EROSION PROCESSES AND CONTROL METHODS IN NORTH AMERICA

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INTRODUCTION

Forest operations in mountainous regions of North America have a major impact on site erosion and accelerated transport of soil materials to the stream. The resultant downstream damage from aggradation and degradation of the channel frequently causes flooding and siltation of terrace and lowland areas, destroys spawning habitat of anadromous fish, and produces deleterious changes to estuarine habitats by siltation and channel alterations. This is particularly true in the northwestern portion of the continent where mountains are in a dynamic stage of geomorphic development. Slopes are steep, drainage densities are low, and large areas are subject to annual precipitation in excess of 200 to 250 cm. Consequently, natural erosion rates are high, and streams respond rapidly to changes in rainfall intensity.

In the undisturbed state, heavy forest vegetation and high infiltration capacity of forest soils protect the slopes from surface erosion, making mass erosion processes (landslides) generally the most dominant natural mechanisms of sediment transport from mountain slopes to stream channels. Only where bare mineral soil is exposed through disturbance of the forest soil cover, either by natural processes or man's activities, does surface erosion become a significant contributor to this slope transport process.

The interaction of these processes, the impact of timber harvesting operations on acceleration of erosion, and practical control methods available to the land manager have been discussed by Swanston (1974), Swanston and Dyrness (1973), and Swanston and Swanson (in press) and will be summarized here.

P R O C E S S E S

Two principal types of rainfall-caused surface erosion are recognized. These are rilling and gullying and sheet erosion (Figure 1). Dominant mass erosion processes on forested slopes are slow, downslope movements involving subtle deformation of the soil mantle (creep) and discrete failures both of the slump-earthflow type (Figure 2), or the rapid, shallow soil and organic debris movement from hill slopes (debris avalanches) (Figure 3A) and stream channels (debris torrents) (Figure 3B).

Forest vegetation plays an important role in stabilizing slopes and reducing rate of movement and occurrence of all these erosion processes. When marginally stable slopes are deforested, whether by natural processes such as wildfire and wind or by the activities of man, temporary acceleration of erosion activity is likely.

The timber harvesting activities of clearcutting and road construction modify factors influencing erosion processes in several ways. Some of the most important are summarized in Table 1 (Swanston and Swanson, in press). Also indicated in Table 1 is whether the harvesting activity usually increases or decreases stability of the landscape.

S u r f a c e   E r o s i o n

Whether rilling and gullying or sheet erosion dominates is determined by the interrelation of rainfall duration and intensity, soil erodibility, topography, and plant and litter cover.

Rilling and gullying is channelized erosion caused by the detachment of soil particles which are carried in suspension by flowing water. This type of accelerated erosion is easily recognized because of the scars it leaves on the land.

In areas of bare mineral soil, particles may be detached and moved downslope by the effects of raindrop splash. This is sheet erosion and may go on virtually unnoticed. However, when severe, it may be detected by noting exposure of roots or pedestalling under some impervious materials such as gravel or wood fragments.

Rainfall intensity and duration are self explanatory. Erodibility includes all these soil properties which determine its inherent susceptibility to surface erosion. Since erosion is a two-phase process involving both detachment and transport of soil particles, the most important soil factors are those influencing infiltration and percolation of water and size and density of surface soil particles. Topographic characteristics which have considerable influence on surface erosion include both slope gradient and slope length; of course, plant and litter cover form the greatest deterrent to surface erosion.

Timber harvesting may increase surface erosion as the result of exposure of bare mineral soil and soil compaction. Tremendous amounts of kinetic energy are expended by falling raindrops as they impinge upon the earth's surface. In undisturbed forests, most of this potentially destructive energy is absorbed by vegetation and litter.

But, with disturbance, at least a portion of this raindrop energy is directed at unprotected bare soil areas. The impact of rain on bare soil has two negative effects: (1) It causes the detachment of soil particles (the first step in the erosion process), and (2) in time, it results in decreased water infiltration rates and thus more surface runoff (providing transport, or the second step in surface erosion). Decreased surface soil porosity is caused by the destruction of soil structure due to raindrop impact. This splash impact breaks down soil aggregates, throws the soil into suspension, and ultimately results in the clogging of surface porosity. When bare soil is exposed as a result of management activities, it is important to remember that both duration and amount are crucial. In high rainfall areas, revegetation of bare areas occurs so rapidly that detrimental effects are minimized.

Compaction from logging or other activities causes decreased infiltration rates and consequent increases in surface runoff and erosion. The two most important factors affecting compaction are soil texture and moisture content. Most studies have indicated that medium texture soils (loams and silt loams) compact to greater densities than do fine or coarse texture soils. Soil moisture contents giving the greatest degree of compaction are neither very wet nor very dry. One study showed optimum moisture for compaction to be about midway between field capacity and the permanent wilting point.

C r e e p

Creep has been defined as the slow downslope movement of soil mantle materials as the result of long-term application of gravitational stress. The mechanics of 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, occurring 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.

Natural creep rates monitored in different geological materials in the western Cascade and Coast Ranges of Oregon and northern California, U.S.A., indicate rates of movement between 7.1 and 15.2 mm/yr, with the average about 10 mm/yr (Swanston and Swanson, in press, Table 2). The zone of most rapid movement usually occurs at or near the surface, although a zone of maximum displacement is usually present at variable depth 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 (Figure 4A), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (Figure 4B). This is consistent with Ter-Stepanian's (1963) theoretical analysis which showed that downslope creeprate of an inclined soil layer was exponentially related to piezometric level in the slope.

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

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 occurrence 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 creep activity and, thereby, the annual creep rate.

Brown and Sheu (1975) have developed a mathematical model of creep which accounts for root strength, wind stress on the soil mantle, weight of vegetation, and soil moisture. The model predicts a brief period of slope stability after clearcutting due to removal of the weight of vegetation and elimination of wind stress. Thereafter, creep rates are accelerated as soil strength is attenuated by progressive root decay and a rising water table occasioned by a drop in evapotranspiration. The net result of the short-term increase and longer term decrease in slope stability is expected to be an overall increase in creep activity.

Slump-earthflow

Where creep deformation 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). Geologic, vegetative, and hydrologic factors have primary control over slump-earth 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 in the amount of available soil water (weeks, months, or annually) (Wilson, 1970).

Because earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than on the occurrence of debris avalanches and torrents. Where planes of slump-earthflow failure are more than several meters deep, weight of vegetation and vertical root-anchoring 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 they are active, rates of movement have been monitored directly by repeated surveying of marked points and inclinometers and by measuring deflection of roadways and other inadvertent reference systems. These methods have been used to estimate rates of earthflow movement shown in Table 3 (Swanston and Swanson, in press).

The aereal occurrence of slump-earthflows is mainly determined by bedrock geology. For example, in the Redwood Creek Basin, northern California, U.S.A., 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 aereal occurrence of slump-earthflows in volcanic terrains has also been closely linked to bedrock type (Swanson, personal communication[1/]). At a study site in the western Cascade Range of Oregon, U.S.A., 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 dramatic impact on slump-earthflow activity (Wilson, 1970). In the forest environment, there are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction. 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 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. However, hydrologic impacts of deforestation appear to be important. Increased moisture availability due to reduced evapotranspiration will increase 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.

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Debris Avalanches

Debris avalanches are rapid, shallow soil mass movements from hillslope areas. Here we use the term "debris avalanche" in general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) 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 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 4 (Swanston and Swanson, in press) shows that annual rates of debris avalanche erosion from forested areas of 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 (Table 4) reveals that clearcutting 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 4, road-related debris avalanche erosion was increased by factors ranging from 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, design, and construction of roads.

Debris Torrents

Debris torrents involve the rapid movement of water-charged soil, rock, 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 slides from adjacent hillslopes which enter a channel and move directly downstream or by the breakup and mobilization of debris accumulations in the channel. 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 environmental hazards in mountainous areas of Northwestern North America, they have received little study (Fredriksen, 1963, 1965; Morrison, 1975; Swanson and Lienkaemper, 1975). Velocities of debris torrents, estimated to be up to several tens of meters per second, are known only from verbal accounts and a few written accounts. The occurrence of torrents has been systematically documented in only two small areas of the Pacific Northwest U.S.A., both in the western Cascade Range of Oregon (Morrison, 1975; Swanston and Swanson, in press). 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 5). 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. Therefore, the susceptibility of an area to debris avalanching is a direct indicator of the potential for debris torrents.

Timber harvesting activities appear 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 harvesting (Rothacher, 1959; Froehlich, 1973; Swanson and Lienkaemper, 1975) and possible increased peak discharges (Rothacher, 1973; Harr et al., 1975) may accelerate the frequency of debris torrents.

The relative impacts of these factors and of clearcutting and roads may be assessed with the frequency of debris torrents (events/km^2/yr) in forest areas used as an estimate of the natural, background level of debris torrent probability against which to compare the rates of debris torrent occurrence attributed to roads and clearcutting. In the H. J. Andrews Experimental Forest and the Alder Creek study sites, Oregon, clearcutting appeared to increase 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 clearcutting 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 5), and the occurrence of debris avalanches is greatly increased by clearcutting and road construction (Table 4).

Control Methods

Several effective engineering control measures are available for slope stabilization, but as a rule, they are expensive and generally applicable to specific occurrences. Current erosion control methods on forest lands in Western North America have been directed toward identification and characterization of unstable ground, avoidance of disturbances damaging to slope stability, and reduction of impact of disturbances on slope erosion processes.

The land manager has a variety of means at his disposal for minimizing impacts on mountainous forest lands. The key is to apply these means in a knowledgeable and consistent manner. One of the most effective means is careful selection of the silvicultural system to be used. After the land manager has carefully considered the potential erosion hazard in an area, he then must decide on the proper level of management. If erosion hazard is unusually high, perhaps the optimum decision would be to forgo logging and intensive management and, instead, practice protective management. If, on the other hand, the manager decides on some sort of manipulation, he must then select a silvicultural approach which is suitable to the site. The options available might range from light thinning to clearcutting and replanting. Whatever the decision, site erosion potential is one of the most important considerations in selection of an appropriate silvicultural system. For example, though clearcutting may be suitable on stable sites, shelterwood management will provide the surface soil protection and maintenance of anchoring and stabilizing root structures necessary in unstable areas. Such a system will also minimize any changes in the hydrological characteristics of the affected area.

In selection of the silvicultural system, it is important to recognize that compromise may be necessary due to possible conflicts between silvicultural and watershed management objectives. For example, silviculturists often favor the exposure of maximum amounts of bare mineral soil during logging to aid in the establishment of certain tree species. In Western North America, this has resulted in increasing use of such measures as clean yarding and machine piling of logging residues. The resultant extensive areas of compaction and bare soil have lead to serious surface erosion problems in some areas, especially if protective vegetation is slow to reinvade the site.

Simple removal of logging debris from narrow gullies and steep channels, on the other hand, may be very effective in reducing the incidence of debris torrent development due to buildup of debris dams and resultant failure during major storms. A recent survey of greatly accelerated torrent flow occurrence in the Coast Ranges of Oregon indicates that ≈ 88 percent of the torrents resulted from failure of debris dams generated by logging.[2/]

A second means of minimizing erosion damage is by careful selection of logging method. Here again, the land manager must attempt to minimize surface disturbance and removal of trees on exceptionally steep ground by careful choice of methods. The following tabulation illustrates percent variation in surface disturbance caused by four yarding methods used in clearcut operations in the Pacific Northwest United States (Swanston and Dyrness, 1973).

	Bare Soil	Compacted
Tractor	35.1	26.4
Highlead	14.8	9.1
Skyline	12.1	3.4
Balloon	6.0	1.7

It should be pointed out that values for tractor logging also include the effects of tractor piling of the slash.

Slash disposal may also increase erosion hazard through the removal of protective organic debris. In a skyline logged clearcut in western Oregon, 12 percent of the area was bare mineral soil after logging. However, after broadcast burning of the slash, 55 percent of this same area was bare mineral soil.

Acceleration of erosion can be strongly influenced by inadequate fire control. It is well known that fires often cause greatly increased rates of surface erosion. Fire is also an effective indicator of more active mass soil movements. Probably the most deleterious effect of fires from the standpoint of the erosion processes is the removal of protective vegetation and litter and the destruction of stabilizing root systems. If fires are sufficiently hot, they may also cause changes in surface soil properties and increase susceptibility of the soil to erosion. Perhaps the most serious changes which occur are breakdown of water-stable aggregates and lowering of organic matter content in the surface soil. Since organic matter is one of the principal cementing agents in the formation of aggregates, its loss is especially serious.

In some sandy-textured soils, high-intensity fires cause the formation of very impervious layers near the surface of the soil. Although we still don't fully understand how these hydrophobic layers are formed, it is increasingly apparent that this soil wettability problem is widespread, especially in the western United States. Because of their resistance to wetting, these soils have very low infiltration rates; thus, runoff and erosion may be severe on steep slopes.

[2/] A summary of Slide Inventory Data - storm events of November 30 to December 4, 1975, Mapleton Ranger District; compiled by Stuart Creswell, David Heller, and David Minor. On file at Mapleton Ranger Station, USDA Forest Service, Siuslaw National Forest, Mapleton, Oregon, U.S.A.

Road construction activities can accelerate surface erosion and disrupt the basic equilibrium of forest soils on steep slopes by (a) interception and concentration of slope drainage, (b) bank exposure and slope undercutting, and (c) slope loading. Some effective road design and construction techniques reducing these impacts are already available to the engineer and land manager. It is largely the correct and consistent application of these techniques which determines the overall impact of this activity on erosion acceleration.

The greatest deterrent to erosion is cover. Accordingly, the manager's first job is to determine where timber should be left to minimize erosion. After disturbance, reestablishing, as quickly as possible, a protective covering of vegetation and litter is imperative. In areas of compaction or exposed subsoil, natural revegetation may occur so slowly that seeding and fertilizing may be necessary. As an example, planting grass seed on bare roadside slopes has become a common practice in many forested areas of North America. Roads may also require special drainage measures, such as waterbars, dips, or open culverts, to divert surface runoff and thus minimize erosion. Specifications for their construction are readily available.

SUMMARY

Creep, slump-earthflows, debris avalanches, and debris torrents are the major erosion processes on mountainous forest land; they function as primary links in the natural transport of soil material to streams.

In deeply weathered, clay-rich mantle materials, creep movement may range as high as 15 mm per year. Where discrete failure occurs, transport rates of material by slump-earthflow may increase by several orders of magnitude. On steep slopes characterized by shallow, coarse-grained mantle materials and steep, incised drainages, debris avalanches and debris torrents transport large volumes of material to the stream at rates as high as 20 m per second.

Clearcutting and road construction accelerate these processes, the former by destroying the stabilizing influence of vegetation cover and altering the hydrologic regime of the site. The latter exposes bare mineral soil and interrupts the balanced strength-stress relationships existing under natural conditions by cut and fill activities, poor construction of fills, and alteration of surface and subsurface water movement.

Once unstable areas are identified and characterized, the forest land manager has several techniques available for minimizing erosion damage. These include various types of stand manipulation--ranging from no logging to clearcutting and replanting, selection of logging methods which can help to minimize surface disturbance and destruction of stabilizing vegetation, and judicious location and design of forest roads.

KEYWORDS

Mass erosion, Steepland geomorphology, Timber harvesting impacts

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TABLE 1. IMPACTS OF ENGINEERING ACTIVITIES ON FACTORS WHICH INFLUENCE SLOPE STABILITY IN STEEP FOREST LANDS OF THE PACIFIC NORTHWEST

Factors	Engineering Activities[1/] Deforestation	Roading	References
I. Hydrologic influences			
A. Water movement by vegetation	reduce evapotranspiration (-)	eliminate evapotranspiration (-)	Gray, 1970 Brown and Sheu, 1975
B. Surface and sub-surface water movement	alter snowmelt hydrology (- or +)	alter snowmelt hydrology (- or +)	Anderson, 1969
		alter surface drainage network (-)	Harr *et al.*, 1975
		intercept subsurface water at roadcuts (-)	Megahan, 1972
	alter concentrations of unstable debris in channels (-)	alter concentration of unstable debris in channels (-)	Rothacher, 1959 Froehlich, 1973
	reduce infiltration by ground surface disturbance (-)	reduce infiltration by roadbed (-)	
II. Physical influences			
A. Vegetation			Swanston, 1970
1. Roots	reduce rooting strength (-)	eliminate rooting strength (-)	Nakano, 1971

TABLE 1. IMPACTS OF ENGINEERING ACTIVITIES ON FACTORS WHICH INFLUENCE SLOPE STABILITY IN STEEP FOREST LANDS OF THE PACIFIC NORTHWEST (continued)

	Engineering Activities[1/]		
Factors	Deforestation	Roading	References
2. Bole & crown	reduce medium for transfer of wind stress to soil mantle (+)	eliminate medium for transfer of wind stress to soil mantle (+)	Swanston, 1969
B. Slope			
1. Slope angle		increase slope angle at cut and fill slopes (-)	Parizek, 1971 O'Loughlin, 1972
2. Mass on slope	reduce mass of vegetation on slope (+)	eliminate mass of vegetation on slope (+)	Bishop and Stevens, 1964
		cut and fill construction redistributes mass of soil and rock on slope (- or +)	O'Loughlin, 1972
C. Soil properties		reduce compaction and apparent cohesion of soil used as road fill (-)	

[1/] Influence which usually increases slope stability denoted by (+); influence which usually decreases stability denoted by (-).

TABLE 2. EXAMPLES OF MEASURED RATES OF NATURAL CREEP ON FORESTED SLOPES IN THE PACIFIC NORTHWEST

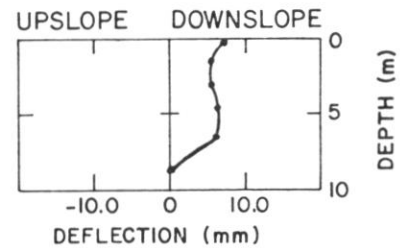
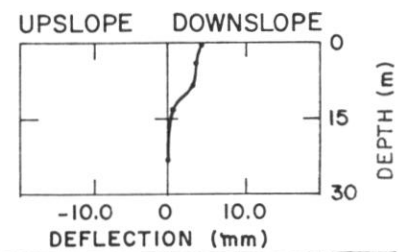
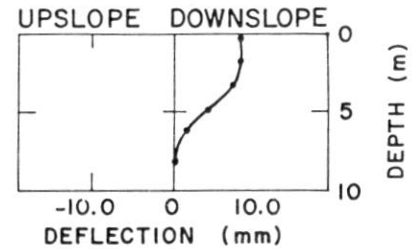
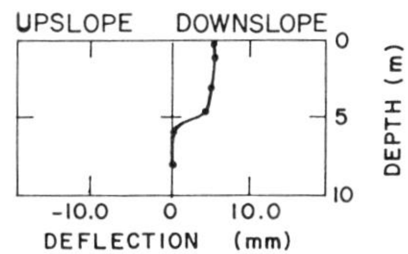
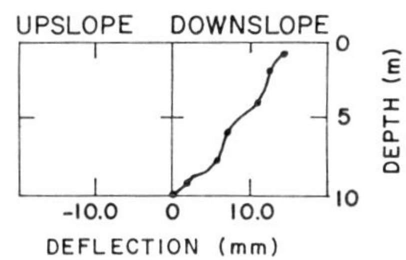
Location	Data Source	Parent Material	Depth of Significant Movement (m)	Maximum Downslope Creep Rate: Surface (mm/yr)	Maximum Downslope Creep Rate: Zone of Accelerated Movement (mm/yr)	Representative Creep Profile
Coyote Creek South Umpqua River Drainage Cascade Range of Oregon Site C-1	Swanston[1/]	Little Butte volcanic series Deeply weathered clay-rich andesitic dacitic volcani-clastic 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 2. EXAMPLES OF MEASURED RATES OF NATURAL CREEP ON FORESTED SLOPES IN THE PACIFIC NORTHWEST (continued)

Baker Creek Coquille River Coast Range, Oregon Site 3-3	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.

TABLE 3. OBSERVATIONS OF MOVEMENT RATES OF FOUR ACTIVE EARTHFLOWS IN THE WESTERN CASCADE RANGE, OREGON, U.S.A.

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

TABLE 4. DEBRIS AVALANCHE EROSION IN FOREST, CLEARCUT, AND ROADED AREAS

Site	Period of Record (yr)	Area 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.

TABLE 5. CHARACTERISTICS OF DEBRIS TORRENTS WITH RESPECT TO DEBRIS AVALANCHES AND LAND USE STATUS OF SITE OF 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.

Figure 1. Gullying in volcanic ash soil along a tractor road in western Oregon, U.S.A.

Figure 2. An example of creep and slump-earthflow processes on forest lands in northern California, U.S.A. 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.

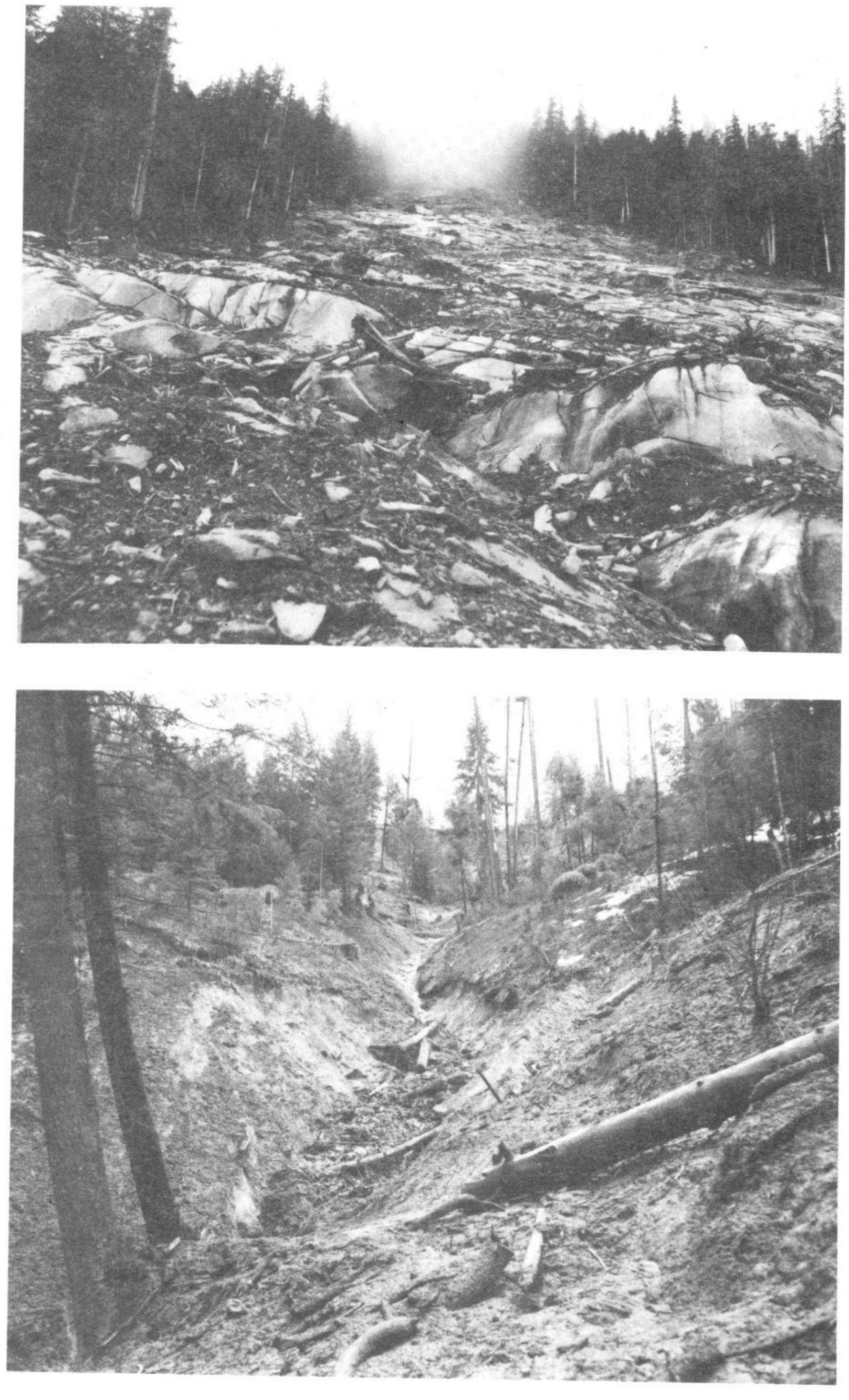


Figure 3. Debris avalanche and debris torrent development on steep forested watersheds in Northwestern North America.
A.) Debris avalanche developed in shallow cohesionless soils on a steep, forested slope in coastal Alaska.
B.) Debris torrent developed in a steep gully, probably caused by failure of a natural debris dam above trees in foreground.

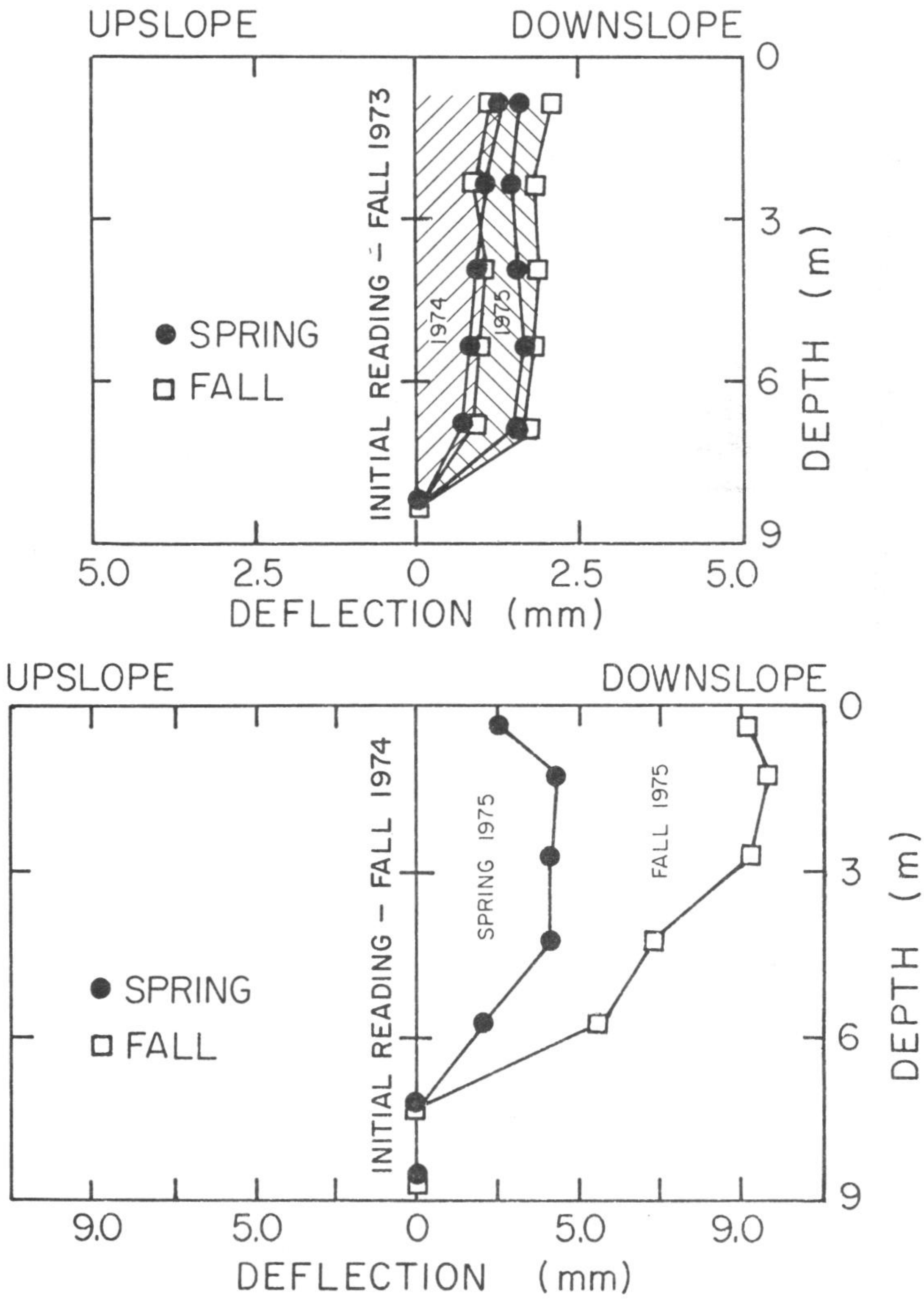


Figure 4. Deformation of inclinometer tubes at two sites in the southern Cascade Range and Coast Range of Oregon, U.S.A.

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 Range, showing constant rate of creep as a result of continual high water levels.