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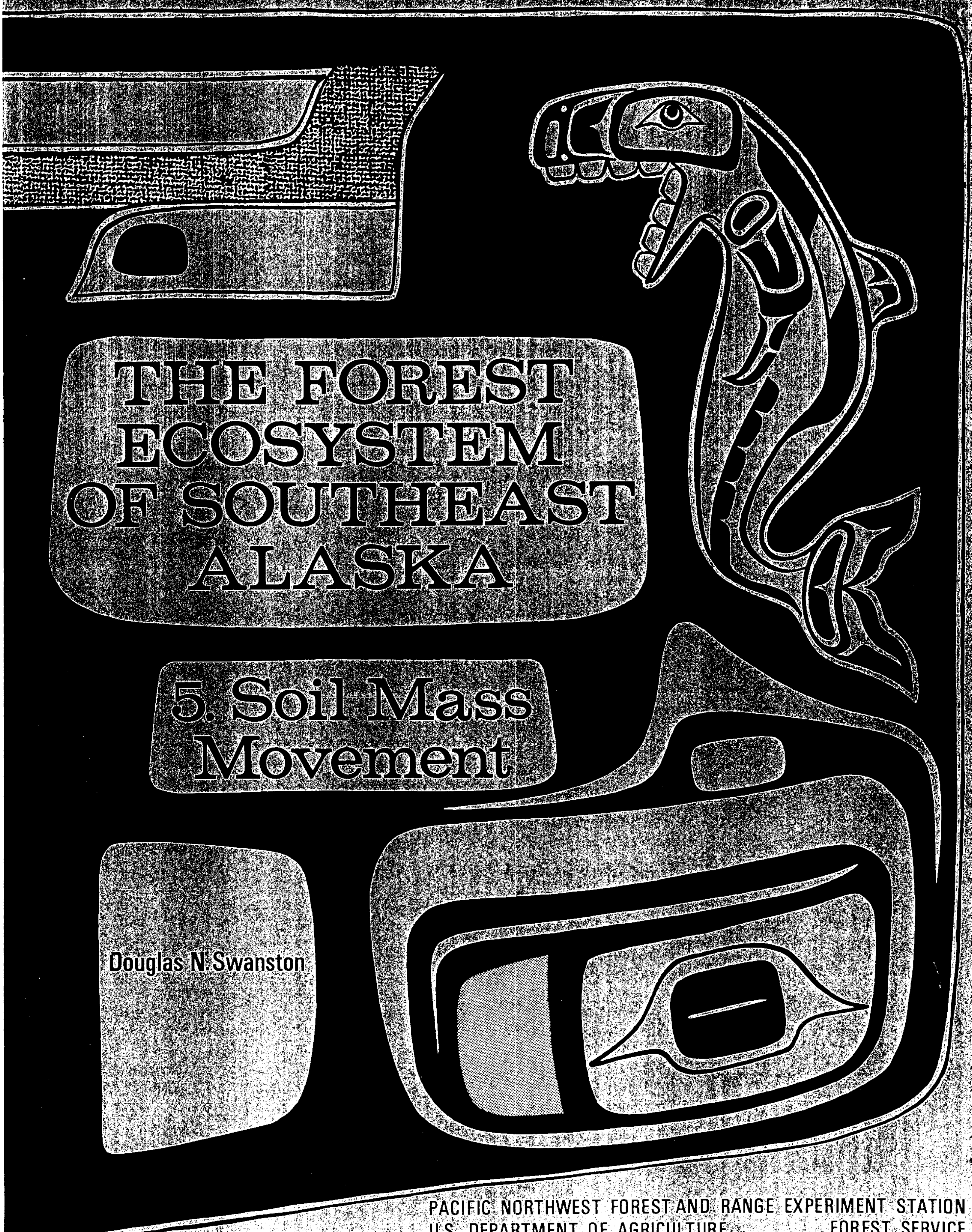

THE FOREST ECOSYSTEM OF SOUTHEAST ALASKA

5. Soil Mass Movement

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ABSTRACT

Research in southeast Alaska has identified soil mass movement as the dominant erosion process, with debris avalanches and debris flows the most frequent events on characteristically steep, forested slopes. Periodically high soil water levels and steep slopes are controlling factors. Bedrock structure and the rooting characteristics of trees and other vegetation exert a strong influence on relative stability of individual sites.

Timber harvesting operations have a major impact on initiation and acceleration of these movements. The cutting of timber itself has been directly linked with accelerated mass movements, and the accumulation of debris in gullies and canyons has been identified as a major contributor to the formation of large-scale debris flows or debris torrents. The limited road construction on steeper slopes thus far has had a relatively small impact.

Effective management practices on such terrain consist of identification and avoidance of the most unstable areas and careful control of forest harvesting operations in questionable zones.

Keywords: Erosion (-forest damage, southeast Alaska.

CONTENTS

INTRODUCTION

Southeast Alaska is characterized by steep slopes, shallow, permeable soils, and exceptionally high rainfall--factors which contribute significantly to unstable conditions in mountainous terrain. Because of high soil permeabilities, slope drainage is primarily by subsurface flow with little or no surface flow outside established channels. When surface flow does occur, the thick mat of forest humus and plant cover is adequate to protect the mineral soil from surface erosion. During major storms, high soil moisture levels and local areas of saturation are produced on the slope, greatly increasing the unstable character of the soils. At the same time, rapid runoff produces high streamflow, maximum bedload movement, and channel scour in the valley bottoms.

Under these conditions, surface erosion is a minimal problem and is mostly restricted to streambank cutting and erosion of bare mineral soil areas. *Soil mass movement, involving the downslope movement of soil primarily under the force of gravity, constitutes the principal natural process of erosion and slope reduction.*

CHARACTERISTICS OF THE MASS MOVEMENT PROCESS

The dominance of soil mass movement as a principal geologic erosion process on steep forested slopes is not unique to southeastern Alaska. Such processes are characteristic of much of the mountainous terrain in western North America where slopes are steep, topographic relief is high, and glacial erosion, tectonic uplift, and rapid or accelerated weathering processes have created extremely unstable natural conditions. Within these sensitive areas, soil mass movements can range widely in surface configuration, speed of movement, and volume of material moved downslope. They can take the form of spectacular debris avalanches and flows or the more subtle, downward creeping movement of an entire hillside.

Based on the mechanics of failure and the factors controlling and contributing to unstable conditions on mountainous forest lands, dominant movements can be grouped into four categories roughly differentiated by movement process, type of failure at the point of initiation, and geometry of the sliding surface. These groups include:

1. Creep. Creep is defined as the slow, gradual, more or less continuous downslope movement of a mass of soil and rock due to gravitational stresses large enough to cause permanent deformation but not large enough to cause failure. Movement is generally by quasi-viscous flow involving the mobilization of the soil mass by breakdown of included

clay structures and progressive failures within the soil mass.[1] Creep occurs in varying degrees on almost all slopes regardless of geology or soil type but dominates as a major process of movement in marine and lacustrine clay deposits and in clay-rich soil materials derived from deeply weathered volcanics, pyroclastics, sandstones, shales, and serpentine-rich rocks.

2. Sliding. Sliding defines mass movements resulting from finite failure of a mass of soil or rock along one or several well-defined planes or surfaces. Sliding can be further divided into rotational or planar failures describing the mode of failure and the geometry of the failure surface.

Rotational failures are characterized by backward rotation of a mass of soil or rock along a more or less circular plane.

Planar failures are characterized by movement of a block of soil or rock along straight or planar surfaces.

Once the mass is in motion, it may (a) move downslope as a unit or in several units, either along rotational failure planes as a slump or along planar surfaces as rock and debris slides; (b) be incorporated as a unit or several units into a mass of unconsolidated material, moving downslope in a semifluid manner as an earth flow; or (c) disintegrate into a rapidly moving debris (soil) avalanche or debris flow.

3. Flows. The flow category discussed above (earth flow) is a mass movement of unconsolidated material exhibiting a continuity of movement and a plastic or semifluid behavior resembling that of a viscous fluid. This movement depends to a large extent on the degree of cohesiveness of the unconsolidated material and the total water content and is the result of either a rotational or planar failure. Earth flows are composed predominantly of cohesive materials. Movements are usually slow, and the water content is highly variable. Debris flows are composed mostly of noncohesive materials (mixed soil, rock, and forest debris) with an exceptionally high water content. They move downslope at high rates of speed as a slurry confined to existing channels and slope depressions.

4. Falls. Falls are a very rapid downward movement of rock or earth, mostly through the air, by free falling, bounding, and rolling. Movements are initiated by rotational or planar failures. A special type of movement included in this category is dry ravel, involving the sliding, rolling, and bounding of individual coarse, cohesionless particles down steep, denuded, or partially vegetated slopes as the result of diurnal freezing and thawing and repeated wetting and drying cycles. A diagram of principal mass movement processes illustrating their major similarities and differences is presented in figure 1.

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[1]Progressive failures begin at a point within the soil mass where gravitational stress becomes equal to stress resistance and spreads outward in a chain reaction as stresses in the surrounding material increase.

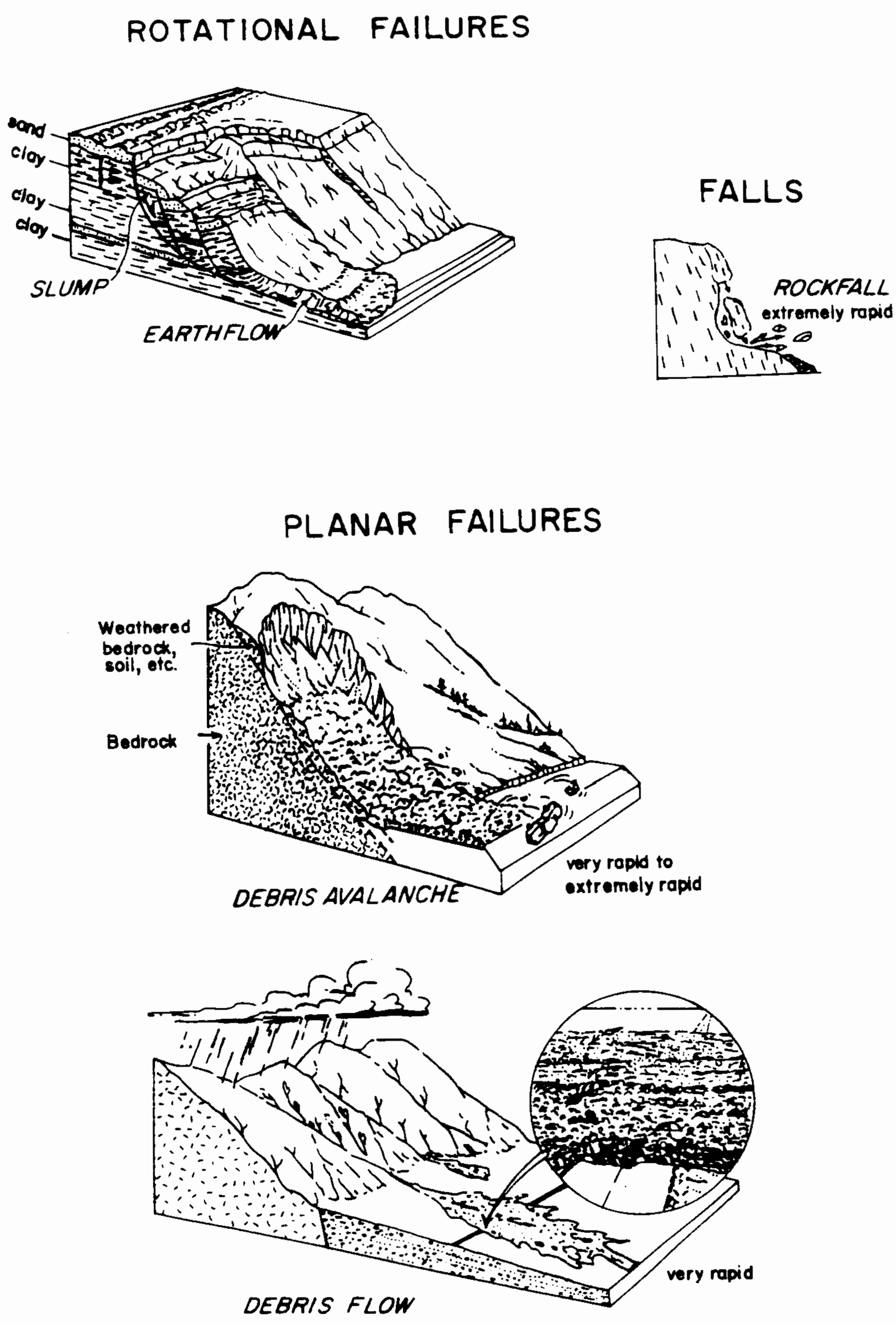

Figure 1.--Diagram of principal mass movement groups found on mountainous forest land. (Adapted from Eckel (1958), with permission of Highway Research Board of the Division of Engineering, National Research Council, National Academy of Sciences, Washington, D.C.)

The mode of failure and downslope movement of these dominant mass erosion mechanisms depends greatly on soil depth, degree of cohesion, and soil water content. As a general rule, debris avalanches and debris flows result from failure of a relatively shallow, cohesionless soil mass on steep slopes as a consequence of surface loading, increased soil water levels, removal of mechanical support, or a combination of all three. Creep, slump, and earth flows most commonly occur on slopes characterized by deep, cohesive soil and parent materials and may be initiated or accelerated by the same modifying conditions. Dry ravel requires bare, granular soil and either lack of surface moisture or presence of surface moisture and active freeze-thaw cycles.

All these types of soil mass movement occur in varying degrees in southeast Alaska, but the great majority develop as debris avalanches and debris flows involving the rapid downslope movement of a mixture of soil, rock, and forest litter with relatively high water content (Swanston 1969) (fig. 2).

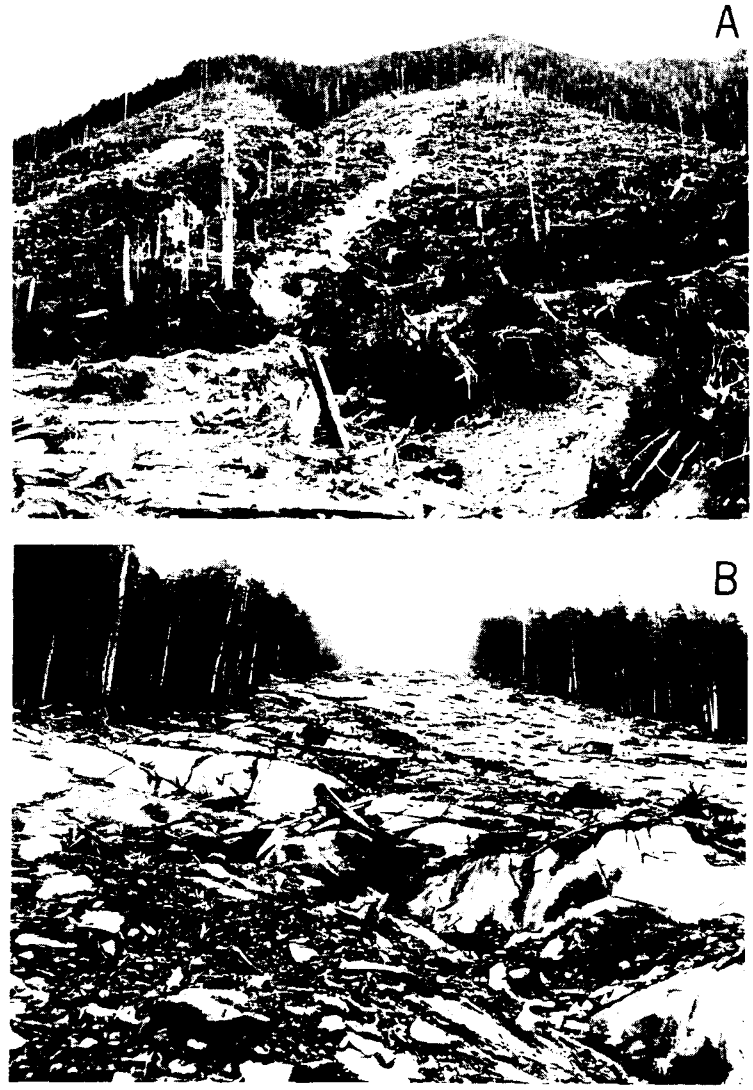

Figure 2.--Recent debris avalanches and debris flows in southeastern Alaska: A, Debris avalanche-debris flow combination developed in a shallow, glacial till soil in the Maybeso valley, Prince of Wales Island. Slope at point of initiation, 37°. B, Debris avalanche on thin, bedrock-derived soil, Martin Creek valley, mainland, Bradfield Canal. Bedrock is diorite jointed parallel to slope. Slope at point of initiation, 40°.

Debris avalanching within canyons and V-notch drainages, coupled with high channel flows and failure of debris dams, frequently produces an especially spectacular, high volume debris flow called a debris torrent (fig. 3). Debris torrents result when debris avalanche material either dams the channel temporarily or accumulates behind temporary obstructions such as logs and forest debris. When these temporary dams fail during periods of high streamflow, a debris torrent results. These are usually confined within the V-notch until the valley floor is reached where the debris spreads out, inundating vegetation and forming a broad surface deposit.

Figure 3.--Debris torrents developed in deep, V-notch side drainages to Maybeso Creek, Prince of Wales Island. All three developed initially above the cutting boundary, probably due to failure of a natural debris dam.

The resulting debris from these mass movement processes may be deposited at the base of the slope or carried directly into a tributary channel or a main stream, producing temporary heavy sediment loads which must be dissipated downstream on the streambed or within bottom gravels. The debris deposit at the base of the slope is usually exposed mineral soil, compacted and impermeable, and is open directly to erosion by surface runoff, at least until vegetation cover is established. Such deposits supply small increments of sediment to the stream over a long period of time and may be much more important to sedimentation of stream gravels than the initial slug supplied during high flow periods.

IDENTIFICATION AND DISTRIBUTION

Air photo reconnaissance of southeastern Alaska[2] has identified more than 3,800 large-scale debris avalanches and debris flows which have occurred within the last 150 years. Evidence of older sliding has been observed in the field in the form of massive landslide deposits, buried soils, and overturned soil profiles.

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[2]A. E. Helmers. Landslide occurrence in coastal Alaska. Study No. 1604-12, data on file, Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, Juneau.

The most recent debris avalanches and debris flows are clearly identified by bare, linear scars down valley side slopes and within V-notch drainages where soil and vegetation are removed. Increasingly older debris avalanche and flow scars are identified successively by strips of pioneering species such as willow (*Salix* spp.) and alder (*Alnus* spp.) and finally by even-age stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (fig. 4). Such successional regrowth on the older slide traces is easily recognized on aerial photographs and provides a convenient means of estimating present stability and past sliding history of a slope.

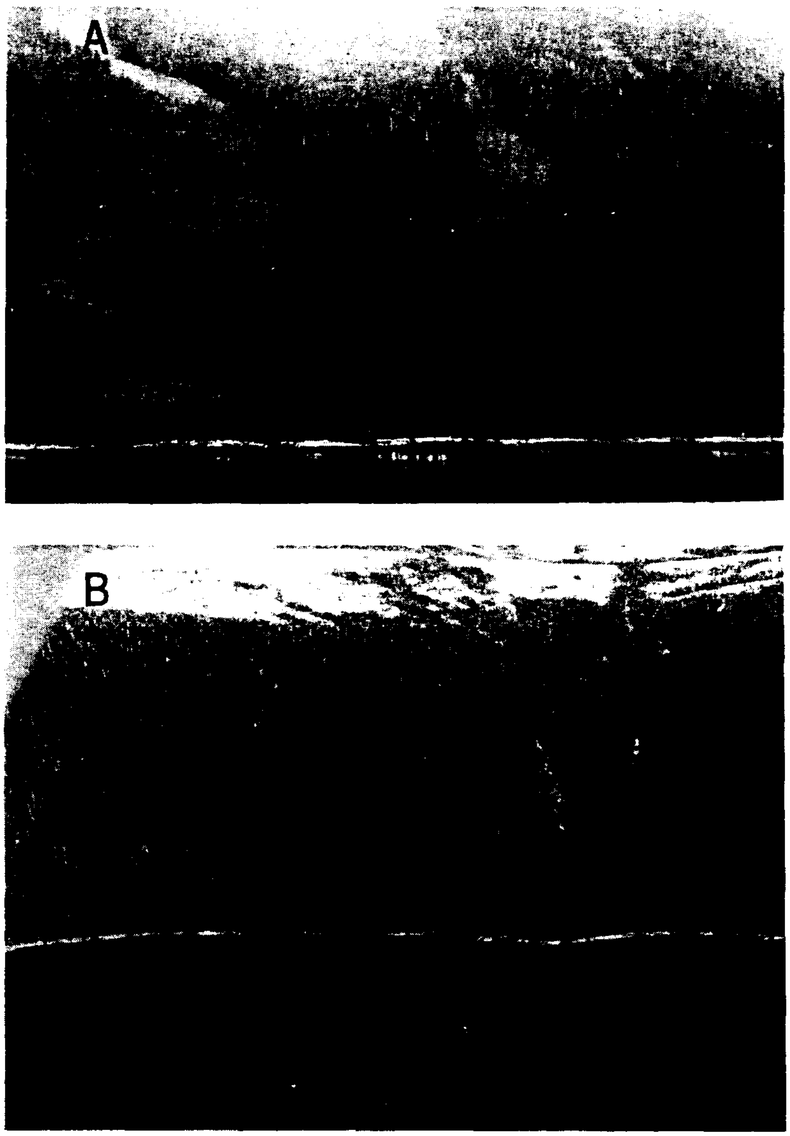

Figure 4.--Aerial views of debris avalanche-debris flow traces showing successive stages of revegetation: A, *Two slide traces revegetated by alder near the head of Walter Island Arm, Port Houghton;* B, *older debris avalanche-debris flow traces along Bradfield Canal marked by even-age stands of Sitka spruce.*

A study of distribution patterns of natural debris avalanches and flows in southeast Alaska (Swanston 1969) has shown principal concentration in two areas roughly corresponding to areas of maximum 5-year, 24-hour rainfall (fig. 5). The larger area includes parts of the mainland adjacent to Behm Canal, Bradfield Canal, and Portland Canal, Revillagigedo Island, and the greater part of Prince of Wales Island. The second area is centered around Peril Strait and includes parts of Chichagof Island, the west coast of Admiralty Island, and the west coast of Baranof Island.

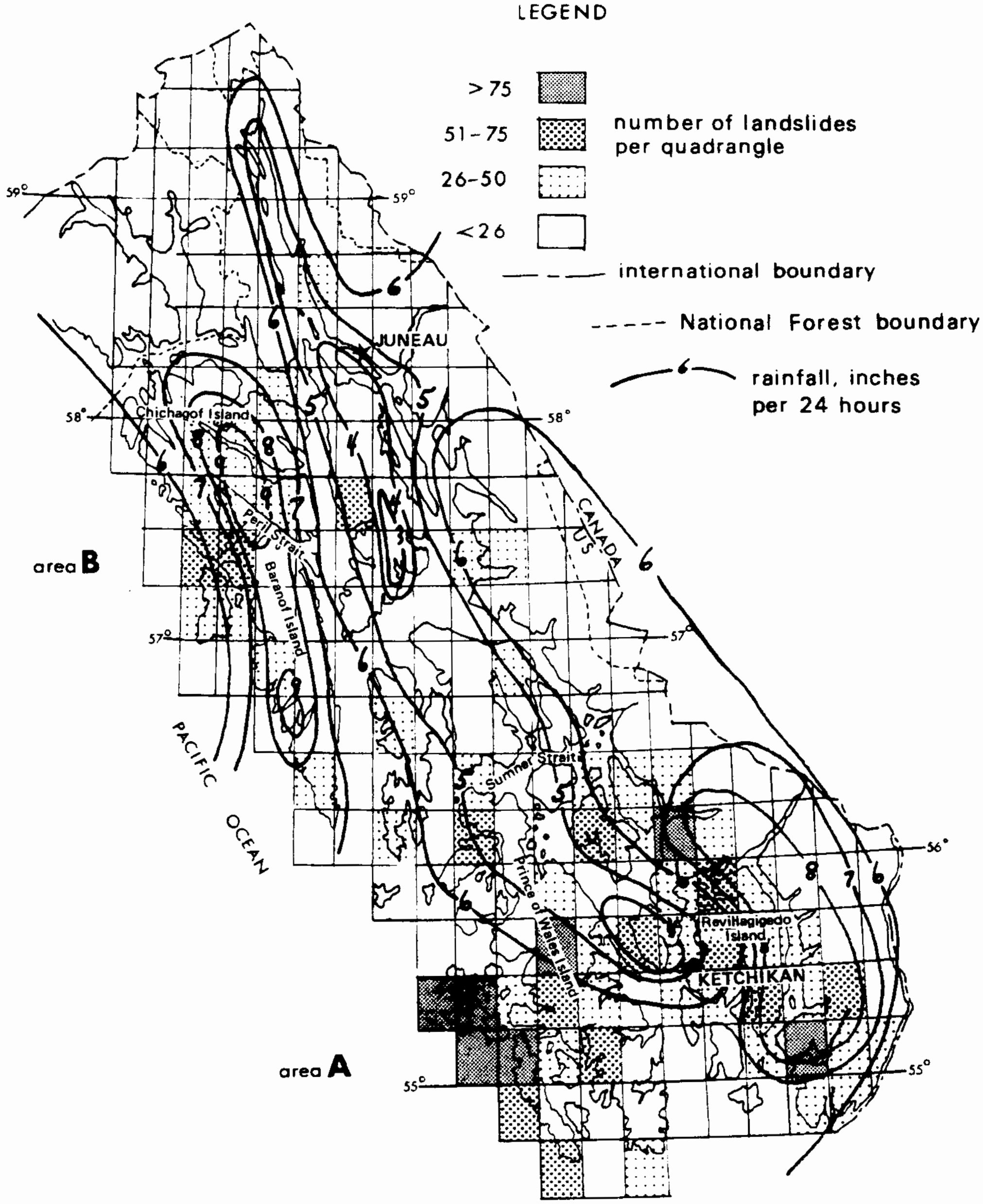

Figure 5.--Relation of landslide distribution to 5-year, 24-hour rainfall occurrence in southeast Alaska. Landslide occurrence expressed as number per 15-minute map quadrangle. Rainfall data adapted from Miller (1963).

These soil mass movements also occur on two distinct parent materials, the distribution of which has been controlled by bedrock type and local glacial activity. Reconnaissance surveys have indicated that debris avalanches and flows occurring on the mainland and interior islands of the Alexander Archipelago (Revillagigedo, Etolin, Mitkof, Kupreanof, and Admiralty) are developed predominantly in shallow soils derived from colluvium or bedrock. Glacial deposits are thin or absent on the upper slopes due partly to resistance of local bedrock to glacial erosion and partly to the distance of the inner island and mainland localities from principal Pleistocene ice centers east of the Alaska-Canada Boundary Range. Failures occur predominantly along planar surfaces controlled by jointing and fracturing parallel to the bedrock surface and produced by stress release following withdrawal of Wisconsin ice.

Debris avalanches and flows occurring on the outer islands of the archipelago (Prince of Wales, Baranof, Chichagof) are developed more commonly in shallow soils derived from the weathering of glacial till. In these areas, bedrock is relatively soft (graywacke, sandstone, shale), and glaciation from local ice centers during the Wisconsin has deposited a veneer of till of varying thickness on many of the valley side slopes to elevations of more than 1,500 feet. Failure in the till soils may be either by rotation along a circular arc tangent to the unweathered till surface or by planar failure along the same surface. Above the level of till deposition, planar failures in colluvial or residual soils again dominate.

FACTORS CONTROLLING STABILITY

The basic mechanics of these soil mass movements is relatively simple; a detailed discussion of the principal characteristics and their interaction can be found in the literature (Terzaghi 1950; Terzaghi and Peck 1962; Taylor 1948; Hough 1957; Swanston 1967a, 1969, 1970, 1971). It is vital that the practicing land manager understand these basics if he is to make sound land use decisions in unstable terrain.

Periodically high soil moisture content and oversteepened slopes are common in all areas. These, along with local parent material type and structure and basic soil characteristics, determine the actual mechanism of failure and the sensitivity of a particular site to perturbations.

Modifying the stability characteristics produced by these basic characteristics are the effects of such external factors as vegetation cover and rooting systems, snow cover, parent material structure, and creep deformation.

Root systems of trees and underlying vegetation may alter soil strength-gravitational stress relationships in several ways. Shear strength tests on roots taken from clearcut units of various ages at Haines, Juneau, Petersburg, Wrangell, and Hollis show a marked decrease in strength 3 to 5 years after cutting.[3] This 3- to 5-year period roughly corresponds to the lag between time of logging and massive debris avalanching at Hollis (Bishop and Stevens 1964). In this case, tree roots are probably functioning to increase shear strength in the unstable soils. Such an external shear strength factor can result from:

1. Roots anchoring through the soil mass and into seams and fractures in the parent material.

2. Roots providing a continuous long fiber adhesive binder to the entire slope soil mass.

3. Roots tying the slope together across zones of weakness and instability to more stable soil masses.

4. Roots providing downslope support to an unstable soil mass through buttressing.

In southeast Alaska soils, all four of these actions are important, but the anchoring effect of the roots dominates and is probably a major factor in stabilization of oversteepened slopes.

Tree roots also accelerate slope failure in these shallow soils through the loosening effect of swaying trees and the total disruption of the soil mass by windthrow. When windthrow occurs, the anchoring effect of roots is destroyed, the soil surface is opened to direct water inflow, the soil mass is loosened, and the toe of the slope immediately above the root wad is undercut. The result is a rapid reduction in soil strength at the site. This natural catastrophe is believed to be an important triggering device for natural debris avalanches and flows in southeast Alaska (Swanston 1967b, 1969).

Vegetation cover helps control the amount of water reaching the soil and the amount of water stored in the soil, largely through a combination of interception and evapotranspiration.

In southeast Alaska, the vegetative influence on water in the soil is highly significant in determining the hydrology of forested slopes but is of little significance in influencing mass soil movement.

Interception is probably negligible due to high total rainfall, particularly during large storm events important to soil mass movement. Evapotranspirational withdrawals of soil moisture may be effective in reducing the rate at which saturation occurs at the beginning of the first storm following a dry period, but the evapotranspirational effect becomes largely overshadowed by total precipitation during the rainy season. These shallow soils probably recharge rapidly and, after reaching full capacity, attain saturated conditions and maximum instability quickly during major storms. Measurements of ground water fluctuations at Hollis

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[3]D. N. Swanston and W. J. Walkotten. Tree rooting and soil stability in coastal forests of southeastern Alaska. Study No. FS-NOR-1604:26 on file at Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, Juneau, Alaska.

(Swanston 1967c; fig. 6) tend to verify this rapid recharge. These measurements show a close correlation between rise in ground water level and increases in rainfall. A short lag in ground water level increase occurred at the beginning of the rainy season reflecting the time necessary for soils to reach saturation after a summer of evapotranspiration, but thereafter, fluctuations in water level closely followed rainfall variations.

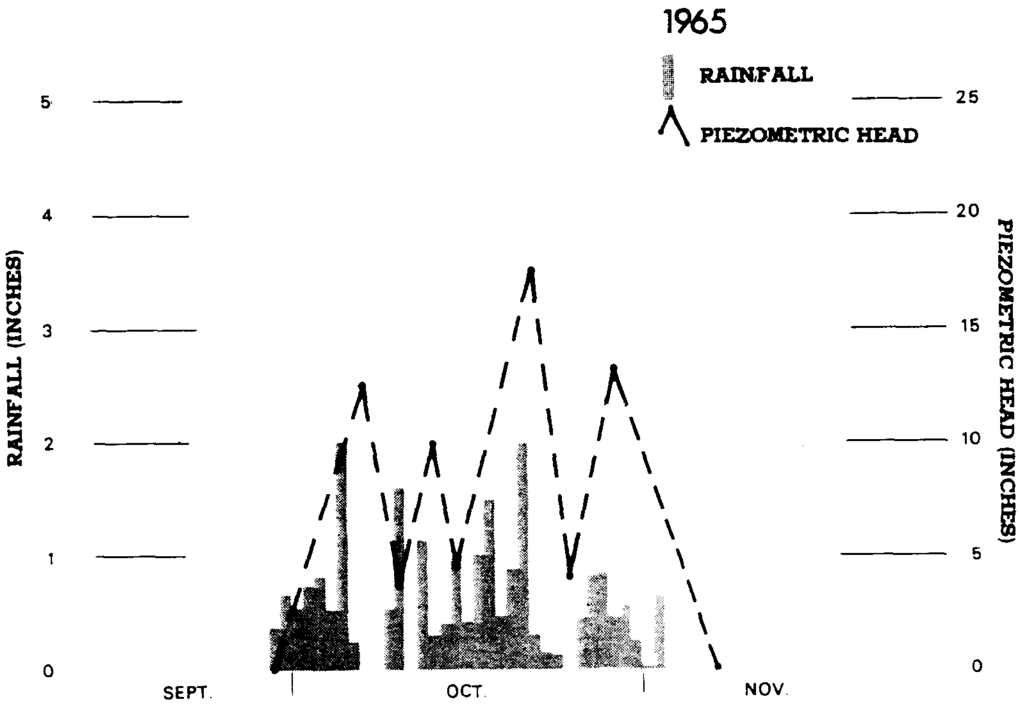

Figure 6.--Representative curve showing relationship between rainfall and piezometric head on slide prone slopes of Maybeso valley, Prince of Wales Island.

Snow accumulations and timing of snowmelt on the upper slopes may add substantial amounts of water to the soil--primarily through retention of rainfall in the snowpack and delayed release of large quantities of water during spring melt. Snow cover early in the fall may also reduce the fluctuations in ground water level with rainfall variations and thus indirectly reduce the maximum pore-water pressure developed in a potentially unstable soil. Again, the ground water measurements at Hollis in 1964 provide an example (fig. 7). Measurements during the fall rainy season exhibited the anticipated rapid fluctuations in water level with rainfall in September and early October; but by late October the fluctuations ceased, and the water level remained relatively constant through the remainder of the recording period. This reduction in ground water flow coincided with the appearance of a semipermanent snow cover on the slope above the measurement sites. Presumably, the snow cover intercepted a large part of the subsequent rainfall above the site and released a fairly constant amount into the soil despite subsequent major storms (Swanston 1967c).

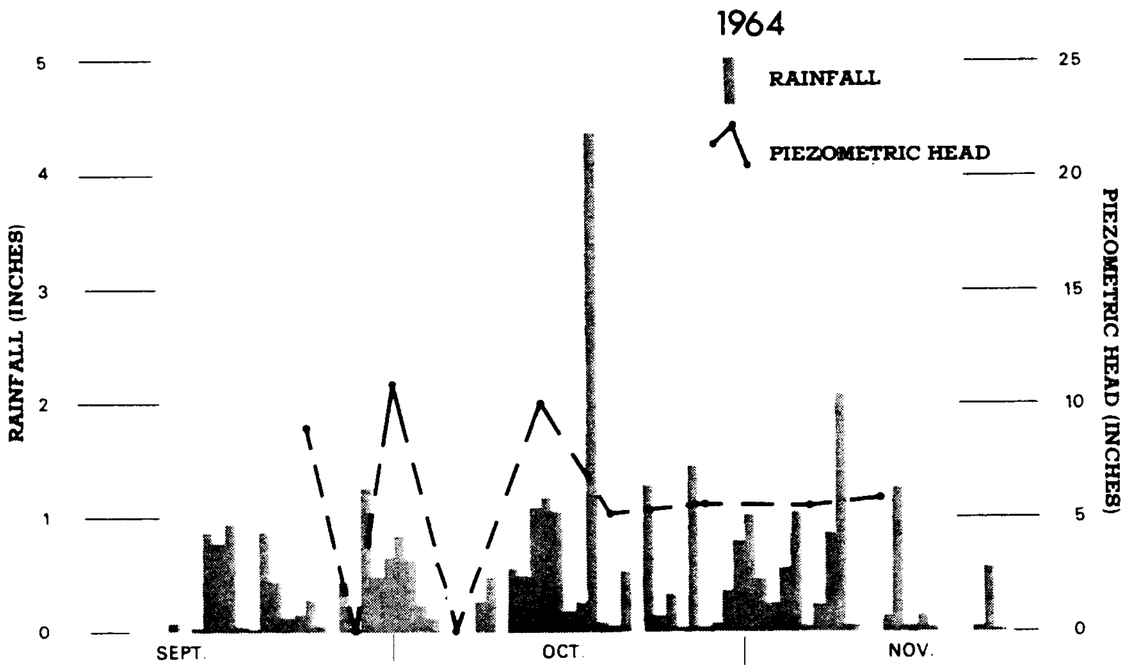

Figure 7.--Representative curve showing relationship between rainfall and piezometric head during the 1964 field season.

Parent material structure is an important factor in the stability of many potentially unstable slopes in southeast Alaska. Highly jointed bedrock slopes with principal joint planes parallel to the slope provide little mechanical support to the slope soils. The joint and bedding planes also create avenues for concentrated subsurface flow and active pore-water pressure development as well as functioning as readymade failure surfaces for overlying material. Swanston (1967b) has identified jointing parallel to the slope surface as an important factor in the occurrence of debris avalanches and flows in shallow bedrock-derived soils. Similar effects due to stress release fracturing have been observed throughout southeast Alaska and recently have been identified as a major contributor to unstable slope conditions in the greater Juneau borough area (Miller 1972, Swanston 1972a). Sedimentary rocks with bedding planes parallel to the slope function in essentially the same way. The uppermost bedding plane provides a smooth surface serving as (1) an impermeable boundary to subsurface water movement, (2) a layer which restricts the penetration of tree roots, and (3) an active failure surface with little frictional resistance to movement of the soil above. Bishop and Stevens (1964) cite the downslope dip of bedding planes as an important factor in debris avalanche and flow occurrence at Neets Bay on Revillagegido Island. Swanston (1967a) attributes the concentration of debris avalanches and flows on the north side of Maybeso valley to smoothness of slope due to downslope-dipping bedrock. In contrast, the south slope of Maybeso valley is broken into short sections by benches due to alternate hardness of inslope-dipping bedrock; debris avalanches are rare because of the mechanical support or "buttressing" effect of these slope breaks.

Creep, the slow, continuous downslope movement of mantle material as the result of the long-term application of gravitational stress, is active on all the oversteepened slopes in southeast Alaska. Relative rates and the mechanism of movement have not been fully determined for Alaskan soils. Such movements undoubtedly produce a stress buildup in the soil over a period of time due to progressive failures and may considerably increase slide susceptibility of the soil in critical areas. Sufficient evidence of active creep can be found on almost any slope in the form of "catsteps,"[4] overturned soil profiles, soil ridges upslope from trees, and recurved or "pistol butted" tree trunks. Quantitative creep measurements made in till soils in the Hollis area (Barr and Swanston 1970) indicate small increments of movement occurring in the first 6 to 12 inches of soil, with the rate decreasing rapidly toward the unweathered till surface. The soil appears to be moving as a flow mass with no well-defined shearing planes (fig. 8). The maximum rate of movement is approximately one-fourth inch per year at the surface. Similar creep movement is indicated in colluvial soils by surficial evidence, but no quantitative measurements have yet been made.

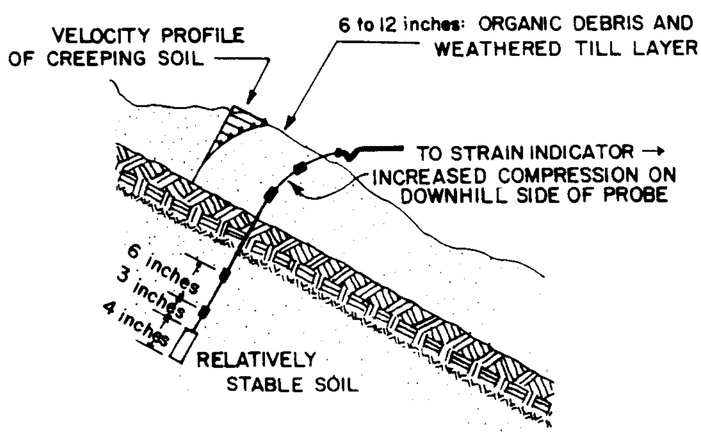

Figure 8.--A typical strain probe configuration produced by surficial creep on a slide prone slope in Maybeso Creek valley, Prince of Wales Island.

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[4]Catsteps are small, narrow terracettes produced on the slope by creep and small scale slumping.

RELATIONSHIP OF DEBRIS AVALANCHE AND FLOW OCCURRENCE TO PARENT MATERIAL AND SITE CHARACTERISTICS

The most common debris avalanche and debris flow situations in southeast Alaska develop in shallow soils on slopes greater than 30°. In shallow soils derived from colluvium or bedrock, bedrock serves as the sliding surface. In shallow soils derived from glacial till, impermeable, unweathered till serves as the sliding surface (Bishop and Stevens 1964; Swanston 1967a, 1967b, 1969). Both types of soil are coarse and permeable, with less than 20 percent of particles finer than silt, and for all practical purposes can be considered cohesionless. The soils derived from bedrock are largely undifferentiated, ranging from Lithosols to Podzols. These are grouped under the McGilvery Soil Complex. The glacial till soils are usually well-developed Podzols and are classified as Karta Soils (Gass et al. 1967).

Debris avalanches and debris flows developed in shallow soil derived from bedrock or colluvium occur on slopes much steeper than the angle of internal friction for that soil. Field measurements of slope angle at sites of recent sliding range from 40° to 60° although an estimated angle of internal friction for these soils lies at about 36° based on triaxial tests made on residual soils in the Juneau area (Swanston 1972a). The slides begin characteristically on valley side slopes and tributary gullies in areas of drainage concentration where maximum fluctuation in soil water levels during high intensity storms is most likely to occur. The soils are coarse and permeable with a high proportion of angular rock fragments and some organic colloidal material. Although the soils are considered essentially cohesionless for analysis purposes, unusually high organic concentrations in some samples, reported by Stephens (1967), may impart a certain amount of secondary cohesion to the soil mass. In all active slide areas investigated, the underlying bedrock surface either dips with or is jointed parallel to the valley's side slope, and the valley walls have been scoured by glacial erosion. This combination of conditions provides little natural obstruction to downward movements of soil under the force of gravity.

If soil physical properties and parent material structure are considered alone, these slopes are probably always at or near the point of failure.

Debris avalanches and debris flows in soils derived from glacial till are initiated most commonly at the head of, or within, shallow, linear hollows or depressions on the valley side slopes. Many of these depressions were probably cut in the till deposits on the side slope by surface runoff shortly after the glacier receded and have since been filled with soil and debris. Some are undoubtedly ancient debris avalanche tracks. Now, they serve to concentrate soil seepage and develop into surface drainages only during major storm periods when the soil becomes completely saturated. The majority of soil mass movements on this type of parent material are initiated on slopes ranging from 30° to 40°, with failures most commonly occurring near 37°. This angle corresponds to the laboratory-determined angle of internal friction for till soil samples in the Hollis area (Swanston 1969). The soils have a somewhat finer texture than the bedrock colluvial soils, with less angular rock fragments, but may still be considered cohesionless for purposes of stability analysis. The effect of bedrock structure on the stability of these slopes is masked by the glacial till cover, and the principal failure surface becomes the surface of the unweathered till.

Whether or not a debris avalanche or flow occurs or is repeated at any single point in these slope materials depends largely on the effectiveness of internal and external shear strength factors at the time of a potential triggering event. The slopes are inherently unstable. Evidence of this natural instability and the repetitive nature of mass movement occurrences is abundant. In almost every valley can be found well-defined single or superimposed landslide deposits, many with old-growth spruce/hemlock forests on them. The deposits include debris cones of stratified soil, rock, and organic debris at the slope base indicative of repeated flow deposition; buried and overturned soil profiles; and shallow, linear soil-filled depressions of the slope containing mature trees indicating ancient debris flow activity. Clearly, soil mass movement processes have been active through several forest successions and have probably dominated as a principal erosion process since withdrawal of glacial ice from the region.

Soil water produced by high intensity storms and steep slopes caused by recent glacial activity have been identified as the most frequent and effective factors affecting internal soil strength on these slide-prone slopes. The influence exerted is mainly through production of active pore-water pressures in the soil mass and along rock fractures which reduce the frictional resistance to sliding and through the increased pull of gravity on the soil mass due to excessively steep slopes. During periods of high intensity rainfall, internal soil strength is frequently reduced to a nominal value, and effective resistance to failure of the slope depends entirely on external factors. In the absence of geologic controls produced by bedrock benches and berms, rooting structures of trees and other vegetation anchor and bind the mantle materials to the slope and stand out as the most important contributors to this failure resistance. Under these conditions, only a small triggering event is required to cause total failure and rapid downslope movement of the soil mass. Such an event can be produced by cutting of the slope toe, rapid increases in the weight of the soil mass, or direct destruction of stabilizing roots. In areas of weakened root systems, the direct effect of pore-water pressure itself may be a triggering factor. Studies relating rainfall to pore-water pressure development near Hollis have shown that shallow till soils can become saturated during a storm producing rainfall in excess of 5 inches in 24 hours. Such storms have 2- to 5-year frequency in southeast Alaska (Swanston 1967c). The resultant active pore-water pressures can reduce internal soil shear strength by as much as 60 percent.

PRINCIPAL DAMAGES FROM SOIL MASS MOVEMENTS ON FOREST LANDS IN SOUTHEAST ALASKA

The impact of soil mass movements on forest lands can be extensive. Destructive debris avalanches and debris flows frequently destroy the entire productive soil zone within their paths. Natural revegetation may occur in as little as 10 years (Fujiwara 1970); but if the landslide remains active by progressive slumping near its head, considerably greater time may elapse before substantial vegetation cover develops. In southeast Alaska, many of the larger debris avalanche and debris flow scars remain unrevegetated for long periods. The debris avalanche tracts left by an August 1962 storm at Hollis, Prince of Wales Island, remain essentially unrevegetated today. Increment cores taken from damaged trees along barren debris avalanche scars at widely scattered locations in the Alaska Panhandle frequently indicate more than 30 years since initial occurrence. How much total land is involved in these soil mass movements is uncertain. Probably only a small percentage of land is taken out of effective timber production at one time. This is particularly true on undisturbed timbered slopes. Out of the total timber acreage in the Maybeso Creek drainage near Hollis, only 31.5 acres were involved in identifiable soil mass movements prior to logging (Bishop and Stevens 1964). During the 10 years of active logging, this acreage increased approximately four times to a cumulative total of 150.1 acres, still a relatively small amount of the total productive acreage in the watershed. These figures, of course, are for only one small area where limited quantitative data are available. As timber harvesting activities expand, more unstable areas will be subjected to increasing landslide activity with a subsequent increase in the total land area removed from production.

Also of rising concern is the esthetic impact of these accelerated soil mass movements. These have yet to receive a meaningful quantitative assessment in terms of damage to scenic values.

Soil mass movements are also prodigious producers of sediment in spawning streams which may directly or indirectly affect fish populations and habitat. Phillips (1971) suggests that salmon production may be effectively reduced by suspended sediment in streams. This is presumably due to turbidity which hampers food access for those visual feeders. Probably much more important is sediment which is deposited on and within spawning gravels. This material blankets the stream bottom and fills the gravel particle interstices inhibiting the flow of oxygen-bearing water to eggs and alevins and blocking the emergence of fry from the gravel (Cooper 1965, Vaux 1962, McNeil 1966). This is probably the greatest single resource damage caused by soil mass movements on forested lands in southeast Alaska.

DIRECT EFFECTS OF TIMBER HARVESTING ACTIVITIES

Under natural conditions, forest vegetation protects the soil surface; and combined soil strength is adequate to resist the downward pull of gravity on the soil mass. Thus, the undisturbed forest floor on the steep, mountain watersheds of southeast Alaska represents a minimum erosion site. Because of the marginal stability of these slopes, however, any disrupting influence, whether a natural catastrophe such as earthquake, rockfall, a large storm, or the activities of man, is a potential initiator of a more active erosion cycle.

Forest operations in southeast Alaska have been identified as an important contributor to accelerated debris avalanches and debris flow development. Reconnaissance investigations of recent landsliding at Hollis and in Neets Bay and Gedney Bay (Bishop and Stevens 1964) have shown a direct correlation between timber harvesting and accelerated soil mass movements, with greatest increases following heavy rains in the fall of 1961. In the years prior to logging at Hollis (before 1952), no recent debris avalanches had occurred on open slopes, and only one had occurred in a V-notch drainage. This strongly contrasts with the 3-year period after logging started (1959-62). By August of 1962, 20 debris avalanches had occurred on the open slopes, and 96 had started in V-notch drainages. Eighty percent of those on the area's open slope and 55 percent of those in V-notch drainages had occurred during or following a 1961 storm, with over 5 inches of rain in 24 hours.

This marked increase in slide occurrence was unrelated to roads, strongly underlining the association of timber cutting with slope instability in southeast Alaska. Destruction of overstory vegetation may be a major cause for this increased debris avalanche activity. Deterioration of stabilizing root systems due to tree cutting may be the most important consequence of overstory destruction.

Accumulation of logging debris in steep ravines and V-notch channels has also been shown to be a major contributor to debris torrents through the formation and collapse of temporary debris dams in gullies and canyons bisecting the logged slopes.

Roadbuilding has been identified as a major contributor to accelerated soil mass movements on steep mountain watersheds elsewhere in the Pacific Northwest, and there is little reason to believe that southeast Alaska watersheds will remain exempt from the impact of this activity. Small slumps and debris avalanches directly associated with logging roads occur regularly, but as yet, their impact has been slight owing to the relatively low road mileage and limited effect soil movements have had on road construction and maintenance costs. As the road network in southeast Alaska is expanded, more unstable areas will be directly affected. In western Oregon and Idaho, roadbuilding activities have been identified directly as the greatest single cause of recent soil mass movements following major storms[5] in logged areas (Dyrness 1967). These included

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[5]Walter F. Megahan. Summary of research on mass stability by the Intermountain Forest and Range Experiment Station, Soil Stabilization Project, Boise, Idaho. (Unpublished proceedings, Mass Erosion Conference, October 17-20, 1967. USDA Forest Service, Berkeley, California.)

slumps and debris avalanches caused by failures of road fill and road backslopes, and obstruction of road drainages. As reported by Dyrness and Megahan, road fill failures were most frequent, followed by those resulting from obstructed road drainages. All three types have been observed in southeast Alaska clearcuts. Road construction activities can disrupt the equilibrium of a slope in three ways: alteration of drainage, loading, and undercutting. Alteration of slope drainage includes interception and concentration of surface and subsurface flow by ditching, bench cutting, and massive road fills. Interception and concentration of water encourages saturation, active pore-water pressure development, and increased soil unit weight in road prisms, side cast materials, and soils upslope from the road. Poor drainage and plugged culverts due to ponding of water on the inside of the road can magnify these problems. Slope loading by massive fill and side casting greatly increases the weight of the soil material and results in increased gravitational stress along the slope below the road. Slope undercutting by benching along an oversteepened slope removes support for the soil upslope from the road.

IDENTIFICATION AND CONTROL OF MASS MOVEMENT PROBLEMS

Practical techniques available for identification and control of soil mass movements on forest lands have been summarized by Swanston (1972b). Based on current levels of knowledge, two main options are available to the land manager operating in unstable terrain. Once he understands the basic mechanics of slope movement, he may either identify problem areas and avoid operations on unstable ground or identify unstable ground and attempt to control the effects of any planned manipulation. In highly unstable areas or in areas of questionable economic value, avoidance of all operations is probably the best and least expensive solution. Controlling the impacts of timber harvesting operations on unstable terrain may be necessary but is difficult and expensive; at best it will be only partially successful.

Identification of unstable areas and at least a qualitative rating of the degree of instability on them are essential parts of the decisionmaking process. These require the accurate determination and mapping of existing and potentially unstable slopes in the area of proposed operations. A careful analysis of the factors controlling and contributing to instability and a classification of unstable areas according to acceptable levels of operation are also prerequisite. Such a stability analysis has been completed by Swanston[6] for a timber sale on northern Kuiu Island as part of an interdisciplinary team effort; and Bailey (1971a, 1971b) has completed similar studies on the Teton National Forest and in the Lake Tahoe area. The Kuiu Island study involved accurate mapping of all active and dormant debris avalanche and debris flow areas from air photos and topographic maps. Estimated maximum and minimum angles of internal friction for local soils were then used to define the limits of questionable and highly unstable terrain. This analysis and

[6]D. N. Swanston. Geology report and landslide hazard analysis of Northwestern Kuiu Island, southwestern Alaska. Unpublished interdisciplinary report, Northwestern Kuiu Island, Petersburg Ranger District, North Tongass National Forest, Alaska.

followup fieldwork to verify mapping units and estimates were the basis for a recommendation that areas above the maximum angle of internal friction or showing evidence of active soil mass movement be withdrawn from proposed timber harvesting operations. Operations in such areas should be, at the very least, limited to light selective cutting and yarding by balloon and helicopter. Roadbuilding would cause or accelerate mass movement occurrence with little chance of effective control. Slopes above the minimum angle of internal friction possess questionable stability and can be operated upon if adequate care is taken in road location, drainage, and maintenance and if surface damage by logging is kept to a minimum.

The effective engineering control measures available for slope stabilization are usually expensive and generally applicable only to specific problems along the road right-of-way. These include, with variable detail, loading of the slope toe, and slope terracing, drainage, and retaining wall construction--all designed to improve the balance of forces acting on the soil mass. Of these, slope drainage and retaining wall construction may be effective, although expensive, outside areas with roads in southeast Alaska--the former to remove water from concentrated flow areas, the latter to hold the soil mass in place. Both have inherent difficulties of access, construction, and maintenance on the steep slopes and shallow soils. Toe loading and terracing have little positive effect on these shallow, cohesionless soils and may actually serve to increase instability on the slope. Toe loading in one spot may increase the weight of the soil mass downslope, and terracing removes support from the soil mass upslope.

A more practical approach to control involves the avoidance of disturbances damaging to slope stability and the reduction of landslide incidence after disturbance. Both balloon logging and helicopter transport have tremendous potential for reducing surface disturbance and associated environmental impact of logging in unstable areas. Reduction in soil mass movement occurrence in logged areas can be best assured by improved road construction and maintenance, and maintenance of maximum stability levels by selective harvesting and vegetation planting in highly unstable zones. Less damaging road design and construction techniques are already available to the engineer and land manager. The conscientious application of these improved techniques largely determines the impact of roads on slope stability. Selective cutting in highly unstable areas would retain at least a minimum amount of anchoring from overstory vegetation, and planting immediately after disturbance would reduce the period of time that root deterioration of stumps might affect the relative stability of the slope materials. Direct vegetational stabilization of debris avalanche tracks has been tried at Hollis with questionable success.[7] The problem appears to be the continual sluffing of the avalanche track which destroys or removes newly started vegetation and the lack of available nutrients to sustain vigorous growth. Some aerial seeding and hand seeding of debris avalanche tracks have also been attempted elsewhere on Prince of Wales Island with similar results.

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[7]Austin E. Helmers. Slide area stabilization trials in the Maybeso Creek valley, southeast Alaska. (Unpublished report on file at Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, Juneau, Alaska.)

CONCLUSIONS

Soil erosion research in coastal Alaska is still in qualitative stage of development. Preliminary work so far has identified the dominant erosion processes, described their principal mechanisms, and related soil mass movement occurrences and distribution to major environmental factors and land use activities. The findings thus far can be summarized as follows:

1. Soil mass movements stand out as the dominant process of erosion and slope reduction on the steep mountain watersheds of southeast Alaska.

2. Debris avalanches and debris flows involving the rapid downslope movement of a mixture of soil, rock,and forest debris are the principal soil mass movement process operating within the region.

3. Sliding soil ranges from gravelly silt loam to gravelly sand developed from glacial till and colluvium. These soils overlie impermeable unweathered till and bedrock which serve as effective failure surfaces.

4. The soils are essentially cohesionless so that angle of internal friction, friction along the sliding surface, and slope gradient control internal soil strength and gravitational stress on the slope.

5. In the absence of active pore-water pressures, the critical angle of stability of southeast Alaska slopes equals the angle of internal friction of the soil on them.

Studies thus far indicate that critical slope angle, corresponding to an average angle of internal friction for till soils, is 37°. An estimated critical angle for colluvial soils is 36°.

6. Soil saturation and active pore-water pressure development during major storms can substantially reduce soil strength and decrease the critical angle of stability of the slope.

7. In till soils, rainfall in excess of 5 inches in 24 hours has been correlated with complete saturation and maximum pore-water pressure development and is believed to have been the main triggering device for the massive debris avalanching at Hollis.

8. Natural catastrophic events such as windthrow and rockfalls associated with high soil moisture levels are also believed to be important triggering devices for debris avalanche and debris flow occurrence. These appear to be particularly effective on colluvial soil slopes.

9. Loss of mechanical slope support by deteriorating root systems has been identified as a potentially important contributor to slope instability in till soils and is probably of equal or greater importance on colluvial soils. Maximum decrease in shear strength of anchoring roots occurs 3 to 5 years after cutting and may represent the period during major storms when logged slopes are most susceptible to failure.

10. Soil creep has also been identified as contributing to slope instability. Creep movement has been quantified in till soils at Hollis at the rate of one-fourth inch per year and is indicated by surficial evidence elsewhere. The buildup of creep stress may contribute substantially to the instability of a slope soil over time.

11. Timber cutting on oversteepened slopes has been identified as the most damaging forest operation in southeast Alaska at present. The decay of anchoring root structures after cutting combined with a storm and exceptional rainfall are believed to have been the major factors in massive debris avalanche and flow development at Hollis. Slash accumulation in deep v-notch canyons also produces temporary debris dams which, on failure, may result in destructive debris avalanches.

12. The impact of roadbuilding has not been felt in the region, but as roads continue to expand onto increasingly unstable terrain, this activity has the greatest potential for accelerating soil mass movement activity.

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