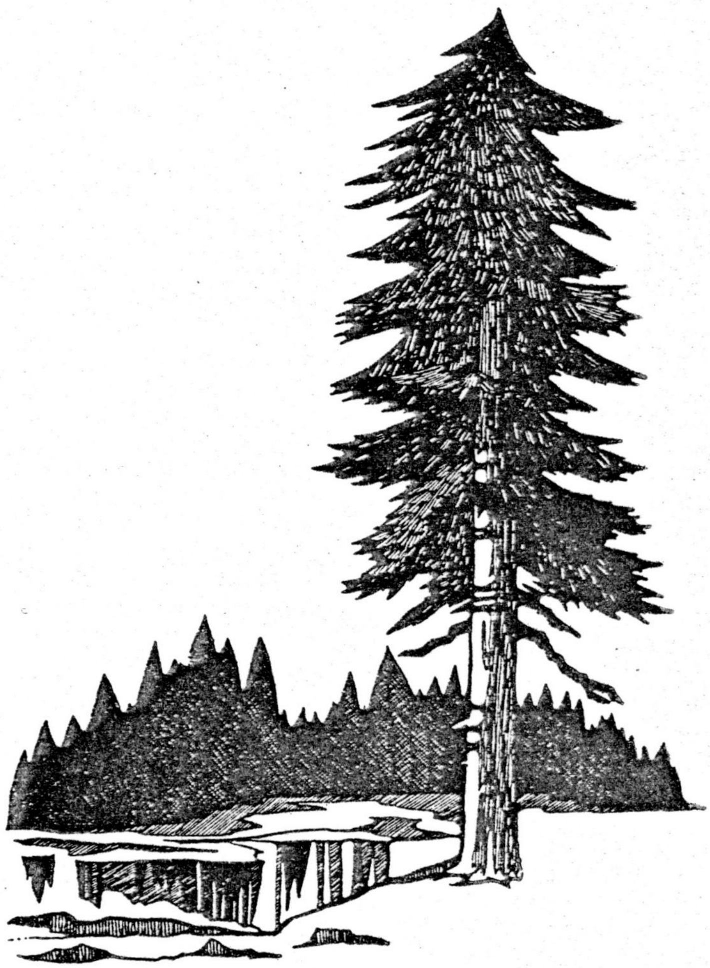
PROCEEDINGS OF WORKSHOP ON

SCHEDULING TIMBER HARVEST FOR

HYDROLOGIC CONCERNS



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FOREST SERVICE

PACIFIC NORTHWEST REGION

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION

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LANDSLIDE PREDICTION and ASSESSMENT

INTERPRETING STABILITY PROBLEMS FOR THE LAND MANAGER

BY

D. N. Swanston

INTRODUCTION

Soil mass movements, that is, downslope movement of a portion of the land surface under the direct application of gravitational forces constitute one of the most common but least investigated processes of natural erosion and slope reduction in mountainous areas of western North America.

In its undisturbed state, the forest floor on steep mountain slopes is in a state of equilibrium between resistance of a soil to failure and gravitational forces tending to move the soil downslope. Any disrupting influence, whether it be natural catastrophic events such as fire, earthquake, or storm, or the cultural activities of man, is a potential initiator of a more active erosion cycle.

The areas of greatest landslide severity lie within the circum-Pacific Mountain belt and the western cordillera (Rocky Mountains, Coast Ranges, and Cascades). These are regions of high relief, characterized by steep slopes and narrow intervalley ridges. Glacial erosion, tectonic uplift, and severe weathering processes have further steepened the slopes, frequently above the angle of internal friction (stability angle) of the soils on them. Periodic storms producing locally saturated soil conditions are also common to most of these areas.

With increasing demand for lumber and pulpwood more of these steep mountain watersheds are being directly influenced by forest operations. The resulting disruption of natural slope stability characteristics has accelerated slope failure in many logged areas, producing excess sediment loads in streams, causing extensive damage to structures and roads, and effectively removing portions of the watershed from immediate reforestation.

It thus becomes essential, for effective forest land management, to be able to recognize and define these unstable areas, to determine primary mass erosion processes operating on the slope, and to identify and understand the interaction of principal and contributing factors controlling slope failure. This requires, first of all, a basic knowledge of the geology and geologic history of the area being managed and at least a rudimentary understanding of the landscape components that control or contribute to unstable conditions. Analytical interpretation and technical evaluation should then be performed, whenever possible, in close cooperation with the engineering geologist, civil engineer and soil scientist.

This paper summarizes published information and concepts dealing with soil mass movement occurence, controling factors, management impacts and identification and assessment techniques. More detailed discussions are available from the principal source documents Swanston, 1976; Swanston and Swanson, 1976; Swanson and Swanston, 1977; Swanston, Swanson and Rosgen, in press).

PRINCIPAL PROCESSES AND MANAGEMENT IMPACTS

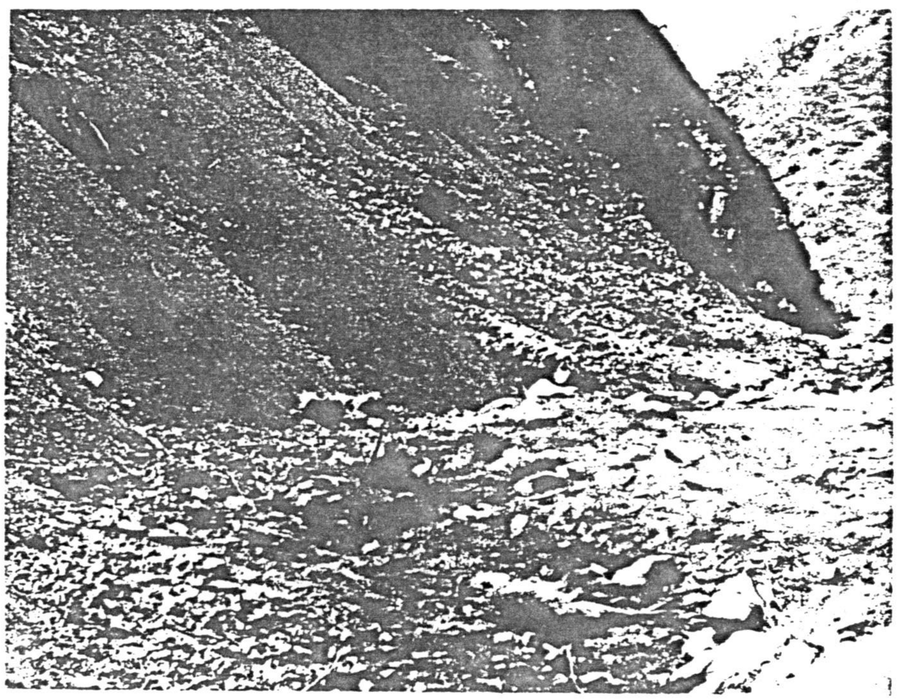
Downslope movement of soil materials by mass wasting processes results primarily from direct application of gravitational stress. It may take the form of: 1) single particle erosion involving transport of soil particles and aggregates by rolling, sliding, and bounding (dry ravel): 2) pure reological flow with minor mechanical shifting of mantle materials over large areas (creep), and 3) failure, both along planar and rotational surfaces, of finite masses of soil and forest debris (debris avalanche-debris flow and slump-earthflows). When material from such failures on a slope enter a confining channel carrying storm runoff, a debris torrent may develop.

Slope gradient, soil depth, soil water content, and intrinsic soil properties, such as cohesion and coefficient of friction, control the mechanics and rates of movement of these processes. Geological, hydrological, and vegetative factors determine occurrence and relative importance of mass wasting processes in a particular area.

DRY RAVEL

Dry ravel, or dry creep and sliding, is characterized by single particle movement of coarse, cohesionless materials on steep, sparsely vegetated or recently denuded hill slopes (fig. 1a, b). This is a common erosion process on steep, unvegetated slopes in all mountainous regions, caused by loss of frictional resistance between individual soil particles due primarily to freeze and thaw, and wetting and drying cycles. In areas characterized by steep slopes, coarse textured soils, and extended summer droughts, dry ravel may be a particularly important process. Deforestation and surface cover removal on steep slopes have a strong influence on initiation and acceleration of this process. Recent observations in the San Gabriel Mountains of southern California, indicate this to be the dominant process during the dry summer season, particularly where natural chaparral cover has been removed causing the destruction of stabalizing root systems. Increases in annual sediment production from dry creep and sliding of 10 to 16 times following wildfire has been reported (Krammer, 1965; Rice, et. al., 1969).

A



B

Figure 1.--Cones of loose, granular soil material produced by dry ravel or dry creep and sliding.

a. Dry ravel during the summer drought along a forest road near Shelton, Washington.
b. Dry ravel into a perennial stream in the semi-arid San Gabriel Mountains of southern California.

SOIL CREEP

Soil creep is defined as the slow, downslope movement of soil mantle materials as the result of long term application of gravitational stress. The mechanics of soil creep have been investigated experimentally and theoretically (Terzaghi, 1953; Goldstein and Ter-Stepanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Haefeli, 1965; Bjerrum, 1967; Carson and Kirkby, 1972). Movement is quasi-viscous, occuring under shear stresses sufficient to produce permanent deformation but too small to result in discrete failure. Mobilization of the soil mass is primarily by deformation at grain boundaries and within clay mineral structures. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, thereby reducing friction within the soil mass. Creeping terrain can be recognized by characteristic rolling, hummocky topography with frequent sag ponds, springs, and occasional benching due to local rotational slumping. Local discrete failures, such as debris avalanches and slump-earthflows, may be present wtihin the creeping mass (fig. 2).

Natural creep rates monitored in different geological materials in the western Cascade and Coast Ranges of Oregon and northern California, indicate rates of movement between 7.1 and 15.2 millimeters per year, with the average about 10 millimeters per year (Swanston and Swanson, 1976) table 1). The zone of most rapid movement usually occurs at or near the surface, although the zone of significant displacement may extend to variable depths associated with incipient failure planes or zones of ground water movement. The depth over which creep is active is quite variable and is largely dependent on parent material origin, degree and depth of weathering, subsurface structure, and soil water content. Most movement appears to take place during the rainy season when maximum soil water levels occur (fig. 3a), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (fig. 3b). This is consistent with Ter-Stapanian's (1963) theoretical analysis which shows that the downslope creep rate of an inclined soil layer is exponentially related to piezometric level in the slope.

There have been no direct measurements of the impact of deforestation on creep rates in the forest environment, mainly because of the long periods of record needed both before and after a disturbance. There are, however, a number of indications that creep rates are accelerated by harvesting and road construction.

In the United States, Wilson (1970) and others have used inclinometers to monitor accelerated creep following modification of slope angle, compaction of fill materials, and distribution of soil mass at construction sites. The common occurence of shallow soil mass movements in these disturbed areas and open tension cracks along roadways at cut and fill slopes suggests that similar features along forest roads indicate significantly accelerated creep movement.

On open slopes where deforestation is the principal influence, impact on creep rates may be more subtle, involving modifications of hydrology and root strength. Where creep is a shallow phenomenon (less than several meters), the loss of root strength due to deforestation is likely to be significant. Reduced evapotranspiration after clearcutting (Gray, 1970; Rothacher, 1971) may result in longer duration of the annual period of

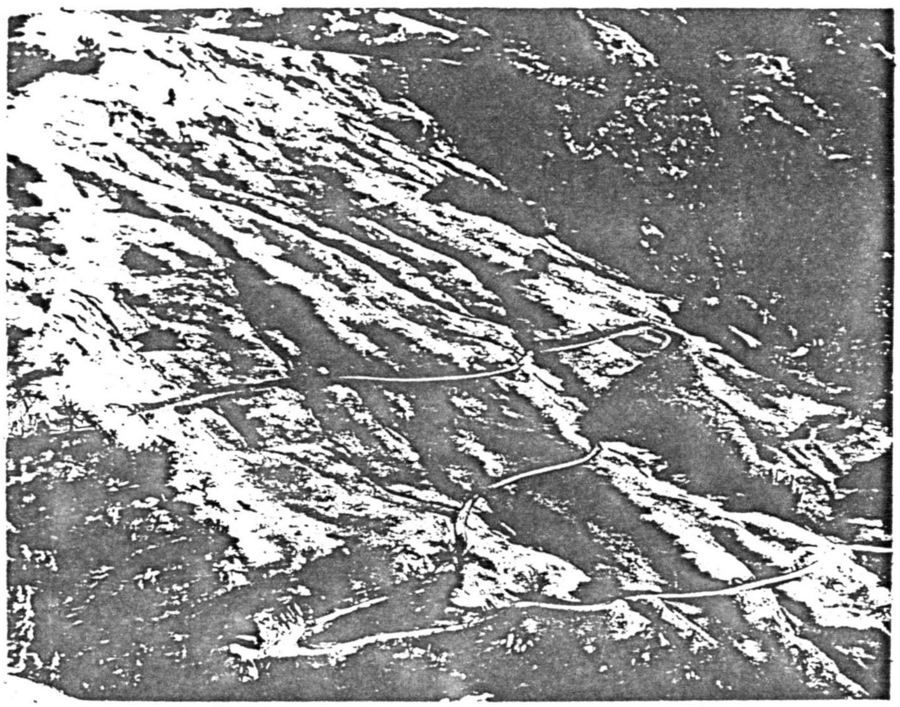


Figure 2. An example of soil creep and slump-earthflow processes on forest lands in northern California. The entire slope is undergoing creep deformation, but note the discrete failure (slump-earthflow) marked by the steep headwall scarp at top center and the many small slumps and debris avalanches triggered by surface springs and road construction.

Table 1.--Examples of Measures Rates of Natural Creep on Forested Slopes in the Pacific Northwest (Swanston and Swanson, 1976)

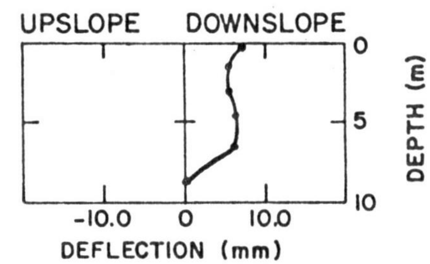
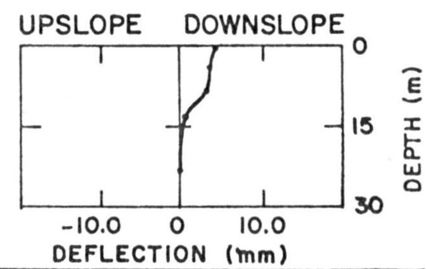
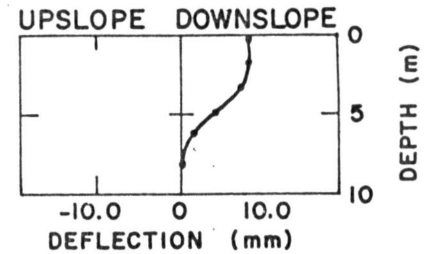
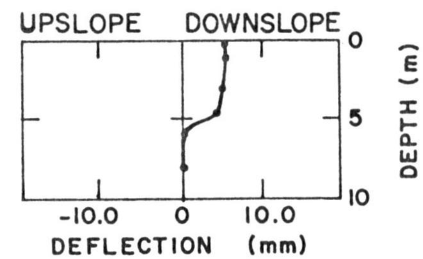
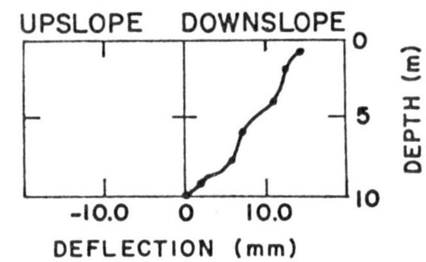
Location	Data Source	Parent Material	Depth of Significant Movement (m)	Maximum Downslope Creep Rate: Surface (mm/yr)	Maximum Downslope Creep Rate: Zone of Accelerated Movement (mm/yr)	Representative Creep Profile
Coyote Creek South Umpqua River Drainage Cascade Range of Oregon Site C-1	Swanston[1/]	Little Butte volcanic series Deeply weathered clay-rich andesitic dacitic volcaniclastic rocks	7.3	13.97	10.9	
Blue River Drainage - Lookout Creek H. J. Andrews Exp. Forest Central Cascades of Oregon Site A-1	Swanston[1/]	Little Butte series Same as above	5.6	7.9	7.1	
Blue River Drainage IBP Experimental Watershed 10 Site No. 4	McCorison[2/] and Glenn	Little Butte volcanic series	0.5	9.0	----	

Table 1.--Examples of Measured Rates of Natural Creep on Forested Slopes in the Pacific Northwest

(continued)

Baker Creek Coquille River Coast Range, Oregon Site B-3	Swanston[1/]	Otter Point Formation Highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7	
Bear Creek Nestucca River Coast Range, Oregon Site N-1	Swanston[1/]	Nestucca Formation Deeply weathered pyroclastic rocks and interbedded, shaley siltstones and claystones	15.2	14.9	11.7	
Redwood Creek Coast Range, Northern California Site 3-B	Swanston[1/]	Kerr Ranch Schist Sheared, deeply weathered clayey schist	2.6	15.2	10.4	

1/ Douglas N. Swanston, unpublished data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, USA.

2/ F. Michael McCorison and J. F. Glenn, data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, USA.

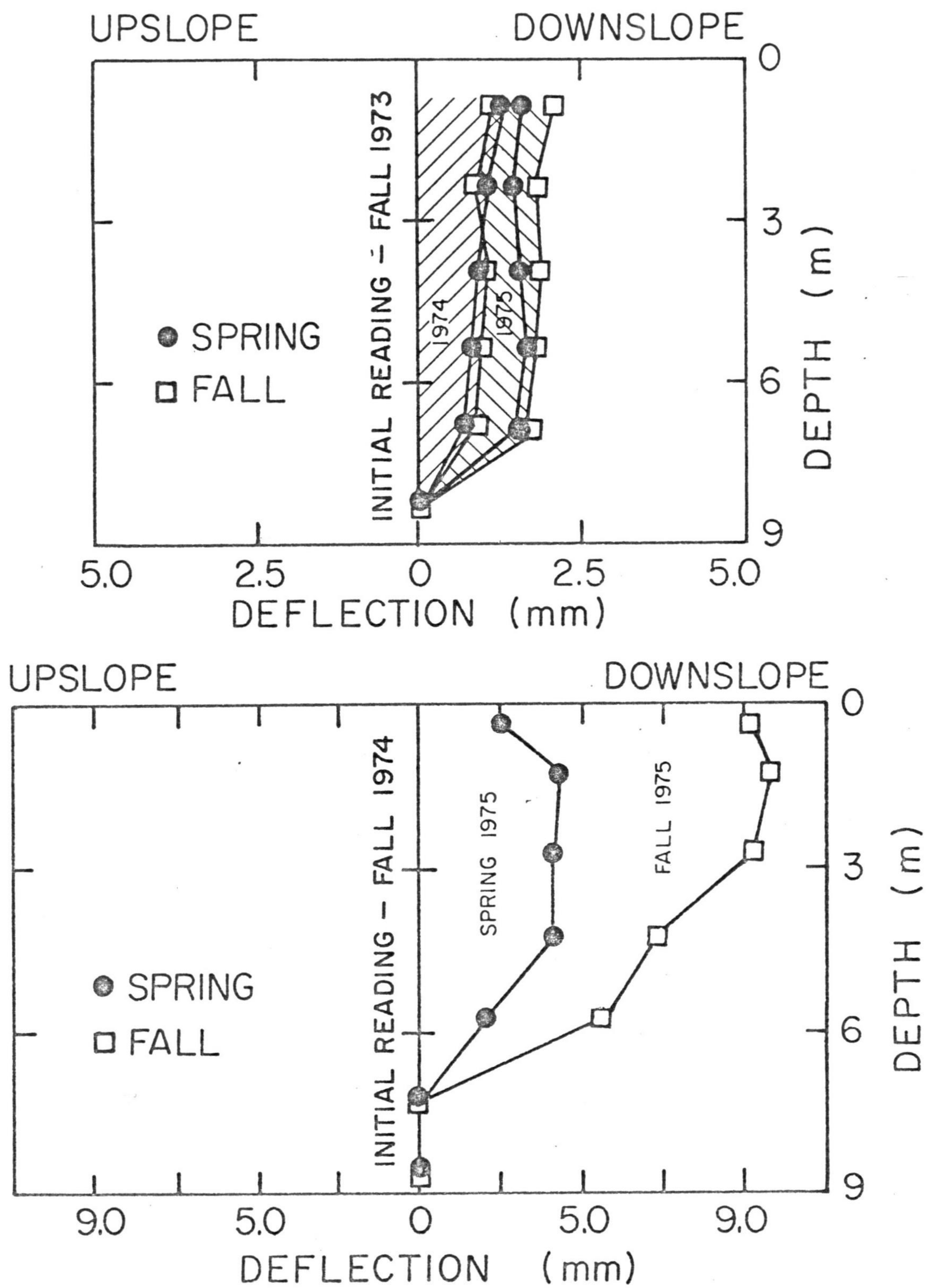


Figure 3.--Deformation of inclinometer tubes at two sites in the southern Cascade and Coast Ranges of Oregon. (Swanston and Swanson, 1976)

a. Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil water levels. Note that the difference in readings between spring and fall of each year (dry months) is very small.

b. Baker Creek, Coquille River, Oregon Coast Ranges, showing constant rate of creep as a result of continual high water levels.

creep activity and, thereby, the annual creep rate.

SLUMP-EARTHFLOWS

Where creep displacement has exceeded the shear strength of soil, discrete failure occurs and slump-earthflow features (Varnes, 1958) are formed. Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow (Varnes, 1958) (fig. 4). Geologic, vegetative, and hydrologic factors have primary control over slump-earthflow occurrence. Deep, cohesive soils and clay-rich bedrock are especially prone to slump-earthflow failure, particularly where these materials are overlain by hard, competent rock (Wilson, 1970; Swanson and James, 1975). Earthflow movement also appears to be sensitive to long term fluctuations (weeks, months, or annually) in the amount of available soil water (Wilson, 1970; Swanston, 1976).

Because earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than on the occurence of debris avalanches and torrents. Where planes of slump-earthflow failure are more than several meters deep, weight of vegetation and vertical root-anchorage effects are insignificant.

Movement rates of earthflows vary from imperceptibly slow to more than a meter per day in extreme cases. In parts of Northwestern North America, many slump-earthflow areas appear to be inactive (Colman, 1973; Swanson and James, 1975). Where slump-earthflows are active, rates of movement have been monitored directly by repeated surveying of marked points and inclinometers.

Figure 4.--Slump and earthflow in deeply weathered volcaniclastic rocks of the western Cascades Range, Oregon. The slump occurred following exceptionally heavy rain and formed an earthflow mass which temporarily dammed Canyon Creek. Much of the earthflow lobe has been removed from the foreground area by heavy machinery.

and by measuring deflection of roadways and other inadvertent reference systems. These methods have been used to estimate the rates of earthflow movement shown in table 2 (Swanston and Swanson, 1976).

The areal occurrence of slump-earthflows is mainly determined by bedrock geology. Fore example, in the Redwood Creek basin, northern California, Colman (1973) observed that, of the 27.4 percent of the drainage which is in slumps, earthflows, and older or questionable landslides, a very high percentage of the unstable areas are located in the clay-rich and pervasively sheared sedimentary rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated mass erosion. The areal occurrence of slump-earthflows in volcanic terrains has also been closely linked to bedrock (Swanston and Swanson, 1976). At a study site in the western Cascade Range of Oregon, for example, approximately 25.6 percent of areas underlain by volcaniclastic rocks are included in active and presently inactive slump-earthflows. Less than 1 percent of areas of basalt and andesite flow rock have undergone slump-earthflow failure.

Engineering activities which involve excavation and fills frequently have a dramatic impact on slump-earthflow activity. There are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction on the western U.S.A. (Wilson, 1970). Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices which influence slump-earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the

Table 2.--Observations of Movement Rates of Four Active Earthflows in the Western Cascade Range, Oregon, (Swanston and Swanson, 1976)

Location	Period of Record (yr)	Movement Rate (cm/yr)	Method of Observation
Landes Creek (Sec 21 T22S R4E)	15	12	Deflection of road
Boone Creek (Sec 17 T17S R5E)	2	25	Deflection of road
Cougar Reservoir (Sec 29 T17S R5E)	2	2.5	Deflection of road
Lookout Creek (Sec 30 T15S R6E)	1	7	Strain rhombus measurements across active ground breaks

slump-earthflow areas. These disturbances may increase movement rates from a few millimeters per year to many tens of centimeters per year or more. Once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Although the impact of deforestation alone on slump-earthflow movement has not been demonstrated quantitatively, evidence suggests that it may be significant. In massive, deep-seated failures, lateral and vertical anchoring of tree root systems is negligible. Hydrologic impacts of deforestation, however, appear to be important. Increased moisture availability due to reduced evapotranspiration will increase the volume of water not used by the vegetation. This water is therefore free to pass through the rooting zone to deeper levels of the earthflow.

DEBRIS AVALANCHE-DEBRIS FLOWS

Debris avalanches are rapid, shallow soil mass movements from hillslope areas. Here we use the term "debris avalanche" in a general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) (fig. 5a) and others on the basis of increasing water content. From a land management standpoint, there is little purpose to differentiating among the types of shallow hillslope failures since the mechanics and the controlling and contributing factors are the same. Debris avalanche-prone areas are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces. Because debris avalanches are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle are potentially important influences. Factors which influence

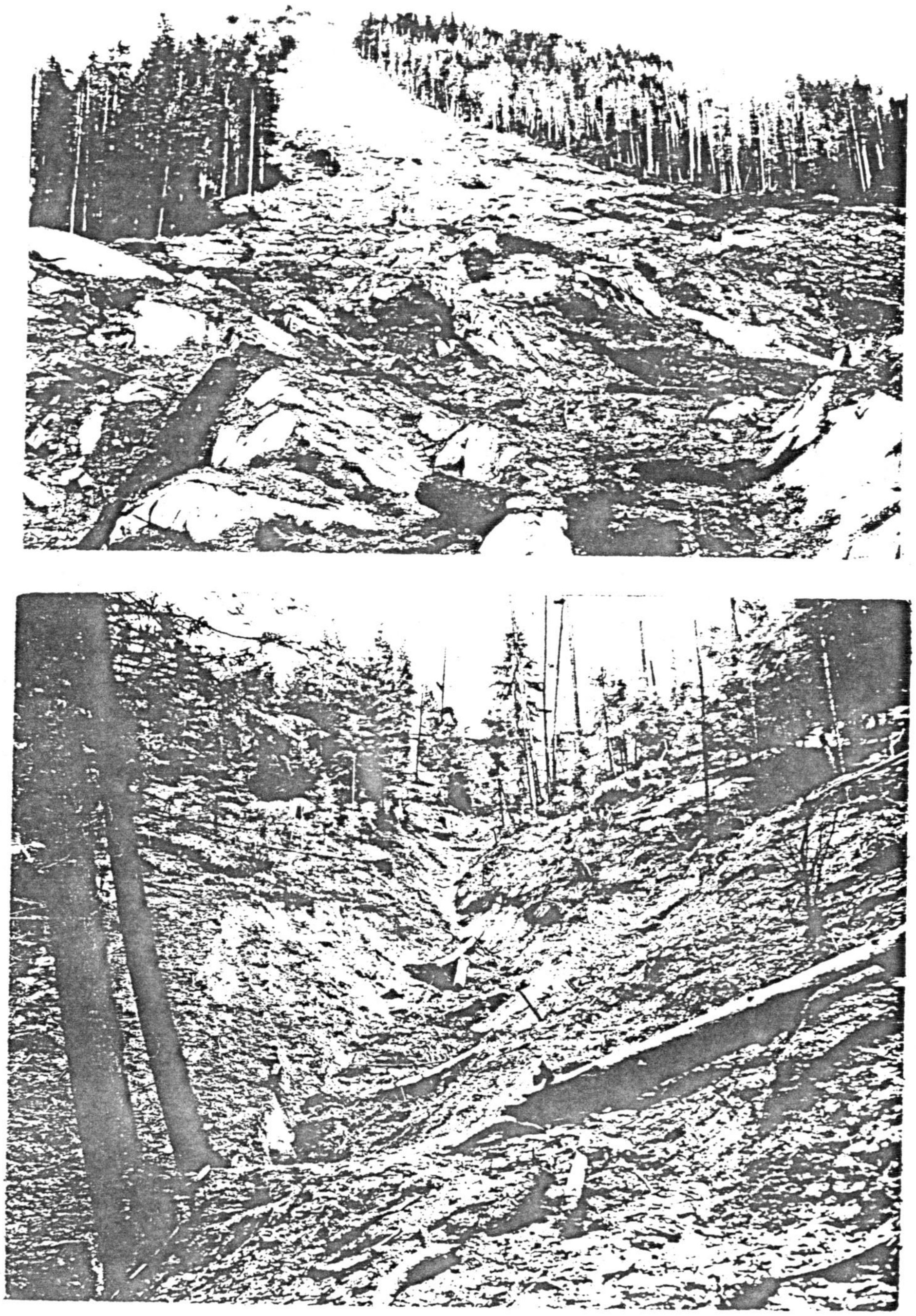


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Figure 5.--Debris avalanche and debris torrent development on steep forested watersheds in Northwestern North America.
a. Debris avalanche developed in shallow cohesionless soils on a steep, forested slope in coastal Alaska.
b. Debris torrent developed in a steep gully, probably caused by failure of a natural debris dam above trees in foreground.

antecedent soil moisture conditions and the rate of water supply to the soil during snowmelt and rainfall also have significant control over when and where debris avalanches occur.

The rate of occurrence of debris avalanches is controlled by the stability of the landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanching will vary from one geomorphic-climatic setting to another. Table 3 (Swanston and Swanson, 1976) shows that annual rates of debris avalanche erosion from forested study sites in Oregon and Washington in the United States and British Columbia in Canada range from 11 to 72 $m^3/km^2/yr$. These estimates are based on surveys and measurements of erosion by each debris avalanche occurring in a particular time period (25 years or longer) over a large area (12 km^2 or larger).

An analysis of harvesting impacts in the Western United States (table 3) reveals that timber harvesting commonly results in an acceleration of erosion by debris avalanches by a factor of 2 to 4. Roads appear to have much more profound impact on erosion activity. In the four study areas listed in table 3, road-related debris avalanche erosion was increased 25 to 340 times the rate of debris avalanche erosion in forested areas. The great variability of the impact of roads reflects not only differences in the natural stability of the landscapes but also, and more important from an engineering standpoint, differences in site location, design, and construction of roads.

DEBRIS TORRENTS

Debris torrents involve the rapid movement of water-charged soil, rock

Table 3.--Debris Avalanche Erosion in Forest, Clearcut, and Roaded Areas (Swanston and Swanson, 1976)

Site	Period of Record (yr)	Percent	Area (km^2)	Number of Slides	Debris Avalanche Erosion ($m^3/km^2/yr$)	Rate of Debris Avalanche Erosion Relative to Forested Areas
Stequaleho Creek, Olympic Peninsula, Washington, U.S.A. (Fiksdal, 1974):						
Forest	84	79	19.3	25	71.8	x 1.0
Clearcut	6	18	4.4	0	0	0
Road	6	3	0.7	83	11825.	x165
			24.4	108		
Alder Creek, Western Cascade Range, Oregon, U.S.A. (Morrison, 1975):						
Forest	25	70.5	12.3	7	45.3	x 1.0
Clearcut	15	26.0	4.5	18	117.1	x 2.6
Road	15	3.5	0.6	75	15565.	x344
			17.4	100		
Selected Drainages, Coast Mountains, S.W. British Columbia, Canada:[1/]						
Forest	32	88.9	246.1	29	11.2	x 1.0
Clearcut	32	9.5	26.4	18	24.5	x 2.2
Road	32	1.5	4.2	11	282.5[2/]	x 25.2
			276.7	58		
H. J. Andrews Experimental Forest, Western Cascade Range, Oregon, U.S.A. (Swanson and Dyrness, 1975):						
Forest	25	77.5	49.8	31	35.9	x 1.0
Clearcut	25	19.3	12.4	30	132.2	x 3.7
Road	25	3.2	2.0	69	1772.	x 49
			64.2	130		

[1/] Calculated from O'Loughlin (1972, and personal communication[2/]), assuming that area involving road construction in and outside clearcuts is 16 percent of area clearcut.

[2/] Colin L. O'Loughlin, presently located at Forest Research Institute, New Zealand Forest Service, Rangiora, New Zealand.

and organic material down steep stream channels.

Debris torrents typically occur in steep, intermittent, and first- and second-order channels. These events are triggered during extreme discharge events by debris avalanches from adjacent hillslopes which enter a channel and move directly downstream or by the breakup and mobilization of debris accumulations in the channel (fig. 5b). The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and living and dead organic material from the streambed and banks. Some torrents are triggered by debris avalanches of less than 100 m^3 but ultimately involve 10 000 m^3 of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of meters of channel may be scoured to bedrock. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material covering areas of up to several hectares.

The main factors controlling the occurrence of debris torrents are the quantity and stability of debris in channels, steepness of channel, stability of adjacent hillslopes, and peak discharge characteristics of the channel. The concentration and stability of debris in channels reflect the history of stream flushing and the health and stage of development of the surrounding timber stand (Froehlich, 1973). The stability of adjacent slopes is dependent on a number of factors described in previous sections on other mass erosion processes. The history of storm flows has a controlling influence over the stability of both soils on hillslopes and debris in stream channels.

Although debris torrents pose very significant envirionmental hazards in mountainous areas of Northwestern North America, they have received little study (Fredriksen, 1963, 1965; Morrison, 1975; Swanson et al., 1976). Velocities of debris torrents, estimated to be up to several tens of meters per second, are known only from verbal and a few written accounts. The occurrence of torrents has been systematically documented in only two small areas of the Pacific Northwest, both in the western Cascade Range of Oregon (Morrison, 1975; Swanston and Swanson, 1976). In these studies, rates of debris torrent occurrence were observed to be 0.005 and 0.008 events km^2/yr for forested areas (table 4). Torrent tracks initiated in forest areas ranged in length from 100 to 2 280 m and averaged 610 m of channel length. Debris avalanches have played a dominant role in triggering 83 percent of all inventoried torrents. Mobilization of stream debris not immediately related to debris avalanches has been a minor factor in initiating debris torrents.

Deforestation appears to dramatically accelerate the occurrence of debris torrents by increasing the frequency of debris avalanches. Although it has not been demonstrated, it is also possible that increased concentrations of unstable debris in channels during forest harvesting (Rothacher, 1959; Froehlich, 1973; Swanson et al., 1976) and possible increased peak discharges (Rothacher, 1973; Harr et al., 1975) may accelerate the frequency of debris torrents.

The impact of clearcutting and road construction on frequency of debris torrents (events km^2/yr) may be compared to debris torrent probability under natural conditions. In the H. J. Andrews Experimental Forest and the Alder Creek study sites, Oregon, timber harvesting appeared to increase

Table 4.--Characteristics of Debris Torrents wtih Respect to Debris Avalanches and Land Use Status of Site Initiation in the H. J. Andrews Experimental Forest[1/] and Alder Creek Drainage (Morrison, 1975)

Site	Area of Watershed (km^2)	Period of Record (yr)	Debris Torrents Triggered by Debris Avalanches	Debris Torrents with no Associated Debris Avalanche	Total	($No./km^2/yr$)	Rate of Debris Torrent Occurrence Relative to Forested Areas
			--------------Number	------------------			
H. J. Andrews Experimental Forest, western Cascades, Oregon U.S.A.:							
Forest	49.8	25	9	1	10	0.008	x 1.0
Clearcut	12.4	25	5	6	11	0.036	x 4.5
Road	2.0	25	17	-	17	0.340	x 42.0
Total	64.2		31	7	38		
Alder Creek Drainage, western Cascade Range, Oregon, U.S.A.:							
Forest	12.3	90	5	1	6	0.005	x 1.0
Clearcut	4.5	15	2	1	3	0.044	x 8.8
Road	0.6	15	6	-	6	0.667	x133.4
Total	17.4		13	2	15		

[1/] Fredrick J. Swanson, unpublished data, on file at Forestry Sciences Laboratory, U.S. Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, U.S.A.

the occurrence of debris torrents by 4.5 and 8.8 times; and roads were responsible for increases of 42.5 and 133 times.

Although the quantitative reliability of these estimates of harvesting impacts is limited by the small number of events analyzed, there is clear evidence of marked acceleration in the frequency of debris torrents as a result of forest harvesting and roadbuilding. The histories of debris avalanches in the two study areas clearly indicate that increased debris torrent occurrence is primarily a result of two conditions: debris avalanches trigger most debris torrents (table 4), and the occurrence of debris avalanches is greatly increased by deforestation and road construction (table 3).

FACTORS CONTROLLING AND CONTRIBUTING TO LANDSLIDE OCCURRENCE

It is essential for effective management of steep mountain lands to be able to identify and understand the interaction of principal and contributing factors controlling slope failure. This requires, first of all, a basic knowledge of the geology, hydrology, and pedology of the area being managed and at least a rudimentary understanding of the principal mechanisms of movement. Thus, local bedrock type and structure, frequency and intensity of storm events, depth and degree of weathering, and basic soil characteristics determine the type of process and the individual failure mechanism. External factors, primarily rooting structures of trees and understory vegetation, and the influences of man modify these mechanisms and have been shown to contribute substantially to the inherent stability of the site.

MECHANICS OF MOVEMENT

An adequate understanding of the mechanisms of failure can best be obtained using simplified concepts of soil mechanics.

Direct application of soil mechanics theory to analysis of mass movement processes is difficult because of the heterogeneous nature of soil materials, the extreme variability of soil water conditions, and the related variations in stress-strain relationships with time. The theory does, however, provide a convenient framework in which to discuss the general mechanism and complex interrelationships of the various factors active in development of soil mass movements on mountain slopes.

In simplest terms, the stability of soils on a slope can be expressed as a ratio between shear strength, or resistance of the soil to sliding, and the downslope pull of gravity or gravitational stress. As long as shear strength exceeds the pull of gravity, the soil will remain in a stable state (Terzaghi, 1950; Zaruba and Mencl, 1969).

It is important to remember that soil mass movements result from changes in the soil shear strength-gravitational stress relationship <u>in the vicinity of failure</u>. This may involve a mechanical readjustment among individual particles or a more complex interaction between both internal and external factors acting on the slope.

The following figure (fig. 6) shows the geometrical relationship of these various factors acting on a small portion of the soil mass. Any increases in gravitational stress will increase the tendency for the soil to move downslope. Increases in gravitational stress result from

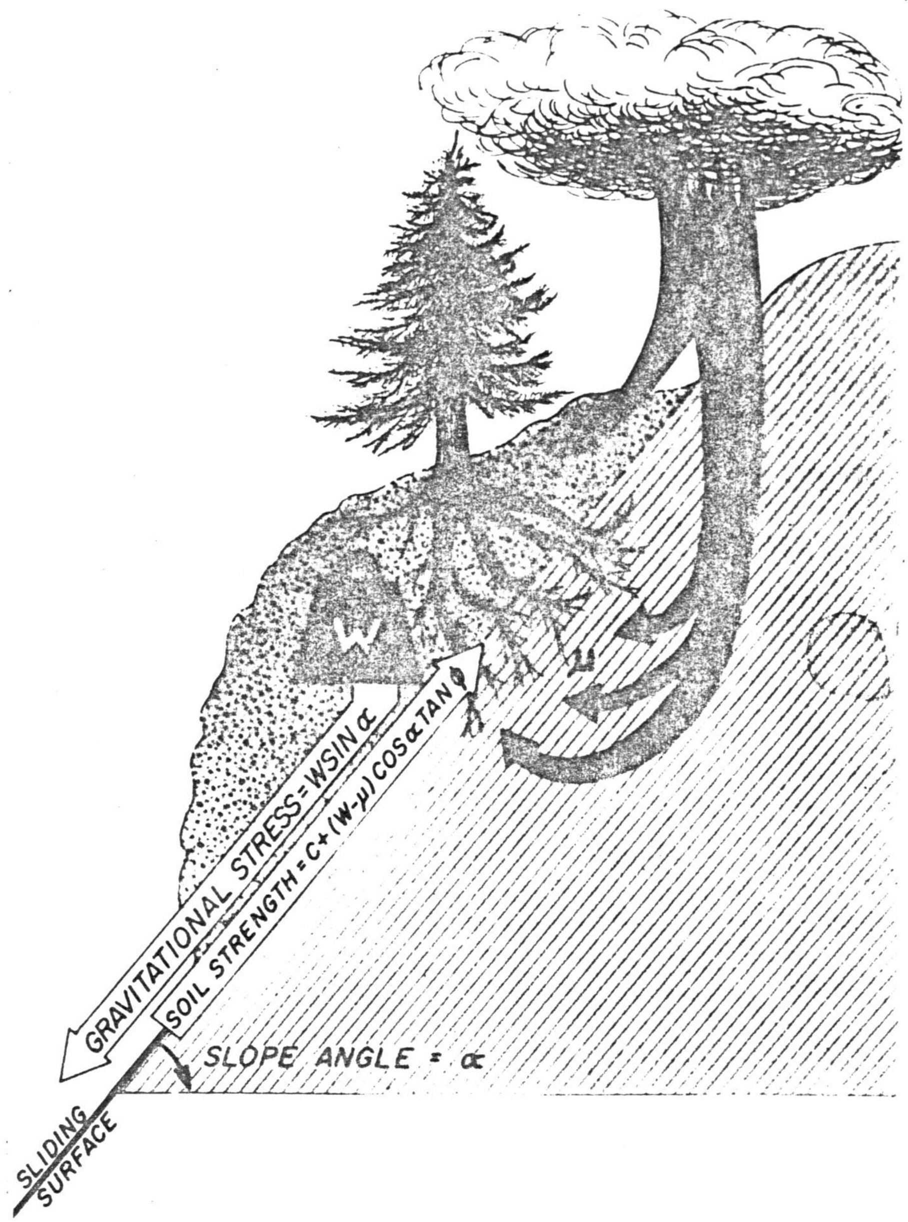

Figure 6.--Simplified diagram of forces acting on a mass of soil on a slope. (Swanston, 1976)

increasing inclination of the sliding surface or increasing unit weight of the soil mass. Stress can also be augmented by (a) the presence of zones of weakness in the soil or underlying bedrock produced by bedding planes and fractures, (b) application of wind stresses transferred to the soil through the root systems of trees, (c) strain or deformation in the soil produced by progressive creep, (d) frictional "drag" produced by seepage pressure, (e) horizontal accelerations due to earthquakes, and (f) removal of downslope support by undercutting.

Shear strength is governed by a more complex interrelationship between the soil and slope characteristics. Two principal forces are active in resisting downslope movement. These are: (1) cohesion (c) or the capacity of the soil particles to stick or adhere together--a distinct soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and (2) the frictional resistance ($W \cos \alpha \tan \phi$) between individual particles and between the soil mass and the sliding surface. Frictional resistance is controlled by the angle of internal friction (ϕ) of the soil--the degree of interlocking of individual grains--and the effective weight $[(W-\mu) \cos \alpha)]$ of the soil which includes both the weight of the soil mass and any surface loading plus the effect of slope gradient and excess soil water.

Pore water pressure--pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water--acts to reduce the frictional resistance of the soil by reducing its effective weight. In effect, its action causes the soil to "float" above the sliding surface.

CONTROLLING AND CONTRIBUTING SITE CHARACTERISTICS

Particle size distribution (which governs cohesion), angle of internal friction, soil moisture content, and angle of slope are the controlling factors in stability of a steepland soil. For example shallow coarse-grained soils low in clay-size particles have little or no cohesion, and frictional resistance determines the strength of the soil mass. Frictional resistance is in turn strongly dependent on the inherent angle of internal friction of the soil and the degree of pore-water pressure development. A low angle of internal friction relative to slope angle or high pore pressures can reduce soil shear strength to negligible values.

Slope angle is a major indicator of the stability of those soils. Slopes at or above the angle of internal friction of the soil indicate a highly unstable natural state.

Soils of moderate to high clay content take on a much more complex character wtih resistance to sliding determined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture content. In a dry state, clayey soils have a high shear strength with the internal friction angle quite high (>30°). Increasing water content mobilizes the clay through adsorption of water into the clay structure. The angle of internal friction is reduced by the addition of water to the clay lattices (in effect reducing "intragranular" friction) and may approach zero in the saturated state. In addition, water between grains--interstitial water--may open the structure of the soil mass. This permits a "remolding" of the clay fraction, transforming it into a slurry, which then lubricates the remaining soil mass. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas characterized by quasi-viscous flow deformation or "creep." Swelling clays of the smectite group are particularly unstable because of their tendency to adsorb large quantities of water and the loosening effect of alternate expansion and contraction during periods of wetting and drying. Thus, clay-rich soils have a much higher potential for failure given excess soil moisture content. Under these conditions, failures are not directly dependent on sliding surface gradient as in cohesionless soils but may develop on slopes with gradients as low as 2 or 3°.

Parent material type has a major effect on the particle size distribution, depth of weathering, and relative cohesiveness of a steepland soil. It can frequently be used as an indicator of relative stability or potential stability problems if local climatic conditions and relative age of the geomorphic surface on which the soil is developed are known. In humid regions where chemical weathering predominates, transformation of easily weathered primary minerals to clays and clay-size particles may be extensive. Siltstones, clay stones, shales, nonsiliceous sandstones, pyroclastics, and serpentine-rich rocks are the most easily altered and are prime candidates for soil mass movements of the creep and slump-earthflow type. Conversely, in arid or semi-arid regions, slopes underlain by these rocks may remain stable for many years due to slow chemical weathering processes and lack of enough soil moisture to mobilize existing clay minerals. On steeplands, underlain by resistant rocks, especially those at high altitude or latitude where mechanical weathering prevails, soils are usually coarse and low in clay-size particles. Such areas are more likely to develop soil mass movements of the debris avalanche or debris flow type.

Parent material structure is a critical factor in stability of many shallow soil slopes. Highly jointed bedrock slopes with principal joint planes parallel to the slope provide little mechanical support to the slope and create avenues for concentrated subsurface flow and active pore-water pressure development as well as ready-made zones of weakness and potential failure surface for the overlying material. Sedimentary rocks with bedding planes parallel to the slope function in essentially the same way with the uppermost bedding plane functioning as an impermeable boundary to subsurface water movement--a layer restricting the penetration and development of tree roots and an active failure surface.

Vegetation cover in general helps control the amount of water reaching the soil and the amount held as stored water against gravity, largely through a combination of interception and evapotranspiration. The direct effect of interception on the soil water budget is probably not large, especially in areas of high total rainfall or during large storms when most soil mass movements occur. The small storms where interception is effective probably have little influence on total soil water available for activating mass movements.

In areas of low rainfall, the effect of evapotranspiration is much more pronounced but is particularly dependent on region and time. In areas characterized by warm, dry summers, evapotranspiration withdrawals of soil moisture have a significant effect in reducing the degree of saturation resulting from the first storms of the fall recharge period. This effect is reduced as soil water deficit is satisfied. Once the soil is recharged, the effect of previous evapotranspirational losses becomes negligible. Conversely, in areas of continuous high rainfall or those with an arid or semi-arid climate, evapotranspirational effects are probably negligible. Also of importance is the depth of evapotranspirational withdrawals. Deep withdrawals may require substantial recharge to satisfy the soil water deficit, delaying or reducing the possibility of attainment of saturated soil conditions necessary for major slide-producing events. Shallow soils, on the other hand, will recharge rapidly, possibly attaining saturated conditions and maximum instability during the first major storm.

Root systems of trees and other vegetation may act to increase shear strength in unstable soils. Such an external shear strength factor can result from roots:

1. Anchoring through the soil mass into bedrock fractures in the rock.
2. Providing continuous long fiber cohesive binders to the soil mass.
3. Tying slope together, across zones of weakness or instability, or stable soil masses.
4. Providing downslope support to an unstable soil mass.
5. Interlacing wtih other vegetation, providing a network of stability through their own strength.

In shallow soils, all five items may be important. In deep soils, the anchoring effect of roots becomes negligible, but the other parameters will remain important. In some extremely steep areas in Western North America, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area (Swanston and Swanson, 1976).

Snow cover increases soil unit weight through surface loading and affects delivery of water to the soil through retention of rainfall and delayed release of large water quantities during spring melt. Delayed release of melt water, coupled with unusually heavy storms during a spring warming trend have been identified as the principal initiating factor in recent major landslide activity on forest lands in central Washington.

Hazard Identification and Assessment

A basic understanding of mass wasting processes and controlling and contributing factors is essential to effective identification, prediction and control of soil mass movements on forest lands. Once he has accomplished this the land manager has several options available to him. He can (1) identify problem areas and avoid operations on unstable terrain; (2) identify and attempt to control operational effects or (3) identify and assess the hazard relative to various forest operations and downstream impacts.

In highly unstable areas or areas of questionable economic value, avoidance of all operations is probably the best and least expensive solution. Controlling operational effects is a much more difficult approach which at best will probably be only partially successful. It is applicable in high value areas of questionable soil stability or where other considerations override a desire for stability maintenance. Assessment of the relative hazard of soil mass movement activity and damage from proposed forest harvest operations provides the most useful approach for the land manager, allowing a comparison of the impacts of various alternatives and selection of the best management approaches to protect watershed values.

Accurate models and the substantial body of input data necessary for the quantitative prediction of failure risk and magnitude of contributions to stream courses over broad areas is currently lacking. Quantitative engineering techniques for site-specific stability analyses exist (based on the Mohr-Columb Theory of Earth Failure) and are quite accurate in assessing the strength-stress relationships in a small area. These techniques, however, require accurate measurement of the engineering properties of the soils involved and specific knowledge of the geology and groundwater hydrology at the site. Such data must be generated at considerable expense and are extremely variable from site to site, even under the same geologic and climatic setting making this mechanistic approach impractical for broad areal risk assessment at the present time.

Given these limitations, a more practical approach is to combine:

a) a subjective evaluation of the relative stability of an area using soils, geologic, topographic, climatilogic and vegetative indicators obtained from aerial photos, maps and field reconnaisance,

b) a limited strength-stress analysis of the unstable sites using available or easily generated field data, and

c) estimates of sediment delivery to streams based on failure type, distance from the stream channel and certain site variables such as slope gradient and slope irregularities.

Together, these data can be integrated to provide a measure of landslide hazard and the level of sediment contributed to adjacent stream channels.

Such an approach has been developed in Chapter V, Soil Mass Movement, Water Resources Evaluation Non-Point Sources-Silviculture Handbook (Swanston, Swanson and Rosgen, in press) and in the Watershed Analysis Procedure, Clearwater National Forest (Bennett and Wilson; 1975).

While the results of this approach are largely qualitative in nature they do provide a viable means of assessing the impacts of various harvest practices on the stability of a watershed and estimation of sediment delivery to channels by mass movement processes.

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