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Slope stability as related to geology at Rainier, Columbia County, Oregon

James Douglas Gless
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AN ABSTRACT OF THE THESIS OF James Douglas Gless for the
Master of Science in Geology presented February 10, 1989.

Title: Slope Stability as Related to Geology at Rainier,
Columbia County, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Leonard A. Palmer, Chairman

Ansel G. Johnson

Marvin H. Beeson

D. Richard Lycan

Rainier, Oregon, has experienced problems in the development of residential and commercial sites, utilities, and transportation facilities as a result of slope instability. This study of slope stability at Rainier was conducted at the request of city officials.

Rainier lies adjacent to the Columbia River near its confluence with the Cowlitz River. Numerous stream terraces are present on the hillsides at Rainier. These terraces are cut primarily in bedrock and many have a thin (<6 m, 20 ft) mantling of alluvium.

The geologic strata of the Rainier area are primarily composed of weak volcanoclastic rocks of the Eocene Gray's River volcanics and the Eocene-Oligocene Goble Volcanics. Lesser amounts of basaltic rocks are present in both formations. At shallow depths beneath the Goble Volcanics and interbedded with the Gray's River volcanics are siltstones and sandstones of the Cowlitz Formation. Unconformably overlying these units are silty and clayey beds of the Troutdale Formation and flows of the Grande Ronde Basalt and Pomona Member of the Saddle Mountains Basalt of the Columbia River Basalt Group. The youngest natural unit in the area is Quaternary Alluvium found adjacent to the Columbia River. Recent man-made artificial fills have been placed on the alluvium in some areas. A post-Eocene andesitic intrusion forms a prominent hill in the area.

Six factors were mapped and analyzed to assess the slope stability of the study area: 1) strength of soil; 2) strength of rock; 3) slope; 4) ground cracks; 5) landslide distribution; and 6) vegetation. These factors were selected because they either influence whether a slope will fail, they are indicative of failing areas, or both.

Slope stability at Rainier is extremely variable. The most stable areas at Rainier are found on nearly flat

ground in alluvium and fill adjacent to the river. The least stable slopes lie on failed stream terraces underlain by tuffaceous conglomerates, silts, and clays of the Troutdale Formation and the Goble Volcanics in the old section of Rainier east of Fox Creek. Ancient landslides are present in weak tuffaceous beds of the Gray's River volcanics.

Slope instability at Rainier is, and will continue to be, a constraint in land use. Planning with regard to slope instability will reduce the impact that unstable areas have on land development.

SLOPE STABILITY AS RELATED TO GEOLOGY

AT

RAINIER, COLUMBIA COUNTY, OREGON

by

JAMES DOUGLAS GLESS

A thesis submitted in partial fulfillment of the
requirement for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Portland State University

1989

TO THE OFFICE OF GRADUATE STUDIES:

The members of the Committee approve the thesis of
James Douglas Gless presented February 10, 1989.

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INTRODUCTION

This thesis presents the results of an investigation of slope stability at Rainier, Oregon. The thesis has been conducted at the request of city officials concerned with the existing and potential effects of landsliding.

STATEMENT OF THE PROBLEM

Rainier provides a number of examples of slope instability (Figures 1 and 2). Slope instability at Rainier has been a problem in the development of residential and commercial sites, utilities, and transportation facilities.

The Soil Conservation Service prepared a map of "Soils Related to Mass Movement" within Columbia County (Figure 3). This map showed that over half of the county lies in soils related to mass movement. All of Rainier except the floodplain area lies in these potentially unstable soils.

The land use plan for Rainier addresses areas subject to natural disasters and hazards. In relationship to slide hazard the land-use plan states (City of Rainier, 1980):

There are several areas of known slide hazard in Rainier. The land with the greatest potential for slides is on the eastern edge, especially between 9th and 10th along U.S. 30. There is an area of unstable soils between "A" Street and the city limits that is bounded by East 3rd and 10th Streets. A smaller slide hazard area lies along East 2nd Street from "D" Street to the end of 2nd. There is some potential for rock slides along the

Figure 1. House on West 2nd Street which has failed as a result of landsliding.

Figure 2. Small cutslope failure on 1st Street between 'C' and 'D' Streets.

Figure 3. Map of soils related to mass movement in Columbia County prepared by the Soil Conservation Services (unpublished).

steep rock face parallel to U.S. 30 in the western portion of the Urban Growth Area. Much of the land within the current city limits is also considered by the Soil Conservation Service to provide a weak foundation for construction.

As a result of the foregoing slope stability information, some property owners have found it difficult to sell their property at Rainier because lending institutions are reluctant to provide mortgages and insurance companies are reluctant to insure properties.

This thesis has been written to provide a better understanding of the slope instability problems in Rainier and aid concerned officials attempting to solve these problems.

LOCATION AND SIZE OF THE AREA STUDIED

The City of Rainier is located on the south bank of the Columbia River midway between Astoria and Portland, Oregon (Figure 4). Rainier lies in northern Columbia County, primarily in Sections 15, 16, 17 and 21, Township 7 North, Range 2 West, Willamette Meridian. The study area is approximately 5 km² (2 mi²).

ACCESS

Access to the study area is via State Highway 30 from the east or west, and via Rainier-St. Helens County Road from the south. Numerous residential roads transect the

0 1 Mile

Figure 4. Location map of study area.

study area providing generally good access throughout. Except for public parks and schools all land within Rainier is private.

PURPOSE

The purpose of this thesis is to present the findings of an investigation of slope stability at Rainier, Oregon, to aid land-use planners in making land-use decisions related to slope stability. The relationship of geologic factors to slope stability and landsliding is presented. The work is a qualitative and quantitative evaluation of relative slope stability.

The maps and text herein define general areas of relative slope stability. This study is not site specific; the geology and landslide hazards for a specific lot or lots may be different from that shown on the maps or discussed in the text. This study is not intended to supplant engineering or geologic studies necessary for the planning of specific engineering projects or to replace site evaluations by qualified experts.

SCOPE

The scope of this investigation has included interpretation of topographic maps and stereo pairs of aerial photographs, field mapping of surface and subsurface geology, logging of trenches and drill core, laboratory

testing, a review of well logs, and a review of published and unpublished literature.

The potential for liquefaction-induced landslides in alluvial deposits adjacent to the Columbia River at Rainier has not been determined and is not within the scope of this report. The cost of borings necessary for obtaining samples to run sieve analyses to determine the liquefaction potential was not within the budget of this investigation. Sediments that have a liquefaction potential have been identified elsewhere along the Columbia River (Schlicker, 1988).

GEOGRAPHY AND GEOMORPHOLOGY

Rainier is an irregularly shaped area approximately 5 km (3 mi) long by less than 1.6 km (1 mi) wide. Rainier is on the southern bank of the Columbia River at the widest part of the mid-lower valley at the confluence of the Cowlitz River with the Columbia River.

The study area has 150 m (500 ft.) of relief over a distance of approximately 1.6 km (1 mi). The area is in a late youth stage of development in the Davisian classification scheme (Butzer, 1976).

Most of Rainier is underlain by weak volcaniclastic rocks. Lesser amounts of strong volcanic flows and intrusives are present. Slopes on the intrusive are particularly steep, greater than 50%. Slopes formed on the

volcaniclastics and flows vary greatly. Most convex and linear profile slopes generally lack landslide features. Most concave hillside profiles are the result of landsliding or stream terrace cuts.

A weakly developed geomorphic surface present at approximately 120 m (400 ft) generally corresponds to a prominent coastal terrace level (Palmer, 1967). A large alluvial flood plain is present in western Rainier adjacent to the Columbia River which formed during the Ingram and Horseshoe geomorphic episodes described by Smythe (1986). River cut and fill terraces are present throughout much of Rainier at many elevations. The most obvious terraces are found at elevations of 25 m (80 ft) to 35 m (120 ft) and at about 75 m (250 ft) (Plate 1). These terrace remnants are likely related to the Champoege or possibly the Senecal or Dolph geomorphic episodes (Smythe, 1986). The terraces from 25 m (80 ft) to 35 m (120 ft) have a scabland-like appearance in west Rainier with thin or absent soils and poorly developed drainage. Many and possibly all of these terraces resulted from the Bretz floods which affected elevations to 90 m (300 ft) at Rainier (Allen, 1986).

Rainier has a population of 1,500. Most of the old section of Rainier (Plate 2 shows areas of reference, field stations and sample locations) is heavily developed with residential homesites. Commercial development is concentrated along the waterfront. The remainder of

Plate 1. Geomorphic features at Rainier, Oregon.

Old section
of Rainier

83 Station

	MBDG4- 1288C	and	1-7-15	Sample location
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Plate 2. Areas of reference, field stations and sample locations.

Rainier is sparsely to undeveloped. The valley of Nice Creek and eastern-most Rainier are noticeably undeveloped. In general, development is concentrated on flatter slopes, and on hillsides and ridgetops with views of the river.

Rainfall averages about 150 cm (60 in) per year. The vegetation is classified as western hemlock type; the dominant species is Douglas fir; the climax species is western red cedar. Disturbed sites are commonly occupied by red alder and big leaf maple (Highsmith, 1973). Blackberry and numerous other shrubs and grasses are also found at Rainier.

Dense vegetation and deep soils have resulted in poorly exposed bedrock which made geologic mapping difficult. Most exposures upon which the geologic mapping was based were created by removing the soil cover with a shovel to expose the underlying weathered rock.

PREVIOUS WORK

The earliest geologic reports on the northern coast range were by J. D. Dana (1848), Thomas Condon (1880) and J. S. Diller (1896). Numerous investigators have studied the area since and the reader is referred to Newton and Van Atta (1976) for a more complete listing.

Prior to the work by Phillips (1987) very little detailed mapping had been done at Rainier. Warren, Norbistrath and Grivetti (1945) had mapped all of the rock

at Rainier except recent alluvium as belonging to the Goble Volcanics. Phillips was able to correlate rocks at Rainier with well-defined units in Washington, including the Gray's River volcanics and the Goble Volcanics.

GENERAL METHODOLOGY

Many methods of assessing slope stability and landslide hazards have been used by geologists throughout the world. In Oregon, the most commonly used technique, and the one which is used by the Oregon Department of Geology and Mineral Industries, is to delineate areas of active landslides, ancient landslides, and landslide topography. Examples of this type of mapping are "Environmental Geology of Lincoln County, Oregon" (Schlicker and Others, 1973), and "Land Use Geology of Central Jackson County, Oregon" (Beaulieu and Hughes, 1977).

In California where landslide studies for planning purposes have been conducted for many years, techniques for assessing the relative likelihood of landsliding in all areas within a region have been used extensively. The maps produced from such studies are usually referred to as slope stability maps, landslide susceptibility maps, landslide hazard maps or landslide risk maps.

Most slope stability maps are produced by first mapping one or more of the factors related to landslide occurrence, such as bedrock geology, slope, landform, rainfall,

vegetation, soils, etc., classifying variations within these factors (e.g., low, moderate and high) and then overlaying the maps to arrive at a relative slope stability rating for the area. Examples of this type of approach to slope stability mapping include "Landslide Susceptibility in San Mateo County, California" (Brabb and Others, 1972), and "Natural Slope Stability as Related to Geology, San Clemente Area, Orange and San Diego Counties, California" (Blanc and Cleveland, 1968); more locally, a factor mapping approach was used to determine relative landslide risk in the Astoria, Oregon, area (Carter, 1975). This factor mapping approach to evaluation of multicausative phenomena in planning was popularized by Ian McHarg (1969). Factor mapping is a somewhat more rigorous approach to the overlaying techniques described earlier.

The methods chosen for this study are based upon mapping factors that indicate unstable ground (landslides and ground cracks) and factors that contribute to landsliding (steep slopes, weak soils, weak rocks and lack of vegetation). Because rock and soil formations and units are related to landslide occurrence, it was necessary to first map the geology in as much detail as possible with the very limited exposures at Rainier.

An understanding of the distribution of lithologies in an area is a fundamental requirement for assessing slope stability (Blanc and Cleveland, 1968). To gain an under-

standing of the geology and its relationship to slope stability, it was necessary to first map the geology with a particular emphasis on determining the rock types present and their distribution as related to landsliding.

When the geological characteristics of a rock or soil unit are defined, the associated engineering properties related to slope stability can be estimated. This provides a powerful predictive tool for determining the probable slope stability of an area for planning purposes prior to site-specific investigations.

The following section on geology provides the fundamental information on the rock types and soil units at Rainier.

A more detailed explanation of methodologies is included, where relevant, throughout the thesis.

GEOLOGY

INTRODUCTION

Each of the geologic units at Rainier has specific physical characteristics. These characteristics have a great influence upon the stability of slopes. The major units in the area are described below.

The lowermost unit in the field area is the Eocene Grays River volcanics (informal) (Phillips, 1987). The rocks in this unit are basalts, breccias, sandstones, and volcaniclastics. This unit is interbedded with tuffaceous feldspathic sandstones and siltstones of the Eocene Cowlitz Formation which was first described by Weaver (1912). The Cowlitz Formation is overlain by volcanic claystones, siltstones, sandstones, conglomerates, and basalts of the Eocene-Oligocene Goble Volcanics (Phillips, 1987).

Basalts of the Miocene Columbia River Basalt Group unconformably overlie older units. The Quaternary-Tertiary Troutdale Formation overlies or is interbedded with the Columbia River Basalt Group. A post-Oligocene andesitic plug-like feature intrudes the Gray's River volcanics. Quaternary Alluvium and artificial fills are present adjacent to the river (Plates 3 and 4).

Tai Post-Eocene andesitic intrusion	Qa Quaternary alluvium	Tp Miocene Columbia River Basalt Group; Pomona Member	Tgrm Eocene-Oligocene Goble volcanic; flow interbeds	Tgrm Eocene Gray's River volcanics; mixed rock unit
Qaf Quaternary artificial fill	QTT Plio-Pleistocene Troutdale Formation	Tgr Miocene Columbia River Basalt Group; Grande Ronde Basalt	Tgrf Eocene-Oligocene Goble volcanic; volcaniclastic rocks	Tgrf Eocene Gray's River volcanics; flow unit
— Contact; all contacts are approximate	— Fault; U, upthrown side; D, downthrown side	— Strike and dip of beds	⊕ Horizontal beds	Ⓔ Station location

Plate 3. Geologic map of Rainier, Oregon.

Plate 4. Geologic cross sections of Rainier, Oregon.

Methodology

The geology was mapped primarily using basic geologic field methods. Field stations (locations in the field) were located by inspection and plotted on various enlarged versions of the Rainier, Oregon-Washington, 7.5 minute quadrangle. A Brunton compass was used for determining attitudes of planar features and bearings. Rocks were examined with 14- and 20-power hand lenses in the field and with a 25-power binocular microscope in the lab. Rocks were classified by standard methods as described in Williams, Turner and Gilbert (1982). In addition to basic field methods, the geologic mapping was aided by interpretation of topographic maps and stereo pairs of aerial photographs, geochemical sampling and analysis, logging of trenches, and examination of drill core.

Trenches were logged during excavation for installation of sewerage lines. Trenches were dug by a track-mounted backhoe. Trench logging was accomplished by visually examining trench walls while standing at the top of the trenches; seldom were trenches entered to inspect trench walls because this would have interfered with the pipe-laying operation. Samples were obtained for examination from the bucket of the backhoe during excavation. The trench logging significantly contributed

to an understanding of the geology in some of the poorest exposed areas (Figure 5).

Recent work by Phillips (1987), Walsh (1987), and Phillips, et al (1989), combined geochemical characterization with field mapping which has allowed these geologists to define new units throughout southwest Washington and into northwest Oregon and to more definitely delineate previously defined units. In this study, similar geochemical methods were also used to help assign the rocks at Rainier to the proper formation.

Regional Geologic Setting

Structurally, the study area lies in the lower Columbia River downwarp composed of Tertiary sedimentary and volcanic rocks (Newton & Van Atta, 1976). Numerous subparallel northwest trending folds are mapped to the northeast and southwest of the study area (Phillips, 1987; and Newton and Van Atta, 1976). A broad anticlinal feature plunges to the north in the Clatskanie and Cathlamet quadrangles to the west of the study area (Newton and Van Atta, 1976). Figure 6 and Figure 7 show the stratigraphic relationships from southwestern Washington and northwestern Oregon, respectively.

Figure 5. Trenching operation for installation of sewerage lines.

GRAY'S RIVER VOLCANICS

The Gray's River volcanics have been informally named for exposures found along logging roads in the headwaters of the Gray's River, T.10N. and T.11N., R.6W., and more locally for the good exposures found along the roadcuts of U.S. Highway 30 immediately west of Rainier and in the quarry at the south end of the Rainier-Longview Bridge in Section 17 and 18, T.7N., R.2W (Phillips, 1987). As defined by Phillips (1987) the unit includes,

...volcanics previously mapped as unit B volcanics of Wolfe and McKee (1968, 1972), much of the Goble Volcanics of Livingston (1966), Henricksen's (1956) Goble Volcanic Member of the Cowlitz Formation and the Goble Volcanics of Wells (1981) and Wells and Coe (1985).

Figure 6. Stratigraphic relationships for the Paleogene of southwest Washington (from Phillips, 1989).

PACIFIC COAST CENOZOIC CORRELATIONS			UPPER NEHALEM RIVER BASIN	UPPER NEHALEM RIVER BASIN	UPPER NEHALEM RIVER BASIN	UPPER NEHALEM RIVER BASIN	SOUTHWESTERN WASHINGTON	INLAND TILLAMOOK AND CLATSOP COUNTIES
AGE	West Coast Form stages 1.	West Coast Molluscan stages 2.	(Van Atta, 1971)	(Deacon, 1953)	(Warren and Norbierath, 1946)	(This report)	(Henrickson, 1956)	(Benaulieu, 1973)
Pleistocene		Terraces Tulare				Alluvium		
Pliocene		Moclipaisian				Troutdale		
Miocene	DeLambertian	Graysian				Sedimentary Reefs at Clifton	Astoria Fm	Upper Miocene sandstone
	Mohnian	Mishakian					Marine sed. and interbedded basalt flows	Nicolai Min
	Luisian	Newportian	Col Riv Basalt		Col Riv Basalt	Col Riv Basalt		Mid-Mio basalt
	Relizian	Pillarion						Mid-Mio ss
	Sauceanian	Juanian	Scappoose Fm		Scappoose Fm	Lower Miocene through middle Oligocene ss		
Oligocene	Zemmerian	Matlockian					Oligocene undifferentiated	Oligocene to Miocene marine sed rocks
			Pittsburg Bluff Fm		Pittsburg Bluff Fm			
	Refugian	Galvinian						
Eocene			Kearney Fm	Kearney Fm	Kearney Fm	Kearney Fm		
				"Nehalem" Fm				
			Goble Vols	"Rocky Point" Fm			Goble Vols	Late
	Marizian	Tejon	Cowlitz Fm		Cowlitz Fm	Cowlitz Fm	Olequa Crk Member	Te ₃
							Stillwater Crk Fe'Ell Vols	Eocene marine ss
	Transition beds		Tillamook Vols (base not exposed)	Tillamook Vols (base not exposed)	Tillamook Vols (base not exposed)	Tillamook Vols and minor interbedded ss (base not exposed)	Metochosin Vols (Crescent Vols equiv) (base not exposed)	undiff
	Ulatian	Domengian						Te ₁

Figure 7. Correlation chart for the upper Nehalem Basin in Northwestern Oregon and for Southwestern Washington (from Newton and Van Atta, 1976).

The unit thins from a thick pile in the headwaters of the Gray's River 58 km (35 mi) northwest of Rainier to 30 m (100 ft) at Kelso (Phillips, 1987) 10 km (6 mi) northeast of Rainier. The unit appears to be generally horizontal in west Rainier at the quarry. Attitudes measured in the channel of Nice Creek in central Rainier have a northeasterly strike and a dip of 10-15° to the southeast. This unit has an exposed thickness of more than 90 m (300 ft) in western Rainier and appears to become complexly interbedded to the east.

Flow Unit

In the study area the lowermost rocks of this unit are basalt breccia greater than 50 m thick which appear to slowly grade into the overlying 35 m thick columnar, dense porphyritic pyroxene basalt having irregular zones of breccia (Figures 8 and 9). The breccias are a chaotic mixture of vesicular basalt in a vesicular basalt matrix with minor pyrite. The contact of basalts exposed in the quarry with the poorly exposed epiclastic and volcaniclastic rocks lying to the east on the border of sections 16 & 17 is hidden under a thick soil mantle. The contact appears to have an inter-fingering relationship.

Mixed Rock Unit

Rocks exposed along the Old Columbia River Highway near the border of Section 16 and 17 are basalts, weathered

Figure 8. Flow unit of Gray's River volcanics exposed in quarry at the south end of the Rainier-Longview Bridge.

Figure 9. Vesicular basaltic breccia from quarry in Figure 8 (enlargement 7x).

volcanic conglomerates, vitric basaltic sandstone, vitric breccias, micaceous volcanic lithic feldspathic sandstones and tuffaceous siltstones. Some of these rocks have as much as 3 or 4 percent well preserved elongate euhedral hornblende. Flows of basalt are found within the more dominant sedimentary rocks such as at Stations 81 and 83. At Station 81 the basalt is, at least in part, basaltic breccia at its base and appears to intrude the underlying sandstones and siltstones (Figure 10). From Station 80 to the summit of the ridge at Station 90, micaceous volcanic tuffaceous quartzo-feldspathic sandstones begin to predominate (Figure 11). Eastward in the vicinity of Stations 23 and 24, micaceous, tuffaceous sandstones and siltstones were exposed during trenching operations for installation of a new sewerage line. Although attitudes could not be obtained, the rocks appeared to strike generally north of east and dip gently to the southeast. The large hill in the western part of the project area having a summit elevation of approximately 120 m (400 ft) is composed primarily of weathered lithic sandstone and vitric breccia.

In the valley of Nice Creek at Station 85, the beds strike N 65° E and dip 10-15° to the southeast. Exposures are good in the stream channel at the small 3 m (10-ft) high waterfall. Although the stream was bank-full at the time of inspection, samples were collected over an

Figure 10. Dark vitric basalt breccia in contact with sandstones. Basalt appears to have intruded the sandstones.

Figure 11. Micaceous tuffaceous quartzo-feldspathic sandstone at Station 80 (enlargement 25x).

approximate 10-foot section just above the waterfall. The lithology here is a vitric breccia. No exposures were found within this unit on the steep slopes adjacent to Nice Creek in the southern part of the study area; however, a handful of float was collected during the traverse from Nice Creek to the ridge in the southwest corner of the project area near Station 88. This float consisted of vitric sandstone, volcanic lithic sandstone, and crystalline tuff.

On the western side of Fox Creek, tuffaceous siltstones are more abundant and overlie deeply weathered volcanic conglomerates. These tuffaceous siltstones are well exposed about 150 m (500 ft) south of Station 39 outside the project area.

The Gray's River volcanics appear to be interfingering with the Cowlitz Formation. Beds of micaceous volcanic feldspathic siltstone and sandstone described earlier are probably interbeds of the Cowlitz Formation interfingering within the Gray's River volcanics.

COWLITZ FORMATION

The Cowlitz Formation was first named by Weaver (1912). Numerous descriptions and definitions exist for the Cowlitz Formation (Walsh, 1987). Wells (1981) restricted the Cowlitz Formation to the sandstone dominated, mixed nearshore marine and terrestrial facies; it is this

definition that is used in this thesis. This definition includes Weaver's original type section and Henriksen's (1956) definition of the Olequa Creek Member. This follows the definition used by Phillips (1987).

Lithologies of the Cowlitz Formation described by Phillips (1987) include, "micaceous feldspathic sandstone with interbedded siltstone, shale, carbonaceous shale and lignite to subbituminous coal; locally contains basalt lava flows and volcanoclastic rocks."

In the study area, the Cowlitz Formation is not exposed at the surface; however, drill core obtained from borings conducted by the Oregon Department of Transportation (O.D.O.T.) for a landslide investigation at Rainier appears to have just penetrated the Cowlitz at an elevation of 6 m (20 ft) below sea level. Because of the lack of exposure of Cowlitz rocks at Rainier, their discussion will be brief.

During the subsurface investigation of a landslide along U.S. Highway 30 at Rainier, the Oregon Department of Transportation cored to 21 m (70 ft) below sea level. The gradational change in this core within a distance of 8 m (25 ft) near sea level was from gray, tan and brown tuffaceous mudstones, siltstones, claystones and conglomerates above (Figure 12) to light gray tuffaceous, micaceous feldspathic sandstone below (Figure 13). It appears as though this change from predominantly tuffaceous

Figure 12. Tuffaceous mudstone of Goble Volcanics from Oregon Department of Transportation (enlargement 15x).

Figure 13. Micaceous feldspathic sandstone of Cowlitz Formation from Oregon Department of Transportation cores (enlargement 25x).

siltstones and claystones above to predominantly micaceous feldspathic sandstones below may be the Goble-Cowlitz contact in the study area. In addition, micaceous quartzofeldspathic arenite found at Station 80 appears to be a Cowlitz interbed within the Gray's River Volcanics as is the micaceous volcanic very fine sandstone and siltstone found at Stations 23 and 24. The Cowlitz Formation has been mapped overlying the Gray's River volcanics approximately 10 km (6 mi) to the northwest of the project area at Longview, Washington (Phillips, 1987).

GOBLE VOLCANICS

The Goble Volcanics were first described by Wilkinson, Lowry and Baldwin (1946) for lava flows and associated pyroclastic rocks exposed at Goble, Oregon. Phillips (1987) divided the Goble Volcanics into a lower, predominantly volcaniclastic member and an upper basaltic-andesite lava flow member.

Outside the study area, 12 km (7 mi) to the northwest at Mount Brynion (T.8N., R.1W.), Phillips has mapped at least a 180 m (590 ft) thick section of the volcaniclastic member thinning to about 50 m (165 ft) 32 km (19 mi) north of the study area, near Castle Rock, Washington (Sec. 11 & 12, T.10N., R.2W.). In the study area it is difficult to accurately determine the thickness of this unit because of a lack of structural control. With the dip of this unit

conservatively estimated to be about 5° S-SE, the unit is about 190 m (620 ft) thick. The upper contact used in determining thickness lies approximately 400 m (1300 ft) south of the project area. Regionally, a general southward thickening of the unit is present.

In the study area, the lowermost rocks of this unit are blue-gray and brown claystones and siltstones inter-bedded with predominantly red-brown and gray-brown pebble to cobble paraconglomerates that have tuffaceous mudstone matrices and carbonaceous beds (Figure 14). Clast lithologies include basalts, basaltic sandstone, mudstones, and siltstones. Minor beds of very light gray and light tan, coarse ash-tuff occur throughout the section. Most of the tuffs appear to be reworked. Above elevations of about 50 m (60 ft), the rocks become slightly more sandy until at 90 m (300 ft) elevation on the south edge of the study area, the rocks are predominantly siltstones and friable silty very fine sandstones. Although only cursory examination was given to rocks outside the project area, lithologies to the top of the unit appeared to be predominantly sandy.

The contact of this unit with the overlying flow rocks is placed south of the study area about 4010 m (1300 ft). Here, overlying flow rocks are exposed in cuts of the first logging road to the east of the paved Rainier-St. Helens County Road. The junction of the logging road with the

paved road is at the powerline. Rocks exposed at upper elevations along the logging road are deeply weathered volcanic conglomerates and brecciated zeolitic basaltic flows; rocks at lower elevations are tuffaceous volcanic lithic feldspathic sandstones. The contact appears to be conformable.

Flow Interbeds

Basaltic-andesite flows in the study area are interbedded with the lower volcanoclastic member of the Goble Volcanics. These flows form the steep slopes adjacent to the highway in eastern Rainier. The flows are present from river level to an elevation of about 60 m (200 ft) and are best exposed along the railroad tracks and along the highway in eastern Rainier. Along the railroad tracks the rocks are predominately purple-brown vesicular to scoriaceous basaltic-andesite with lesser quantities of purple-brown dense basaltic-andesite. The latter contains euhedral plagioclase phenocrysts in a glassy groundmass and anhedral to subhedral mafic phenocrysts. Vesicles are commonly lined with clear to white zeolite(?) minerals (Figure 15). A dark brown-black staining and vesicle filling of unknown composition (probably a zeolite(?)) is present in some samples. Zeolites are reportedly common in flows of the Goble Volcanics (Warren and Others, 1945).

Figure 14. Conglomeratic mudstone overlying carbonaceous bed in the Goble Volcanics.

Figure 15. Well formed zeolite in vesicle of flow interbed of Goble Volcanics (enlargement 15x).

Along the highway, the rocks are predominantly dense to vesicular purple-brown basaltic-andesites. Phenocrysts consist of predominantly plagioclase and a brown-black pyroxene(?) with a golden sheen and excellent parting that under initial examination looked like biotite. Variations in appearance from the core to the surface of these crystals indicated that alteration had occurred. Vesicles are commonly lined with clear, stubby euhedral crystals of zeolites(?), or pale green earthy zeolite(?), or partly or completely filled by green-brown earthy zeolite(?). Both upper and lower contacts of any one flow were not exposed in the field area; therefore, it was impossible to determine flow thicknesses. Flows are at least 6 m (20 ft) thick based on the exposure in any single outcrop.

These flows are interbedded within the volcanoclastics. The lower flow contact is exposed along the highway where the somewhat brecciated basalt rests conformably on the tuffaceous rocks (Figure 16). The tuffaceous rocks have been baked to a hardness greater than that found elsewhere in the volcanoclastics. The contact strikes N90°E and dips SE 20° here. In exposures along the railroad tracks, the flows overlies volcanoclastic mudstones, carbonaceous mudstones, and conglomerates. The contact is nearly horizontal here. The upper contact is not exposed; however, poor exposures along logging roads above the flows

reveal overlying tuffaceous volcanoclastics. The total thickness of the flow interbed is about 60 m (200 ft).

Figure 16. Contact of flow interbed of Goble Volcanics with underlying volcanoclastic unit of Goble Volcanics.

COLUMBIA RIVER BASALT

The Columbia River Basalt Group was named for exposures found in the Columbia Basin in northeastern Oregon and southeastern Washington and for excellent exposures in the Columbia River Gorge.

Hard, dense flows of Grande Ronde Basalt of the Columbia River Basalt Group are found at some of the highest elevations in the field area. In the southwest corner of the project area at elevations above 120 m (400 ft), a massive, poorly exposed flow crops out in the small

stream channel west of Station 89. The rock is a very fine-grained basalt with minor plagioclase phenocrysts and minor vesicles (Figure 17). The contact of this basalt with underlying rocks is not exposed. The contact is drawn based on float mapping and geomorphic expression. Geochemistry (Appendix A) indicates that this flow is part of the Grande Ronde Basalt of the Columbia River Basalt Group.

Dense brown-gray columnar jointed porphyritic basalt is exposed over a horizontal distance of about 150 m (500 ft) along the highway west of Nice Creek. Geochemistry indicates that this flow is part of the Pomona Member of the Saddle Mountain Basalt. The generally vertical jointing in this flow indicates that it probably has a horizontal attitude. The contact of this flow with the underlying Gray's River volcanics is unconformable.

INTRUSIVE ANDESITE

The hill at Station 38 is underlain by a small plug-like to sill-like hypabyssal intrusion of pyroxene andesite. The rock is dark gray, very hard and dense. It is composed of plagioclase and pyroxene phenocrysts in a fine-grained ground mass.

The intrusion is best exposed in a very small quarry southwest of the intersection of West 4th Street and "E" Street. The intrusion has blocky to crudely columnar

jointing. The intrusion is also well exposed in roadcuts of West 4th Street.

Figure 17. Fine-grained basalt of the Grande Ronde Basalt showing phenocrysts and minor vesicles (enlargement 25x).

The intrusion was emplaced adjacent to the faulted contact of the Gray's River volcanics with the Goble Volcanics. The intrusion appears to be in contact with severely fractured volcanic conglomerate on the north side, a tuffaceous siltstone on the south side, and vitric basaltic breccia on the west side. On the east side, the intrusion is exposed down near the creek at Station 51. Unconformably overlying the intrusion are sediments of the Troutdale Formation.

The age of the intrusion is obviously post Gray's River volcanics and pre-Troutdale Formation. Other small tertiary intrusive andesites have been mapped 8 to 12 km (5 to 7 mi) to the northwest intruding rocks of the Goble Volcanics and Cowlitz Formation. These intrusions are described as being lower Oligocene to upper Miocene (Phillips, 1987).

TROUTDALE FORMATION

The Troutdale Formation was named by Hodge (1933) for quartzose and lithic sands and gravels exposed at Troutdale, Oregon. Schlicker and others (1972) described quartzitic and acid igneous gravels set in a light-colored, fine-grained matrix on the Astoria Peninsula and suggest that the gravels are correlative with the Troutdale Formation based on lithology and outcrop expression. In the Mount St. Helens quadrangle, in which Rainier lies, the Troutdale Formation is thought to be upper Miocene to lower Pleistocene (Phillips, 1987).

In the study area, the Troutdale Formation consists of unconsolidated conglomerates (gravels), clayey silts, silty clays and minor sands (Figure 18). Clast content ranges from 0 to 80%. Clasts are predominantly volcanic with quartzitic pebbles and cobbles comprising 15 to 40% of all clasts. Many of the quartzite clasts are a distinctive light orange. Rare plutonic clasts are present. The

matrix ranges from gray-white silty clays and silts to a dark brown sandy silt. On many slopes underlain by the Troutdale Formation, lag gravel resulting from slope wash covers the surface. The actual clast content is usually far less than surface exposures indicate.

Interbedded clayey silts and silty clays are present throughout the unit. They are generally light gray, gray-brown, and blue-gray. Most have an orange-brown mottling. These clayey silts and silty clays are difficult to distinguish from claystones and siltstones of the weathered portions of the underlying volcanoclastics of the Goble Volcanics.

Within the study area, the Troutdale Formation is a bench-forming valley-fill unit and unconformably rests upon all other units except for recent alluvium. At Rainier, the Troutdale Formation is particularly unstable and is prone to landsliding. As a result, Troutdale sediments can be found at nearly any elevation. Because of this, it is difficult to determine the thickness of the Troutdale Formation in the study area. Based on surficial exposures and drill core provided by the Oregon Department of Transportation, the Troutdale Formation appears to seldom exceed 6 m (20 ft) thick for any one bench deposit.

In the study area, the Troutdale Formation coarsens to the west. West of Nice Creek there is a notable increase in clast size, the matrix of gravels become more silty and

Figure 18. Exposure of a cobble-poor bed of the Troutdale Formation. Note the light colored tuffaceous clayey material.

sandy, and the silty and clayey interbeds have graded laterally into sandy silt and sand interbeds. However, pockets consisting of gravels having a clayey silt matrix are present.

The lack of consolidation, thin nature of deposits, abundant fine-grained matrix, and the bench forming and the blanketing nature of what has been mapped as Troutdale Formation in the study area may indicate that most, and possibly all, of these deposits are reworked sediments from the Troutdale Formation rather than what is typically mapped as Troutdale Formation upstream near Troutdale, Oregon. It is possible that what has been mapped as

Troutdale Formation in the study area is actually deposits of the Columbia River related to the Bretz floods or more common stream terrace deposits associated with down cutting of the Columbia River.

ALLUVIUM

Quaternary alluvium is present on the flood plain of the Columbia River and although not observed, it likely underlies all areas of fill. The alluvium consists of gray-brown and brown sandy to clayey silts interbedded with peat and muck (Smythe, 1986).

ARTIFICIAL FILL

Artificial man-made fills are present adjacent to the Columbia River throughout much of Rainier. Fills consist of wood products resulting from past lumber mill operations, sandy dredge material, and miscellaneous rock and debris fills. The most recent fills, post 1984 Mount St. Helens eruption, are a dredged material composed of coarse volcanic sand, granules and pebbles that are commonly vesicular to scoriaceous and pumiceous.

STRUCTURAL FEATURES

Numerous lineaments were mapped from topographic maps, aerial photographs, and radar imagery (Figure 19). In the study area, however, only one fault was identified which

lies in the valley of Fox Creek. The fault has been mapped on the basis of the abrupt termination of resistant beds of the mixed rock unit of the Gray's River volcanics on the west side of Fox Creek. The fault may be short and have little regional significance.

All beds in Rainier are generally horizontal. Locally, However, beds can dip as much as 10 or 20° to the south or southeast.

GEOLOGIC HISTORY

During the Eocene, at the present site of Rainier, two major events were occurring. One, a large basaltic volcanic pile, the Gray's River volcanics, was building at or near sea level. The center of this pile was probably located west and north of Rainier near the headwaters of the Gray's River as shown by increasing thickness. Concomitant with this volcanism, deposition of the Cowlitz Formation micaceous feldspathic sandstones and siltstones was occurring in a basin marginal to or containing the volcanic highland. Upward fining in the sedimentary rocks obtained from cores of the Oregon Department of Transportation at minus 21 m (70 ft) to near sea level indicate that the basin may have been subsiding during this time. Significant quantities of mica and quartz in the rocks indicate that a distal plutonic source was supplying

Figure 19. Lineaments at Rainier mapped from topographic maps, aerial photographs, and radar imagery.

sediment to the basin in addition to the local volcanic sources.

Near the close of the Eocene and into the Oligocene, increasing volcanic activity immediately to the east caused an influx of volcanic detritus to the basin. Initially, the detritus was primarily clay and silt; later, silt and sand predominated. This crudely coarsening-upward transitional fluvial sequence of volcaniclastic rocks containing minor coal and carbonaceous shale beds may, in part, have been deposited in a deltaic environment. During the time that these volcaniclastics were being deposited, basaltic lavas would occasionally flow onto the sediment and become interbedded. Later into the Oligocene, a change to dominantly basaltic-andesite flows and interbedded pyroclastics occurred to the east and south of the study area (Wilkinson and others, 1946; Phillips, 1987).

After the Eocene, the andesite intrusion was emplaced. In the study area the next event was an erosional period and subsequent deposition of flows of the Miocene Columbia River Basalt Group. Initially, flows of the Grande Ronde Basalt were deposited followed by uplift and erosional downcutting. After the Columbia River had downcut, the flow of the Pomona Member was deposited.

Primarily during the Plio-Pleistocene, the ancestral Columbia River deposited the Troutdale Formation. The

quaternary alluvium has been deposited by the same alluvial processes that operate today.

SLOPE STABILITY

BRIEF SUMMARY OF SLOPE STABILITY THEORY

The following description of slope stability theory briefly summarizes information that is typically addressed in much greater detail in most general reference texts on slope stability.

Landslides are caused when forces driving landsliding become greater than forces resisting landsliding. The ratio of these forces to each other is called the factor of safety and can be represented by the following equation:

$$\text{Factor of Safety (F.S.)} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

Theoretically, when the factor of safety is 1.0 or greater, the slope is not moving, and when the factor of safety is less than one, the slope is moving.

In general, below the root zone in a soil the forces resisting sliding are a result of the shear strength (s) of the soil or rock and the normal force. In clays, the shear strength is provided primarily by cohesion (c) which is the shear strength of the soil without any applied normal force (σ_n) and is the result of an electrochemical bonding between soil particles. In purely cohesive soils, the shear strength is the same at any normal force. In

cohesionless soils, for example, clean dry sands, the shear strength is provided by the frictional resistance of the soil grains as they contact one another. With increasing normal force on the grains, an increasing frictional resistance to sliding is realized. This property is referred to as internal friction, and the angle of a line connecting points of failure on a plot of normal stress versus shear stress is the angle of internal friction (Figure 18). The proportion of shearing resistance increase to increase in applied normal force is the tangent of the angle of internal friction (ϕ). Most soils, such as sandy clays, have both cohesion and internal friction. For soils having internal friction the shear strength can be reduced by pressure exerted by intergranular fluids. This pressure is referred to as pore pressure (u). Pore pressure is subtracted from the normal force to arrive at the effective normal force, that is, the normal force available to increase the frictional component of shear strength. Pore pressures are commonly increased by a rise in the water table or by loading. A rise in the water table is often the result of heavy rains or a prolonged wet season. Landslides are often triggered by these pore pressure increases. All of these relationships are evident in the shear strength equation (Mathewson, 1981):

$$s = c + (\sigma_n - u) \tan \phi$$

where:

s = shear strength

c = cohesion

σ_n = normal force

u = pore pressure

ϕ = angle of internal friction

Cohesion (c) and angle of internal friction (ϕ) are usually determined by laboratory shear testing. Through this testing the Mohr envelope can be constructed and c and ϕ can be read directly from the Mohr envelope diagram (Figure 20).

Cohesion, angle of internal friction, and pore pressure can be estimated through back-calculation using slope stability equations or models. This usually involves

Figure 20. Typical Mohr envelope diagrams.

(A) internal friction only; (B) cohesion and internal friction; (C) cohesion only (from Mathewson, 1981).

assuming or estimating a slip surface, then estimating two of the unknown variables (c , ϕ , or σ_n) and solving for the third.

The stability of a slope can be analyzed by using these strength parameters in conjunction with the driving forces which, for static conditions, are the weight of the soil and the slope angle. For a simple potential planar failure parallel to the ground surface (Figure 21), the stability equation is (Carson and Kirkby, 1972):

$$F.S. = \frac{c + (\sigma_n - u) \tan \phi}{\gamma \cdot z \cdot \sin \theta \cdot \cos \theta} = \frac{\text{soil shear strength}}{\text{downslope force of soil mass}}$$

where:

γ = weight of soil

z = depth to potential failure plane

θ = slope of ground

Figure 21. Stability analysis of an infinite slope subject to shallow slides. $E_n=E_{n+1}$; $X_n=X_{n+1}$; vertical stress = $W/d = \gamma \cdot z \cdot \cos \theta$; shear stress = $\tau = \gamma \cdot z \cdot \cos \theta \cdot \sin \theta$; normal stress = $\sigma = \gamma \cdot z \cdot \cos^2 \theta$; γ = unit weight of soil; $d = 1/\cos \theta$ (from Carson and Kirkby, 1972).

Four types of landslides are generally recognized:

- 1) falls or topples; 2) translational slides; 3) rotational

slides; and 4) fluid flows. Falls generally occur on steep rock slopes. Translational slides generally occur along discontinuities in soil or rock. Rotational slides generally occur in fairly homogenous materials. Fluid flows generally occur as a result of a dynamic force being applied to loose, cohesionless silts and sands or as a result of water mixing with one of the other types of landslides listed above (Mathewson, 1981).

METHODOLOGY

This study has classified the relative slope stability at Rainier by factor mapping methods. The study uses factors that are evidence of slope instability (landslides and ground cracks), factors which control slope stability (strength of geologic units, strength of soil units, and slope), and a factor that is both (vegetation)).

Factor Mapping

Factor mapping relies on identifying, classifying through qualification or quantification, and mapping individual factors that either cause or are associated with a phenomena. For example, weak soils do not cause landslides in and of themselves; however, weak soils in the presence of steep slopes, may result in landsliding. Therefore, the steepness of the slope can be classified

mapped and related to soil strength to determine landslide susceptibility.

After each factor selected is mapped, the maps are overlaid and for any particular area the classes of the different factors are summed. The sums determine the final composite map of probable slope stability.

Compilation of the final relative areal slope stability map requires that data of unequal significance presented on the factor maps be integrated into a single scale of relative slope stability. The individual factor maps vary in the number of classes used to classify any particular factor which has the effect of unequally weighting the factors mapped. At Rainier, the number of classes to be used for any particular factor was determined by observing natural class boundaries. For example, at Rainier three classes were used for landslide distribution because there were areas in landslide, areas of hummocky ground that might be in landslides, and areas that were not in landslides. Vegetation, for another example, had only two obvious classes, areas with dense tree cover and areas without dense tree cover. To equally weight all factors would be nearly impossible because for any specific area the importance of any one factor depends upon the other factors. If the classes in the various factors were weighted so that the maximum value of each factor were the same, the absolute value of the final Relative Areal Slope

Stability Map values would change, but not the relative rank order. For example, the maximum value for vegetation is a 2; if it were weighted so that it was a 4, all areas that are presently 2's would become 4's and the relative rank order of the final map would remain the same.

Factor Selection

Factors selected should be those that are available and useful for determining the probability that an area will experience landsliding. Theoretically, the properties that determine if a soil or rock mass will slide are the soil and rock, or rock mass shear strength parameters cohesion and angle of internal friction, slope, pore pressure, seepage pressure, depth to water table, soil weight, soil depth, root strength, discontinuities, geometry, and dynamic behavior.

Direct determination of these factors through laboratory or field testing cannot be economically measured for planning studies in an area the size of Rainier; however, these properties can be estimated or other factors which relate to or indicate the slope stability of an area can be selected as the factors to be mapped.

The selection of factors and division of factors into classes is judgmental. Different mappers will choose different factors and classify variations within these factors differently. The factors chosen for mapping at

Rainier might be different than those chosen for some other area.

The factors that have been selected for mapping at Rainier are:

1. Strength of Soil Units
2. Strength of Geologic Units
3. Landslide Distribution
4. Slope
5. Ground Cracks
6. Vegetation

Strength of soil units, strength of geologic units, and slopes were selected as factors to be mapped because they are three of the major properties that determine whether or not a slope will fail. It is for this reason that strength of soil or rock, and slope are found in most stability equations.

Landslide distribution and ground cracks were selected as factors to be mapped because they are obvious indicators of unstable ground. Landslides occur only in unstable areas and, therefore, are probably the single best indicator of unstable ground. Ground cracks occur as a result of differential movement of the ground. As such, ground cracks are an indicator of how active the ground is in any area; more active areas tend to have more numerous ground cracks. Vegetation was selected as a factor to be mapped because it is primarily a property that partially

determines whether or not a slope will fail and to a lesser extent because it is an indicator of unstable ground. The root strength provided by vegetation, particularly trees, directly contributes to soil strength. Areas that have experienced, or are experiencing, landsliding can disrupt root growth (e.g., shearing of roots) and thereby inhibit tree growth. In addition, trees can be toppled during landsliding. Lack of trees in an area may indicate that the area has experienced landsliding while dense tree cover tends to strengthen slopes.

Groundwater was not chosen as a factor to be mapped because of its unpredictable variability at this scale and detail.

Use of Factor Maps

The factor maps have been constructed for use in compiling a regional slope stability map. Single factor maps by themselves do not generally provide a valid assessment of slope stability and should not be used independently.

FACTORS

This section describes how the factors are related to slope stability, the methods used in mapping them, and the findings of the factor maps.

Strength of Soil Units

Relationship to Slope Stability. The relationship of soils to slope stability is a function of the shear strength of the soil and the soil depth. Soils which have high shear strengths and are thin are less prone to fail than soils having low shear strengths. Soil strength is controlled primarily by soil texture (grain size distribution). Soil depth at Rainier is controlled primarily by slope, bedrock geology, time exposed to weathering, and geomorphic position.

Methodology. Soils were identified and classified in the field and laboratory. Field methods for classifying soils were primarily qualitative. However, field methods also utilized quantitative techniques for estimating the shear strength of soils. Laboratory tests included tests for plasticity and shear strength of soils. Soil properties published by the Soil Conservation Service and contained in reports of the Oregon Department of Transportation were also reviewed.

Landslides fail in shear, therefore, methods of soil description and classification to determine areal slope stability should determine the shear strength properties of the soils.

A complete and thorough boring, sampling and laboratory shear testing program to characterize the shear strengths of soils at Rainier is beyond the scope of this planning study. As a result, the shear strengths of the soils are estimated by other methods.

Qualitative techniques have been developed which rely on visual examinations of the soils to classify them (Table I). In addition, 8 Atterburg Limits Tests (ASTM D 4318) were run on samples and three 3-point remolded saturated direct shear tests (ASTM D 3080) were conducted (Figures 22 and 23). Also, a Pilcon vane shear apparatus was used in the field (Figure 24). Atterburg's limits tests were run on the direct shear samples to aid in comparison of soils. It is believed that comparing tested soils to untested soils resulted in better estimates of soil shear strengths and soil classes for areas that had no laboratory test data. Outside sources of information were used where available. Soils were classified according to the Unified Soil Classification System (Table II).

Findings. Within Rainier there are large variations in soil strength (Table III). Where slopes are steepest, such as on the north side of the andesitic intrusion, soils tend

TABLE I
FIELD DETERMINATION OF SOIL COMPONENTS
(From Hunt, 1984)

Component	Characteristic	Determination	Component	Characteristic	Determination
Gravel	Dia. 5-76 mm	Measurable	Clay	Dispersion test	Mixed with water in container, particles settle out in 1 to 1 hour (L = 10 cm)
Sand	Coarse	Dia. 2-5 mm		Thread test	Rolls into thin threads in wet state, but threads break when picked up by one end
	Medium	Dia. 0.4-2.0 mm		Strength	High when air-dried, breaks with difficulty
Fine	Dia. 0.074-0.4 mm	Barely discernible to unaided eye		Plasticity	When mixed with water to form paste and squeezed in hand, specimen merely deforms and surface does not change in appearance
Silt coarse	Dia. 0.02-0.074 mm	Distinguishable with hand lens		Dispersion test	Remains in suspension from several hours to several days in container
Sand-silt mixtures	Apparent cohesion	Measured by ball test (Burmister (1949)*)	Organic Soils	Thread test	Can be rolled into fine threads that remain intact. Fineness depends on clay content and mineralogy. Thread diameter when saturated vs. PI and identification given on Table 5.35
		Form ball in hand by compaction moist soil to diameter 1 in (25 mm)		Adhesion	Sticky and greasy feel when smeared between fingers
		Medium to fine sand forms weak ball with difficulty; cannot be picked up between thumb and forefinger without crushing		Strength	Relatively high when air-dried
		Ball can be picked up with difficulty; 50% silt		Odor	Decayed organic matter; gases
Silt vs. clay	Dia. <0.074 mm	See also Table 5.37	Organic matter		Root fibers, etc.
Silt	Strength	Low when air-dried, crumbles easily		Shrinkage	Very high
	Dilatancy test	Mixed with water in thick paste consistency. Appears wet and shiny when shaken in palm of hand, but when palm is cupped and sample squeezed, surface immediately dulls and dries.			

SYMBOL	SAMPLE LOCATION	FIELD MOISTURE (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTICITY INDEX (%)	UNIFIED SOIL CLASS
⊙	1- 7-15	---	51.0	33.1	17.9	MH
△	1-11-9	---	44.2	34.0	11.2	ML
x	1- 7-5	---	43.0	30.8	12.2	ML
□	8- 6-3	---	43.1	26.9	16.2	ML
⬡	1- 7-14	---	43.0	22.1	20.9	CL
•	1-12-2	---	48.0	NP	---	ML/SM
◇	7- 6-2	---	67.0	28.7	38.3	CH
▽	9-25-5	---	87.5	28.1	59.3	CH

ATTERBERG LIMITS TEST RESULTS

Figure 22. Atterburg limits test results (ASTM D 4318).

SYMBOL	SAMPLE LOCATION	COHESION (psf)	FRICTION ANGLE (°)	REMARKS
□	8-6-3	350	31.5	7 points run because of pore pressure effects
○	1-7-15	230	26.0	
◇	7-6-2	100	22.0	

DIRECT SHEAR TEST RESULTS

Figure 23. Direct shear test results (ASTM D 3080).

Figure 24. Pilcon vane shear apparatus.

to be thin, rocky, and strong. Plate 5 shows the distribution of soil strengths at Rainier. Flatter slopes tend to have deeper, finer-grained soils that are relatively weak. Most soils in Rainier are greater than 2 m (6 ft) deep. Soils within Rainier include residual and alluvial soils, and artificial fills. Most moderately and steeply sloping ground has residual soils developed on the underlying bedrock. Alluvial soils have developed on alluvium along the Columbia River. Large areas of sandy artificial fill are present adjacent to the Columbia River.

Atterburg Limits test results (Figure 24) and field examination show that soils in Rainier are primarily low

TABLE II

UNIFIED SOIL CLASSIFICATION SYSTEM (From Hunt, 1984)

UNIFIED SOIL CLASSIFICATION SYSTEM (ASTM D-2487)

Major Divisions	Group Symbols	Typical Names	Laboratory Classification Criteria
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size) Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines
		GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
		GM ^a d	Silty gravels, gravel-sand-silt mixtures
		GM ^a u	Clayey gravels, gravel-sand mixtures
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size) Clean sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines
		SP	Poorly graded sands, gravelly sands, little or no fines
		SM ^a d	Silty sands, sand-silt mixtures
		SM ^a u	Clayey sands, sand-clay mixtures
	Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows: Less than 5 per cent More than 12 per cent 5 to 12 per cent		$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3 Not meeting all gradation requirements for GW
			Atterberg limits below "A" line or P.I. less than 4 Above "A" line with P.I. between 4 and 7 are <i>borderline</i> cases requiring use of dual symbols Atterberg limits below "A" line with P.I. greater than 7 $C_u = \frac{D_{60}}{D_{10}}$ greater than 5; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3 Not meeting all gradation requirements for SW Atterberg limits above "A" line or P.I. less than 4 Limits plotting in hatched zone with P.I. between 4 and 7 are <i>borderline</i> cases requiring use of dual symbols
Fine-grained soils (More than half material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
		OL	Organic silts and organic silty clays of low plasticity
	Silts and clays (Liquid limit greater than 50)	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
		CH	Inorganic clays of high plasticity, fat clays
		OH	Organic clays of medium to high plasticity, organic silts
	Highly organic soils	Pt	Peat and other highly organic soils

^a Division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is based on Atterberg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less, the suffix u used when L.L. is greater than 28.
^b Borderline classifications, used for soils possessing characteristics of two groups, are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder.

TABLE III
STRENGTH, DEPTH, AND CLASSIFICATION OF SOIL UNITS

Soils Overlying	Depth (ft.)	Cohesion lb/ft. ²	Angle of Internal Friction (degrees)	Unified Soil Classification
Gray's River Volcanics Flow Unit	None	N.A.	N.A.	N.A.
Volcaniclastic Unit	4 - >6	100 - 250	25 - 33	MH, ML, CL, SM
Goble Volcanics Volcaniclastics Flow Interbed	>>10 >4	100 - 350	23 - 28	ML, MH to CH ML to MH
Columbia River Basalt	0 to >6	200	30	ML
Intrusive Andesite	0 to 3	50	40	GM
Troutdale Formation	>10	100 - 200	20 - 35	ML to CH
Alluvium	>>10	100 - 200	25 - 35	ML to CL
Artificial Fill	Variable	Variable	Variable	Variable

plasticity silty soils to high plasticity clayey and silty soils. Low plasticity soils are generally located in those areas where the underlying parent material is basaltic lavas, breccia and coarser-grained volcanic sediments. These rock types are generally found in the Gray's River volcanics. Weaker high-plasticity clayey soils are generally found on tuffaceous rocks of the Goble Volcanics and the weakly consolidated tuffaceous rocks of the Troutdale Formation in the eastern part of the study area. These weak soils cover nearly the entire old section of Rainier east of Fox Creek. In some of the area of the Troutdale Formation, particularly in western Rainier, gravelly, strong alluvial soils are present. In eastern Rainier strong gravelly soils are commonly underlain by and interbedded with very weak clayey soils. Where this occurs, the overall strength of the soil mass is low.

Soils developed on recent alluvium and artificial fill in Rainier have variable strengths with depth. Coarse-grained alluvial soils that have developed from sandy material are interbedded with weak clayey and silty soils developed from fine-grained material. The alluvial soils and artificial fills lie on flat or nearly flat ground and, therefore, do not pose a landslide hazard except possibly for liquefaction potential which has not been assessed in this study.

Plate 5. Factor map of soil strength at Rainier, Oregon.

Strength of Geologic Units

Relationship to Slope Stability. Like soils, the relationship of the geologic bedrock units to slope stability is a function of their shear strength. Rocks and rock masses with high shear strengths are less prone to failure than rocks and rock masses having low shear strengths. Another important factor is the depth at which the rock is found. Strong rocks at shallow depths inhibit deep-seated landslides. Each unit described in this section is shown on the geologic map (Plate 3). Geologic units in this area are defined primarily on the basis of an association of rock types. For a more detailed description of the geology of these units, see the section entitled "Geology."

The geologic units at Rainier have been subjected to fracturing, and physical and chemical weathering. Because the intensity of these processes among and within the geologic units has varied, and because the lithologies vary within and among the geologic units, the strength properties also vary within and among the geologic units. However, strength properties within geologic units are generally less variable than among geologic units. As a result, using geologic units is a convenient method of defining different groups of strength properties. Statements regarding strength properties of a unit should not be

considered accurate for every area in that unit; extreme variabilities do exist.

Methodology. Shear strength testing of rock and rock masses is much more expensive than shear strength testing of soils. Therefore, simple methods for estimating rock strength have been developed. The method utilized herein was developed by Williamson (1984) and is based on observing the reaction of a rock hammer struck on an outcrop (Appendix B). Depth to rock is estimated from field observations.

The strength of rock masses is affected by discontinuities such as bedding, jointing, fracturing, faulting, and weak beds. The geometry of the discontinuities tend to weaken the rock mass when they are daylighted (have an angle less than the slope of the ground surface).

The strength of a rock joint is determined by:

1) joint roughness (i.e., the number and angle of asperities); 2) filling material; 3) water within the joint; and 4) strength of the rock material (Mogilevskaya, 1974). However, in the study area a simple joint description scheme was used that merely involved describing joint patterns.

Findings. The strength of geologic units in Rainier is extremely variable (Table IV and Plate 6). The unconfined compressive strength of rocks in the geologic units ranged

from less than 7 MPa (1000 psi) to greater than 103 MPa (15000 psi).

The strongest geologic unit in Rainier is the basalt unit of the Gray's River volcanics exposed in the quarry by the Rainier-Longview bridge. The rocks here had unconfined compressive strengths greater than 8000 psi. The mixed rock unit of the Gray's River volcanics has extremely variable strength rocks. Rocks in this unit hammer tested from less than 1000 psi to greater than 8000 psi unconfined compressive strength. Because these varying strength rocks are interbedded, the overall strength of the unit is intermediate between very strong and very weak.

The Goble Volcanics consist of rocks with less than 1000 psi unconfined compressive strength in the volcanoclastics and 3000 to greater than 8000 psi unconfined compressive strength rocks in the interbedded flows.

The Troutdale Formation is composed of less than 1000 psi unconfined compressive strength rock throughout and in most areas behaves like a soil with no rock-like characteristics.

Landslide Distribution

Relationship to Slope Stability. The distribution of landslides is one of the most important factors in determining regional slope stability. The fact that the ground in an area has undergone landsliding is indicative

TABLE IV
STRENGTH OF GEOLOGIC UNITS

Geologic Unit	Unconfined * Compressive Strength (psi)	Jointing
Gray's River Volcanics Flow Unit	8000 to >15000	Columnar to Blocky
Volcaniclastic Unit	<1000 to 15000	Sheared to Massive
Goble Volcanics Volcaniclastics Flow Interbed	<1000 3000 to 15000	None Blocky
Columbia River Basalt	8000 to 15000	Columnar to Blocky
Intrusive Andesite	8000 to 15000	Columnar to Blocky
Troutdale Formation	<1000	None
Alluvium	<1000	None
Artificial Fill	<1000	None

*See Appendix B for description of methods of determination.

Plate 6. Factor map of strength of geologic units at Rainier, Oregon.

of the ground's weakness. In addition, the process of landsliding further weakens the ground even though the driving forces may have been reduced after sliding because of a decrease in slope angle. Within a landslide the ground can become severely disrupted, even chaotically mixed, altering the groundwater regime which can increase pore pressures. Soil shear strengths are reduced by landsliding because shearing of the soil along slip planes reduces soil shear strength values from peak to residual.

Often times, the only indication of very ancient landslides is hummocky topography. Landslide hummocky topography results from the lumpy nature of some landslide deposits and the deranged drainage which occurs on landslides.

Scarps formed by landsliding are oversteepened slopes. As a result, they are prone to failure and so were considered to be within the landslide.

Methodology. Landslide features were mapped from stereo pairs of aerial photographs. Photographs from the years 1983, 1982, 1980, 1970, 1963 and 1953 were interpreted. False color infrared, and black and white panchromatic photos were used in the interpretation. Photo scales varied from 80 m/cm to 470 m/cm (670 ft/in to 3,920 ft/in). Information obtained from the aerial photos was plotted on the factor map of landslide distribution.

Landslide scarps and deposits and hummocky ground were delineated from the aerial photos. All landslides on the photos appear to be large, ancient slides; no recent slides were observed on the photos. However, young, active slides that are not discernible on aerial photos were observed in the study area.

Recognition of both recent and ancient landslides is dependent upon identifying geologic and morphologic features indicative of landslides. The following features are some of the common indicators of landsliding (Nilsen, 1972; Zaruba and Mencl, 1969):

1. Anomalous drainage patterns
2. Anomalous stream channel features
3. Topographic lumps
4. Large scale changes in slope
5. Scarps
6. Hummocky topography
7. Lobate forms
8. Surface cracks and linear depressions
9. Springs
10. Closed depressions and ponds
11. Disrupted bedrock geology
12. Anomalous or disturbed vegetation

Not all of these features are found on all landslides.

The formation of landslides is an extremely rapid process when compared to most other slope-forming

processes. As a result, landslides often sharply contrast with the uniform appearance of the adjacent slopes. Recognition of landslides becomes increasingly difficult as landslides age. Initially, landslide features are sharp, but with time weathering and erosion modify landslide features to the point where they become difficult or even impossible to recognize.

Findings. Landslides and hummocky topography large enough to be identified on aerial photographs are shown on Plate 7. Areas of active landsliding in Rainier are primarily located on the deep, weak soils and rocks found in the old section of Rainier east of Fox Creek. Within the older section of Rainier, active landslides exist that have features too small to identify on aerial photographs. These landslides were identified during field inspection using features such as tension and shear cracks, and displacements in structures such as walls, foundations, curbs, and sidewalks. The cracking in these structures indicates that these landslides have been active since the structures were built.

Ancient landslides were identified on aerial photographs in the area west of Fox Creek underlain by Gray's River volcanics and the Troutdale Formation. None of the landslides west of Fox Creek showed any evidence in the field of being presently active.

Plate 7. Factor map of landslide distribution at Rainier, Oregon.

Active landslides too small to identify on aerial photographs do exist throughout much of Rainier.

Generally, no evidence of landsliding was observed on flatter ridge-top areas and areas within Rainier along the Columbia River that are underlain by alluvium and fill.

Slope

Relationship to Slope Stability. The effect of increasing slope as a contributing factor to landsliding is critical. All slope stability equations have slope as one of the variables that must be defined. The importance of slope is clearly illustrated in that for a slope composed of dry, cohesionless sand, the factor of safety may be expressed as:

$$\text{Factor of Safety} = \frac{\text{tangent of angle of internal friction}}{\text{tangent of slope angle}}$$

Therefore, no slope on clean dry sand can attain an angle greater than the angle of internal friction (Terzaghi and Peck, 1948). Most soils have at least some cohesion which allows them to stand at angles greater than the angle of internal friction for at least short periods of time.

Methodology. The slope map for Rainier was modified from the soil survey map prepared by the Soil Conservation Service (Smythe, 1986). Boundaries between slope classes shown on the soil survey map were altered or omitted and additional classes were added based on the expression of

slope as shown on the United States Geological Survey (U.S.G.S.) 7.5-minute series topographic map of the Rainier Quadrangle, Oregon-Washington.

Six slope classes were delineated based on natural slope breaks. The slope classes are as follows: 1) 0-3%; 2) 3-7%; 3) 7-15%; 4) 15-30%; 5) 30-50%; 6) 50% and greater. There is a 1% overlap in each category; this reflects the difficulty in drawing the class boundaries. Any one class may contain small areas of any other class.

Findings. The distribution of different slope classes in Rainier is shown on Plate 8. The steepest natural slopes in Rainier are found on the north side of the andesitic intrusion, the north side of the hill west of the intrusion, and on the flow interbeds of the Goble Volcanics. These slopes, like many in Rainier, are stream terrace escarpments. Slopes steeper than 30% have formed on much of the Gray's River volcanics. Slopes of 3 to 30% have formed on the volcaniclastics of the Goble Volcanics and the Troutdale Formation where it overlies volcaniclastics of the Goble Volcanics. Slopes less than 3% are present on recent alluvium and artificial fill. The steepest slopes in the study area are the man-made slopes found on the quarry face at the south end of the Rainier-Longview bridge.

Plate 8. Factor map of percent slope at Rainier, Oregon.

Ground Cracks

Relationship to Slope Stability. Cracks in the ground are commonly associated with areas of active creep or landslide. As such, they are a useful indicator of unstable ground. Ground cracks often result from differential rates or direction of movement. However, cracks showing differential movement can also have other causes, such as settlement or shrink-swell of soils.

Methodology. In Rainier, cracks were mapped at a scale of 1 cm = 24 m (1 in = 200 ft) on a plat map of the city. Cracking in street pavement, curbs, sidewalks, and buildings was observed and mapped. The number of cracks on each side of each city block in sidewalks and curbs that were thought to be related to soil movement were counted.

The determination of which cracks were related to soil movement is subjective. Only cracks showing significant vertical or horizontal displacement were considered to be related to soil movement.

Because the area of Rainier showing cracking had clay soils, there existed the possibility that the cracking resulted from shrink-swell of the soils. Therefore, one soil from the volcanoclastics of the Goble Volcanics, one sample from the Troutdale Formation, and one sample from colluvium in the mixed rock unit of the Gray's River volcanics was analyzed by x-ray diffraction methods

(Appendix C). It was hoped that x-ray diffraction would determine the amount and types of clays present in the samples. Clay content of the soil was somewhat higher in the area of Rainier showing cracking and, therefore, some cracks showing displacements may have been caused by shrink-swell. However, the swelling clay content was not significantly higher.

Crack mapping was complicated by many factors. These factors included variance in age of structures and areas of the city that lacked structures such as curbs or sidewalks. In areas having no sidewalks or curbs, other structures were examined such as pavement, building foundations, and walls. From the plat map, general areas of cracking were noted and plotted on the base map. One general area of cracking and one general area of more frequent cracking were observed.

Findings. The distribution of ground cracks in Rainier is shown on Plate 9. All areas having substantial ground cracking lie in volcanoclastic rocks of the Goble Volcanics and the overlying Troutdale Formation in the old section of Rainier east of Fox Creek. More frequently cracked ground on the lower slopes here appears to have resulted from active creep and landsliding.

West of Fox Creek areas of minor extent having cracked ground were observed in the field. These areas of cracked ground west of Fox Creek were associated with small, active

landslides and were too small to show on the map of ground cracks.

Vegetation

Relationship to Slope Stability. The presence of deep-rooted vegetation such as trees has been shown to have a significant impact on reducing the likelihood of landsliding in an area (Burroughs, 1980). The following quote from Burroughs (1980, p.10), a prominent researcher in the field dealing with the effects of vegetation in landslide prevention supports this point:

Vegetation directly influences slope stability by providing root tensile strength to increase soil shear strength, although this process is not yet completely understood or quantitatively defined for all situations. Much of our knowledge of the relationship between tree root strength and mass failures is correlative based upon observations of increased frequency of landslides 3-5 years after timber harvest and decreasing with time thereafter.

In addition to improving slope stability through soil strengthening, vegetation also improves stability by reducing the amount of water held in storage by the soil through evapotranspiration processes, lowering pore pressures within the soil mass (Swanston and Swanson, 1976). This decrease in pore pressure increases stability.

All of the tree root strength is contributed as apparent cohesion. The amount of increase in slope stability as a result of tree root strength varies depending on tree species. This apparent cohesion is

Plate 9. Factor map of ground cracks at Rainier, Oregon.

provided by the tensile strength of the roots which for coastal Douglas fir averages 510 Kg/cm^2 (Gray, 1978).

The effect of tree root strength is greater for shallow soils (<2m, (6 ft)) than for deep soils. In shallow soils the tree roots penetrate into the bedrock below, therein anchoring the soil to the bedrock (Burroughs, 1980).

Methodology. Areas of dense tree cover were observed on stereo pairs of aerial photographs and delineated on the base map.

Findings. Vegetation distribution is shown on Plate 10. Trees are most prevalent on the sides of the hills; ridge tops and flatter developed areas have very few trees. Most of the more clayey soils lack tree cover. Recent alluvium is generally not wooded.

RELATIVE AREAL SLOPE STABILITY MAP

Methodology

For any given area in Rainier the relative slope stability of that area was determined by summing the classes on each of the different factor maps for that given area. After doing this for all areas on the map, the lowest number obtained was subtracted from all the numbers so that the final numbers on the relative areal slope stability map (Plate 11) would begin at "0" representing the least unstable areas and continue to "10" representing the most unstable areas.

Plate 10. Factor map of vegetation at Rainier, Oregon.

Interpretive license was used to increase or decrease the relative areal slope stability class by one point. This was done because none of the factors accounted for conditions such as small-scale natural benching of slopes or anchoring of thin soils to bedrock by vegetation on very steep slopes. This interpretive license was particularly necessary on the north side of the andesitic intrusion where the relative areal slope stability was increased by one class over the summed value. The vast majority of the areas on the relative areal slope stability map were neither increased or decreased from their summed values.

During compilation of the relative areal slope stability map, it was necessary to omit small areas of different summed values to keep the map readable and so that the map would not be overly detailed for city planning.

Findings

The most stable areas, 0 and 1 on Plate 11, in Rainier are on the flatter areas underlain by alluvium and fill adjacent to the Columbia River, on the scabland terrace west of Fox Creek and on the flatter ridge-top underlain by Grande Ronde Basalt in the southwest corner of the study area. The least stable areas, 7 through 10 on Plate 11, lie east of Fox Creek on ancient landslides underlain by the volcanoclastic rocks of the Goble Volcanics and

NOTE:

The purpose of this map is to give a broad picture of the slope stability of Rainier for use in regional planning. The map should not be used for any kind of detailed stability analyses of sites to be occupied by specific engineering structures.

Decreasing Stability

000000	111111	222222	333333	444444	555555	666666	777777	888888	999999	10 10
000000	111111	222222	333333	444444	555555	666666	777777	888888	999999	10 10
000000	111111	222222	333333	444444	555555	666666	777777	888888	999999	10 10

Numerous factors that control slope stability have been integrated to show the relative stability within the mapped area.

Plate 11. Relative areal slope stability at Rainier, Oregon.

tuffaceous beds of the Troutdale Formation. Recent activity in much of the old section of Rainier east of Fox Creek is indicated by cracks in structures. Areas not included above can be considered moderately stable, 2 through 6 on Plate 11. These moderately stable areas are underlain by Gray's River volcanics, Goble Volcanics and the Troutdale Formation. The least stable of the moderately stable areas are found on ancient landslides and hummocky ground.

DISCUSSION OF FINDINGS

The most active landslide area large enough to have a photo interpretable boundary lies in the old section of Rainier east of Fox Creek and is delineated on the crack map (Plate 9) as the area of more frequently cracked ground. This slide area appears to have been the result of the failure of stream terrace escarpments. Downcutting by the Columbia River in the weak Troutdale Formation and volcaniclastics of the Goble Volcanics produced oversteepened slopes which have failed.

Two slope profiles constructed in a generally north-south direction approximately perpendicular to the Columbia River, structure sections B-B' and C-C' on Plate 4, are very different. Profile B-B' shows a well developed terrace cut in strong rock. This well formed terrace was probably present at one time at the same elevation in the area of the old section of Rainier east of Fox Creek, but was probably destroyed by landsliding.

Areas in the old section of Rainier east of Fox Creek that are shown as having cracked ground on the crack map (Plate 9) appear to have experienced deep-seated landsliding in the past. Presently, landsliding in areas of cracked ground is probably primarily shallow.

West of Fox Creek the ancient landslides occurred in weaker rocks within the Gray's River volcanics and the

Troutdale Formation. It is likely that weak tuffaceous interbeds of the Cowlitz Formation and weak tuffaceous beds of the Troutdale Formation are the beds that the slip planes of these ancient landslides primarily lie in.

Future landslides are likely to occur in the same areas as past landslides. In addition, cutting, filling and building on slopes, diverting and concentrating surface drainage, changing groundwater flows, and cutting trees may cause landslides in areas that presently have little or no landslide problem. The areas particularly likely to experience an increase in landsliding as development progresses are those areas which are presently heavily forested or lie on steep slopes. When development of roads and homesites occurs in these areas, slopes will be cut, fills constructed, trees removed and drainage conditions altered. All of these activities have the potential to decrease slope stability. Landslides that occur on the steeper slopes can have a life-threatening potential.

There is a significant potential for future landsliding throughout much of Rainier. Most of Rainier lies in hillside areas mantled by weak soils. When cuts are made, fills constructed, drainage altered and trees removed for land development, the likelihood of landsliding will increase. The amount of increase in landslide hazards will be dependent upon the planning, design and construction utilized in the land development process. Many slopes in Rainier will be difficult to develop because of existing or

CONCLUSIONS

Geologic information necessary for the assessment of slope stability is seldom available in a form readily useable in the planning process. This thesis has been an attempt to provide planners with slope stability data in a form that can be readily used in the planning process.

This thesis provides a regional framework of slope stability within which site-specific studies can be set. It was not the goal of this study to accurately determine the slope stability of every lot in Rainier; rather, the goal was to provide a broad picture of the slope stability at Rainier. The map of relative areal slope stability (Plate 11) achieves this goal.

Initially, it was hoped that the depth and characteristics of the materials involved in landsliding in the more unstable ground in the old section of Rainier east of Fox Creek could be determined. Insufficient information made this impossible. Future studies of landsliding at Rainier should probably concentrate on determining the exact causes and mechanisms of landsliding in the old section of Rainier east of Fox Creek.

The information presented in this study should be of great benefit to parties concerned with the slope stability problems at Rainier.

REFERENCES

- Allen, J. E., 1986, Cataclysms on the Columbia: Allen, Burns, and Sargent, 211 p.
- Beaulieu, J. D.; and Hughes, P. W., 1977, Land use geology of central Jackson County, Oregon: Ore. Dept. of Geo. and Mineral Ind., Bull. 94, 87 p.
- Blanc, R. P.; and Cleveland, G. B., 1968, Natural slope stability as related to geology, San Clemente area, Orange and San Diego counties, California: Calif. Div. Mines Geo., Special Rpt. 98, 19 p.
- Brabb, E. E., Pampeyan, E. H., and Bonilla, M. G., 1972, Landslide susceptibility in San Mateo County, California: U.S. Geological Survey, Miscellaneous field studies map, MF-360.
- Burroughs, Jr., Edward R., 1980, Proposal to develop guidelines for management of unstable lands in the northwestern United States: USDA Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, 50 p.
- Butzer, K. W., 1976, Geomorphology from the earth: Harper and Row, 463 p.
- Carson, M.A.; and Kirkby, J. J., 1972, Hillslope form and process: Cambridge Univ. Press, 475 p.
- Carter, J. W., 1975, The environmental and engineering geology of the Astoria peninsula area Clatsop County, Oregon: Ore. St. Univ. master's thesis, 138 p., unpub.
- City of Rainier, 1989, City of Rainier comprehensive land use plan: Unpub.
- Condon, Thomas, 1880, Astoria shales: American Naturalist, vol. 14, pp. 457.
- Dana, J. D., 1848, Geology of U.S. exploring expeditions under Charles Wilkes: American Journ. of Sci., vol. 45, pp. 104-311.

- Diller, J. S., 1896, Geological reconnaissance in northwestern Oregon: U.S. Geol. Survey, 17th annual report pt. 1, pp. 441-457.
- Gray, D. H., 1978, The role of woody vegetation in reinforcing soils and stabilizing slopes: Unpub. paper presented at Symposium on Soil Reinforcing and Stabilizing Techniques in Engineering Practice, Sydney, Australia, Oct. 13-16, 1978.
- Henriksen, D. A., 1956, Eocene stratigraphy of the lower Cowlitz River-eastern Willapa Hills area, southwestern Washington: Wash. Div. of Mines and Geology, Bull. 43, 122 p., 2 plates.
- Highsmith, R. M., Jr., 1973, Atlas of the Pacific Northwest: Oregon State Univ. Press, 128 p.
- Hodge, E. T., 1933, Age of Columbia River and Lower Canyon (abs.): Geol. Soc. Amer. Bull. vol.44, p. 156-157.
- Hunt, R. E., 1984, Geotechnical engineering investigation manual: McGraw-Hill Book Company, 983 p.
- Lowry, W. D.; and Baldwin, E. M., 1952, Late Cenozoic geology of the lower Columbia River valley, Oregon and Washington: Geol. Soc. Amer. Bull., V.63, p. 1-24.
- Mathewson, G. G., 1981, Engineering geology: Charles E. Merrill Publishing Co., 410 p.
- McHarg, I. L., 1969, Design with nature: Amer. Museum of Natural History, Doubleday and Company, Garden City, New York, 198 p.
- Mogilevskaya, S. E., 1974, Effect of geological factors on the shearing resistance along joints in rocks: Proc. 3rd Cong. Int. Soc. Rock Mechanics, vol. II, part A, p. 276-282.
- Newton, V. C.; and Van Atta, R. O., 1976, Prospects for natural gas production and underground storage of pipeline gas in the upper Nehalem River Basin Columbia-Clatsop Counties, Oregon: Ore. Dept. Geol. and Mineral Industries, Oil and Gas Investigations #5, 56 p., 1 plate.
- Nilsen, T. H., 1972, The preparation and use of photo interpretation maps of landslide and other surficial deposits in regional environmental geologic studies: Unpub. 89 p.

- Palmer, L. A., 1967, Marine terrace deformation in Pacific coastal United States: J. Geosciences, vol. 10, art. 1-9, p. 69-81.
- Phillips, W. M., 1987, Geologic Map of the Mt. St. Helens Quadrangle, Washington and Oregon: Washington Div. Geo. and Earth Resources. Open File Rpt. 87-4, 1 sheet, scale 1:100,000, 59 p.
- Phillips, W. M.; Walsh, T. J.; and Hagen, R. A., 1989, Eocene transition from oceanic to arc volcanism, Southeast Washington: Unpublished, U.S.G.S. Red Book Version, January 17, 1989.
- Schlicker, H.G.; Deacon, R. J.; Beaulieu, J. D.; and Olcott, G. W., 1972, Environmental geology of the coastal region of Clatsop and Tillamook Counties, Oregon: Ore. Dept. Geo. and Mineral Ind., Bull. 74, 164 p.
- Schlicker, H. G.; Deacon, R. J.; Olcott, G. W.; and Beaulieu, J. D., 1973, Environmental Geology of Lincoln County, Oregon: Ore. Dept. of Geo. and Mineral Ind., Bull. 81, 171 p.
- Schlicker, H. G., 1988, Foundation investigation report, Dano Compost Facility, 55th Avenue and Columbia Boulevard,, Sec. 18, T. 1.N, R.2E., WM, Portland, Oregon: unpub. rpt., H. G. Schlicker and Associates, Portland, Oregon, 39 p.
- Smythe, R. T., 1986, Soil survey of Columbia County, Oregon: USDA Soil Conservation Service, 197 p.
- Swanston, D. N.; and Swanson, F. J., 1976, Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest: in Donald R. Coates, eds., Geomorphology and engineering; Dowden, Hutchinson and Ross, Stroudsburg, Penn., pp. 199-221.
- Terzaghi, Karl; and R. B. Peck, 1948, Soil mechanics in engineering practice: John Wiley and Sons, 729 p.
- Tolan T. L.; Beeson, M. H.; and Vogt, B. F., 1984, Exploring the Neogene history of the Columbia River: Discussions and geologic field trip guide to the Columbia River Gorge: Oregon Geology, vol. 46, no. 8, pp. 87-97.

- Walsh, T. J., 1987, Geologic map of the Astoria and Illwaco Quadrangles, Washington: Washington Div. of Geo. and Earth Resources, Open File Rpt. 86-4, 1 sheet, scale 1:100,000.
- Warren, W. C.; Grivetti, R. M.; and Norbistrath, Hans, 1945, Geology of northwestern Oregon, west of Willamette River and north of latitude 45°15': U.S. Geol. Survey Oil and Gas Investigation Preliminary Map [OM 42], scale 1:145,728.
- Weaver, C. E., 1912, A preliminary report on the Tertiary paleontology of Western Washington: Washington Geological Survey, Bulletin 15, 80 p.
- Wilkinson, W. D.; Lowry, W. D.; and Baldwin, E. M., 1946, Geology of the St. Helens Quadrangle, Oregon: Oregon Dept. of Geo. and Mineral Ind., bull. 31, 39 p., 1 plate.
- Williams, Howel; Turner, F. J.; and Gilbert, C. M., 1982, Petrography: an introduction to the study of rocks in thin sections: Freeman, 626 p.
- Williamson, D. A., 1984, Unified rock classification: Association of Engineering Geologist Bulletin, Vol. 21, No. 3, pp. 345 354.
- Zaruba, Q.; and Mencl, V., 1969, Landslides and their control: Prague, Elsevier Publishing Company, 202 p.

APPENDIX A

GEOCHEMISTRY

Rock samples from the study area were collected for chemical analysis to help in placing flow rocks into units mapped elsewhere. Nine igneous rock samples from the study area were analyzed by XRF methods for major oxides and trace elements (Table V). Locations where samples were collected are shown on Plate 2.

Two of the samples were suspected of being rocks of the Columbia River Basalt Group (CRBG) (Beeson, 1989, personal communication) and so their chemistry was compared with published geochemical data for rocks of the CRBG (Table VI). Major oxides for sample MBDG9-172 appear to correlate well with Low MgO Grand Ronde Basalt. Sample MBDG4-1188A appeared to correlate well with the Pomona Member of the Saddle Mountains Basalt.

All of the remaining samples (except high SiO₂ Sample MBDG4-1288A) were believed to be either Goble Volcanics or Gray's River volcanics and were, therefore, plotted on a %P₂O₅ versus %TiO₂ plot compiled by Phillips (1987) to distinguish Gray's River volcanics from Goble Volcanics (Figure 25). Samples MBDG4-1188B, C, D and E fell in the

Gray's River volcanics field and samples MBDG4-1288B and C fell in the Goble Volcanics field.

Field relationships indicated that sample MBDG4-1288A was from an andesitic intrusion.

TABLE V
GEOCHEMISTRY OF FLOW ROCKS

Date	MBDG4- 1188A 03NV88	MBDG4- 1188B 03NV88	MBDG4- 1188C 03NV88	MBDG4- 1188D 04NV88	MBDG4- 1188E 04NV88	MBDG4- 1288A 04NV88	MBDG4- 1288B 04NV88	MBDG4- 1288C 04NV88	MBDG9- 1172 04NV88
UNNORMALIZED RESULTS (WEIGHT %)									
SI02	52.74	49.15	50.05	48.70	50.16	59.34	52.18	51.38	56.50
AL2O3	15.18	13.62	13.79	13.03	13.81	17.28	17.74	17.91	13.94
TI02	1.679	3.240	3.491	3.583	3.457	0.917	1.271	1.341	2.012
FE0*	10.22	13.33	13.83	14.14	13.71	6.31	8.62	9.26	11.30
MNO	0.178	0.158	0.205	0.206	0.206	0.106	0.128	0.122	0.175
CAO	10.82	7.59	9.34	9.34	9.26	7.51	9.80	10.48	7.09
MGO	6.80	5.29	4.80	5.08	4.75	4.40	6.46	5.70	3.45
K2O	0.65	0.87	0.95	0.78	0.90	0.62	0.46	0.15	1.64
NA2O	2.49	4.49	3.22	2.31	3.27	3.66	2.86	2.81	3.16
P2O5	0.235	0.575	0.618	0.628	0.609	0.198	0.189	0.190	0.361
TOTAL	100.99	98.31	100.29	97.80	100.13	100.34	99.71	99.34	99.63
NORMALIZED RESULTS (WEIGHT %)									
SI02	52.22	49.99	49.90	49.80	50.09	59.14	52.33	51.72	56.71
AL2O3	15.03	13.85	13.75	13.32	13.79	17.22	17.79	18.03	13.99
TI02	1.663	3.296	3.481	3.664	3.452	0.914	1.275	1.350	2.020
FE0*	10.12	13.56	13.79	14.46	13.69	6.29	8.65	9.32	11.34
MNO	0.176	0.161	0.204	0.211	0.206	0.106	0.128	0.123	0.176
CAO	10.71	7.72	9.31	9.55	9.25	7.48	9.83	10.55	7.12
MGO	6.73	5.38	4.79	5.19	4.74	4.39	6.48	5.74	3.46
K2O	0.64	0.88	0.95	0.80	0.90	0.62	0.46	0.15	1.65
NA2O	2.47	4.57	3.21	2.36	3.27	3.65	2.87	2.83	3.17
P2O5	0.233	0.585	0.616	0.642	0.608	0.197	0.190	0.191	0.362
TRACE ELEMENTS (PPM)									
NI	44	33	23	27	24	62	75	67	6
CR	110	47	42	43	40	69	132	126	21
SC	36	27	28	28	28	20	33	33	28
V	295	271	316	315	311	141	186	180	341
BA	227	249	240	304	249	309	63	68	770
RB	15	14	23	11	21	11	7	3	48
SR	236	292	447	1005	450	556	337	405	325
ZR	134	255	275	289	273	169	115	120	176
Y	29	36	37	40	38	15	19	20	41
NB	14.6	51.8	56.7	58.0	56.5	15.1	9.9	10.7	13.3
GA	20	24	21	24	23	20	17	17	20
CU	43	43	43	51	46	94	114	135	17
ZN	91	118	129	134	130	71	75	74	125

TABLE VI
MAJOR OXIDE COMPOSITION OF COLUMBIA RIVER
BASALT GROUP UNITS
(from Tolan and others, 1984)

Oxide	Grande Ronde Basalt		Wanapum Basalt				Saddle Mts. Basalt	
	Low MgO (23)	High MgO (23)	Frenchman Springs Member (49)	Roza Member (9)	Priest Rapids Member		Pomona Member (5)	
					Rosalia flow (20)	Lolo flow (5)		
SiO ₂	55.23	53.73	51.66	51.22	50.17	49.62	52.37	
Al ₂ O ₃	14.91	15.31	14.65	14.11	14.01	14.26	15.70	
TiO ₂	2.14	1.89	2.97	3.16	3.54	3.09	1.63	
FeO	12.18	11.59	13.87	13.93	14.91	14.34	10.45	
MnO	0.20	0.20	0.22	0.22	0.24	0.25	0.18	
CaO	7.01	8.50	8.12	8.27	8.38	9.01	10.36	
MgO	3.56	4.80	4.24	4.73	4.29	5.05	6.79	
K ₂ O	1.70	1.17	1.23	1.25	1.23	1.04	0.57	
Na ₂ O	2.53	2.32	2.32	2.31	2.36	2.41	1.51	
P ₂ O ₅	0.33	0.29	0.52	0.59	0.68	0.64	0.23	

APPENDIX B

ESTIMATION OF UNCONFINED COMPRESSIVE STRENGTH OF ROCK

The following has been adapted from Williamson (1984):

A reasonable estimate of specimen strength can be made by striking a sample, piece of rock core, or outcrop with the round end of a ballpeen hammer (or with the rounded head end of a 20-penny nail if the specimen is to be preserved). The resulting characteristic impact reaction indicates a range of unconfined compressive strength (Williamson, 1961). The rock specimen or outcrop is struck several times to permit evaluation of uniformity of response, and quality is assigned based on the distinct reaction. The five kinds of reaction are illustrated in Figure 26.

The reaction of a rock specimen to the impact of a ballpeen hammer is distinct and characteristic depending on the range of unconfined compressive strength. The nature of the reaction, not the magnitude of the reaction is used to assign a strength quality to the specimen. Therefore, the reaction is independent of the intensity of the blow within the limitations of the tool used and the investigator's strength.

The five design-limiting conditions of strength based on impact reaction are: 1) rebound quality (RQ), 2) pit quality (PQ) designated by C, 4) crater quality (CQ) designated by D, and 5) moldable quality (MQ) designated by E.

Rebound Quality (RQ)

RQ rock material shows no reaction under the point of impact and is a true brittle-elastic substance in a mechanical sense. The estimated unconfined compressive strength of RQ material is greater than 15,000 psi (103 MPa).

Pit Quality (PQ)

PQ rock material produces a shallow rough pit under the point of impact due to explosive departure of mineral grains. This quality of specimen has an estimated unconfined compressive strength ranging from 8,000 to 15,000 psi (55 to 103 MPa).

Dent Quality (DQ)

DQ rock material produces a dent or depression under the point of impact indicating the presence of pore spaces between mineral grains. This quality of specimen has an estimated unconfined compressive strength ranging from 3,000 to 8,000 psi (21 to 55 MPa).

Crater Quality (CQ)

CQ rock material produces a shearing and upthrusting of mineral grains surrounding the point of impact resulting in a depression which resembles a moon crater. This quality of specimen has an estimated unconfined compressive strength ranging from 1,000 to 3,000 psi (7 to 21 MPa).

Moldable Quality (MQ)

MQ rock is in a condition which can be molded by finger pressure but retains the fabric of intact rock. The unconfined compressive strength for this quality of specimen is less than 1,000 psi (7 MPa).

Figure 26. Reaction to impact of ballpeen hammer: A) rebound quality, no reaction; B) pit quality, rough pit; C) dent quality, smooth depression; D) crater quality, depression with upthrust material around perimeter; E) moldable quality, crumbles with finger pressure.

APPENDIX C

X-RAY DIFFRACTION ANALYSIS

Three samples were analyzed by x-ray diffraction methods to determine bulk mineralogy and clay mineralogy. Table VII presents the results of the analysis and Plate 2 shows the sample locations.

Sample 7-6-2 is from a high plasticity clay soil formed in a tuffaceous bed of the Troutdale Formation. Sample 4-22-88H is from what appears to be a clayey paleosol formed in a tuffaceous pebbly mudstone of the Goble volcaniclastic unit; this sample was obtained from an Oregon Department of Transportation core. Sample 8-6-3 is from a sandy borderline low plasticity silt/low plasticity clay soil formed in a mixed colluvial-residual soil weathered from andesite, volcanic conglomerate, and basalt of the mixed rock unit of the Gray's River volcanics.

The purpose of conducting the clay analysis was to determine if the cracking in the old section of Rainier east of Fox Creek could possibly be the result of a large swelling clay content in the soils there which could cause significant shrink-swell and, therefore, cracking of structures.

The results show that the clay content of samples from the old section of Rainier east of Fox Creek are 6 to 18% higher than for the sample west of Fox Creek. Samples 7-6-2 and 4-22-88H have kaolinite, dehydrated kaolinite, illite, chlorite, and smectite. In addition, sample 7-6-2 has 8% of an expandable mixed layer clay. Sample 8-6-3 is composed of smectite, vermiculite, and dehydrated halloysite.

Although the results do not conclusively show that the old section of Rainier east of Fox Creek has significantly higher amounts of swelling clays than elsewhere, the results do show that clay content of soils are greater in the old section of Rainier east of Fox Creek. This higher clay content may be responsible for the large number of surficial shrinkage cracks noticed during the summer at Rainier and may be responsible for some of the cracking found in structures in the old section of Rainier east of Fox Creek.

TABLE VII
X-RAY DIFFRACTION ANALYSIS

SAMPLE	BULK MINERALOGY			RELATIVE % of <5μ CLAY MINERALS				
	QUARTZ	FELDSPARS	TOTAL CLAY MINERALS	KAOLINITE	ILLITE	CHLORITE	SMECTITE	EXPANDABLE MIXED LAYER NON-EXPANDABLE MIXED LAYER
7-6-2	56		44	12 / 20	21	8	31	8
4-22-88H	44		56	19 / 23	27	20	11	
8-6-3	41	21	38	-- / 13			50	37

Vermiculite

K = Kaolinite

dH = Dehydrated Halloysite