Abstract

Slope disturbance produced by forest operations on mountainous terrain has been identified as a major contributor to initiation and acceleration of erosion by soil mass movement processes. Roadbuilding is the most damaging operation, but timber cutting and slash burning are effective initiators in local areas. Factors controlling slope stability and current techniques for identification and control are discussed.

Forest operations in mountainous regions have a major impact on soil erosion processes. Forest vegetation protects the soil surface, and internal soil strength is adequate to resist the downward pull of gravity on the soil mass. In the undisturbed state, the forest floor of steep, mountain watersheds represents a minimum erosion site. It exists in a state of semi-equilibrium between erosional processes and soil forming processes. Any disrupting influence, whether it be a natural catastrophe, such as fire, earthquake, or large storms, or the activities of man, is a potential initiator of more active erosion cycle.

Major Erosion Processes

Downslope movement of soil may take the form of surface or single-particle erosion involving transportation of soil particles by running water or the form of mass soil movement involving the transport of a finite mass of soil and forest debris primarily by gravity. In surface erosion, the degree of movement is directly related to angle of slope, amount of water available for surface runoff, and ground disturbance produced by a disrupting event. Mass erosion is a much more subtle process involving the interaction of slope angle and soil water content with a number of different factors which determine the physical and biological character of the soil.

We frequently think of surface erosion as the principal erosion process in forested areas, and, in fact, it does constitute the most visible and active process in disturbed areas and along lower slopes and valley bottoms. In the steep mountainous regions of western North America, however, soil mass movements are the dominant natural process of erosion and slope reduction. They present a major problem during timber harvesting and reforestation operations in these areas. A map of aerial extent and severity of landslides in the United States (Baker and Chieruzzi, 1959) reveals just how extensive this problem is (Fig. 1). While the severity ratings are based primarily on frequency of problems encountered during road construction activities, they reflect naturally unstable conditions in the mapped areas and indicate some interesting general relationships between geology and climatic conditions conducive to soil mass movement problems. The areas of greatest landslide severity in the West lie within the circumpacific mountain belt and the western cordillera (Rocky Mountains, Coast Ranges and Cascade Range). These are regions of high relief, characterized by steep slopes and narrow intervalley ridges. Glacial erosion, tectonic uplift, and severe weathering processes have further steepened the slopes, frequently above the angle of internal friction (stability angle) of the soils on them. Periodic storms producing locally saturated soil conditions are also common to most of these areas. Both oversteepened slopes and saturated soil conditions have been identified in the literature as principal contributors to soil instability and landslide hazard under a wide range of geologic conditions. Note, also, that these are areas of intensive timber harvesting activity.

Principal Processes of Mass Movement

Within these high-hazard areas, soil mass movements range widely in surface configuration, speed of movement, and volume of materials involved. In terms of principal processes, however, dominant forms can be classified into two groups according to their principal movement mechanism. These groups overlap geologic and physiographic boundaries and are controlled primarily by slope gradient, soil depth, soil water content, and specific soil physical characteristics.

The first and most widespread group are mass movements of debris produced by initial failure in shallow residual or colluvial soils overlying an impermeable surface. Soil depths range from several inches to over 4 feet. This group includes, with increasing water content, debris slides, avalanches, flows, and torrents. Movement velocities are high, frequently in excess of 5 ft/sec., and volume of material depends largely on width of slide and length of slope on which it develops (Fig. 2). Sizes range from small slips between trees and stumps to long downslope avalanche tracks and associated debris deposits covering several acres.
The second group includes deep-seated soil creep, slumping, and earth flows resulting from quasi-viscous flow and progressive failure of weathered pyroclastics, sandstones, and shales (Fig. 3). Movement can range from imperceptible creep of .1 — .5 inch per year to high velocity flows moving at speeds of tens of feet per second. Sizes range from small slumps and flows of several cubic yards in volume to an entire hillside. In areas of extremely deep, cohesive soils, a combination of creep, progressive slumping, and earth flows frequently involves an entire watershed. In such areas, slumps and earth flows occur in zones of concentrated subsurface drainage.

**Characteristics of Unstable Areas**

High soil-moisture content and oversteepened slopes are common characteristics of all areas of recent accelerated soil mass movements on forested lands (Swanston, 1971). Local bedrock type, climate, and basic soil characteristics determine the individual failure mechanisms. External factors, primarily rooting structures of trees and understory vegetation, have been shown to contribute to the inherent stability of some sites.

Geology and climate together control precipitation distribution, dominant weathering processes, and geomorphic surface development. These in turn determine slope angle, soil depth, and the basic soil characteristics: cohesion, angle of internal friction, particle size distribution, unit soil weight, and permeability. Cohesion is an expression of the capacity of soil particles to stick or adhere together, largely through the weak electrical bonding of clay particles and organic colloids. The angle of internal friction is a measure of frictional resistance between particles, a degree of interlocking between grains. Particle size distribution defines the size and shape of soil particles and their relative distribution in the soil. Unit weight is the total weight of material, including soil, soil water, and any surface loading, being acted on directly by the force of gravity. Permeability expresses the rate at which water is transmitted through the soil.

The stability of a soil can be expressed most simply as a ratio between shear strength or resistance of a soil to gravitational stress and the gravitational stress itself. As long as shear strength exceeds stress, the soil will remain in a relatively stable state. In its simplest form, gravitational stress is determined directly by the action of gravity on effective soil weight. Shear strength is determined by the interaction of the basic soil characteristics with soil water content and angle of slope. As slope angles approach the angle of internal friction of a soil, gravitational stress begins to exceed the shear strength of the soil.
stress increases while the frictional component of shear strength is reduced.

The size distribution of the soil particles determines the relative importance of the basic soil characteristics in maintenance of soil shear strength. The shear strength of soils composed predominantly of coarse materials depends largely on frictional resistance between particles as expressed by the angle of internal friction of the soil. Cohesion plays only a minor role. The character of mixed-grain soils, on the other hand, is determined almost entirely by the character of the smallest soil constituents, and cohesion becomes a major factor in shear strength development.

For noncohesive soils (soils with little or no clay), shear strength can be expressed directly as the ratio between angle of internal friction and angle of slope. Thus, cohesionless soils on slopes at or above their angle of internal friction are highly unstable under the best of conditions. Soil saturation during high intensity storms results in local development of active pore-water pressure (pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore-water). This decreases stability even further by decreasing the effective weight of the soil mass.

The shear strength and angle of internal friction for dry cohesive (high in clay content) soils initially may be quite high. With increasing water content, however, the angle of internal friction decreases rapidly due to mobilization of clay particles by adsorption of water into the clay structure. Increased creep rates result with ultimate failure where saturation reduces the angle of internal friction to nearly zero.

Root systems of trees and other vegetation act to increase shear strength in shallow unstable soils, either by serving as cohesive binders for the soil mass or by penetrating the soil zone and anchoring the soil mantle to the substrate. In some extremely steep areas in the western United States, this may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area (Bishop and Stevens, 1964; Croft and Adams, 1950; Swanston, 1969). Zaruba and Mencl (1969) have reported the stabilizing effect of tree roots in landslide areas in Czechoslovakia, and Fujiwara (1970) reports similar effects for unstable areas in Japan.

Impact of Mass Erosion Processes on Forest Lands

The impact of soil mass movements on forest lands can be extensive. Destructive debris avalanches and debris and earth flows frequently destroy the entire productive soil zone within their paths. Natural revegetation may occur in as little as 10 years (Fujiwara, 1970), but if the landslide remains active by progressive slumping near its head, a considerably greater time may elapse before substantial vegetation cover develops. Conversely, the zone of deposition at the base of the slope may actually serve as an area of more rapid regeneration because of the mixture of soil and organic debris. Soil mass movements are also prodigious producers of sediment directly affecting quality of water leaving the watershed. A slug of sediment may be deposited directly into a stream during sliding or surface erosion may occur at the zone of deposition. Active creep continually adds sediment to

Figure 2. — Debris avalanche, debris-flow combination on a recently logged slope. Failure occurred during a period of high intensity rainfall in a zone of concentrated subsurface drainage. The sliding material was a weathered till soil less than 3 feet thick overlying compacted unweathered till. The slope angle is about 34° (75 percent grade). Note scoriing of the avalanche path below spoon-shaped zone of initial failure and flow development at slope base.

Figure 3. — Massive slope failure in the northern California Coast Ranges with local slumps and earth flows. The failure has resulted from creep and progressive failure in a deeply weathered series of graywackes, shales, bedded cherts, and limestone lenses of Cretaceous Age.
the stream largely through progressive slumping along the banks.

Finally, soil mass movements are a major problem in terms of personnel safety and construction and maintenance costs in active timber harvesting areas. Such problems result primarily from reactivation of old, partially stabilized slumps and soil flows, timber harvesting operations on oversteepened slopes deliberately stabilized by natural vegetation, and failures due to oversteepened back slopes and excessive fills on forest roads.

Impact of Forest Operations on Soil Mass Movements

Slope disturbance produced by forest operations in mountainous regions has been clearly identified as a major contributor to accelerated soil mass movements. Roadbuilding is the most damaging operation, but timber cutting and slash burning have also been shown to be effective initiators of mass erosion activity.

Roadbuilding

Dyrness (1967b), investigating accelerated soil mass movements on the west flank of the Cascade Range, reported 78 percent were directly associated with logging and roadbuilding. Slumps and earthflows caused by failures along road rights-of-way constituted more than 65 percent of all the mass movements. In Idaho, Megahan1 reports that about 90 percent of the soil mass movements which occurred along the South Fork of the Salmon River during a storm in April 1965 resulted from soil failures along the logging road right-of-way. Road construction activities can disrupt the basic equilibrium of steep slope forest soils in three ways: (1) alteration of drainage, (2) loading, and (3) undercutting.

Alteration of slope drainage includes interception and concentration of surface and subsurface flow by ditching, bench cutting, and massive road fills. Interception and concentration of water encourages saturation, active pore water pressure development, and increased unit weight in road prisms, side cast materials, and soils upslope from the road cut. Poor road drainage and plugged culverts can magnify these problems due to ponding of water on the upslope side of the road.

Slope loading by massive fill and side casting greatly increases the weight of the soil materials and results in increased gravitational stress acting along the slope below the road.

Slope undercutting by benching along an oversteepened slope removes support for the soil upslope from the road.

Old slumps and landslides are particularly susceptible to disturbance by these activities. These areas have stabilized themselves naturally according to the slope conditions existing at the time of initial failure. They are in a delicately balanced state of equilibrium with the slope on either side, and construction activity which involves appreciable excavation or filling is highly likely to reactivate the soil movement zone through changes in distribution of stress within the dormant mass.

Timber Cutting

Cutting of trees does not by itself significantly increase surface soil erosion; however, on steep slopes there is some evidence that it may adversely affect soil stability through changes in soil hydrology and mechanical support provided by vegetation. Decay of anchoring roots in shallow soils and root binders in all soils may greatly reduce the mechanical stability provided by these root structures.

Deterioration of mechanical support provided by roots as an important factor in accelerating soil mass movements on shallow soils was first identified on recently logged slopes along the North Fork of the Ogden River in Utah, Croft and Adams, (1950). Here debris avalanches were initiated by combined heavy spring rains and snowmelt, but the authors felt that a contributing factor was a lessening of the mechanical support of the slope, chiefly by timber cutting and burning. In southeast Alaska, Bishop and Stevens (1964) also suggested a direct correlation between timber harvesting and accelerated soil mass movements following heavy rains, presumably as the result of decreased anchoring effect of roots.

Timber cutting removes overstory vegetation, greatly decreasing evapotranspiration and increasing water available for subsurface and streamflow. Destruction of the principal soil water users also results in a much higher stored-water content in the soil at the end of the dry season. Beginning with wetter soils, saturation and active pore-water pressure develop more rapidly during fall storms.

Slash Burning

Fire is an effective management tool to dispose of logging debris and to prepare a seedbed. It may also be an effective agent for accelerating soil mass movements on already unstable slopes. Unfortunately, most work which can be directly related to effects of fire on soil mass movements has come from the chaparral covered slopes of southern California where past erosion from fire is a major problem. Some interesting and applicable general analogies, however, can be made on the effects of logging and slash burning.

At its worst, fire removes all protecting vegetation from the surface. This can lead to progressive deterioration of the mechanically stabilizing roots systems. In the California Coast Ranges, land conversion by fire for forage production and increased water yields is a common practice and has produced significant increases in soil mass movement occurrence. Stearns2 estimates 10 to 20 percent of the high sediment yield from soil mass movements in the northern California Coast Ranges is directly attributable to land conversion (burning), roadbuilding, and logging activities. Corbett and Rice (1966),

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in the San Gabriel Mountains of southern California, found five times as many debris avalanches occurring on slopes where chaparral had been converted to grass (by burning), as on unconverted slopes presumably due to destruction of stabilizing chaparral root systems. Krammes (1965) reports a 10- to 16-fold increase in annual sediment production from soil mass movements following a wildfire on monitored watershed slopes in the same area.

**IMPACT REDUCTION**

Steep slopes, periodic high rainfall, and unstable soils characterize large areas of commercial forest land in western North America. Under these conditions, slope soils remain in place largely as the result of a delicate natural balance between gravitational forces tending to pull them to a lower level and the various resisting factors constituting soil strength. Any disrupting event, whether natural or man-made, is highly likely to upset this balance, creating renewed conditions of accelerated soil mass movement. Since timber harvesting is a major economic activity in these areas and is rapidly advancing onto increasingly unstable terrain, it is essential that the land manager be able to recognize potential problem zones and identify major factors contributing to instability.

**Options**

There are two main options available to the land manager. He can: (1) identify problem areas and avoid operations on unstable terrain, or (2) identify and attempt to control operational effects. In highly unstable areas or areas of questionable economic value, avoidance of all operations is probably the best and least expensive solution. Controlling operational effects is a much more difficult approach which at best will probably be only partially successful. It is applicable in high value areas of questionable soil stability or where other considerations override a desire for stability maintenance.

**Identification**

Identification of unstable areas is an essential part of both options. This involves, first of all, the accurate determination and mapping of unstable and potentially unstable slopes in the area of proposed timber operations. This should be followed by a careful analysis of the factors contributing to unstable conditions and a classification of unstable areas according to the level of operations that can be safely performed within them. Thus, areas within the highly unstable class should be withdrawn from timber harvesting activities entirely or, at the very least, have operations limited to light selective cutting and yarding by helicopter. Roadbuilding in these areas is almost sure to cause or accelerate landslide occurrence with little chance of effective control.

Areas in the potentially unstable class should be carefully examined for locally unstable conditions and operation criteria designed to fit each stability situation encountered.

Such stability analysis has been done recently for timber sales in southeast Alaska using air photos and topographic maps. Estimated maximum and minimum angles of internal friction of local soils were used to define the limits of highly unstable and questionable terrain.3

As a result of the analysis, it was recommended that areas above the maximum angle of internal friction or showing evidence of active soil mass movement should be entirely withdrawn from the proposed timber sale. Slopes above the minimum angle of internal friction possess questionable stability and could be operated on if adequate care is taken in choosing logging methods, controlling road construction activities, and in post-stabilization and reforestation procedures. Bailey (1971) performed a similar landslide hazard analysis on the Teton National Forest in northwest Wyoming using degree of active landsliding to designate slopes of high instability. Air photo identification of unstable terrain in southern California has proven 80 percent effective in predicting areas affected by landslides during a large storm in 1969.4

**Control Measures**

A number of effective engineering control measures are available for slope stabilization but, as a rule, they are expensive and generally applicable to specific occurrences. Current investigations of stability of forested slopes have been directed more toward: (1) avoidance of disturbances damaging to slope stability and (2) reduction of landslide incidence after disturbance.

The former can best be accomplished by reduction in forest road construction in unstable areas and substantially reducing slope disturbance by logging processes. A number of promising new timber harvesting methods are currently being investigated. These include balloon logging and helicopter transport, both of which have a tremendous potential for reducing the environmental impact of logging in unstable areas.

The latter is best approached through improved road design and construction and stabilization of disturbed areas by vegetation planting. Some effective road design and construction techniques are already available to the engineer and land manager. It is largely the successful application of these techniques which determines the impact of roadcutting on slope stability. Stability of road cuts and side cast slopes has been substantially increased by

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4. E. Kojan, G. T. Foggin, and R. M. Rice, Prediction and analysis of debris slide incidence by photogrammetry, Santa Ynez-San Rafael Mountains, California. (To be presented at 24th Geologic Congress, August 1972. Copy on file, Pacific Southwest Forest & Range Experiment Station, Glendora, Calif.)

planting of grass and legumes (Bethlahmy and Kidd, 1966; Wollum, 1962; Dyrness, 1967a) in the western States. Several debris avalanche tracks have been partially stabilized in southeast Alaska using a mixture of reed canary grass and alder wildlings.5

SUMMARY

A major impact of forest operations in mountainous regions is the acceleration in soil erosion processes. In mountainous watersheds, characterized by steep slopes, periodic high rainfall, and potentially unstable soil characteristics, soil mass movement dominates as the principal erosion process.

Soil mass movements on forest lands remove standing timber and frequently destroy the entire productive soil zone within their paths. In addition, sediment, added directly to a stream by landsliding or indirectly by surface erosion of a landslide deposit, may substantially reduce quality of water leaving the watershed.

Slope disturbance produced by forest operations in such naturally unstable areas has been identified as a major contributor to accelerated soil mass movements. Roadbuilding is the most damaging operation, but timber cutting and slash burning can be effective initiators in local areas. Principal causative factors include slope loading, slope-toe undercutting, disruption and concentration of slope drainage, and destruction of stabilizing root systems.

Based on current knowledge and the "state of the art" of soil mass movement prediction and control, the best approach to limiting soil mass movements in these areas is identification and qualitative rating of landslide potential. Highly unstable areas can then be withdrawn from any timber harvesting activities or limited to light selective cutting or yarding by helicopter and balloon.

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Well, I think that's about it. I think probably I had best answer some questions from the floor. (Applause)

Mr. Johnston: Thank you, sir. Now, although I had a rather dictatorial tone when we got started, I am going to put you on the back and thank you for the fact that we are, according to my clinometer, only 5 minutes behind schedule. So I would suggest then that while the next panel is making its way up here that perhaps they stand aside and let just a couple of questions come from the floor to these two gentlemen to keep this thing current. (silence)

In any event, let me make these remarks about your moderator from this point on. I'm going to yield this spot now to Mr. Bill Sauerwein who will be the moderator for this next panel which is "Land Use and the Soil." Bill Sauerwein is Regional Forester for the Soil Conservation Service here at Portland, and he provides the forestry services and the program direction for the Soil Conservation Service, for regional and field personnel in the western states. He knows his soils, and he knows well what he is here for. So, Bill Sauerwein will take care of the program from this point and will conduct the panel.

Maybe you can find it convenient to run out and
run back if you wish to, but we're not going to adjourn this thing, you are here and we're going to hold you.

(short, informal break)

Mr. William J. Sauerwein: While Bill Stein is rewinding the tape, I would urge you to again take your seats, please. (long pause)

Will you gentlemen in the back please be seated? (pause)

While we are getting ready, I have a couple of announcements to make. First of all we have an attendance register going around, and it doesn't seem to be making too much progress. So we would appreciate it if you would keep this going and please sign it and move it on, and we'll also keep the lights up just a little bit during the pictures that we have to show, and this will facilitate your signing the register.