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An Approach To WATER RESOURCES EVALUATION OF NON-POINT SILVICULTURAL SOURCES (A Procedural Handbook)

by

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Chapter V

SOIL MASS MOVEMENT

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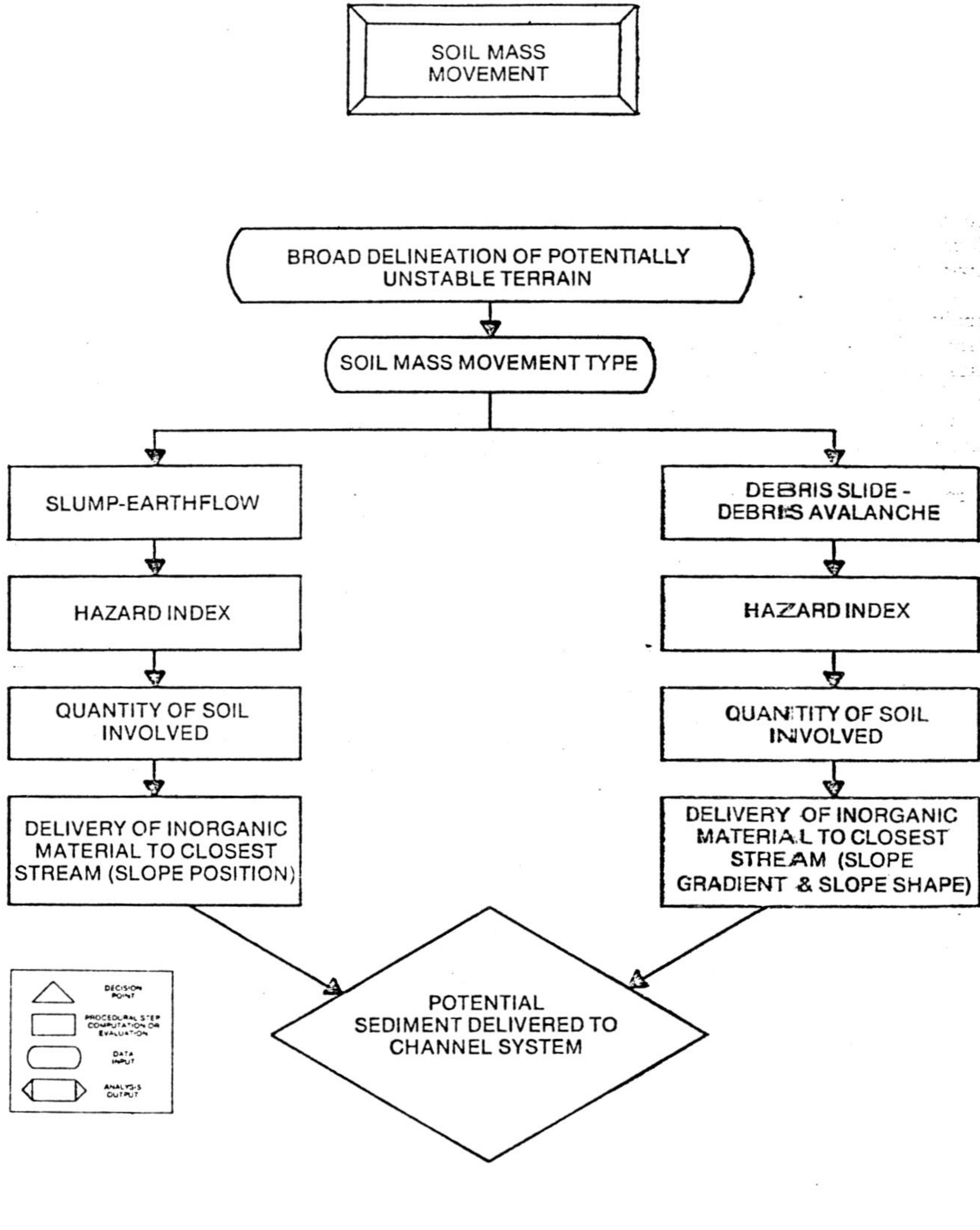


Figure V.1.—General flow chart of the soil mass movement procedure.

DISCUSSION

REVIEW OF RELEVANT WORK

Although quantitative assessment of all factors contributing to mass movement is complex and difficult, a consistent analysis of the major contributing factors can benefit the land manager, whose activities may affect slope stability. Burroughs and others (1976) discuss the effects of geology and structure in northern California and western Oregon on landslides generated by road construction; Swanston and Swanson (1976) describe the effects of geomorphology, climate, and forest management activities on debris avalanche and slump-earthflow activity in the western Cascades; Greswel, and others (in press) have assessed the effects of clearcut logging and road construction on accelerated debris avalanche activity during a single high intensity storm in the Oregon Coast Range; Burroughs and Thomas (1977) have analyzed the declining root strength in Douglas-fir, after felling, as a factor in slope stability; and Flaccus (1958), Hack and Goodlet (1969), and Williams and Guy (1973) discuss the effects of hurricane and cloudburst triggered soil mass movement in the eastern United States.

Some interesting and successful techniques also have been developed for predicting unstable ground and identifying controlling and contributing factors. Pillsbury (1976), for example, using a linear discriminant functions analysis, attributed 90.5 percent of the debris avalanches in clearcut areas of a northern California watershed to the factors of slope percent and percent cover by dominant and understory vegetation. Both of these factors were determined by photogrammetric techniques with no ground control. An additional 1.5 percent of debris avalanche occurrences was determined by adding in the site factors of soil weathering and percent quartz in bedrock. Using photogrammetric procedures, Kojan, Foggin, and Rice (1972) were able to predict 84.4 percent of the debris slides following major storms in the Santa-Ynez-San Rafael Mountains, California, based on past landslide activity.

The factor of safety is commonly used as a quantitative expression of the hazard index of a soil mass movement. In soil mechanics, it is customary to express the balance of forces acting on a simple slope as:

$$\text{Factor of safety } (F) = \frac{\text{Resistance of the soil to failure (shear strength)}}{\text{Forces promoting failure (shear stress)}}$$

A safety factor of one (F=1) would indicate imminent failure. For broad land use planning purposes, this technique is valid only for rapid, shallow soil mass movements, such as debris avalanches and debris flows. Quantitative models utilizing this approach have been outlined in Swanson and others (1973), Brown and Sheu (1975), Bell and Swanston (1972), and Simons and Ward (1976). The difficulty in determining some of the factors (such as tensile strength of roots, location of the failure surface, and water table position for various storm intensities) has until recently, restricted the use of such models to highly instrumented sites where expensive investigations were warranted. New data and techniques are being developed, however, which are making these models more practical as land management tools.

Swanston (1972, 1973) has employed a factor of safety technique using a simplified infinite slope model to predict slope stability hazard and stratify lands according to management impact in southeast Alaska. This technique uses slope gradient as a prime hazard index. Bell and Keener (1977) have developed a method of predicting stable cut-slope heights based on the factor of safety analysis of natural slopes. Burroughs and Thomas (1977) have analyzed the effects of soil shear strength, slope gradient, soil depth, ground water rise, and root strength on stability hazard in the central Coast Range of Oregon. Prellwitz (1977) has made substantial progress in utilization of the factor of safety approach without the need for expensive site investigation. The equations account for buoyant density, fluctuating water tables, and moisture density.

Soil mass movements can yield substantial sediment. Megahan (1972) and Megahan and Kidd (1972a, 1972b) evaluated the effects of logging and road construction on high erosion hazard land in the Idaho Batholith. They report sediment yields 1.6 times greater from jammer logged sites than from undisturbed areas (they did not differentiate between surface erosion and soil mass movement). Soil mass movements from logging roads in the same area average 550 times greater than control areas. Swanston and Swanson (1976) report debris avalanche erosion rates 2 to 4 times greater from clearcuts and 25 to 344 times greater from roads than from undisturbed sites in selected areas of the Coast Range and Cascade Mountains of Oregon, Washington, and British Columbia.

Prediction of sediment yield from individual soil mass movement processes is not well documented. Individual failure release volumes are available for a few areas, but there is little information on how much of the total volume initially reaches the stream versus how much remains on the slope for slow release over time. A summary of average debris avalanche volume from six studies in the Pacific Northwest reveals a broad range in average volumes from area to area (Swanson and others 1977). For example, in the Mapleton Ranger District of the Oregon Coast Range, an area of steep, intricately dissected terrain with very shallow soil, average debris avalanche volume is less than 100 yd^3 (76 m^3), whereas steep areas of lower drainage density and deeper soils have had debris avalanches averaging more than 1,000 yd^3 (765 m^3). In the Mapleton area, Swanson and others (1977) estimated that 65 percent of the material moved by debris avalanches in forests entered streams.

Since sediment yield values for individual soil mass movements are very limited, a series of conceptual delivery curves were developed for this handbook to approximate the sediment transport potential of dominant soil mass movement processes. These curves are presented as first approximations only, and it may be necessary to develop specific delivery curves to more accurately represent local conditions. Delivery relations are needed to estimate sediment supply to streams where it will be routed through the channel network. The delivery curves in the analysis section were developed from studies of recent failures in the western Cascades and Coast Range of Oregon, and were based on estimates of the percent of material released during the initial failure that actually entered a stream. The site variables which appeared particularly sensitive to the amount of soil delivered to a drainageway were: slope gradient and slope irregularity for debris avalanche-debris flows, and slope position with respect to the closest drainageway for slump-earthflows.[1] Slump-earthflow failures not adjacent to streams, are not considered principal contributors to channel loading in this analysis since their potential impact on short-term sediment loading is negligible because of their low delivery efficiencies. Most of the sediment from mid- and upper-slope failures of this type remain on the slope following initial failure and is delivered to the channel over extended periods, mainly by surface erosion and creep.

ASSUMPTIONS

The procedures in this chapter are presented as a guide for assessing the stability of natural slopes, the potential impacts of silvicultural activities on slope stability, and predicting sediment contributions to drainageways from soil mass movements. In the absence of proven local techniques, these procedures will provide the best available estimates of soil mass movement. The procedures are not rigid. They are a frame of reference within which local data and variables may be applied to provide better estimates of relative soil stability and contributions by soil mass movement to nonpoint source pollution.

Because of the complex nature of processes and variables and the need to present the procedures in a format usable on an inter-regional basis, the following simplifying assumptions are necessary:

1. The determination of hazard index will be based on the assumption of a maximum 10-year return period, 24-hour rainfall (precipitation intensity/duration) as a potential storm event triggering mass movement. If slides in a particular region occur frequently, with storms less than a 10-year return period, the hazard evaluation should reflect this (i.e., a 10-year event is not necessary for a high hazard index).
2. A three-part hazard index will be used. The numerical ratings are subjective and depend on what is considered to be acceptable for a particular land management activity. For purposes of this analysis:
   a. "High hazard" means a greater than 66 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.
   b. "Medium hazard" means a greater than 33 and less than 66 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.

[1] *Swanston and Swanson, unpublished data.*

c. "Low hazard" means a less than 33 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.

3. Large organic debris contributions to drainageways, resulting from soil mass movement are not considered in estimates of sediment delivery. Although large quantities of organic debris are incorporated in the total volume of material released to the channel by soil mass movement, much of it remains in the channel near the point of entry.
4. Sediment delivery to the stream can be estimated from relationships between failure type and slope gradient, slope position (point of origin of failure), and morphology of the surface.
5. Volume of sediment delivered to the channel per unit area is a more realistic measure of soil mass movement impact than is number of events.
6. The instructions provided for quantifying volumes can be readily applied by field scientists.
7. Processes of soil mass movement described at this broad planning level can be readily identified and characterized regardless of geographic location.
8. Only slump-earthflows and debris avalanches-debris flows will be used to evaluate direct, short-term contributions of sediment to streams.

   Each of these two categories have been identified and described on the basis of material characteristics, failure geometry, and mechanism of movement. These categories are most affected by silvicultural activities and have the greatest potential for short-term water quality degradation.
9. Surface erosion of landslide material remaining on the slope will be determined in another section which deals with surface erosion delivery to stream channels.
10. Debris torrents will not be evaluated directly. It is assumed that when the hazard is high for debris avalanches-debris flows, it will also be high for debris torrents.
11. Sediment delivered to streams from erosion caused by creep will not be directly evaluated because of the close interrelationships of the variables involved in both creep and slump-earthflow processes. Sediment contributions from creep will be indirectly assessed using the channel erosion processes evaluated in "Chapter VI: Total Potential Sediment".

PRINCIPLES AND INTERPRETATIONS OF SOIL MASS MOVEMENT PROCESSES

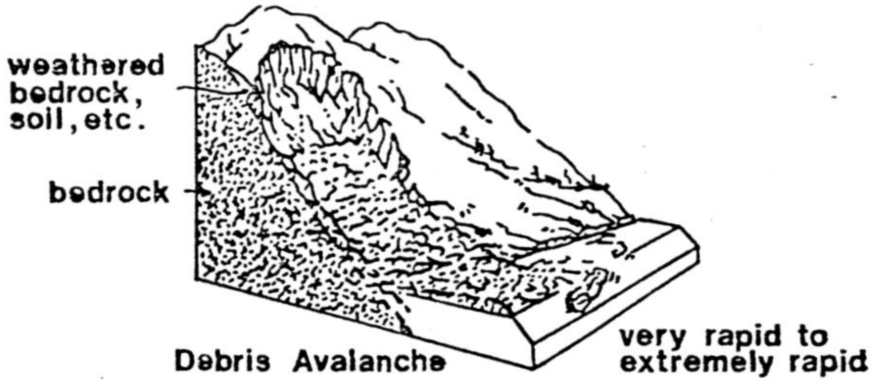
Silvicultural activities in mountainous regions, particularly forest harvest and road construction, can have a major impact on site erosion and can accelerate transport of soil materials downslope by soil mass movement. The resultant downstream damage from aggradation and degradation of the channel may cause bank erosion, disrupt aquatic habitat, and produce undesirable changes in estuarine configuration and habitat by siltation and channel alterations. This is particularly true for areas with steep slopes subject to high intensity rain and/or rapid snowmelt.

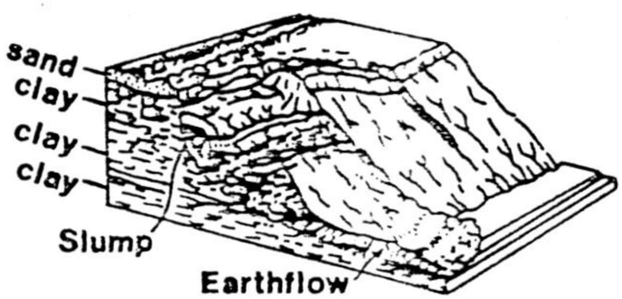
Where heavy forest vegetation covers the slope, the high infiltration capacity of the forest soils and covering organic materials generally protect the slopes from surface erosion. Under these conditions, soil mass movement processes are generally the dominant natural mechanisms of soil transport from mountain slopes to stream channels. Only where bare mineral soil is exposed by disturbance of the vegetative and organic litter cover, either by natural processes or silvicultural activities, does surface erosion significantly contribute to this slope transport process.

Principal Soil Mass Movement Processes

Downslope soil mass movements result primarily from gravitational stress. It may take the form of: (1) failure, both along planar and concave surfaces, of finite masses of soil and forest debris which move rapidly (debris avalanches-debris flows) or slowly (slump-earthflows) (fig. V.2); (2) pure rheological flow with minor mechanical shifting of mantle materials (creep); and (3) rapid movement of water-charged organic and inorganic matter down stream channels (debris torrents).

Slope gradient, soil depth, soil water content, and physical soil properties, such as cohesion and coefficient of friction, control the mechanics and rates of soil mass movement. Geological,





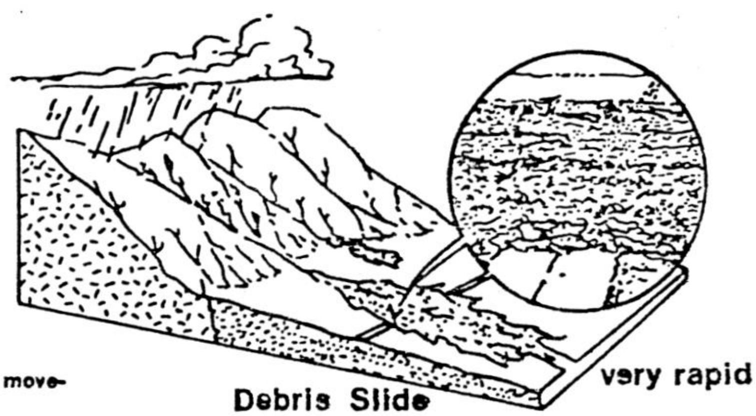


Figure V.2.—Illustration of various types of soil mass movement processes.

hydrological, and vegetative factors determine occurrence and relative importance of such processes in a particular area.

Slump-Earthflows

Where creep displacement has exceeded the shear strength of soil, discrete failure occurs and slump-earthflow features are formed (Varnes 1958). 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. V.3). 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 in soil water content (Wilson 1970, Swanston 1976).

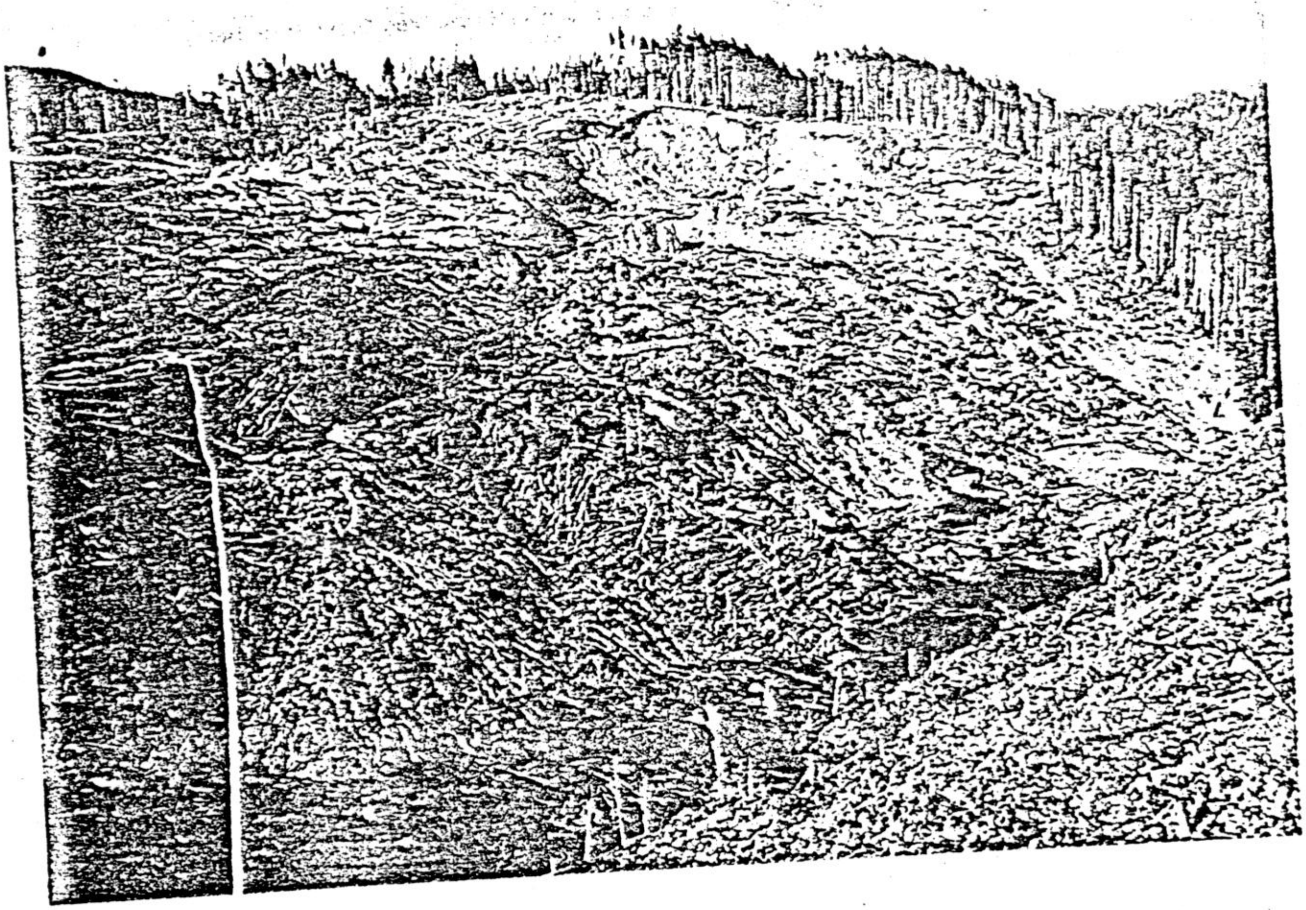


Figure V.3.—Slump and earthflow in deeply weathered sandstones and siltstones in the Oregon Coast Ranges. The slump occurred almost instantaneously. The resulting earthflow, over a period of several hours, dammed a perennial stream and produced the lake in the lower foreground.

Because earthflows are slowly moving, deep-seated, poorly drained features, individual storms probably have much less influence on their movement than on the likelihood of occurrence of debris avalanches-debris flows. Where planes of slump-earthflow are more than several meters deep, weight of vegetation and vertical root anchoring effects are insignificant.

Earthflows can move imperceptibly slowly to more than 1 m/day in extreme cases. In parts of northwest North America, many slump-earthflow areas appear to be inactive (Colman 1973, Swanson and James 1975). Where slump-earthflows are active, rates of movements 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 the rates of earthflow movement shown in table V.1 (Swanston and Swanson 1976, Kelsey 1977).

The area of occurrence of slump-earthflows is mainly determined by bedrock geology. For 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 soil mass movements, a very high percentage of the unstable areas are located in clay-rich and pervasively sheared sedimentary rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated soil mass movement. The area of occurrence of slump-earthflows in volcanic

Table V.1.—Observations of movement rates of active earthflows in the western Cascade Range, Oregon (Swanston and Swanson 1976) and Van Duzen River Basin, northern California (Kelsey 1977)

Location	Period of record	Movement rate	Method of observation
	years	cm/yr	
Landes Creek[1] (Sec.21 T.22S, R.4E.)	15	12	Deflection of road
Boone Creek[1] (Sec.17 T.17S, R.5E.)	2	25	Deflection of road
Cougar Reservoir[1] (Sec.29 T.17S, R.5E.)	2	2.5	Deflection of road
Lookout Creek[1] (Sec.30 T.15S, R.6E.)	1	7	Strain rhombus Measurements across active ground breaks
Donaker Earthflow[2] (Sec.10 T.1N, R.3E.)	1	60	Resurvey of stake line
Chimney Rock Earthflow[2] (Sec.30 T.2N, R.4E.)	1	530	Resurvey of stake line
Halloween Earthflow[2] (Sec.6 T.1N, R.5E.)	3	2,720	Resurvey of stake line

[1]Swanston and Swanson 1976.
[2]Kelsey 1977.

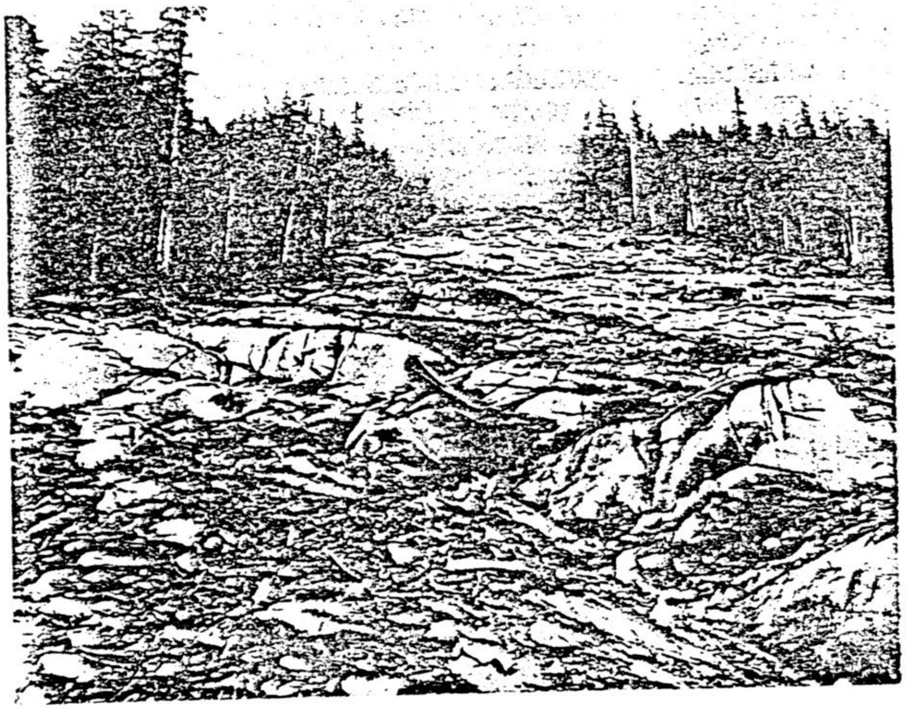
terrains has also been closely linked to bedrock (Swanston and Swanson 1976). There are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction in the western United States (Wilson 1970). Undercutting the toes of earthflows and piling rock and soil debris 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 centimeters. 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 by tree root systems is negligible. Hydrologic impacts of deforestation, however, appear to be important. Reduced evapotranspiration will increase soil moisture availability. This water is, therefore, free to pass through the rooting zone to deeper levels of the earthflow.

Debris Avalanches-Debris Flows

Debris avalanches-debris flows are rapid, shallow soil mass movements from hillslope areas. Here the term "debris avalanche-debris flow" is used in a general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) (fig. V. 4) and others on the basis of increasing water content and type of included material. 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. Areas prone to debris avalanches-debris flows 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-debris flows are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle are potentially important influence. 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 the time and place of debris avalanches-debris flows.

The rate of occurrence of debris avalanches-debris flows is controlled by the stability of the



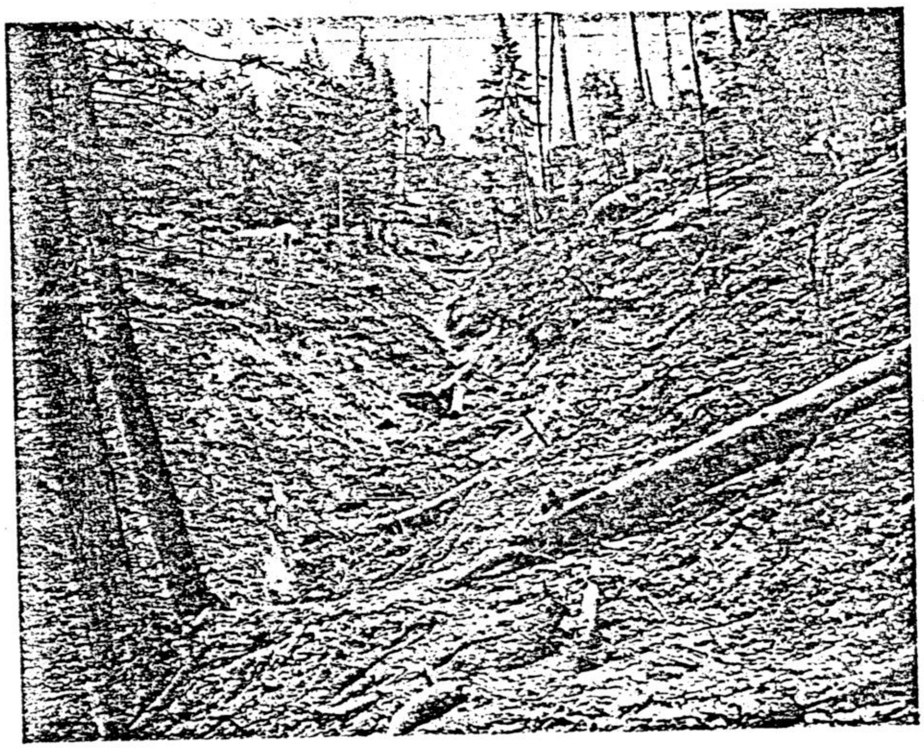


Figure V.4.—Debris avalanche and debris torrent development on steep forested watersheds in northwestern North America. (a.) Debris avalanche developed in shallow cohesionless soils on a steep, forested slope in coastal Alaska. (b.) Debris torrent developed in a steep gully, probably caused by failure of a natural debris dam above trees in foreground.

landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanches-debris flows will vary from one geomorphic-climatic setting to another. Table V.2 (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 m³/km²/yr. These estimates are based on surveys and measurements of debris avalanche erosion during a particular time period (15 to over 32 years) over a large area (12 km² or larger).

An analysis of harvesting impacts in the western United States (Swanston and Swanson 1976) (table V.2) reveals that timber harvesting commonly results in an acceleration of soil mass movement activity by a factor of 2 to 4 times relative to forested areas. In the four study areas listed in table V.2, 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 in the impact of roads reflects not only differences in the natural stability of the landscape, but also, and more importantly from an engineering standpoint, differences in site location, design, and construction of roads.

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; it occurs under shear stresses sufficient to produce permanent deformation, but too small to result in discrete failure. Mobilization of

Table V.2.—Debris avalanche erosion in forest, clearcut, and roaded areas (Swanston and Swanson 1976)

Site	Period of record	Area		Number of slides	Debris avalanche erosion	Rate of debris avalanche erosion relative to forested areas
	years	percent	km²		m³/km²/yr	
Stequaleho Creek, Olympic Peninsula, Washington, U.S.A. (Fiksdal 1974):						
Forest	84	79.0	9.3	25	71.8	1.0
Clearcut	6	18.0	4.4	0	0.0	0.0
Road	6	3.0	0.7	83	11,825.0	165.0
			24.4	108		
Alder Creek, Western Cascade Range, Oregon, U.S.A. (Morrison 1975):						
Forest	25	70.5	12.3	7	45.3	1.0
Clearcut	15	26.0	4.5	18	117.1	2.6
Road	15	3.5	0.6	75	15,565.0	344.0
			17.4	100		
Selected drainages, Coast Mountains, S.W. British Columbia, Canada:[1]						
Forest	32	83.9	246.1	29	11.2	1.0
Clearcut	32	9.5	26.4	18	24.5	2.2
Road	32	1.5	4.2	11	[1]282.5	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	1.0
Clearcut	25	19.3	12.4	30	132.2	3.7
Road	25	3.2	2.0	69	1,772.0	49.0
			64.2	130		

[1]Calculated from O'Loughlin (1972, and personal communication), assuming that area involving road construction in and outside clearcuts is 16 percent of area clearcut. Colin L. O'Loughlin, is now at Forest Research Institute, New Zealand Forest Service, Rangiora, New Zealand.

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 within the creeping mass (fig. V.5).

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 mm/yr, with the average about 10 mm/yr (Swanston and Swanson 1976) (table V.3). The most rapid movement usually occurs at or near the surface, although the significant displacement may extend to variable depths associated with incipient failure planes or zones of ground water movement. Active creep depth varies greatly and largely depends on parent material origin, degree and depth of weathering, subsurface structure, and soil water content. Most movement appears to take place during rainy season maximum soil water levels (fig. V.6 a), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (fig. V.6 b). This is consistent with Ter-Stepanian'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.

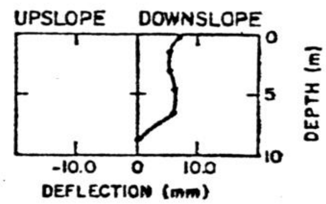
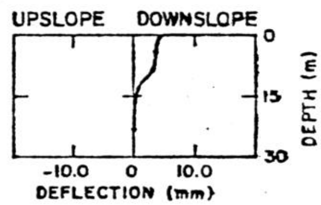
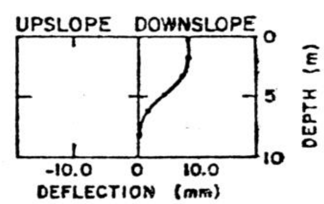
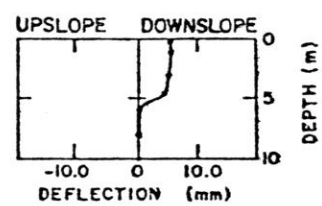
There have been no direct measurements of the impact of deforestation on creep rates in the forest environment, mainly because of the long periods of records needed both before and after a disturbance. There are, however, a number of indications that creep rates are accelerated by harvesting and road 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 occurrence of shallow soil mass movements in these disturbed areas and open tension cracks in fills along roadways 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

Figure V.5.—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.

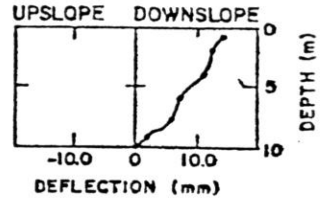
Table V.3—Examples of measured rates of natural creep on forested slopes in the Pacific Northwest (Swanston and Swanson 1976)

Location	Data source	Parent material	Depth of significant movement	Maximum downslope Creep rate		Representative creep profile
				Surface	Zone of accelerated movement	
			m	mm/yr	mm/yr	
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 volcanic 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	---	
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	

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

[2]F. Michael McCorison and L. F. Glenn, data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

Table V.3—Examples of measured rates of natural creep on forested slopes in the Pacific Northwest (continued)

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	

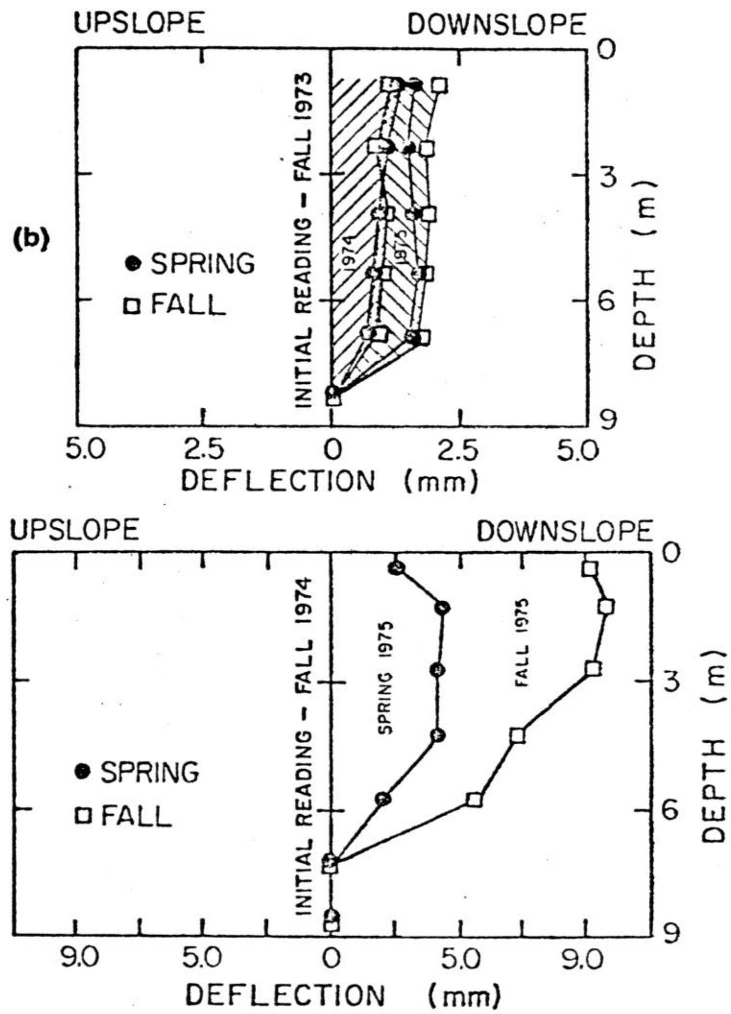


Figure V.6.—Deformation of inclinometer tubes at two sites in the southern Cascade and Coast Ranges of Oregon (Swanston and Swanson 1976). (a) Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil water levels. Note that the difference in 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.

root strength caused by 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, increase the annual creep rate.

Debris Torrents

Debris torrents involve the rapid movement of water-charged soil, rock, and organic material down steep stream channels. They typically occur in steep, intermittent, and first- and second-order channels. They are triggered during extreme discharge 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. V.4b). The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and organic material from the streambed and banks. Some torrents are triggered by debris avalanches of less than 100 yd^3 (76 m^3), but ultimately involve 1,000 yd^3 (760 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 depends on factors described in previous sections. 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 significant environmental hazards in mountainous areas of northwestern North America, they have received little study (Fredriksen 1963, 1965; Morrison 1975; Swanson and others 1976). Velocities of debris torrents, estimated to be up to several tens of meters/second, are known only from a few verbal and written accounts. Torrents have 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 V.4). Torrent tracks initiated in forest areas ranged in length from 328 to 7,480 ft (100 to 2,280 m) and averaged 2,000 ft (610 m) of channel length. Debris avalanches have played a dominant role in triggering 83 percent of inventoried torrents

Table V.4—Characteristics of debris torrents with respect to debris avalanches[1] and land use status of initiation in the H. J. Andrews Experimental Forest[1] and Alder Creek Drainage (Morrison 1975)

Site	Area of watershed	Period of record	Debris torrents triggered by debris avalanches	Debris torrents with no associated debris avalanche	Total		Rate of debris torrent occurrence relative to forested areas
	km^2	yr	number	number	number	km^2/yr	
H. J. Andrews Experimental Forest, western Cascades, Oregon							
Forest	49.8	25	9	1	10	0.008	1.0
Clearcut	12.4	25	5	6	11	0.036	4.5
Road	2.0	25	17	-	17	0.340	42.0
	64.2		31	7	38		
Alder Creek drainage, western Cascade Range, Oregon							
Forest	12.3	90	5	1	6	0.005	1.0
Clearcut	4.5	15	2	1	3	0.044	8.8
Road	0.6	15	6	-	6	0.667	133.4
	17.4		13	2	15		

[1]Frederick J. Swanson, unpublished data, on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

(Swanston and Swanson 1976). Mobilization of stream debris not immediately related to debris avalanches has been a minor factor in initiating debris torrents in headwater streams.

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 and others 1976) and possible increased peak discharges (Rothacher 1973, Harr and others 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 occurrence under natural conditions. In the H. J. Andrews Experimental Forest and the Alder Creek study sites in Oregon, timber harvesting appeared to increase occurrence of debris torrents by 4.5 and 8.8 times; and roads were responsible for increases of 42.5 and 133 times relative to forested areas.

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 avalanches-debris flows as a result of forest harvesting and road building. The histories of debris avalanches-debris flows 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 V.4) and the occurrence of debris avalanches-debris flows is temporarily accelerated by deforestation and road construction (table V.2).

Mechanics of Movement

Direct application of soil mechanics theory to analysis of soil 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. However, the theory provides a convenient framework for discussing the general mechanism and the complex interrelationships of the various factors active in development of soil mass movements on mountain slopes.

In terms of factor of safety analysis, 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 in the vicinity of failure. This may involve a mechanical readjustment among individual particles or a more complex interaction between both internal and external factors acting on the slope.

Figure V.7 shows the geometrical relationship of 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 increasing inclination of the sliding surface or increasing unit weight of the soil mass. Stress can also be augmented by: (1) the presence of zones of weaknesses in the soil or underlying bedrock produced by bedding planes and fractures, (2) application of wind stresses transferred to the soil through the stems and root systems of trees, (3) strain or deformation in the soil produced by progressive creep, (4) frictional "drag" produced by seepage pressure, (5) horizontal accelerations due to earthquakes and blasting, and (6) 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 or the capacity of the soil particles to adhere together, a soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and (2) the frictional resistance between individual particles and between the soil mass and the sliding surface. Frictional resistance is controlled by the angle of internal friction of the soil — the degree of interlocking of individual grains — and the effective weight 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 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.

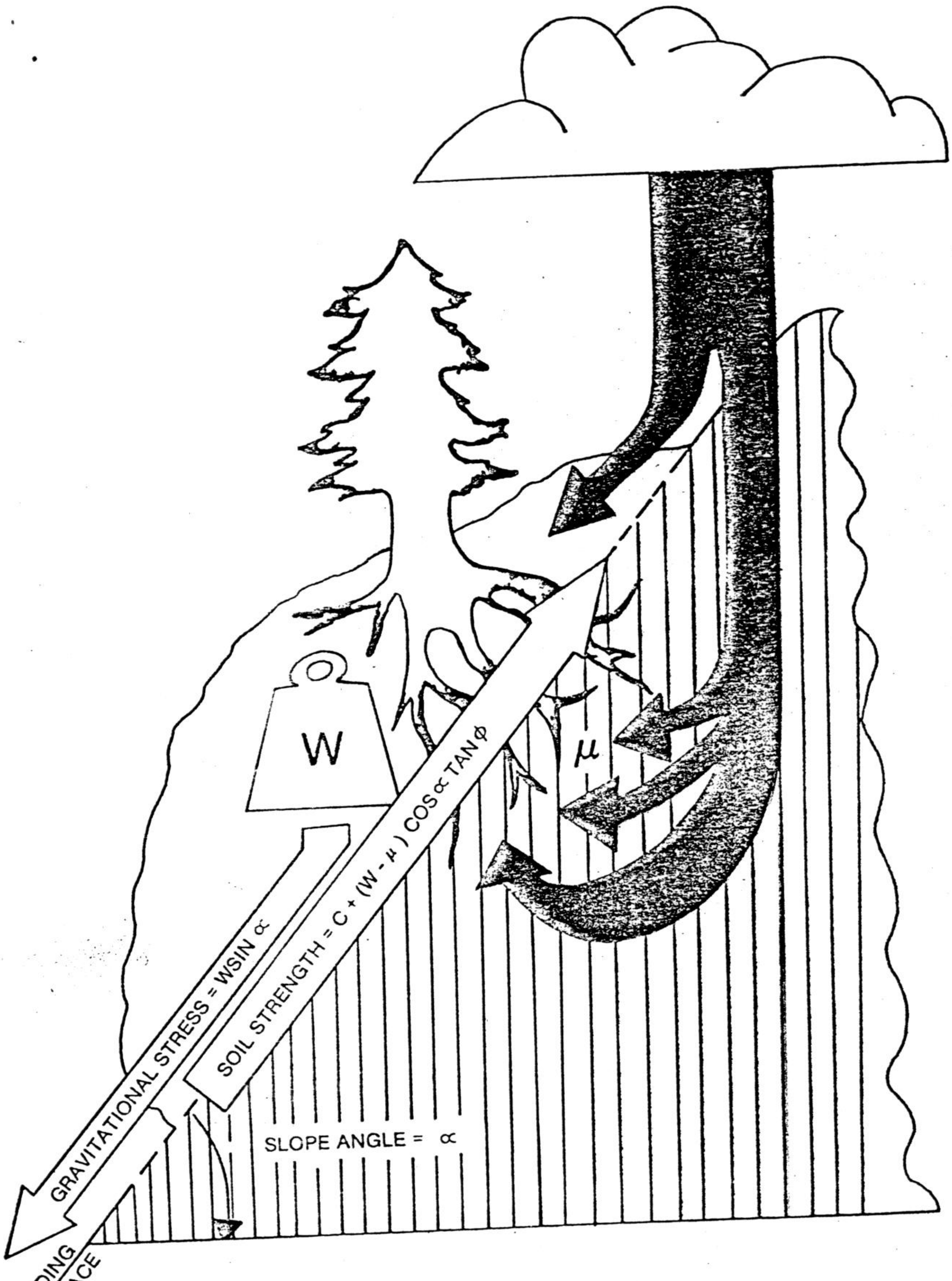


Figure V.7.—Simplified diagram of forces acting on a mass of soil on a slope (Swanston 1974a).

Controlling And Contributing Factors

Particle size distribution or "texture" (which governs cohesion), angle of internal friction, soil moisture content, and angle of sliding surface are the controlling factors in determining 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 angle of internal friction of the soil and pore water pressure. A low angle of internal friction relative to slope angle or high pore water pressure can reduce soil shear strength to negligible values.

Slope angle is a major indicator of the stability of low cohesion 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 exhibit more complex behavior because resistance to sliding is determined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture. In a dry state, clayey soils have a high shear strength with the internal angle of friction quite high (>30°). Increasing water content mobilizes the clay through absorption of water onto 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 saturated conditions. 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 of "creep." Swelling clays of the smectite group (montmorillenite) are particularly unstable because of their tendency to absorb large quantities of water and to experience alternate expansion and contraction during periods of wetting and drying which may result in progressive failure of a slope. Thus, clay-rich soils have a high 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 frequently can be used as an indicator of relative stability or potential stability problems. 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 movement of the creep and slump-earthflow types. Conversely, in arid or semiarid 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 steep lands underlain by resistant rocks, especially 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-debris flow type.

Parent material structure is a critical factor in stability of many shallow soils. 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 surfaces for the overlying material. Sedimentary rocks with bedding planes parallel to the slope, function in essentially the same way, with the uppermost bedding plane forming an impermeable boundary to subsurface water movement, a layer restricting the penetration and development of tree roots, and a potential failure surface.

Vegetation cover generally 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. 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 it is particularly dependent on region and rainfall. In areas characterized by warm, dry summers, evapotranspiration significantly reduces the degree of saturation resulting from the first storms of the fall recharge period. This effect diminishes as soil water deficit is satisfied. Once the soil is recharged, the effects of previous evapotranspirational losses become negligible. Conversely, in areas of continuous high rainfall or those with an arid or semiarid climate, evapotranspirational effects are probably negligible. Depth of evapotranspirational withdrawals is important also. Deep withdrawals may require substantial recharge to satisfy the soil water deficit, delaying or reducing the possibility of saturated soil conditions necessary for major slide-producing events. Shallow soils, however, recharge rapidly, possibly becoming saturated and most unstable during the first major storm.

Root systems of trees and other vegetation may increase shear strength in unstable soils by anchoring through the soil mass into fractures in bedrock, providing continuous long fiberous binders within the soil mass, and tying the slope together across zones of weakness or instability.

In shallow soils, all three effects 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 by surface loading and affects delivery of water to the soil by retaining rainfall and delaying release of much water. Delayed release of melt water, coupled with unusually heavy storms during a midwinter or early spring warming trend, has been identified as the principal initiating factor in recent major landslide activity on forest lands in central Washington (Klock and Helvey 1976).

CHARACTERIZING UNSTABLE SLOPES IN FORESTED WATERSHEDS

The following guidelines are designed to help delineate the hazards of unstable slopes on forested lands.

There are six environmental qualities that should be carefully considered when judging stability of natural slopes in terms of surface erosion and soil mass movement. They are:

A. landform features
B. soil characteristics
C. bedrock lithology and structure
D. vegetative cover
E. hydrologic characteristics of site
F. climate

Each of these qualities encompasses a group of factors which control stability conditions on the slope and determine or identify the type of processes and movements which are most likely to occur.

Key factors identifying potentially unstable slopes on any mountainous terrain include slope gradient (a landform quality) and concentration of precipitation (both intensity and duration). Soil properties, including soil depth and such diagnostic characteristics as texture, permeability, angle of internal friction, and cohesion determine the types of processes that will dominate and, to some degree, determine the stable slope gradient within a particular soil type. Bedrock structure, especially attitude of beds and degree of fracturing or jointing, are important contributing factors controlling local stability conditions. Many of these factors are identifiable on the ground or in readily available support documentation (climatological records, etc.).

The following outline discusses the six environmental qualities important for judging stability of natural slopes and the key factors associated with each.

A. Landform features

1. **Landforms on which subject area occurs.** — A qualitative indicator of potentially unstable landform types. Obtainable from air photos and topographic maps. For example, alpine glaciated terrain characteristically exhibits U-shaped valleys with extensive areas of very steep slope. Fracturing parallel to the slope is common, and soils, either of colluvial or glacial origin, are usually shallow and cohesionless. The underlying impermeable surface may be either bedrock or compact glacial till. Such terrain is frequently subject to debris avalanche-debris flow processes.

   Areas formed by continental glaciation commonly exhibit rolling terrain consisting of low hills and ridges composed of bedrock, glacial till, and stratified drift separated by areas of ground moraine and glacial outwash. Glaciolacustrine deposits may be present locally, consisting of thick deposits of silt and clay which may be particularly subject to slump-earthflow processes if disturbed.

Fluvially formed landscapes underlain by bedded sedimentary and meta-sedimentary rocks may have slope steepness controlled by jointing, fracturing, and faulting; by orientation of bedding; and by differential resistance of alternating rock layers. Debris avalanche-debris flow failures frequently occur in shallow colluvial soils along these structurally controlled surfaces. Slump-earthflow failures may occur in clay-rich or deeply weathered units, in deeply weathered soils and colluvial debris on the lower slopes, and in valley fills adjacent to active stream channels.

Volcanic terrain consisting of units of easily weathered volcaniclastic rocks and hard, resistant flow rock commonly exhibit slump-earthflow failures in deeply weathered volcaniclastic materials. Such failures usually occur just below a capping flow or just above an underlying flow due to concentration of ground water. Debris avalanche-debris flow failures are common in shallow residual or colluvial soils developed on the resistant flow rock units.

Because of the large variability in landform processes and the modifying influence of climatic conditions on weathering rates and products, geologists with some knowledge of the area should be consulted.

2. **Slope configuration.** — Shape of the slope in the area of consideration. A qualitative indicator of location and extent of most highly unstable areas on a slope. Obtainable from air photos and topographic maps. On both concave and convex slopes, usually the steepest portions have the greatest stability hazard. Convex slopes may have oversteep gradients in lower portions of the slope. Concave slopes have oversteep gradients in their upper elevations.

3. **Slope gradient.** — A key factor controlling soil stability in steep mountain watersheds. Slope gradient may be quantified on the ground or from topographic maps. It determines effectiveness of gravity acting to move a soil mass downslope. For debris avalanche-debris flow failures, this is a major indicator of the natural soil mass movement hazard. For slump-earthflow failures, this is not as important since, given the right conditions of soil moisture content, soil texture, and clay mineral content, failures can occur on slope gradients as low as 2° or 3°. Slope gradient also has a major effect on subsurface water flow in terms of drainage rate and subsequent susceptibility to temporary water table buildup during high intensity storms.

B. Soil Characteristics

1. **Present soil mass movement type and rate.** — Obtainable from air photos and field checks. This is a qualitative indicator of size and location of potential stability problems, type of recent landsliding, and kinds of soil mass movement processes operative on the slope. These, in turn, suggest probable soil depth and certain dominant soil characteristics. For example, debris avalanches-debris flows most frequently develop in shallow, coarse-grained soils which have a low clay content and low internal cohesion. Soil creep, massive slumping, and large-scale earthflows usually develop in deep, cohesive soils high in clay content or in deeply weathered pelitic sediments, serpentinite, and volcanic ash and breccia.

2. **Parent material.** — A qualitative indicator of probable shape of soil particles, bulk density (or weight), degree of cohesion or clay mineral content, soil depth, permeability, and presence or absence of impermeable layers in the soil. These, in turn, suggest types of soil mass movement processes operative within an area. This information is obtainable from existing geologic and soil survey maps, by air photo interpretation, and by field check.

   Soils developed from colluvial or residual materials and some tills and pumice soils commonly possess little or no cohesion. Failures in such soils are usually of the debris avalanche-debris flow type.

   Soils developed from weathered fine grained sedimentary rocks (mudstones, claystones, nonsiliceous sandstones, shales), volcaniclastics, and glacio-lacustrine clays and silts possess a high degree of cohesion and characteristically develop failures of the slump-earthflow type.

   The mica content also has a major influence on soil strength. Ten to twenty percent mica will produce results similar to high clay content.

3. **Occurrence of compacted, cemented, or impermeable layer.** — A qualitative indicator of the depth of potentially unstable soil and probable principal planes of failure

on the slope. This information is obtainable from borings, soil pits, and inspection of slope failure scars in the field.

4. **Evidence of concentrated subsurface drainage (including evidence of seasonal saturation).** — A qualitative indicator of local zones of periodic high soil moisture content including saturation and potentially active pore water pressures during high rainfall periods. These identify potential areas of slope failure. This information is obtainable by air photo interpretation and ground observation. Diagnostic features include broad linear depressions perpendicular to slope contour, representing old landslide sites and areas of concentrated subsurface drainage, and damp areas on the slope, representing springs and areas of concentrated ground water movement.

5. **Diagnostic soil characteristics.** — Key factors in determining dominant types of soil mass movement process mechanics of motion and probable maximum and minimum stable slope gradients for a particular soil. This is identifiable through field testing, sampling, and laboratory analysis. Data on benchmark soils also may be obtained from soil surveys and engineering analyses for road construction in or adjacent to the proposed silvicultural activity.
   a. **Soil depth.** — Principal component of the weight of the soil mass and an important factor in determining soil strength and gravitational stress acting on an unstable soil.
   b. **Texture.** — (Particle size distribution) the relative proportions of sand (2.0 - 0.5 mm), silt (.05 - .002 mm), and clay (<.002 mm) in a soil. Texture, along with clay mineral content, are important factors in controlling cohesion, angle of internal friction, and hydraulic conductivity of an unstable soil.
   c. **Clay mineralogy.** — An indicator of sensitivity to deformation. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas where creep occurs. "Swelling" clays of the smectite group (montmorillonite) are particularly unstable.
   d. **Angle of internal friction.** — An indicator of the internal frictional resistance of a soil caused by intergranular friction and interlocking of individual grains. an important factor in determining soil shear strength or resistance to gravitational stress. The tangent of the angle of internal friction times the weight of the soil constitute a mathematical expression of frictional resistance. For shallow, cohesionless soils, a slope gradient at or above the angle of internal friction is a good indicator of a highly unstable site.
   e. **Cohesion.** — The capacity of soil particles to stick or adhere together. This is a distinct soil property produced by cementation, capillary tension, and weak electrical bonding of organic colloids and clay particles. Cohesion is usually the direct result of high (20 percent or greater) clay particle content and is an important contributor to shear strength of a fine grained soil.

C. Bedrock Lithology and Structure

1. **Rock type.** — A qualitative indicator of overlying soil texture, clay mineral content, and relative cohesiveness. It provides a regional guide to probable areas of soil mass movement problems and dominant processes. For example, in the Cascades and Coast Range of Oregon and Washington, areas underlain by volcanic ash and breccias and silty sandstone are particularly susceptible to slump-earthflows. Where hard, resistant volcanic flow rock is present, shallow planar failures dominate. Slopes underlain by granites and diorites are also more susceptible to shallow planar failures, although where extensive chemical weathering has occurred, such rocks may exhibit slump-earthflow features. The slope stability characteristics of a particular rock type or formation largely depend on mineralogy, climate, and degree of weathering, and must be determined for each particular area.
2. **Degree of weathering.** — A qualitative indicator of soil depth and type of soil mass movement activities. In some rock types, it is also an indicator of degree of clay mineral formation.
3. **Attitude of beds.** — Quantifiable on the ground, from geologic maps, and occasionally

from air photos. This is an important contributing factor to unstable slopes, especially where attitude of bedding parallels or dips in the same direction as the slope. Under these conditions, the bedding planes form zones of weakness along which slope failures can occur due to high pore water pressures and decreases in frictional resistance. Conversely, bedding planes dipping into the slope frequently produce natural buttresses and increase slope stability. Care must be taken in assessing the stabilizing influence of horizontal or in-dipping bedding planes particularly where well-developed jointing is present (see no. 4).

4. **Degree of jointing and fracturing.** — Quantifiable on the ground and occasionally from geologic maps as dip and strike of faults, fractures, and joint systems. Joints in particular are important contributing factors to slope instability, especially on slopes underlain by igneous materials. Joints parallel to or dipping in the same direction as the slope, create local zones of weakness along which failures occur. Jointing also provides avenues for deep penetration of groundwater with subsequent active pore water pressure development along downslope dipping joint planes.

   Valleys developed along high angle faults in mountainous terrain may have exceptionally steep slopes. Deep penetration of ground water into uneroded fault and shear zones can result in extensive weathering and alteration of zone materials, resulting in generation of slump-earthflow failures. Such zones can also form barriers to ground water movement causing redirection and concentration of water into adjacent potentially unstable sites.

D. Vegetative Characteristics

1. **Root distribution and degree of root anchoring in the subsoil.** — An indicator of effectiveness of tree roots as a stabilizing factor in shallow steep slope soils. Quantifiable on the ground by observing the degree of penetration of roots through the soil and into a more resistant substratum and by measuring the biomass of the roots contained in a potentially unstable soil. High biomass of contained roots is an expression of the binding capacity or "reinforcing" effect of roots to the soil mass.

2. **Vegetation type and distribution.** — Cover density, vegetation type, and stand age are qualitative indicators of the history of soil mass movement on a site and soil and ground water conditions. This information is obtainable by air photo interpretation and ground checking.

E. Hydrologic Characteristics

1. **Hydraulic conductivity.** — A measure of water movement in and through soil material. This is quantifiable in the field and in the laboratory using pumping tests and permeameters. Low hydraulic conductivities mean rapid storm generated saturation and a high probability of active pore water pressure, which produces highly unstable conditions in steep slope soils.

2. **Pore water pressure.** — A measure of the pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water. This is quantifiable in the field through measurement of free water surface level in the soil. Pore water pressure is a key factor in failure of a steep slope soil, and operates primarily by reducing the weight component of soil shear strength.

F. Climate

1. **Precipitation occurrence and distribution.** — A key factor in predicting regional soil mass movement occurrences. Most soil mass movements are triggered by soil saturation and active pore water pressures produced by rainfall of high intensity and long duration. Isohyetal maps of rainfall occurrences and distribution, constructed from data obtainable from local monitoring stations or from the Weather Bureau, can be used to pinpoint local areas of high rainfall concentration. It is advisable to develop a simple relationship between rainfall intensity and pore water pressure development for a particular soil type or area of interest so that magnitude and return period of damaging storms can be identified. This can be done simply by locating a rain gage at the site or using nearby rainfall data and correlating this with piezometric data obtained from open-ended tubes installed to the probable depths of failure at the site. Each storm should be monitored.

THE PROCEDURE

ESTIMATING SOIL MASS MOVEMENT HAZARD AND SEDIMENT DELIVERED TO CHANNELS

This section delineates a procedure to be used on potentially unstable areas to analyze the hazard of soil mass movement associated with silvicultural activities and to determine the potential volume and delivery of inorganic material to the closest drainageway. This is a broad level analysis designed to determine where specific controls or management treatment variations are required because of possible water quality changes resulting from soil mass movement. This procedure will not substitute for site specific analysis of road design, maintenance, and rehabilitation as may be required under current management procedures.

To assess soil mass movement hazards that might deliver inorganic material to a stream course, a basic qualitative evaluation is undertaken based on the following information:

1. A delineation of hazard areas and dominant soil mass movement types using aerial photo and topographic map interpretation with minimum ground reconnaissance.
2. An estimate of the likelihood of failure or "sensitivity" of an area caused by both natural and man-induced events, using subjective analysis of controlling and contributing factors within defined hazard areas.
3. An estimate of the volume of material released by soil mass movements during storm events with a 10-year return interval or less.
4. An estimate of the volume of sediment released by soil mass movements which actually reach a water course based on slope position, gradient, and shape and type of movement.

Although soil mass movements are too infrequent for effective direct annual evaluation, delivery volumes can be expressed on an average annual basis for purposes of comparison between pre- and post-silvicultural activity conditions.

A broad delineation of potentially unstable terrain by slope characteristics and soil mass movement types is an essential part of the hazard analysis. A detailed flow chart (fig. V.8) shows the sequence of analysis once the delineation of unstable terrain is accomplished.

The limits placed on variable ranges for high, medium and low hazard indices are approximations based on the collective experience of practicing professionals. The weighted values for hazard indices are guides only, and they were determined from consultation with practicing professionals as well as a limited analysis of several unstable areas in Colorado and western Oregon. However, they do reflect the relative importance of the individual factors and their effects on likelihood of failure by the major soil mass movement types. These weightings and the ranges of hazard index should be adjusted to reflect the conditions prevalent within a given area.

PROCEDURAL DESCRIPTION

The following information describes each step of the procedural flow chart, fig V.8. Data from the Horse Creek example are used to illustrate the following procedure. This complete example is presented in "Chapter VIII: Procedural Example."

BROAD DELINEATION OF POTENTIALLY UNSTABLE AREAS

Guidelines have been presented that provide a qualitative characterization of unstable or potentially unstable slopes on forested lands. Using these guidelines, evaluate the area of the proposed silvicultural activity to ascertain the stability of the site.

IDENTIFY AND MAP AREAS BY SOIL MASS MOVEMENT TYPE

If the area is generally unstable or potentially unstable, delineate the hazard areas and dominant soil mass movement types (debris avalanches-debris flows and slump-earthflows) using aerial photos and topographic map interpretation. Potentially unstable areas are those that may become unstable due to the proposed silvicultural activity. Unstable areas are those that have or presently are undergoing a soil mass movement.

CHARACTERIZE SOIL MASS MOVEMENT TYPE

Soil mass movements have been classified into two major types: debris avalanches-debris flows and slump-earthflows. Several site parameters and management activities can be used to evaluate the possibility of soil mass movement. Although both movement types have similar factors that can be used to evaluate the hazard of a failure, the relative importance of these factors may be different between the two movement types. In addition, each kind of soil mass movement has some site or management activity parameters that are specific for that movement. Therefore, to evaluate the hazard of a soil mass movement, each type must be evaluated separately using the factors that have been found to be significant in characterizing that particular kind of failure.

DEBRIS AVALANCHE-DEBRIS FLOW

Areas prone to debris avalanches-debris flows are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces.

NATURAL HAZARD SITE CHARACTERISTICS

For debris avalanches-debris flows, the following site characteristics have been found to be critical in evaluating the potential hazard of a natural soil mass movement: slope gradient, soil depth, subsurface drainage characteristics, soil texture, bedding structure and orientation, surface slope configuration, and precipitation input. This information can be obtained from geologic and soils maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site characteristic is indicated in table V.5 and worksheet V.1 by the weighting value assigned.

MANAGEMENT INDUCED HAZARD CHARACTERISTICS

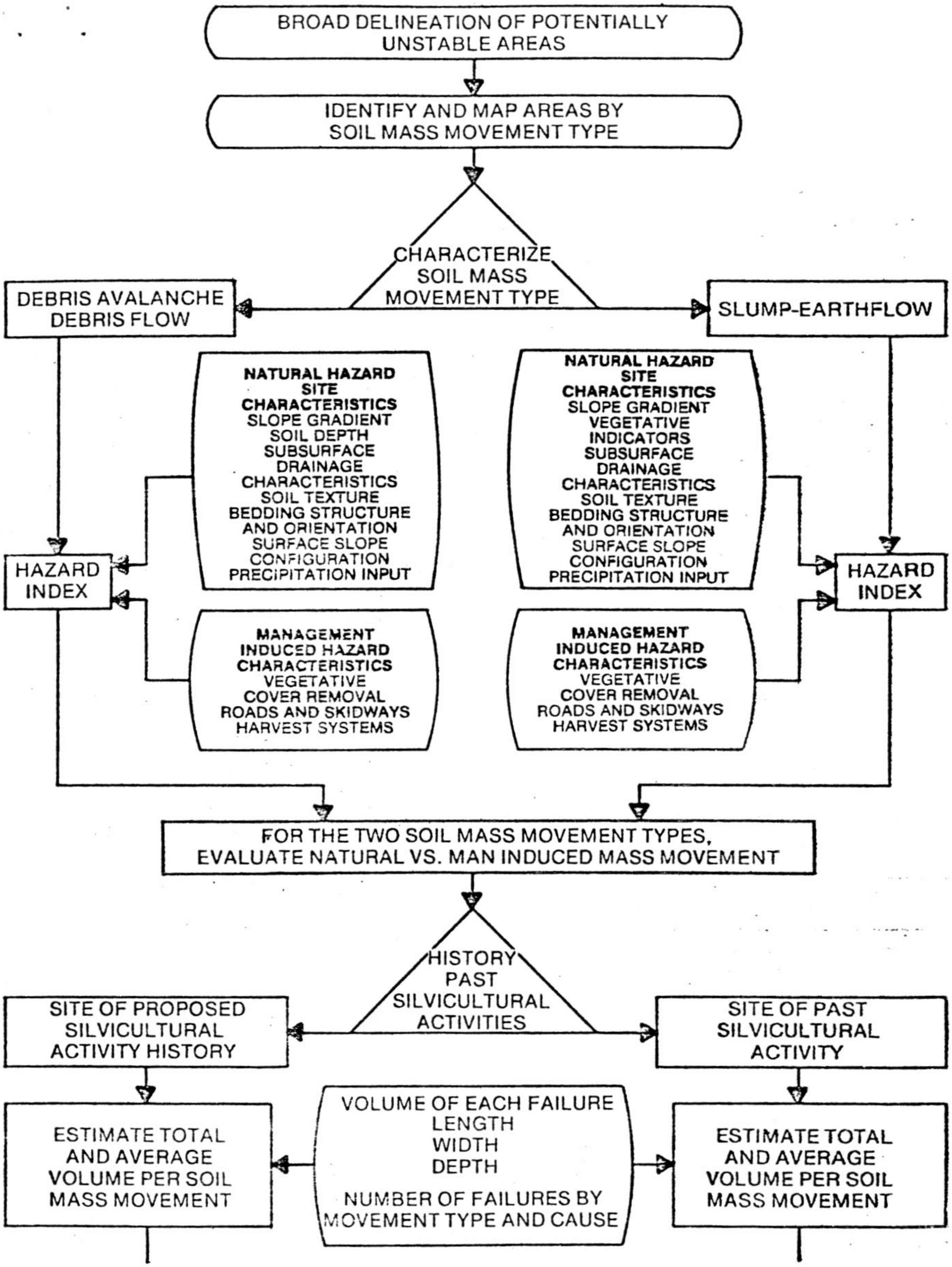
For debris avalanches-debris flows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement: vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities or from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table V.6 and worksheet V.2 by the weighting value assigned.

HAZARD INDEX

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numerical ratings are subjective and depend on what is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for debris avalanches-debris flows is determined by summing the weighted values from worksheet V.1 and comparing this value to the ranges of values for high, medium, and low hazard indices. For example, if the sum of the weighted values for the natural hazard index (worksheet V.1) was 31, the hazard index would be medium. The value 31 falls within the range of values (21-44) for the medium hazard.

The relative hazard for debris avalanches-debris flows caused by silvicultural activities is determined by summing the weighted values from worksheet V.2. The overall hazard index caused by natural plus existing or proposed silvicultural activities is determined by adding the total weighted value for the natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 31, the overall weighted value of both the natural (31) plus the silvicultural activity (31) would be equal to 62 and the overall hazard index would be high.


BROAD DELINEATION OF POTENTIALLY UNSTABLE AREAS
IDENTIFY AND MAP AREAS BY SOIL MASS MOVEMENT TYPE
CHARACTERIZE SOIL MASS MOVEMENT TYPE
DEBRIS AVALANCHE DEBRIS FLOW
SLUMP-EARTHFLOW
NATURAL HAZARD SITE CHARACTERISTICS
SLOPE GRADIENT
SOIL DEPTH
SUBSURFACE DRAINAGE CHARACTERISTICS
SOIL TEXTURE
BEDDING STRUCTURE AND ORIENTATION
SURFACE SLOPE CONFIGURATION
PRECIPITATION INPUT
NATURAL HAZARD SITE CHARACTERISTICS
SLOPE GRADIENT
VEGETATIVE INDICATORS
SUBSURFACE DRAINAGE CHARACTERISTICS
SOIL TEXTURE
BEDDING STRUCTURE AND ORIENTATION
SURFACE SLOPE CONFIGURATION
PRECIPITATION INPUT
HAZARD INDEX
HAZARD INDEX
MANAGEMENT INDUCED HAZARD CHARACTERISTICS
VEGETATIVE COVER REMOVAL
ROADS AND SKIDWAYS
HARVEST SYSTEMS
MANAGEMENT INDUCED HAZARD CHARACTERISTICS
VEGETATIVE COVER REMOVAL
ROADS AND SKIDWAYS
HARVEST SYSTEMS
FOR THE TWO SOIL MASS MOVEMENT TYPES, EVALUATE NATURAL VS. MAN INDUCED MASS MOVEMENT
HISTORY PAST SILVICULTURAL ACTIVITIES
SITE OF PROPOSED SILVICULTURAL ACTIVITY HISTORY
SITE OF PAST SILVICULTURAL ACTIVITY
ESTIMATE TOTAL AND AVERAGE VOLUME PER SOIL MASS MOVEMENT
VOLUME OF EACH FAILURE
LENGTH
WIDTH
DEPTH
NUMBER OF FAILURES BY MOVEMENT TYPE AND CAUSE
ESTIMATE TOTAL AND AVERAGE VOLUME PER SOIL MASS MOVEMENT

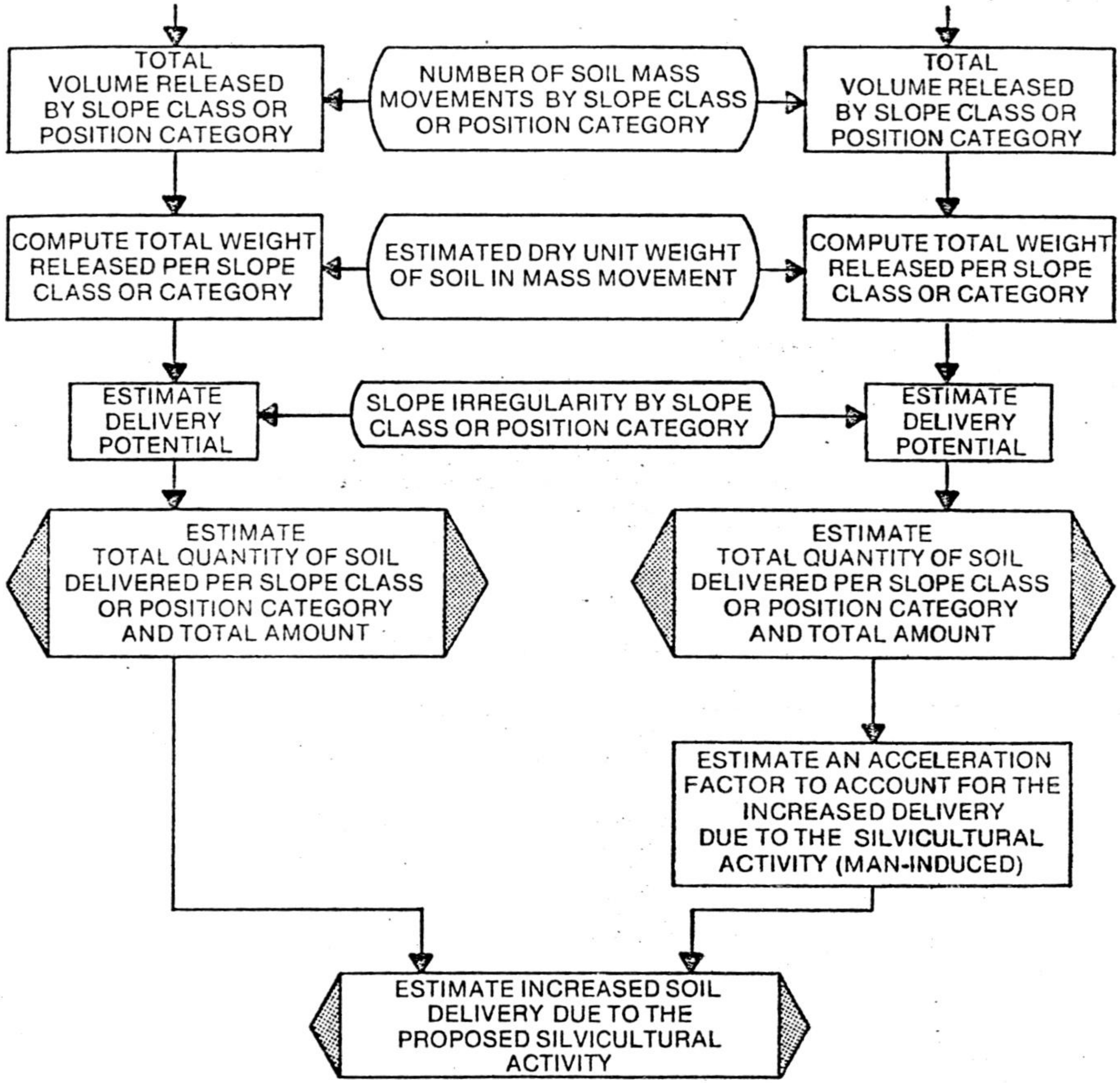


Figure V.8.—Detailed flow chart of the soil mass movement procedure.

Table V.5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Slope gradient	High >34°	30
	Medium 29°-34°	15
	Low <29°	5
Soil depth	High Shallow soils, <5 ft	3
	Medium Moderately deep soils, 5-10 ft	2
	Low Deep soils, >10 ft	1
Subsurface drainage characteristics	High High density, closely spaced incipient drainage depressions Presence of bedrock or impervious material at shallow depth which restricts vertical water movement and concentrates subsurface flow Presence of permeable low density zones above the restricting layer indicative of saturated flow parallel to the slope Evidence of springs on the slope	3
	Medium Presence of incipient drainage depressions, but widely spaced Presence of impervious material at shallow depths, but no low density zones present Springs are absent	2
	Low Incipient drainage depressions rare to absent No shallow restricting layers present No indications of near-surface flow	1
Soil texture	High Unconsolidated, non-cohesive soils and colluvial debris including sands and gravels, rock fragments, weathered granites, pumice and noncompacted glacial tills with low silt content (<10%) and no clay	3
	Medium Unconsolidated, non-cohesive soils and colluvial debris with moderate silt content (10-20%) and minor clay (<10%)	2
	Low Fine grained, cohesive soils with greater than 20% clay sized particles or mica	0
Bedding structure and orientation	High Extensive jointing and fracturing parallel to the slope Bedding planes parallel to the slope Faulting or shearing parallel to the slope (the stability influence of bedding planes horizontal or dipping into the slope is offset by extensive parallel jointing and fracturing)	3
	Medium Bedding planes are horizontal or dipping into the slope with minor jointing at angles less than the natural slope gradient Minor surface fracturing — no faulting or shearing evident	2
	Low Bedding planes are horizontal or dipping into the slope Jointing and fracturing is minor — no faulting or shearing evident	1

Table V.5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures — continued

Factor	Hazard index and range	Weight
Surface slope configuration	High Smooth, continuous slopes unbroken by benches or rock outcrops Intermittent steep channels occur frequently with lateral spacing of 500 ft (152 m) or less Perennial channels frequently deeply incised with steep walls of rock or colluvial debris Numerous breaks in canopy due to blow-downs — frequent linear or tear-drop shaped even-age stands beginning at small scarps or spoon-shaped depressions indicative of old debris avalanche-debris flow activity	3
	Medium Smooth, continuous slopes broken by occasional benches and rock outcrops Intermittent, steep gradient channels occur less frequently with a lateral spacing of 500-800 ft (152-244 m) Infrequent evidence of blow-down or past landslide activity	2
	Low Slope broken by rock benches and outcrops intermittent, steep gradient channels spaced 900 ft (275 m) or more apart	1
Precipitation input	High Area characterized by rainfall greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity storms capable of generating saturated soil conditions on the slope leading to active pore-water pressure development and high stream flow — area has a high potential for mid-winter or early spring rainfall-on-snowpack events Storm intensities may exceed 6 in/24 hr at 10 yr recurrence intervals or less	12
	Medium Area characterized by moderate rainfall of 20 to 40 in/yr (51 to 102 cm/yr) Storms of moderate intensity and duration are common High intensity storms are infrequent, but do occasionally occur Moderate snowpack, but rain-on-snow events very rare Storm intensities may exceed 6 in/24 hr (15 cm/24 hr) at recurrence intervals greater than 10 yrs.	5
	Low Rainfall in area is low (less than 20 in/yr) Storms infrequent and of low intensity Stored water content in snowpack, when present, is low and only rarely subject to rapid melting	3

WORKSHEET V.1

Debris avalanche-debris flow natural factor evaluation form

Index	Slope gradient	Soil depth	Subsurface drainage characteristics	Soil texture	Bedding structure and orientation	Slope configuration	Precipitation input
High	30	3	3	3	3	3	12
Medium	15	2	2	2	2	2	5
Low	5	1	1	0	1	1	3

Factor summation table

Gross hazard index	Factor range	Natural
High	Greater than 44	
Medium	21 - 44	31
Low	Less than 21	

Table V.6.—Weighting factors for determination of management-induced hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	High	8
	Total removal of cover — large clearcuts with openings continuous downslope — such removal is sufficient to increase soil moisture levels and reduce strength	
	Broadcast burning of slash	
	Medium	5
	Cover partially removed with slope sections >34° left undisturbed — clearcuts in small patches or strips less than 20 ac (8 ha) and discontinuous on slopes	
	Low	2
	Cover density altered through partial cutting — no clearcutting — no broadcast burning of sites with >34° slope	
Roads and skidways	High	20
	High density (>15% of area in roads) on potentially unstable slopes (>28°) — cut and fill construction	
	Roads and skidways located on steep, unstable portions of the slope (>34°)	
	Uncontrolled fills with poor compaction produced by side-casting over organic debris	
	Inadequate cross drainage (poor location; improper spacing and maintenance, size too small for 10 yr storm flow)	
	Lack of fill slope protection of drainage outlets	
	Concentrations of drainage water directed into identifiable unstable areas	
	Medium	8
	Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area)	
	Areas with slopes >34° or with identifiable landslide activity have been avoided or fully benched	
	On potentially unstable slopes >29° skidways and cut-and-fill type construction are limited	
	Ridgetop roads have large fills in saddles	
	Fills, where present, are constructed by sidecasting over organic debris with little controlled compaction	
	Roads generally have adequate cross drains for normal runoff conditions (number and location) but are undersized for the 10 yr storm flow	
	Fill slopes below culvert outfalls protected by rip-rap dissipation structures at potentially unstable sites	
	Major concentrations of water into identifiable unstable areas avoided	
	Low	2
	Very few roads on slopes above 28° — low road density (less than 8% of area) with roads on potentially unstable terrain (slopes between 29° and 34°) predominantly of full bench type — most road locations or construction limited to ridgetops with minimum fills in saddles and lower slopes — adequate cross drains with major water courses bridged and culverts designed for 10 yr storm flow or larger	
Harvest systems	High	3
	Operation of tractor yarding, jammer yarding and other ground lead systems on slopes >29° (53%)	
	Medium	2
	No tractor logging — high lead with partial suspension on slopes >29° (53%)	
	Low	0
	Helicopter and balloon yarding — full suspension of logs by any method — yarding by any method on slopes <29° (53%)	

WORKSHEET V.2

Debris avalanche-debris flow management related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	8	20	3
Medium	5	8	2
Low	2	2	0

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	31+31 = 62
Medium	21 - 44	
Low	Less than 21	

SLUMP-EARTHFLOW

Slump-earthflow prone areas are typified by deep, cohesive soils and clay-rich bedrock overlying hard, competent rock. Slump-earthflow soil mass movement also appears to be sensitive to long-term fluctuations.

NATURAL HAZARD SITE CHARACTERISTICS

For slump-earthflows, the following site characteristics have been found to be critical in evaluating the potential hazard of a natural soil mass movement: slope gradient, sub-surface drainage characteristics, soil texture, surface slope configuration, vegetative indicators, bedding structure and orientation, and precipitation input. This information can be obtained from soils maps, vegetative cover maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site characteristic is indicated in table V.7 and worksheet V.3 by the weighting value assigned.

MANAGEMENT INDUCED HAZARD CHARACTERISTICS

For slump-earthflows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement: vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities or from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table V.8 and worksheet V.4 by the weighting value assigned.

HAZARD INDEX

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numerical ratings are subjective and depend on what is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for slump-earthflows is determined by summing the weighted values from worksheet V.3 and comparing this value to the ranges of values for high, medium, and low hazard index. For example, if the sum of the weighted values for the natural hazard index (wksht. V.3) was 38, the hazard index would be medium. The value 38 falls within the range of values (22-44) for the medium hazard.

The relative hazard for slump-earthflows caused by silvicultural activities is determined by summing the weighted values from worksheet V.4. The overall hazard index resulting from natural plus existing or proposed silvicultural activities is determined by adding the total weighted value from silvicultural activities to the total weighted value for the natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 8, the overall weighted value of both the natural (38) plus the silvicultural activity (8) would be equal to 46, and the overall hazard index would be high.

FOR THE TWO TYPES OF SOIL MASS MOVEMENTS, EVALUATE NATURAL VS. MAN-INDUCED MASS MOVEMENT

Determine the quantity of material delivered to a stream channel for each soil mass movement type and evaluate any man-induced increase in mass movement over that naturally occurring.

Table V.7.—Weighting factors for determination of natural hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Slope gradient	High greater than 30° (58%)	6
	Medium 15 - 30° (27%-58%)	4
	Low under 15° (27%)	2
Subsurface drainage characteristics	High Area exhibits abundant evidence of impaired groundwater movement resulting in local zones of saturation within the soil mass — short, irregular surface drainages which begin and end on the slope Impaired drainage, indicated at the surface by numerous sag ponds with standing water, springs and patches of wet ground Impaired drainage involves more than 20% of the area	6
	Medium Some indications of impaired drainage, but generally involving less than 10% of the area Active springs are uncommon, infrequent, or contain no standing water	4
	Low No evidence of impaired drainage	2
Soil texture	High Predominantly fine grained cohesive soils derived from weathered sedimentary rocks, volcanics, aeolian and alluvial silts and glaciolacustrine silts and clays Clay sized particle content generally greater than 20% Clay minerals predominantly of the smectite group (montmorillonite), exhibiting swelling characteristics upon wetting	15
	Medium Soils of variable texture including both fine and coarse grained components in layers and lenses The fine grained, cohesive component may contain a clay sized particle content greater than 20%, but clay minerals are predominantly of the illite and kaolinite groups, exhibiting lower sensitivity to changes in stress	10
	Low Soils of variable texture Some clayey soils present but widely dispersed in small layers or lenses	5
Slope configuration	High 40% or more of the area is characterized by hummocky topography consisting of rolling, bumpy ground, frequent benches and depressions locally enclosing sag ponds Tension cracks and headwall scarps indicating slumping are unvegetated and clearly visible Slopes are irregular and may be slightly concave in the upper 1/2 and convex in the lower 1/2 as a result of the downslope redistribution of soil materials Zones of active movement are abundant	5
	Medium 5% to 40% of the area is characterized by hummocky topography Occasional sag ponds occur, but slump depressions are generally dry Headwall scarps are revegetated and no open tension cracks are visible Active slump-earthflow features are absent	2

Table V.7.—Weighting factors for determination of natrual hazard of slump-earthflow — continued

Factor	Hazard index and range	Weight
	Low Less than 5% of the area is characterized by hummocky topography Old slump-earthflow features are absent or subdued by weathering and erosion No active slump earthflow features present, slopes are generally smooth and continuous from ridge to valley floor	1
Vegetative indicators	High Phreatophytic (wet site) vegetation widespread Tipped (jackstrawed) and split trees are common Pistol-butted trees occur in areas of obvious hummocky topography (note: pistol-butted trees should be used as indicators of active slump-earthflow activity only in the presence of other indicators — pistol-butting can also occur in areas of high snowfall and is often the result of snow creep and glide)	5
	Medium Phreatophytic vegetation limited to occasional moist areas on the open slope and within sag ponds Tipped trees absent	3
	Low Phreatophytic vegetation absent	0
Precipitation input	High Area characterized by high rainfall of greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity, long duration storms capable of generating continuing saturated conditions within the soil mass leading to active pore water pressure development and mobilization of the clay fraction Area has a high potential for rain-on-snow events	13
	Medium Area characterized by moderate rainfall of 20 to 40 in/yr (51 cm/yr to 102 cm/yr) Storms of moderate intensity and duration are common Snowpack is moderate, but rain-on-snow events are rare	10
	Low Rainfall in the area is low (less than 20 in/yr) storms are infrequent and of low intensity and duration Stored water content in the snowpack, when present, is low throughout the winter with no mid-winter or early spring releases due to climatological events	2

WORKSHEET V.3

Slump-earthflow natural factor evaluation form

Index	Slope gradient	Subsurface drainage characteristics	Soil texture	Slope configuration	Vegetative indicators	Precipitation input
High	6	6	15	5	5	18
Medium	4	4	10	2	3	10
Low	2	2	5	1	0	2

Factor summation table

Gross hazard index	Range	Natural
High	Greater than 44	
Medium	21 - 44	38
Low	Less than 21	

Table V.8.—Weighting factors for determination of management induced hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	High	3
	Total removal of cover or large clearcuts with openings continuous downslope — such removal would be sufficient to increase soil moisture levels and reduce root strength	
	Medium	2
	Cover partially removed — clearcuts in small patches or strips less than 20 acres (8 ha) is size and discontinuous downslope	
	Low	1
	Cover density altered through partial cutting, no clearcutting evident	
Roads and skidways	High	7
	High density (>15% of area in roads) cut-and-fill type (balanced) construction	
	Roads and skidways located or planned across identifiable unstable ground	
	Roads crossing active or dormant slump-earthflow features	
	Massive fills or spoil piles on slump benches	
	Inadequate drainage creating concentrations of water at the surface with diversion of surface drainage into unstable areas	
	Medium	4
	Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area in roads), unstable areas features avoided	
	Roads generally have adequate cross drains for normal runoff conditions but are undersized for 10 yr storm flows	
	Diversions of concentrations of water into unstable sites avoided	
	Low	2
	No roads present — if present, predominantly fully benched	
	Road density less than 8%	
	Most road location and construction on ridgetops or in alluvial valley floors	
	Adequate cross drainage with dispersal rather than heavily concentrated surface flow	
Harvest systems	High	3
	Operation of tractor yarding, jammer yarding or other ground lead systems causing excessive ground disturbance	
	Medium	2
	High lead yarding with partial suspension and skyline with partial suspension	
	No tractor yarding	
	Low	1
	Helicopter and balloon yarding	
	Full suspension of logs by any method	

WORKSHEET V.4

Slump-earthflow management
related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	3	7	3
Medium	2	4	2
Low	1	2	1

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	38+8=46
Medium	21 - 44	
Low	Less than 21	

HISTORY OF PAST SILVICULTURAL ACTIVITIES

To estimate the man-induced increase in the amount of soil delivered to a stream channel caused by silvicultural activities, it is necessary to compare soil mass movement in an area that has not been subjected to silvicultural activities with soil mass movement in an area that has been subjected to silvicultural activities. It is essential that the area selected for its previous silvicultural activities be identical or very similar to the undisturbed area, not only in physical site conditions, but also in proposed silvicultural activities. The proposed site of the silvicultural activity may or may not have existing soil mass movement which could be measured and quantified. The other area should have a history, if possible, of soil mass movements from both natural and man-induced causes.

SITE OF PROPOSED SILVICULTURAL ACTIVITY

If the proposed silvicultural activity is to be conducted in a previously undisturbed area, the inherent natural instability of the site can be estimated based upon existing failures or upon failures occurring on a similarly undisturbed site.

SITE OF PAST SILVICULTURAL ACTIVITY

Select an area adjacent to the proposed site of the silvicultural activity, with similar site characteristics and a history of similar silvicultural activities. The inherent natural instability of the area can be estimated based upon existing failures. Failures caused or accelerated by the silvicultural activity can also be measured.

VOLUME OF EACH FAILURE AND NUMBER OF FAILURES BY MOVEMENT TYPE & CAUSE

The site is inventoried using aerial photos and possibly a limited field reconnaissance and a record is made of each soil mass movement (the length, width, and depth), (figs. V.9 and V.10). The cause of each mass movement, either natural or in the case of areas that have been subjected to past silvicultural activity, man-induced, and the type of mass movement are noted. The number of soil mass movements by cause (natural vs. man-induced) and type is computed.

ESTIMATE TOTAL & AVERAGE VOLUME PER SOIL MASS MOVEMENT

The volume of individual soil mass movements (V) is computed on worksheet V.5 by multiplying the length (L), width (W), and depth (D) to obtain cubic feet of soil moved. The total soil mass movement by type (debris avalanche-debris flow and slump-earthflow) is computed by summing the volumes of the individual failures (wksht. V.5). These values are summed and recorded on worksheet V.6, step 1. The total number (N) of failures by soil mass movement type is recorded on worksheet V.6, step 2. The average volume per soil mass movement (V_A) by movement type is computed by dividing the total volume (V_t) by the number of failures (N) or $V_A = V_t/N$ and is recorded on worksheet V.6, step 3. For example, if the total volume (V_t) for debris avalanches-debris flows was 17,205 ft^3 (487 m^3) and the number of debris avalanche-debris flow (N) was 5, the average volume per debris avalanche-debris flow (V_A) would equal 3,441 ft^3 (162 m^3) or $V_A = 17{,}205\ ft^3/5 = 3{,}441\ ft^3$.

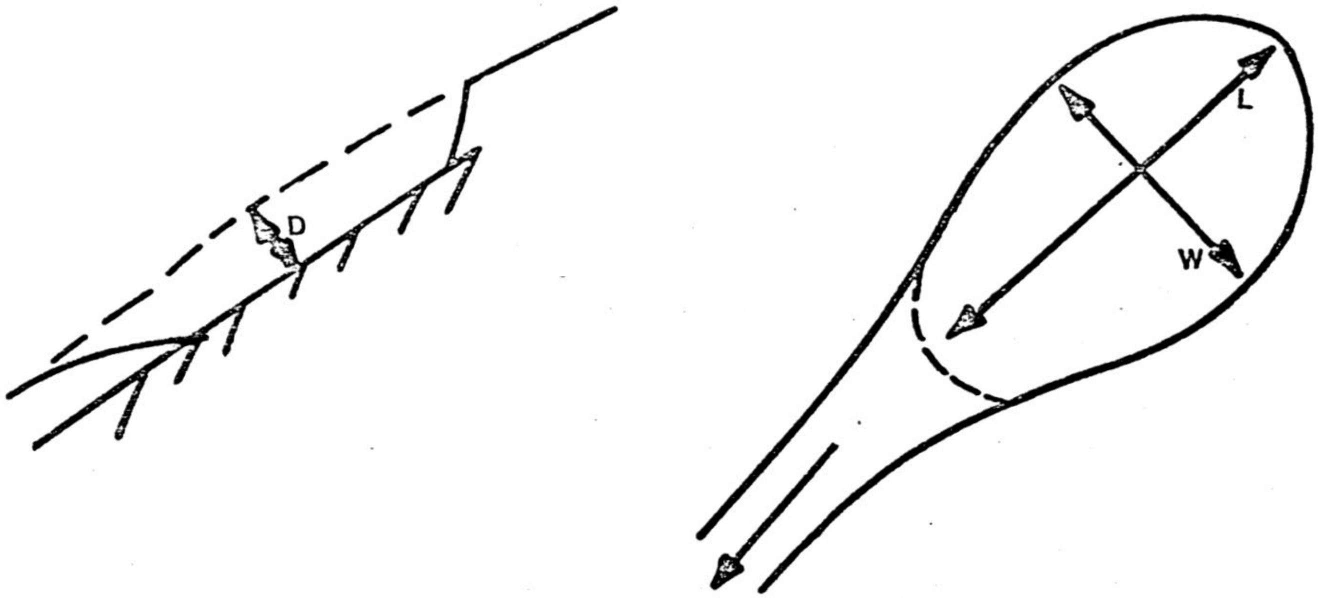


Figure V.9.—Dimensions of debris avalanche-debris flow failures for determining potential volumes. W = width; L = length; D = depth.

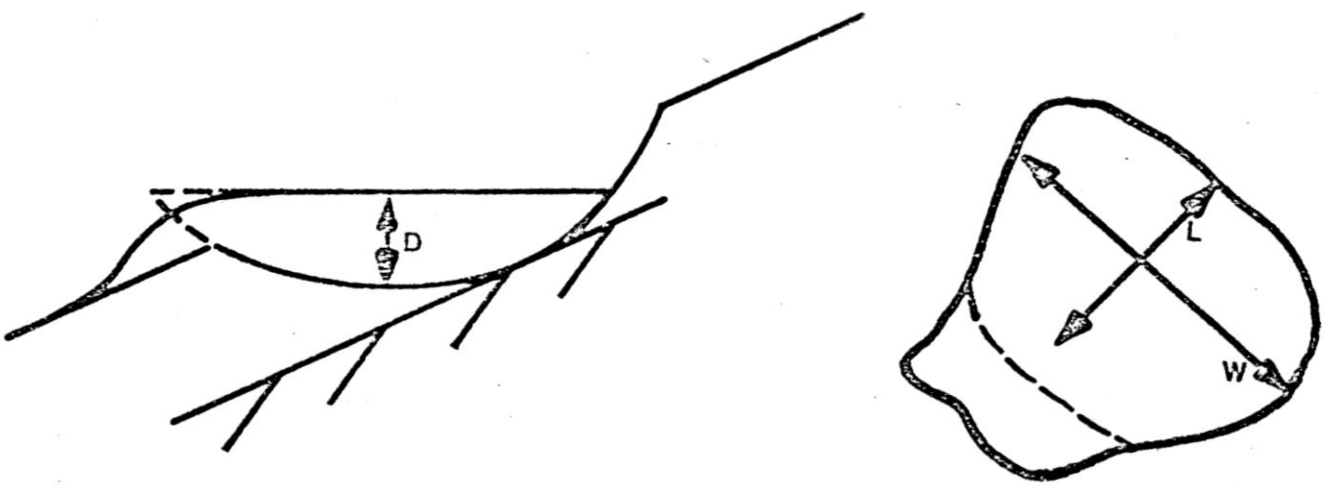


Figure V.10—Dimensions of slump-earthflow failures for determining potential volumes. W = width; L = length; D = depth.

WORKSHEET V.5

Estimation of volume per failure

	Debris avalanche-debris flow						Slump earthflow					
Slide Number	Natural	Man-Induced	Length (ft)	Width (ft)	Depth (ft)	Volume (ft^3)	Natural	Man-induced	Length (ft)	Width (ft)	Depth (ft)	Volume (ft^3)
Horse	Creek											
1	X		84	28	1.5	3,528						
Mule	Creek											
1		X	80	24	1.5	3,880						
2		X	129	26	1.5	5,031						
3		X	121	17	1.5	3,086						
4		X	113	18	1.5	3,041						
5		X	95	23	1.5	3,278						
1	X		115	19	1.5	3,280						

WORKSHEET V.6

Estimation of soil mass movement delivered to the stream channel

(1) Watershed name Mule Creek

Factor (2)		Debris avalanche-Debris flow: Natural (3)	Debris avalanche-Debris flow: Man-induced (4)	Slump flow: Natural (5)	Slump flow: Man-induced (6)
1 Total volume (V_t) in ft^3		3280	17205	—	—
2 Total number of failures (N)		1	5	—	—
3 Average volume per failure (V_A)(ft^3)		3280	3441		
4 Number of failures per slope class	a	1	2		
	b	—	2		
	c	—	1		
5 Number of failures per slope position category	a'			—	—
	b'			—	—
	c'			—	—
	d'			—	—
6 Total volume per slope class or position category (V) in ft^3	V_a $V_{a'}$	3280	6882	—	—
$V = V_A \times N$	V_b $V_{b'}$	—	6882	—	—
	V_c $V_{c'}$	—	3441	—	—
	$V_{d'}$			—	—
7 Unit weight of dry soil material (γ_d) (lb/ft^3)		99	99	—	—

8 Total weight per slope class or position category (W) in tons $W = \frac{V \times \gamma_d}{2,000}$	W_a $W_{a'}$	163	341	—	—
	W_b $W_{b'}$	—	341	—	—
	W_c $W_{c'}$	—	171	—	—
	$W_{d'}$			—	—
9 Slope irregularity--smooth or irregular		smooth	smooth	—	—
10 Delivery potential (D) as a decimal percent for slope class or position category	D_a $D_{a'}$	0.62	0.50	—	—
	D_b $D_{b'}$	—	0.30	—	—
	D_c $D_{c'}$	—	0.15	—	—
	$D_{d'}$			—	—
11 Total weight of soil delivered per slope class or position category (S) in tons $S = W \times D$	S_a $S_{a'}$	101	171	—	—
	S_b $S_{b'}$	—	102	—	—
	S_c $S_{c'}$	—	26	—	—
	$S_{d'}$			—	—
12 Total quantity of sediment delivered to the stream channel in tons		101	299 (400)	—	—
13 Acceleration factor (f) $f = TS_{silvicultural\ activity}/TS_{natural}$		3		—	
14 Estimated increase in soil delivered to the stream channel due to the proposed silvicultural activity (TS) in tons $TS_{silvicultural\ activity} = TS_{natural} \times f$		—		—	

NUMBER OF SOIL MASS MOVEMENTS BY SLOPE CLASS OR POSITION CATEGORY

The soil mass movement recorded previously by type and cause must be differentiated by slope class or category. Debris avalanches-debris flows are differentiated by slope class which is based upon slope steepness. There are three classes: *a* is greater than 35° (70%), *b* is less than 35° (70%), and greater than 28° (53%), and *c* is less than 28° (53%). Slump-earthflows are differentiated by position on the slope. There are four position categories: *a'* is adjacent to the stream, *b'* is the lower 1/3 of the slope, *c'* is the middle 1/3 of the slope, and *d'* is the upper 1/3 of the slope. This information is recorded on worksheet V.6, step 4 for slope classes and step 5 for slope position categories.

TOTAL VOLUME RELEASED BY SLOPE CLASS OR POSITION CATEGORY

For both the proposed silvicultural activity area and the area previously subjected to a silvicultural activity, the total volume of soil mass movement (V_t) by type and slope class *(a,b,c)* or position category *(a',b',c',d')* is computed. The average volume per failure (V_A) is multiplied by the number of failures in each slope class *(a,b,c)* or position category *(a',b',c',d')* and recorded on worksheet V.6, step 6. For example, if the average volume per failure (V_A) was equal to 3,441 ft^3 (162 m^3) and there were two debris avalanches-debris flows in the 28° to 35° slope class *(b)*, the total volume for that soil mass movement type and slope class *(b)* would equal 6,882 ft^3 (324 m^3) or 3,441 ft^3 × 2 = 6,882 ft^3.

ESTIMATED DRY UNIT WEIGHT OF SOIL MASS MOVEMENT

Estimate the dry unit weight (γ_d) of the soil materials included in the failures (V), expressed in pounds/cubic foot. Use soil samples from the assessed area for this determination if possible. Otherwise, use the values for typical soils provided in table V.9. For example, the soil was measured, the dry unit weight was 99 lb/ft^3 (1.57 g/cm^3). The dry unit weight of soil material is recorded on worksheet V.6, step 7.

Table V.9—Unit weight of typical soils in the natural state (Terzaghi 1953)

Description	Unit weight γ_d[1]	γ_d
	lb/ft^3	g/cm^3
Uniform sand, loose	90	1.43
Uniform sand, dense	109	1.75
Mixed-grained sand, loose	99	1.59
Mixed-grained sand, dense	116	1.86
Glacial till	132	2.12

[1] γ_d = unit weight in dry state.

COMPUTE TOTAL WEIGHT RELEASED PER SLOPE CLASS OR CATEGORY

Estimate the total weight of material (W) released per slope class *(a,b,c)* or category *(a',b',c',d')*. For the previously disturbed site (that area subjected to a past silvicultural activity), differentiate between natural and man-induced failures. For example, if the dry unit weight was 99 lb/ft^3 and the total volume released by debris avalanche-debris flow with a slope class of 28° to 35° was 6,882 ft^3, the total weight released for this slope class would be 681,318 lb or 6,882 ft^3 × 99 lb/ft^3 = 681,318 lb. This is converted to tons by dividing by 2,000 lb/ton or 681,318 lb divided by 2,000 lb/ton = 341 tons (309 metric tons). These values are recorded on worksheet V.6, step 8, by slope class *(a,b,c)* or position category *(a',b',c',d')*, type of mass movement, and for the previously disturbed site, natural vs. man-induced failures.

SLOPE IRREGULARITY BY SLOPE CLASS OR POSITION CATEGORY

Estimate, by slope class *(a,b,c)* or position category *(a',b',c',d')*, the gross irregularity of the slope within the area of the proposed silvicultural activity and the area of the past silvicultural activity. Two general classifications are used: smooth and irregular. Smooth slopes generally have a uniform profile with a few major breaks or benches which may serve to trap and collect soil mass movement material. Incipient drainage depressions and intermittent drainages have a constant grade and lead directly to main drainage channels. Irregular slopes generally have an uneven profile with frequent benching or breaks, which tend to trap and collect soil mass movement material. Incipient drainage depressions and intermittent drainageways have an uneven grade with frequent grade flattening and changes in direction. The classification is recorded on worksheet V.6, step 9.

ESTIMATE DELIVERY POTENTIAL

Determine the percentage of soil mass movement material delivered (D) to the stream channel. An estimated delivery relationship is presented in figure V.11, for debris avalanches-debris flows, and is based upon the slope class *(a,b,c)* and irregularity. An estimated delivery relationship is presented in figure V.12 for slump-earthflows and is based upon the slope position category *(a',b',c',d')*. Delivery in percent, is recorded on worksheet V.6, step 10. For example, the delivery potential of a debris avalanche-debris flow on a smooth 29° (55%) slope is 30%.

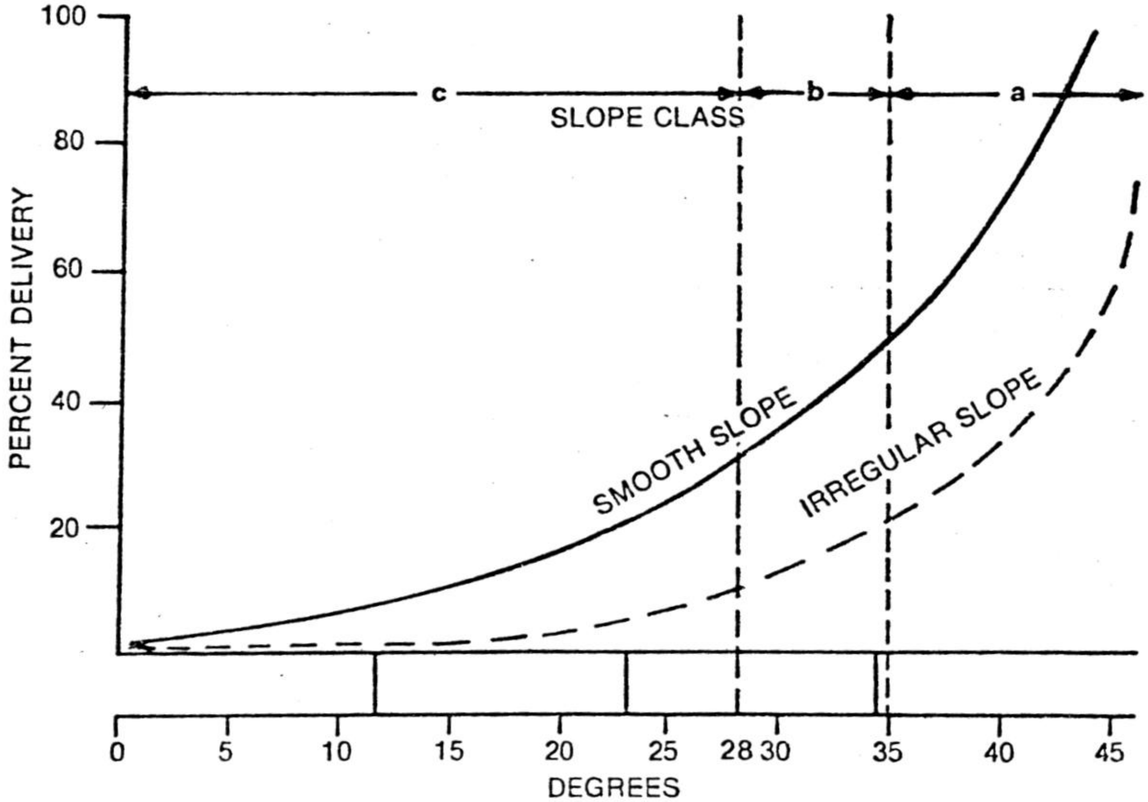


Figure V.11—Delivery potential of debris avalanche-debris flow material to closest stream.

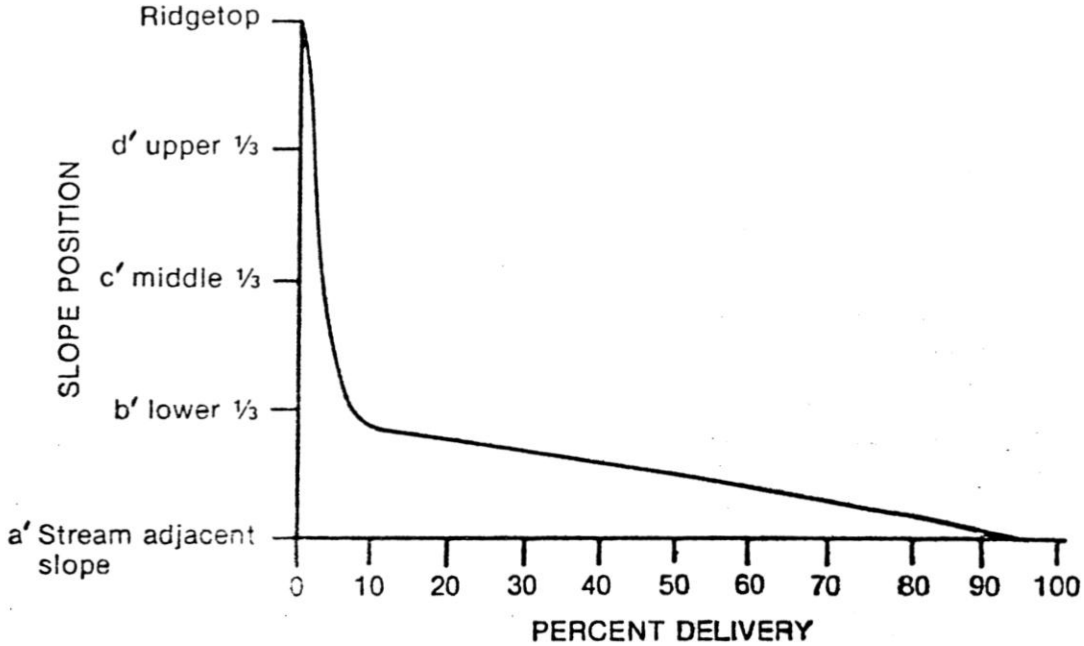


Figure V.12—Delivery potential of slump-earthflow material to closest stream.

ESTIMATE TOTAL QUANTITY OF SOIL DELIVERED PER SLOPE CLASS OR POSITION CATEGORY AND TOTAL AMOUNT

Determine the estimated quantity of soil mass movement material delivered to the stream channel (S) for each slope class *(a,b,c)* or position category *(a′,b′,c′,d′)*. For the area subjected to the past silvicultural activity, separate by natural vs. man-induced. The quantity of soil mass movement material delivered to a stream (S) is computed by multiplying the estimated total weight of released soil material (W) by the delivery potential (D) expressed as a decimal percent. This should be done for each slope class or position category. For example, if the total weight of a released debris avalanche-debris flow with a slope class of 28° to 35° class *(b)* was 341 tons, and the delivery potential was 30 percent, the amount of material delivered to a stream channel would be 102 tons or 341 tons × 0.3 decimal percent. These values are recorded in worksheet V.6, step 11. The total quantity of soil mass movement material (TS) delivered to the stream channel is computed by summing the material delivered by each slope class *(a,b,c)* or position category *(a′,b′,c′,d′)*. The total quantity delivered is recorded on worksheet V.6, step 12. For example, if the slope classes *(a,b,c)* for debris avalanche-debris flow had the following values: S_a = 171 tons, S_b = 102 tons, and S_c = 26 tons, the total quantity of material delivered to the stream channel by debris avalanche-debris flows would be equal to 299 tons. If slump-earthflows were present or possible, these values *(a′,b′,c′,d′)* would also be summed and added to the debris avalanche-debris flow value to get the quantity of total sediment delivered to the stream (TS).

The computation provides an estimate of the average total volume of material delivered to the stream channel (TS) in the area of proposed silvicultural activities under natural conditions and can be used directly in "Chapter VI: Total Potential Sediment."

ESTIMATE AN ACCELERATION FACTOR TO ACCOUNT FOR THE INCREASED DELIVERY DUE TO THE SILVICULTURAL ACTIVITY (MAN-INDUCED)

Estimate the change in sediment delivery to the stream channel on the previously disturbed area as a result of all silvicultural activities by comparing quantities and delivery rates for both natural and man-induced failures. The acceleration factor (f) is estimated by dividing the total quantity of soil delivered to the stream channel due to silvicultural activities (man-induced) (TS silvicultural activity) by that due to natural causes (TS natural), record on worksheet V.6, step 13. For example, if the quantity of soil delivered due to silvicultural activities was 299 tons and that delivered due to natural cause was 101 tons, the acceleration factor (f) would be 3.0. The acceleration factor is recorded on worksheet V.6, step 13. Note total from both natural and man-induced failures would be equal to 299 tons (silvicultural activity) plus 101 tons (natural) or 400 tons.

ESTIMATE INCREASED SOIL DELIVERY DUE TO THE PROPOSED SILVICULTURAL ACTIVITY

Estimate the increase in amount of soil mass movement material that would be delivered from the area being considered for the proposed silvicultural activity. The total quantity of soil mass movement material (TS) delivered to the stream channel (natural conditions) is multiplied by the acceleration factor (f) estimated from a site previously subjected to similar silvicultural activity, record on worksheet V.6, step 14. For example, if the existing natural condition delivered a total quantity of soil mass movement material to the stream channel of 64 tons and the acceleration factor estimated from a similar site subjected to a similar silvicultural activity was 3.0, the estimated potential soil mass movement material delivered to the stream channel would be equal to 192 tons. This completes the procedure for determining increased soil delivery.

APPLICATIONS, LIMITATIONS, AND PRECAUTIONS

Relating magnitude of management impact to hazard index ranking has the shortcoming that once a site is ranked as high hazard, alternate management practices do not change the estimate of management impact. Where data permit, quantification of hazard index should be set up so that management-caused changes in hazard index are directly proportional to degree of accelerated erosion. Such a system would permit realistic assessment of various management alternatives on the mass erosion rate. However, additional studies are needed to quantify the impact of numerous silvicultural activities.

CONCLUSIONS

This procedure is designed to quantify the potential volume of soil mass movement material that is delivered to the closest drainageway as a result of a proposed silvicultural activity. The analysis is conducted on areas that have previously been delineated as unstable. It should be reemphasized that if the user does not have experience in delineating unstable or potentially unstable areas, additional assistance from qualified specialists should be obtained.

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