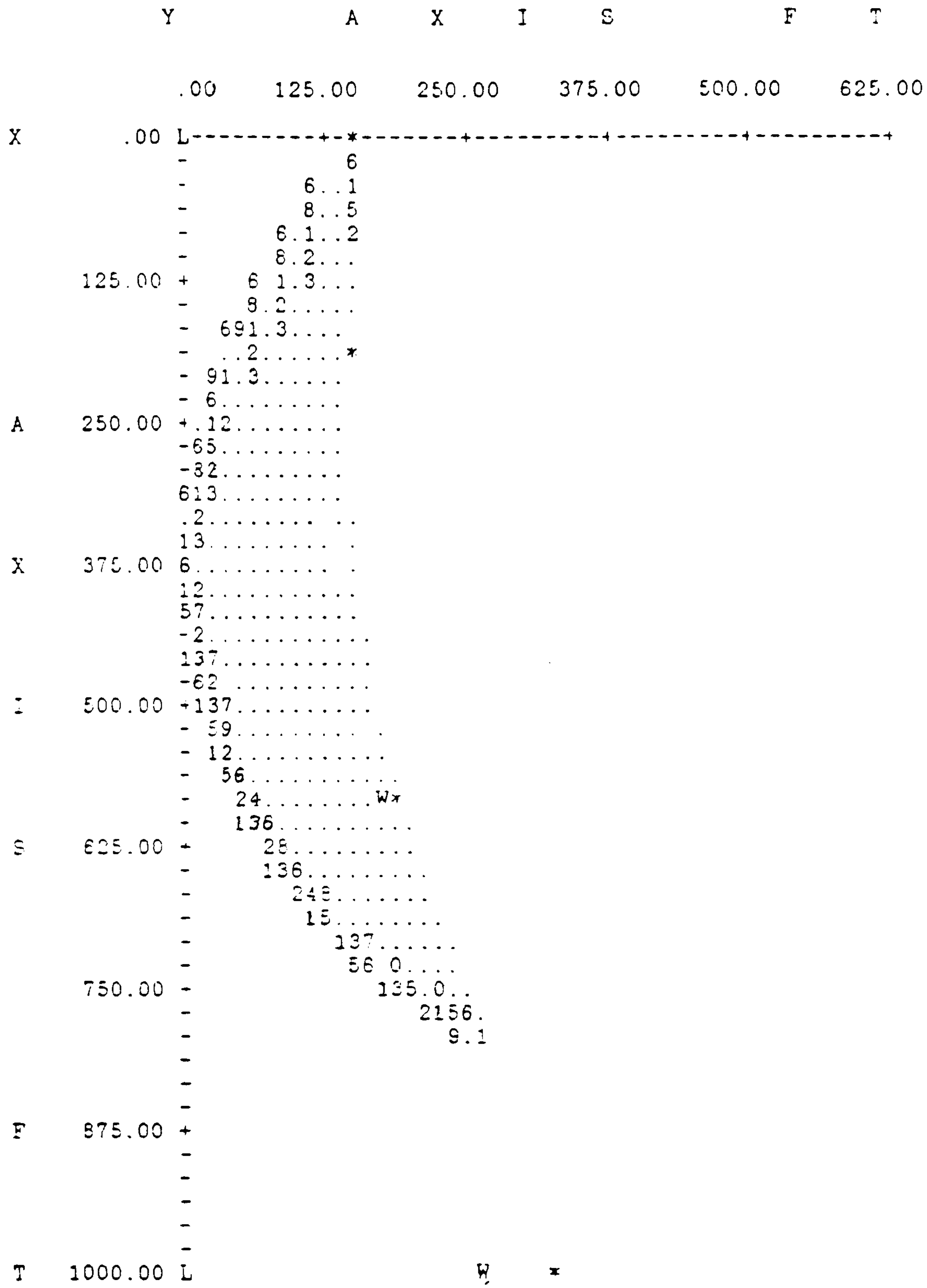
Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	44.44	150.00
2	80.11	114.96
3	119.38	84.00
4	161.77	57.50
5	206.80	35.76
6	253.92	19.04
7	302.58	7.55
8	352.21	1.42
9	402.20	.71
10	451.98	5.45
11	500.94	15.56
12	548.52	30.95
13	594.14	51.41
14	637.27	76.71
15	677.39	106.55
16	714.02	140.57
17	746.75	178.37
18	775.17	219.51
19	798.61	262.87

*** 1.202 ***


Y AXIS FT
.00 125.00 250.00 375.00 500.00 625.00
X AXIS FT
.00 125.00 250.00 375.00 500.00 625.00 750.00 875.00 1000.00

APPENDIX B-5

INPUT AND PARTIAL OUTPUT FILES FOR ANALYSIS ALONG PROFILE D-D' AFTER FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE D-D'
4 4
0. 130. 250. 130. 1
250. 130. 300. 160. 1
300. 160. 580. 190. 1
580. 190. 1000. 330. 1
SOIL
1
90. 100. 1350. 0. 0. 0. 1
WATER
1 62.4
4
0. 130.
250. 130.
580. 170.
1000. 260.
LIMITS
1 1
0. 0.
1000. 0.
CIRCLE
10 10
25. 100. 700. 800.
0. 50. 0. 0.
EXECUT
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

```
Run Date:               9 MARCH 1988
Time of Run:            11:50
Run By:                 D. UMSTOT
Input Data Filename:    d2.dat
Output Filename:        d2.out
```

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE D-D'

BOUNDARY COORDINATES

```
        4 Top     Boundaries
        4 Total   Boundaries
```

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	130.00	250.00	130.00	1
2	250.00	130.00	300.00	160.00	1
3	580.00	160.00	580.00	190.00	1
4	580.00	190.00	1000.00	330.00	1

ISOTROPIC SOIL PARAMETERS

1 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	90.0	100.0	1350.0	.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 4 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	130.00
2	250.00	130.00
3	580.00	170.00
4	1000.00	260.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1000.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 25.00 ft.
and X = 100.00 ft.

Each Surface Terminates Between X = 700.00 ft.
and X = 800.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	75.00	130.00
2	133.55	98.15
3	155.33	70.69
4	199.86	47.95
5	246.60	30.19
6	295.00	17.63
7	344.47	8.64
8	394.44	12.32
9	444.31	21.40
10	493.47	35.79
11	541.36	55.31
12	587.39	79.73
13	631.02	79.73
14	671.73	108.76
15	709.04	142.04
16	742.50	179.20
17	771.71	219.78
18	795.50	261.83

*** .982 ***

```
                      Y            A     X     I     S           F     T

                       .00      125.00    250.00    375.00    500.00    625.00
X             .00 L---------*---------+---------+---------+---------+
                  -         .
                  -         3
                  -       3.2
                  -       ..1
                  -    .3.1.4
          125.00 +    ...5..
                  -  ...1.4..
                  -  .3.5....
                  - ..2.4...
                  - 3.19... .
                  - 2.48....
A         250.00 +317......*
                  -.64......
                  317........   *
                  .649. .... .
                  .278.... .
                  319........
X         375.00 245.......
                  31..........
                  .45.........
                  -17........
                  -359...... ..
                  -248........
I         500.00 + 19..........
                  - 648........
                  -  17.........
                  -   48.........
                  -   13........W*
                  -     4.........
S         625.00 +     13........
                  -       4........
                  -       21.......
                  -         54.......
                  -          13.......
                  -            52.....
          750.00 +             1354...
                  -                21.6
                  -                  941
                  -
                  -
                  -
F         875.00 +
                  -
                  -
                  -
                  -
                  -
T        1000.00 L                    W    *
```

APPENDIX B-6

INPUT AND PARTIAL OUTPUT FILES
FOR ANALYSIS OF THE LOWER FAILURE
SURFACE ALONG PROFILE C-C'
PRIOR TO FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE C-C'
10 8
0. 460. 880. 540. 3
880. 540. 1280. 760. 1
1280. 760. 1480. 680. 1
1480. 680. 1612. 750. 1
1612. 750. 1640. 950. 1
1640. 950. 1718. 1000. 1
1718. 1000. 1735. 1050. 1
1735. 1050. 1800. 1122. 1
0. 282. 940. 400. 2
940. 400. 1800. 400. 2
SOIL
3
110. 115. 500. 15. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
90. 100. 1350. 0. 0. 0. 1
WATER
2 62.4
3
0. 460.
880. 520
1620. 620.
2
1620. 842.
1800. 842
LIMITS
1 1
0. 0.
1800. 0.
CIRCLE
10 10
200. 300. 1000. 1050.
0. 50. 0. 0.
EXECUT
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 4 MARCH 1988
Time of Run: 16:10
Run By: D. UMSTOT
Input Data Filename: C1A.DAT
Output Filename: C1A.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE C-C'

BOUNDARY COORDINATES

8 Top Boundaries
10 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	460.00	880.00	540.00	1
2	880.00	540.00	1280.00	760.00	1
3	1280.00	760.00	1480.00	680.00	1
4	1480.00	680.00	1612.00	750.00	1
5	1612.00	750.00	1640.00	950.00	1
6	1640.00	950.00	1718.00	1000.00	1
7	1718.00	1000.00	1735.00	1050.00	1
8	1735.00	1050.00	1800.00	1122.00	1
9	.00	282.00	940.00	400.00	2
10	940.00	400.00	1800.00	400.00	2

ISOTROPIC SOIL PARAMETERS

3 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1
2	100.0	105.0	500.0	15.0	.00	.0	1
3	90.0	100.0	1350.0	.0	.00	.0	1

1 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 3 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	460.00
2	880.00	520.00
3	1620.00	620.00

Piezometric Surface No. 2 Specified by 2 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	1620.00	842.00
2	1800.00	842.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1800.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 200.00 ft.
and X = 300.00 ft.

Each Surface Terminates Between X = 1000.00 ft.
and X = 1050.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

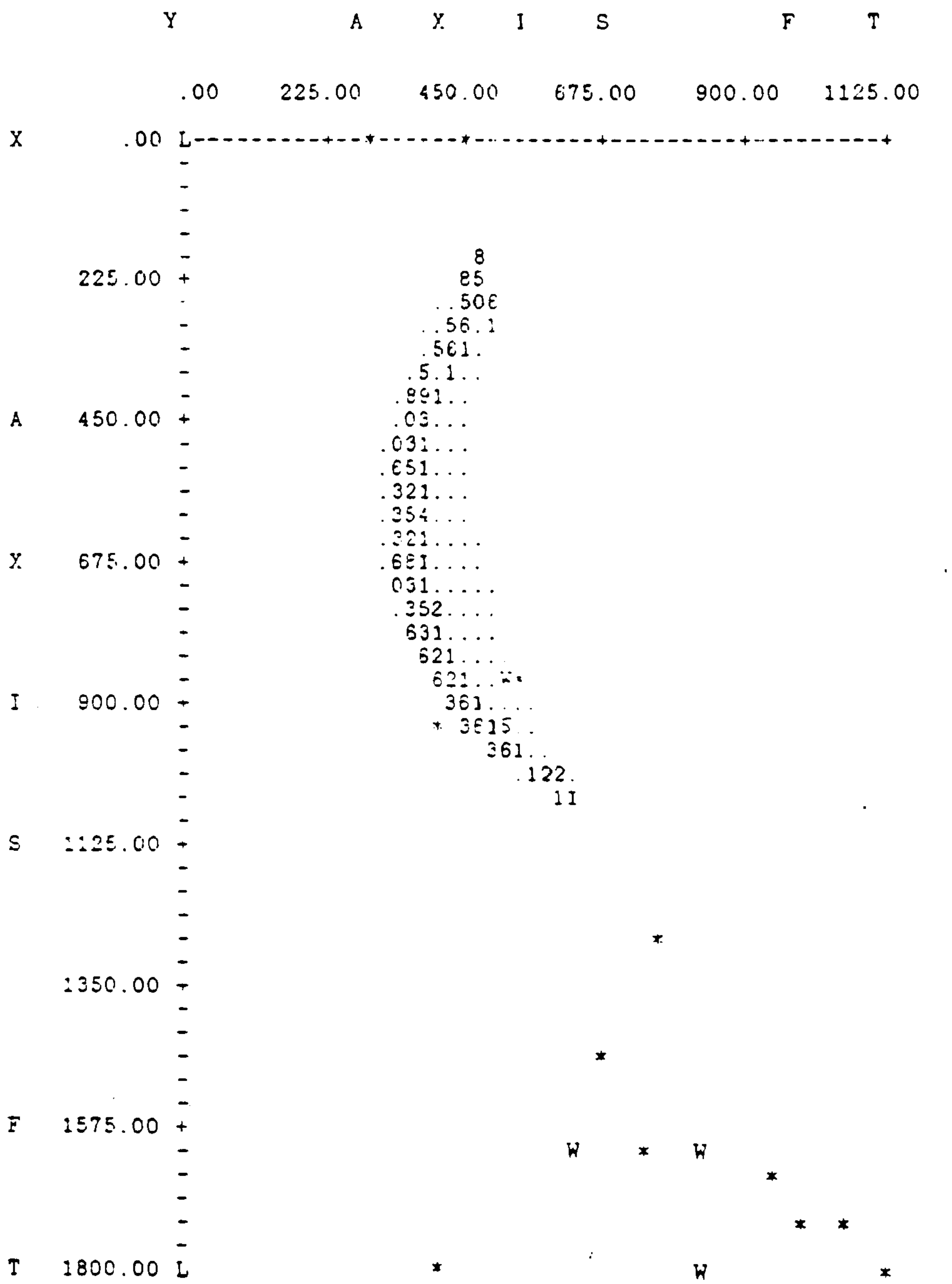
Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)	Point No.	X-Water (ft)	Y-Water (ft)
1	300.00	487.27	5	475.15	393.45
2	339.96	457.22	6	523.76	381.73
3	382.77	431.39	7	573.31	375.03
4	427.99	410.06	8	623.28	373.41

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)	Point No.	X-Water (ft)	Y-Water (ft)
9	673.16	376.89	15	942.10	499.24
10	722.43	376.89	16	977.50	534.55
11	770.56	398.95	17	1009.11	573.29
12	817.07	417.31	18	1036.61	615.04
13	861.47	440.31	19	1044.72	630.59
14	903.29	467.71			

*** .982 ***



APPENDIX B-7

INPUT AND PARTIAL OUTPUT FILES FOR ANALYSIS OF THE LOWER FAILURE SURFACE ALONG PROFILE C-C' AFTER FAILURE ALONG A-A'

```
PROFILE ROAN CREEK LANDSLIDE FAILURE C-C'
12 10
0. 440. 200. 445. 3
200. 445. 260. 460. 3
260. 460. 880. 540. 3
880. 540. 1280. 760. 1
1280. 760. 1480. 680. 1
1480. 680. 1612. 750. 1
1612. 750. 1640. 950. 1
1640. 950. 1718. 1000. 1
1718. 1000. 1735. 1050. 1
1735. 1050. 18000. 1122. 1
0. 282. 940. 400. 2
940. 400. 1800. 400. 2
SOIL
3
110. 115. 500. 15. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
90. 100. 1350. 0. 0. 0. 1
WATER
2 62.4
4
0. 440.
200. 445.
880. 520.
1620. 620.
2
1620. 842.
2
1620. 842.
1800. 842.
LIMITS
1 1
0. 0.
1800. 0.
CIRCLE
10 10
200. 300. 1000. 1050.
0. 50. 0. 0.
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 4 MARCH 1988
Time of Run: 15:20
Run By: D. UMSTOT
Input Data Filename: C1B.DAT
Output Filename: C1B.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE C-C'

BOUNDARY COORDINATES

10 Top Boundaries
12 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	440.00	200.00	445.00	3
2	200.00	445.00	260.00	460.00	3
3	260.00	460.00	880.00	540.00	3
4	880.00	540.00	1280.00	760.00	1
5	1280.00	760.00	1480.00	680.00	1
6	1480.00	680.00	1612.00	750.00	1
7	1612.00	750.00	1640.00	950.00	1
8	1640.00	950.00	1718.00	1000.00	1
9	1718.00	1000.00	1735.00	1050.00	1
10	1735.00	1050.00	1800.00	1122.00	1
11	.00	282.00	940.00	400.00	2
12	940.00	400.00	1800.00	400.00	2

ISOTROPIC SOIL PARAMETERS

3 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
2	100.00	105.0	500.0	15.0	.00	.0	1
3	90.00	100.0	1350.0	.0	.00	.0	1

2 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 4 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	440.00
2	200.00	445.00
3	880.00	520.00
4	1620.00	620.00

Piezometric Surface No. 2 Specified by 2 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	1620.00	842.00
2	1620.00	842.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1800.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 200.00 ft.
and X = 300.00 ft.

Each Surface Terminates Between X = 1000.00 ft.
and X = 1050.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

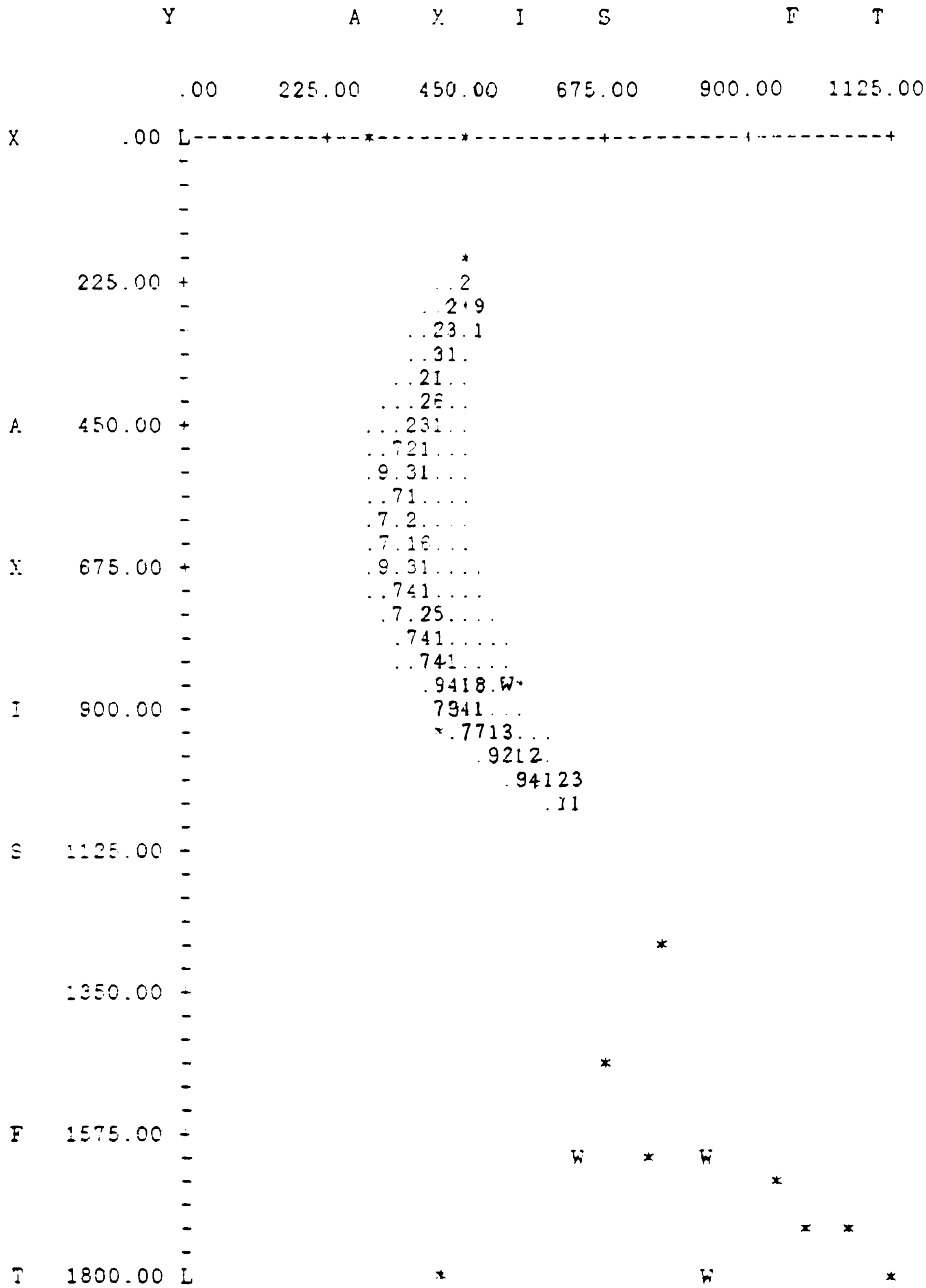
Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	300.00	465.16
2	341.73	437.62
3	385.95	414.29
4	432.25	395.40
5	480.17	381.14
6	529.26	371.64
7	579.05	366.99
8	629.05	367.24
9	678.78	372.38
10	727.77	382.37
11	775.55	397.11
12	821.66	416.45
13	865.65	440.22
14	907.10	468.17
15	945.62	500.06
16	980.83	535.56
17	1012.39	574.33
18	1040.01	616.02
19	1048.97	632.93

*** .969 ***


Y AXIS FT
.00 225.00 450.00 675.00 900.00 1125.00
X AXIS FT
.00
225.00
450.00
675.00
900.00
1125.00
1350.00
1575.00
1800.00

APPENDIX B-8

INPUT AND PARTIAL OUTPUT FILES
FOR ANALYSIS OF THE UPPER FAILURE
SURFACE ALONG PROFILE C-C'
PRIOR TO FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE C-C'
12 10
0. 440. 200. 445. 3
200. 445. 260. 400. 3
260. 460. 880. 540. 3
880. 540. 1280. 760. 1
1280. 760. 1480. 760. 1
1280. 760. 1480. 680. 1
1612. 750. 1640. 950. 1
1640. 950. 1718. 1000. 1
1718. 1000. 1735. 1050. 1
1735. 1050. 1800. 1122. 1
0. 282. 940. 400. 2
940. 400. 1800. 400. 2
SOIL
3
110. 115. 500. 15. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
90. 100. 1350. 0. 0. 0. 1
WATER
2 62.4
4
0. 440
200. 445.
880. 520.
1620. 620.
2
1620. 842.
1800. 842.
LIMITS
1 1
0. 0.
1800. 0.
CIRCLE
10 10
800. 1000. 1600. 1620.
0. 50. 0. 0.
EXECUT
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 4 MARCH 1988
Time of Run: 15:00
Run By: D. UMSTOT
Input Data Filename: C2A.DAT
Output Filename: C2A.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE C-C'

BOUNDARY COORDINATES

10 Top Boundaries
12 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	440.00	200.00	445.00	3
2	200.00	445.00	260.00	460.00	3
3	260.00	460.00	880.00	540.00	3
4	880.00	540.00	1280.00	760.00	1
5	1280.00	760.00	1480.00	680.00	1
6	1480.00	680.00	1612.00	750.00	1
7	1612.00	750.00	1640.00	950.00	1
8	1640.00	950.00	1718.00	1000.00	1
9	1718.00	1000.00	1735.00	1050.00	1
10	1735.00	1050.00	1800.00	1122.00	1
11	.00	282.00	940.00	400.00	2
12	940.00	400.00	1800.00	400.00	2

ISOTROPIC SOIL PARAMETERS

3 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1
2	100.00	105.0	500.0	15.0	.00	.0	1
3	90.00	100.0	1350.0	.0	.00	.0	1

2 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 4 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	440.00
2	200.00	445.00
3	880.00	520.00
4	1620.00	620.00

Piezometric Surface No. 2 Specified by 2 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	1620.00	842.00
2	1800.00	842.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1800.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 800.00 ft.
and X = 1000.00 ft.

Each Surface Terminates Between X = 1600.00 ft.
and X = 1620.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

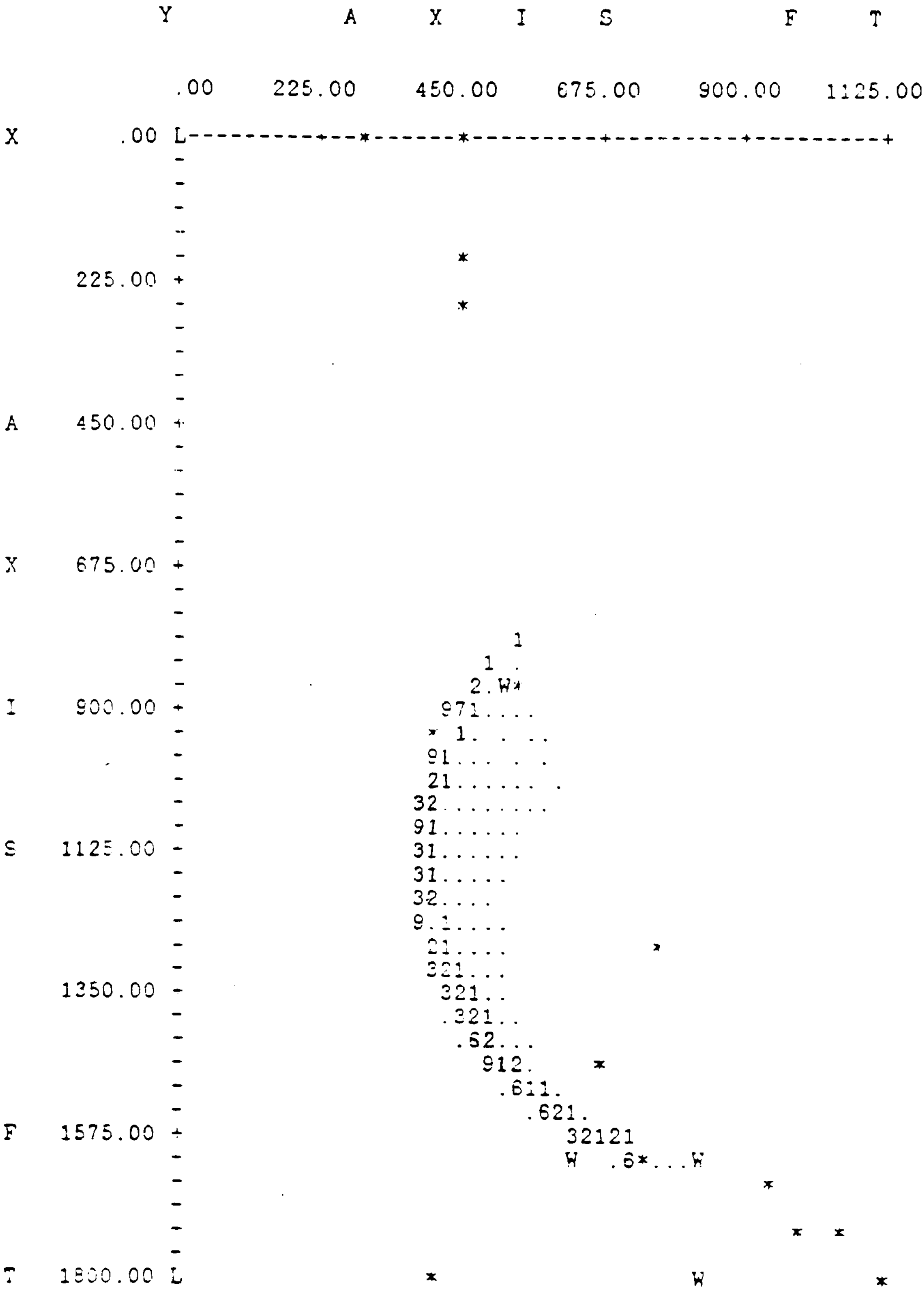
Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	800.00	529.68
2	839.56	499.10
3	881.96	472.59
4	926.77	450.43
5	973.57	432.82
6	1021.89	419.95
7	1071.24	411.94
8	1121.15	408.86
9	1171.11	410.75
10	1220.64	417.60
11	1269.24	429.32
12	1316.45	445.82
13	1361.78	466.91
14	1404.79	492.40
15	1445.06	522.04
16	1482.19	555.53
17	1515.81	592.54
18	1545.60	632.70
19	1571.25	675.62
20	1592.51	720.87
21	1600.68	744.00

*** 1.125 ***


Y AXIS FT
.00
225.00
450.00
675.00
900.00
1125.00
X AXIS FT
1350.00
1575.00
1800.00

APPENDIX B-9

INPUT AND PARTIAL OUTPUT FILES
FOR ANALYSIS OF THE UPPER FAILURE
SURFAC ALONG PROFILE C-C'
AFTER FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE C-C'
10 8
0. 440. 880. 520. 3
880. 520. 1280. 760. 1
1280. 760. 1480. 680. 1
1480. 680. 1612. 750. 1
1612. 750. 1640. 950. 1
1640. 950. 1718. 1000. 1
1718. 1000. 1735. 1050. 1
1735. 1050. 1800. 1122. 1
0. 282. 940. 400. 2
940. 400. 1800. 400. 2
SOIL
3
110. 115. 500. 15. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
90. 100. 1350. 0. 0. 0. 1
WATER
2 62.4
3
0. 440.
880. 520.
1620. 620.
2
1620. 842.
1800. 842.
LIMITS
1 1
0. 0.
1800. 0.
CIRCLE
10 10
800. 1000. 1600. 1620.
0. 50. 0. 0.
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 4 MARCH 1988
Time of Run: 15:50
Run By: D. UMSTOT
Input Data Filename: C2B.DAT
Output Filename: C2B.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE C-C'

BOUNDARY COORDINATES

8 Top Boundaries
10 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	440.00	880.00	520.00	3
2	880.00	520.00	1280.00	760.00	1
3	1280.00	760.00	1480.00	680.00	1
4	1480.00	680.00	1612.00	750.00	1
5	1612.00	750.00	1640.00	950.00	1
6	1640.00	950.00	1718.00	1000.00	1
7	1718.00	1000.00	1735.00	1050.00	1
8	1735.00	1050.00	1800.00	1122.00	1
9	.00	282.00	940.00	400.00	2
10	950.00	400.00	1800.00	400.00	2

ISOTROPIC SOIL PARAMETERS

3 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
2	100.00	105.0	500.0	15.0	.00	.0	1
3	90.00	100.0	1350.0	.0	.00	.0	1

2 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 3 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	440.00
2	880.00	520.00
3	1620.00	620.00

Piezometric Surface No. 2 Specified by 2 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	1620.00	842.00
2	1800.00	842.00

Searching Routine Will Be Limited To An Area Defined By 1 Boundaries Of which The First 1 Boundaries Will Defect Surface Upward

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)
1	.00	.00	1800.00	.00

A Critical Failure Surface Searching Method, Using A Random Technique for Generating Circular Surfaces, Has Been Specified.

100 Trial Surface Have Been Generated.

10 Surface Initiate From Each of 10 Points Equally Spaced Along The Ground Surface Between X = 800.00 ft.
and X = 1000.00 ft.

Each Surface Terminates Between X = 1600.00 ft.
and X = 1620.00 ft.

Unless Further Limitations Were Imposed The Minimum Elevation At Which A Surface Extends IS Y = .00 ft.

50.00 ft. Line Segments Define Each Trial Failure Surface.

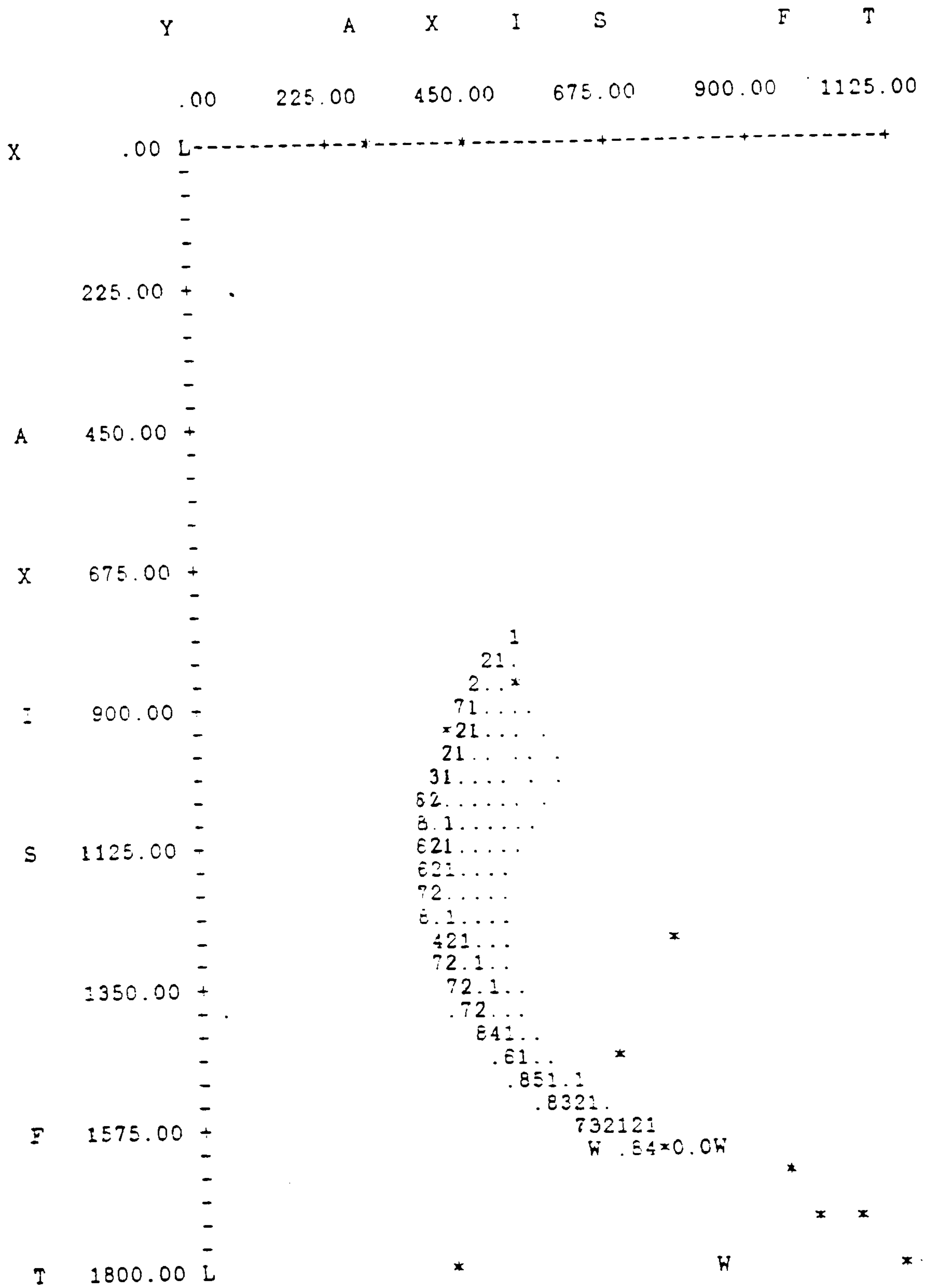
Following Are Displayed the Ten most Critical Of The Trial Failure Surfaces Examined. They Are Ordered - Most Critical First.

* * Safety Factors Are Calculated By the Modified Janbu Method * *

Failure Surface Specified By 19 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	800.00	512.73
2	840.95	484.73
3	884.48	459.44
4	930.19	439.17
5	977.65	423.43
6	1026.40	412.35
7	1076.00	406.05
8	1125.98	404.57
9	1175.87	407.94
10	1225.20	416.13
11	1273.50	429.05
12	1320.32	446.58
13	1365.23	468.57
14	1407.80	494.79
15	1447.63	525.02
16	1484.34	558.96
17	1517.60	596.30
18	1547.09	636.67
19	11572.53	679.72
20	1593.69	725.02
21	1600.33	743.81

*** .995 ***


Y AXIS FT
.00
225.00
450.00
675.00
900.00
1125.00
X AXIS FT
.00
225.00
450.00
675.00
900.00
1125.00
1350.00
1575.00
1800.00

APPENDIX B-10

INPUT AND PARTIAL OUTPUT FILES
FOR ANALYSIS OF A SINGLE FAILURE
SURFACE AND PROFILE C-C'
AFTER FAILURE ALONG A-A'

```
PROFILE
ROAN CREEK LANDSLIDE FAILURE C-C'
12 10
0. 440. 200. 445. 3
200. 445. 260. 460. 3
260. 460. 880. 540. 3
880. 540. 1280. 760. 1
1280. 760. 1480. 680. 1
1480. 680. 1612. 750. 1
1612. 750. 1640. 950. 1
1640. 950. 1718. 1000. 1
1718. 1000. 1735. 1050. 1
1735. 1050. 1800. 1122. 1
0. 282. 940. 400. 2
940. 400. 1800. 400. 2
SOIL
3
110. 115. 500. 15. 0. 0. 1
100. 105. 500. 15. 0. 0. 1
90. 100. 1350. 0. 0. 0. 1
WATER
2 62.4
4
0. 440.
200. 445.
880. 520.
1620. 600.
2
1620. 842.
1800. 842
SURFACE
14
300. 487.
400. 450.
500. 440.
600. 425.
700. 425.
800. 420.
900. 418.
1000. 415.
1100. 412.
1200. 420.
1300. 435.
1400. 485.
1500. 560.
1600. 760.
EXECUTE
```

** PCSTABL4 **

by
Purdue University

--Slope Stability Analysis--
Simplified Janbu Method of Slices
or Simplified Bishop Method

Run Date: 11 MARCH 1988
Time of Run: 10:45
Run By: D. UMSTOT
Input Data Filename: CLONG.DAT
Output Filename: CLONG.OUT

PROBLEM DESCRIPTION ROAN CREEK LANDSLIDE FAILURE C-C'

BOUNDARY COORDINATES

10 Top Boundaries
12 Total Boundaries

Boundary No.	X-Left (ft)	Y-Left (ft)	X-Right (ft)	Y-Right (ft)	Soil Type Below End
1	.00	440.00	200.00	445.00	3
2	200.00	445.00	260.00	460.00	3
3	260.00	460.00	880.00	540.00	3
4	880.00	540.00	1280.00	760.00	1
5	1280.00	760.00	1480.00	680.00	1
6	1480.00	680.00	1612.00	750.00	1
7	1612.00	750.00	1640.00	950.00	1
8	1640.00	950.00	1718.00	1000.00	1
9	1718.00	1000.00	1735.00	1050.00	1
10	1735.00	1050.00	1800.00	1122.00	1
11	.00	282.00	940.00	400.00	2
12	950.00	400.00	1800.00	400.00	2

ISOTROPIC SOIL PARAMETERS

3 Type(s) of Soil

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
1	110.0	115.0	500.0	15.0	.00	.0	1

Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion Intercept (psf)	Friction Angle (deg)	Pore Pressure Param.	Pressure Constant (psf)	Piez. Surface No.
2	100.00	105.0	500.0	15.0	.00	.0	1
3	90.00	100.0	1350.0	.0	.00	.0	1

2 PIEZOMETRIC SURFACE(S) HAVE BEEN SPECIFIED

Unit Weight of Water = 62.40

Piezometric Surface No. 1 Specified by 4 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	.00	440.00
2	200.00	445.00
3	880.00	520.00
4	1620.00	600.00

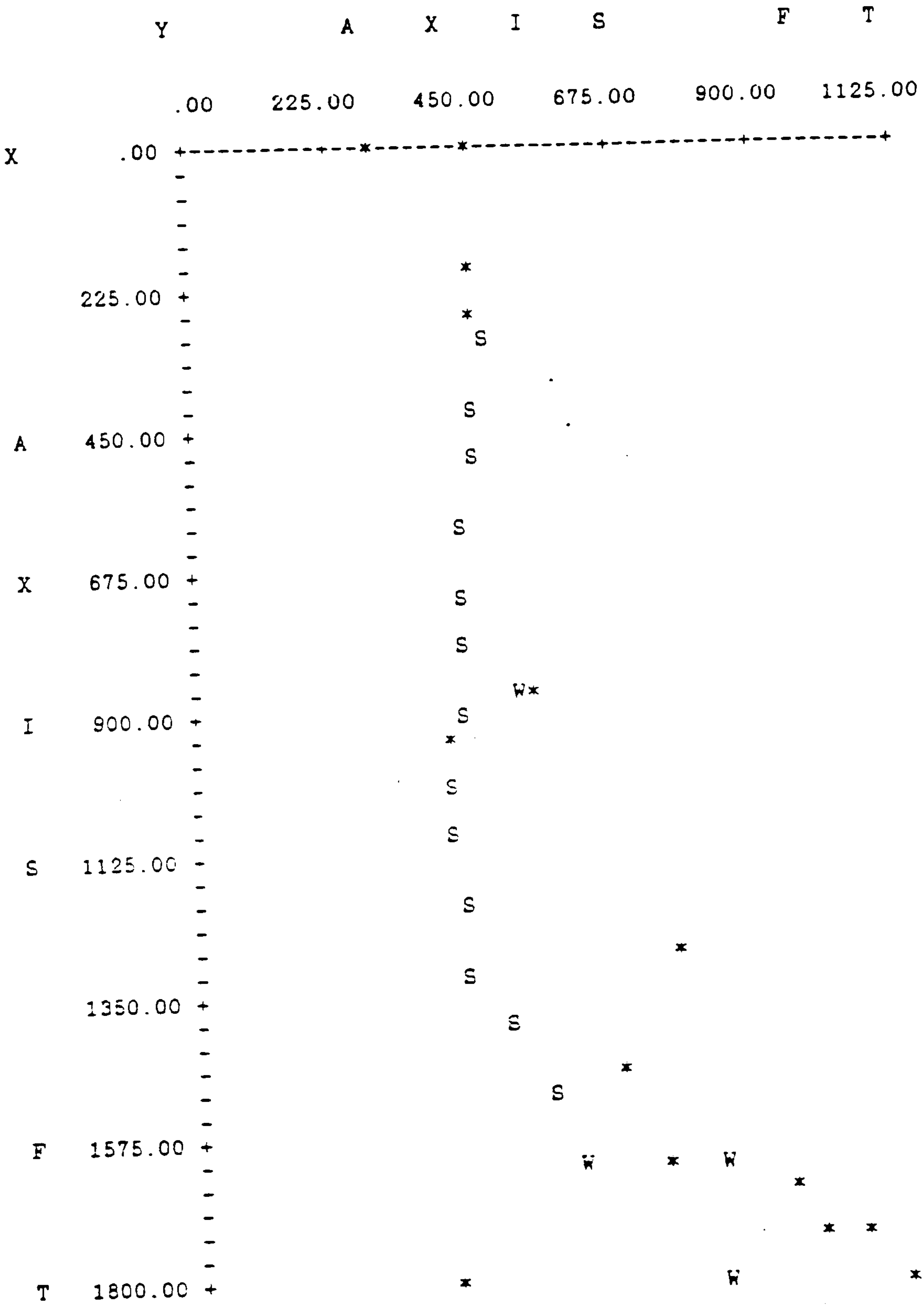
Piezometric Surface No. 2 Specified by 2 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	1620.00	842.00
2	1800.00	842.00

Trial Failure Surface Specified By 14 Coordinate Points

Point No.	X-Water (ft)	Y-Water (ft)
1	300.00	465.16
2	400.00	450.00
3	500.00	440.00
4	600.00	425.00
5	700.00	425.00
6	800.00	420.00
7	900.00	418.00
8	1000.00	415.00
9	1100.00	412.00
10	1200.00	420.00
11	1300.00	435.00
12	1400.00	485.00
13	1500.00	560.00
14	1600.00	743.64

Factor Of Safety For the Preceding Specified Surface = 1.110


Y AXIS FT
.00 225.00 450.00 675.00 900.00 1125.00
X AXIS FT
.00
225.00
450.00
675.00
900.00
1125.00
1350.00
1575.00
1800.00
S
W

APPENDIX C

DIAGRAM AND TABLES USED FOR HAND SOLUTION OF FACTOR OF SAFETY ALONG PROFILE A-A', PRIOR TO AND AFTER SURCHARGE LOADING

TABLE FOR HAND SOLUTION OF FACTOR OF SAFETY ALONG PROFILE A-A" PRIOR TO SURCHARGE LOADING USING A TOTAL STRESS ANALYSIS (PHI = 0)

Slice	W(i) (kips)	theta (degrees)	sin(theta)	W(i)*sin(theta) (kips)	l(i) (ft)
1	150	-10	-0.174	-26	102
2	400	-2	-0.035	-14	100
3	600	0	0	0	100
4	700	5	0.087	0	100
5	800	5	0.087	70	100
6	850	5	0.087	74	100
7	900	5	0.087	78	100
8	1000	5	0.087	87	100
9	1000	5	0.087	87	100
10	1050	5	0.087	91	100
11	1150	5	0.087	100	100
12	1200	5	0.087	104	100
13	1200	5	0.087	104	100
14	1200	8	0.139	167	101
15	1100	10	0.174	191	102
16	1000	15	0.259	259	103
17	450	40	0.643	289	155
				---	---
				W(t) = 1661	L(t) = 1763

$$\text{Factor of safety} = \frac{C(u) + L(t)}{W(t)}$$

Where C(u) = undrained shear strength,
L(t) = total arc length of failure surface
and W(t) = weight component creating a driving moment

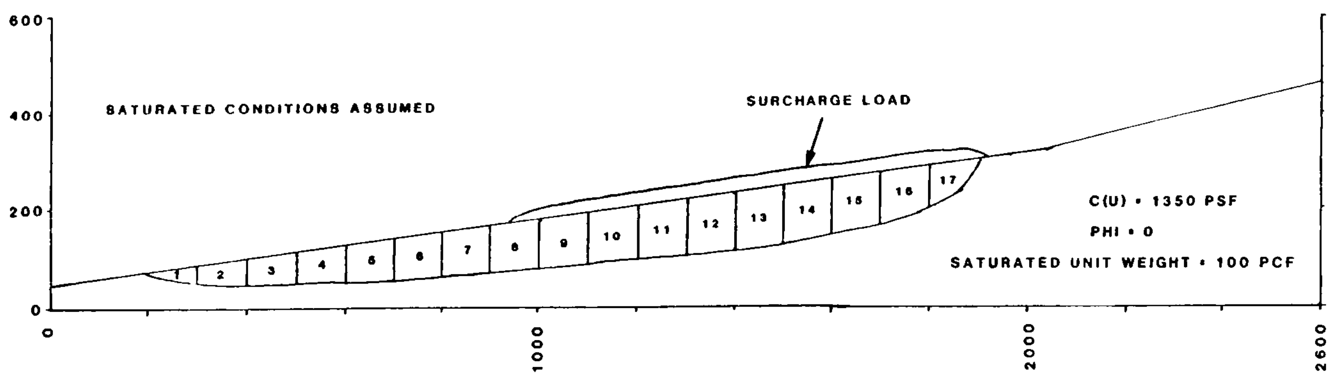
For a C(u) value of 1350 psf from computer modeling, the factor of safety =

$$\frac{1.35 \text{ ksf} + (1763 \text{ ft}) * 1\text{ft}}{1661 \text{ kips}}$$

= 1.43

for the defined failure surface prior to surcharge loading.

DIAGRAM USED IN TOTAL STRESS ANALYSES PRIOR TO AND AFTER SURCHARGE LOADING FOR HAND COMPUTATIONS OF FACTORS OF SAFETY ALONG PROFILE A-A'.



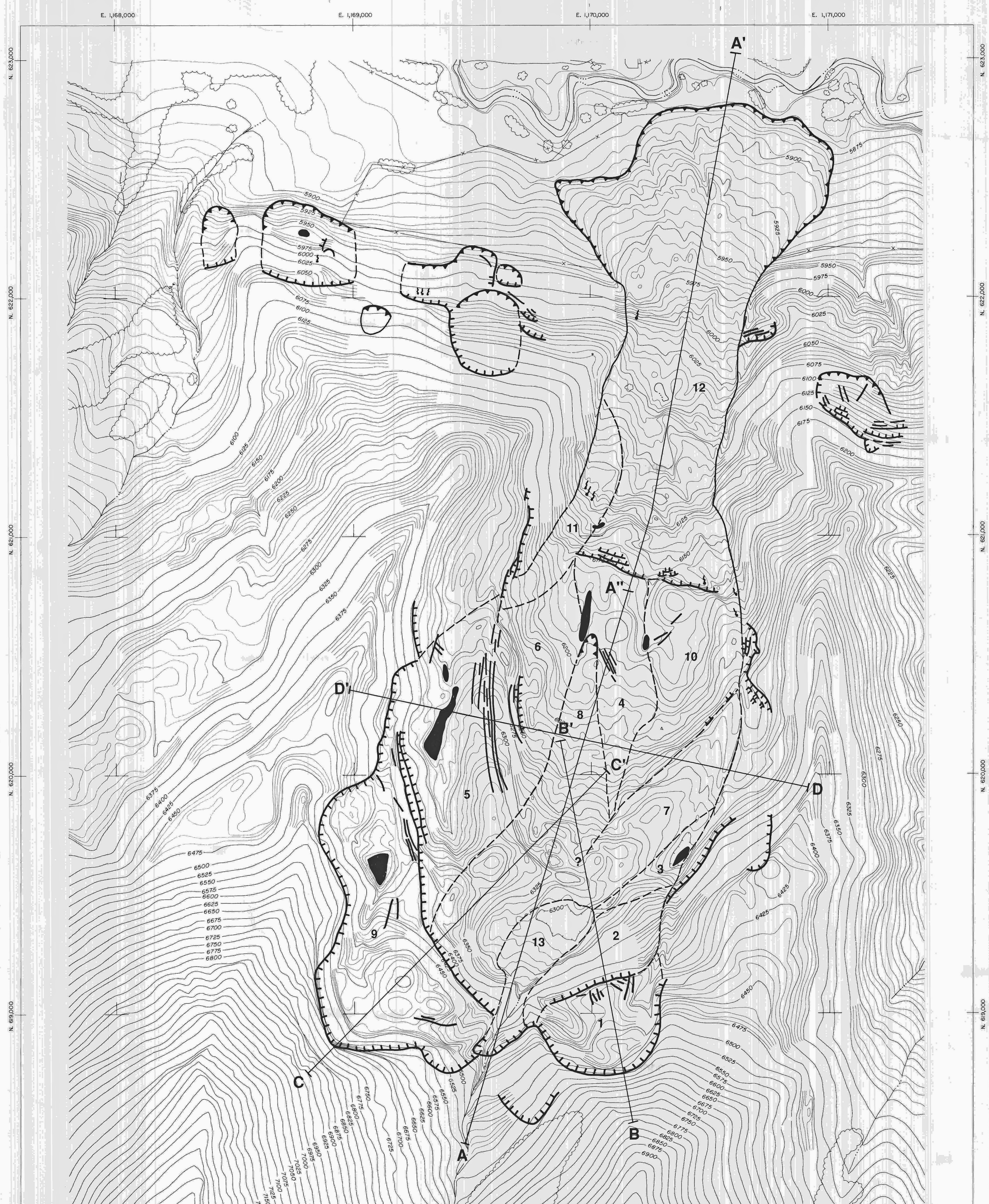
ALL SCALES IN FEET

Colorado Geological Survey
Department of Natural Resources
John W. Rold, Director

Open-File Report 89–1
Plate 1
1989

Primary Structures and Surficial Deposits Map of the Roan Creek Landslide, Garfield County, Colorado

By David Umstot



GEOLOGIC EXPLANATION

Geologic contact, dashed where approximate
Scarp
Toe
Tension crack
Seep
Standing water
A——A' Cross-section line

UNITS

Unit	Order	Description
1	(First)	Rotational block
2		Rotational block
3		Flow deposit
4		Flow deposit
5		Secondary-slump block
6		Secondary-slump block
7		Flow deposit
8		Flow deposit
9		Rotational block
10		Flow deposit
11		Flow deposit
12		Flow deposit
13	(Last)	Debris-flow deposit

Numbers of units indicate order of postulated failure.

Based on field work conducted in the summer of 1986.

200 100 0 200 400

SCALE: 1" = 200'
CONTOUR INTERVAL: 5'
PHOTO DATE: 8-8-85
JOB NUMBER: 350-5834