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431

STABILITY OF STEEP LAND

One of the most important factors affecting stability of steeply sloping terrain is disturbance. As a general rule, with increasing disturbance comes increasing erosion.

On-site erosion reduces site productivity by removing soil material and lowering nutrient capital available for plant growth. The resulting soil and debris causes damage to roads and other improvements, ranging from roadblocks by landslide debris to houses buried by mudslides. Continuing instability may cause difficulty in reestablishing protective vegetation and tree seedlings.

Downstream effects include lowering of water quality by increased sediment and dissolved chemical content; shortened life span of reservoirs due to excessive siltation; and degradation of fish habitat through increased sediment in spawning gravels and blockage of fish passage by landslides.

The actual erosion processes include both surface erosion and mass soil movement.

Surface Erosion

Surface erosion is essentially a two-stage process—detachment of soil particles and their subsequent transport by flowing water. The size and density of surface soil particles and the degree of soil protection from plant and litter cover control the detachment process. Transport is influenced by rainfall duration and intensity, slope gradient and length, and soil infiltration rate.

The two principal types of rainfall-caused erosion are rilling and gullying, which involve channelized erosion easily recognized by the scars left on the land (*Fig. 1*); and sheet erosion, which occurs in areas of bare mineral soil, where particles may be detached and moved downslope by raindrop splash. This form of erosion may go on virtually unnoticed. But when severe, exposure of roots or the formation of pedestals under some impervious material such as gravel or wood fragments will give it away.

To determine whether proposed management activities may increase surface erosion potential, the land manager must first examine the inherent site characteristics, which give at least a rough idea of how potentially erodible the area is.

Slope and landform characteristics, such as length, whether or not the slope is unbroken, or whether the slope profile is convex or concave, are the first, obvious considerations. With increasing slope gradient there is an increasing potential for surface erosion.

Soil properties are equally influential. The parent materials can give the first indication as to erodibility. For example, studies in several of the western states have shown that soils derived from granite, quartz diorite, granodiorite, and certain high-quartz sandstones are the most erodible. Relatively nonerodible soils are derived from basalt, andesite, and gabbro. Thus the higher the quartz content of the parent material, the greater the potential erosion hazard of the resultant soil.

Since detachment and transport are the essential steps of surface erosion, it is easy to see why large soil particles are much more resistant than smaller ones. Actually, those soil particles most resistant are aggregates of primary particles cemented together by colloidal materials. The amount of these water-stable aggregates in the surface soil offers perhaps the single most valuable index of soil erodibility.

In general, fine-textured soils contain far larger amounts of water-stable aggregates than coarse-textured soils, mainly because fine clay-sized particles constitute the principal cementing agent in the formation of aggregates. This also explains why parent materials high in quartz give rise to erodible soils. Since quartz is resistant to weathering, such soils tend to be course-textured in the surface layers (loamy sand or sandy loam).

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The rapidity with which water flows into and through the soil profile is likewise relevant to soil erodibility. Soil porosity is dependent on amounts of soil pore space, especially on the proportion of large, noncapillary-sized pores. Fortunately, most undisturbed forest soils are sufficiently porous in the surface that rainfall intensities seldom surpass the infiltration capacity.

Meteorological factors such as the expected type of precipitation influence potential erodibility, too. Does it come mainly in the form of rain or snow? What is the potential duration and intensity of rainstorms? Magnitude of both detachment and transport of soil particles varies directly with rainfall intensity—low intensity rainstorms typical of coastal areas in the Pacific Northwest cause less surface erosion than do the high-intensity convection storms common in the intermountain west.

Plant and litter cover is the greatest deterrent to surface erosion. It is also the only site characteristic over which the land manager has any direct control.

Tremendous amounts of kinetic energy are expended by falling raindrops as they hit the earth's surface. Most is absorbed by vegetation and litter in undisturbed forests. But with the disturbed soil, at least a portion is directed at unprotected, bare areas. The impact of rain on bare soil detaches soil particles (the first step in the erosion process), and, in time, results in decreased water infiltration rates, thus more surface runoff (providing transport, or the second step in surface erosion). The impact decreases surface porosity by destroying soil structure. It breaks down soil aggregates, throws the soil into suspension, and ultimately results in the clogging of surface porosity. Both duration and amount are crucial in considering exposure of bare soil as a result of management activities. In high rainfall areas, revegetation of bare areas occurs so rapidly that deterimental effects are minimized.

Fig. 1. Deep gully produced by concentrated surface runoff from a skid trail in western Oregon. The gully developed over a two-year period in a deep pumice soil after vegetation removal and surface compaction.

Compaction caused by logging or other activities also causes decreased infiltration rates and consequent increases in surface runoff and erosion. No one knows

Fig. 2. The principal forces acting on a sloping soil mass. Gravitational stress represents the downslope component of gravity acting on the soil mass. Sliding resistance is the sum of cohesion of the soil particles and the frictional resistance between particles and between the soil mass and the sliding surface. As long as slide resistance is greater than gravitational stress, the soil mass will remain relatively stable. Adding water to the soil decreases stability by increasing weight and decreasing frictional resistance. The rooting structures of trees and other vegetation can serve as external stabilizers, binding soil material and anchoring the soil mass to a more stable substratum.

exactly how long these effects persist. One study conducted for five years after logging in the intermountain west found little improvement in infiltration rates of skidroads. Furthermore, compaction was severe, with infiltration rate for skidroads only 5 percent of that for undisturbed soil.

The two most important soil factors affecting compaction are texture and moisture content. Medium-textured soils (loams and silt loams) seem to compact to greater densities than fine- or coarse-textured soils. Soil moisture contents giving the greatest degree of compaction are neither very wet nor very dry. One study showed optimum moisture for compaction to be about midway between field capacity and the permanent wilting point.

Minimizing Surface Erosion

Fortunately, in choosing the proper level of management, the land manager has many ways to minimize surface erosion on steep lands. If erosion hazard is unusually high, the optimum decision might be to forego logging and intensive management and instead practice protective management. If, on the other hand, the manager decides on some sort of stand manipulation, he must then select a suitable silvicultural approach—maybe anything from light thinning to clearcutting and replanting. Site erosion potential should influence this decision. For example, although clearcutting may be suitable on stable sites, shelterwood management may provide the soil protection necessary in erodible areas. Compromise may be necessary due to possible conflicts between silvicultural and watershed management objectives.

Logging methods can also help minimize surface erosion. The following tabulation illustrates variation in disturbance caused by four yarding methods used in clearcut operations in the Pacific Northwest:

	Percent bare soil	Percent compacted
Tractor	35.1	26.4
Highlead	14.8	9.1
Skyline	12.1	3.4
Balloon	6.0	1.7

Obviously, tractor logging would be a poor choice in an area where soil erodibility is a problem.

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

Fires also can increase surface erosion, primarily through the removal of protective vegetation and litter. Sufficiently hot fires may also cause changes in surface soil properties. Perhaps the most serious of these are the breakdown of water-stable aggregates and lowering of organic matter content (one of the principal cementing agents in the formation of aggregates). Of interest also is the formation of nonwettable or hydrophobic layers in some sandy-textured soils after high-intensity fires. Although we still don't fully understand how these layers are formed, it is becoming increasingly apparent that this soil wettability problem is widespread, especially in the western United States. Such soils have very low infiltration rates and thus runoff and erosion may be severe on steep slopes.

Since compacted soil areas are most often the critical sources of erosion after logging, judicious location and design of skidroads and trails is another way to decrease erosion potential.

Treatment of bare and compacted soil areas is essential. Since the greatest deterrent to erosion is cover, the manager's first job after disturbance should be to reestablish, as quickly as possible, a protective covering of vegetation and litter. In areas of compaction or exposed subsoil, natural revegetation may occur so slowly that seeding, fertilizing, and mulching are necessary. Compacted skidroads may also require special drainages to divert concentrated surface runoff.

Mass Soil Movement

High soil-moisture content and steep slopes are common to most recent accelerated mass movements of soil on forest lands. Local bedrock type, climate, and basic soil characteristics determine the individual failure mechanisms. External factors, including parent materal structure and rooting structures of trees and understory vegetation, affect stability conditions at some sites.

Ideally, the stability of a soil is defined by its resistance to the downslope pull of gravity (*Fig. 2*). Gravitational stress is controlled by the weight of the soil mass and the gradient of the sliding surface. Increased steepness can result from geologic uplift and stream dissection or modification by glacial activity; increased soil weight can result from high soil-water content or surface loading. Other forces include wind stresses transferred to the soil through the root sytems of trees, frictional "drag" produced by seeping water, and horizontal accelerations due to earthquakes.

The resistance of a soil to sliding is governed by a more complex interrelationship between soil and slope characteristics. Two active secondary forces are: cohesion, or the capacity of the soil particles to stick together, a distinct soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and 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, which describes the interlocking of individual grains, and the effective weight of the soil mass and any surface loading plus the effect of slope gradient and excess soil water.

Pore water pressure (pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water) lessens the frictional resistance by reducing the soil's effective weight. Its action causes the soil to "float" above the sliding surface.

The three major types of mass soil movements are:

Debris avalanches and debris flows (*Fig. 3*), produced by instantaneous failure in shallow soils overlying an impermeable surface. These soils are usually of coarse texture and low in clay content.

Creep, slumps, and earthflows (*Fig.4*), resulting from quasi-viscous flow and progressive failure of deeply weathered materials. Speed of movement ranges from a barely perceptible creep to high velocity slumps and earthflows.

Dry ravel, dry creep, and sliding (*Fig. 5*), involving downslope movement of single particles and thin sheets of coarse, cohesionless material on steep,sparsely vegetated slopes.

The site characteristics which control mass soil movement include particle size distribution, angle of internal friction, soil moisture content, and angle of slope. For example, shallow coarse-grained soils low in clay-size particles have little or no cohesion, and frictional resistance determines the strength of the soil mass. Frictional resistance is in turn strongly dependent on the inherent angle of internal friction and the degree of pore-water pressure development. A low angle of internal friction relative to slope angle or high pore pressures can reduce soil shear strength to negligible values.

Fig. 3. Debris avalanche on a glaciated slope near Ketchikan, Alaska. The soil is approximately 12 inches deep overlying a granite, jointed parallel to the slope. The slope is about 40 degrees.

Slopes at or above the angle of internal friction of the soil indicate a highly unstable natural state.

In soils of moderate to high clay content 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 content. When dry, clay soils have a high shear strength with high internal friction angle (greater than 30 degrees). Increasing water content mobilizes the clay through adsorption of water. The angle of internal friction is reduced by the addition of water to the clay lattices (in effect reducing "intragranular" friction) and may approach zero in the saturated state. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas characterized by quasi-viscous flow deformation or "creep." Swelling clays of the montmorillonite type are particularly unstable because of both their tendency to adsorb large quantities of water and the loosening effect of alternate expansion and contraction during periods of wetting and drying. Thus, clay-rich soils have a far higher potential for failure, given excess soil moisture content. Under these conditions failures may develop on slopes with gradients as low as 2 or 3 degrees.

Factors Contributing To Soil Stability

Parent material type has a major effect on the particle size distribution, depth of weathering, and relative cohesiveness of a steep-land soil. In humid regions where chemical weathering predominates, transformation of easily weathered primary minerals to clays and clay-size particles may be extensive. Siltstones, claystones, shales, nonsiliceous sandstones, pyroclastics, and serpentine-rich rocks are the most easily altered and prime candidates for soil mass movements of the creep, slump, and earthflow type. Conversely, in arid or semiarid regions, slopes underlain by these rocks may remain stable for many years because of slow chemical weathering processes and lack of enough soil moisture to mobilize existing clay minerals. On steep lands underlain by rocks with a high quartz content, or on those recently exposed to weathering, or at high altitudes or latitudes where mechanical weathering prevails, soils are usually coarse and low in clay-size particles. Such areas are more likely to develop soil mass movements of the debris avalanche or debris flow type.

Parent material structure is a critical factor in stability of many shallow soil slopes. Highly jointed bedrock slopes with principal joint planes paralled to the slope, and sedimentary rocks with bedding planes parallel to the slope, provide little mechanical support. They create avenues for concentrated subsurface flow and active pore water pressure development as well as ready-made zones of weakness and potential failure surfaces independent of the overlying material.

Vegetative cover in general helps control the amount of water reaching the soil and the amount held as stored water against gravity. The direct effect of interception on the soil water budget is probably not large, especially in areas of high total rainfall or during large storms when most soil mass movements occur. The effect of evapotranspiration is much more pronounced but is particularly dependent on region and time. In arid and semiarid regions and in areas characterized by warm, dry summers, evapotranspiration of soil moisture significantly reduces the saturation produced by infrequent summer storms or the first storms of the fall recharge period. Once the soil is recharged, the effect of previous evapotranspirational losses becomes negligible.

Root systems of trees and other vegetation may also increase shear strength in unstable soils. This is particularly true when roots anchor through the soil mass into the parent material, and provide continuous long-fiber cohesive binders to the soil mass proper and across local zones of weakness within the soil mass. In shallow soils, both of these may be important. In deep soils, the anchoring effect of roots probably becomes negligible. In some extremely steep, shallow soil areas in the western United States, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area.

Fig. 4. A watershed slope in the Coast Range of northern California undergoing massive creep and slumping. Note deep gullys within intermittent drainage channels and below road crossdrains. The slope is undergoing creep, as indicated by the hummocky nature of the surface, with local slumps occurring below spring outlets and above road cuts. Numerous springs at the surface sugget that the entire soil mass is well lubricated with water, probably the chief mobilizing factor.

Fig. 5. Dry ravel from a road cut in western Washington.

Snow cover increases soil unit weight through surface loading and affects delivery of water to the soil through retention of rainfall and delayed release of large quantities of water during spring melt. Such delay has been the principal initiating factor of many landslides on the east side of the Cascade Range in Washington and Oregon.

Forest operations influence mass movement, too. Roadbuilding, for example, has been identified as the greatest single cause of recent soil mass movements in the western states. Road construction disrupts the basic equilibrium of steep slope forest soils through alteration of slope drainage, slope loading, and slope undercutting. The first includes interception and concentration of surface and subsurface flow by ditching, bench cutting, and massive roadfills. This encourages saturation, active pore water pressure development, and increased unit weight in road prisms, side-cast materials, and soils upslope and downslope from the road cut. Poor drainage and plugged culverts can greatly magnify these problems by ponding water on the inside of the road. Slope loading by massive fill and side-casting greatly increases the weight of the soil material, resulting in increased gravitational stress along the slope below the road. Slope undercutting by benching along an oversteepened slope removes support for the upslope soil.

Old slumps and landslides are particularly susceptible to disturbance by road construction. These areas have stabilized themselves naturally. They are in a state of delicate semiequilibrium with the slope on either side, and construction activity which involves excavation or filling is likely to upset the distribution of stress within the dormant slide mass.

Cutting of trees alone does not greatly increase surface soil erosion so long as ground cover is maintained; however, on steep slopes cutting may cause debris accumulation and loss of the mechanical support from rooting structures of trees and other vegetation. Several investigations in the western states have linked increased occurrences of debris flows to logging after high-intensity storms. The deterioration of stabilizing root systems seems to play an important part in this increased activity. Accumulation and flow of debris in steep ravines, both logged and unlogged, has also been cited as a major factor in mass soil movements.

Fire is an effective management tool to dispose of logging debris and to prepare a seed bed. It also can accelerate mass soil movement. At its worst, fire removes or destroys all protective vegetation. This can lead to mechanical unravelling of the slope and progressive deterioration of root systems. In southern California as well as in the Wasatch Mountains of Utah, fire has been directly linked to massive increases in dry ravel or debris avalanching.

Minimizing Mass Soil Movement

A basic understanding of mass wasting processes and controlling and contributing factors is essential to effective identification, prediction, and control of soil mass movements on forest lands. Only with this can the land manager either identify problem areas and avoid operations on unstable terrain, or 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 of unstable and potentially unstable areas is an essential part of both options. Their accurate determination and mapping should be followed by careful analysis of the contributing factors and classification according to the level of operating that can be safely performed. This is already being done on a qualitative basis. The resulting cut-slope stability maps and land-slide hazard maps are important tools in development of land-use plans.

A number of effective engineering control measures are available for slope stabilization, but as a rule, they are expensive and applicable only to specific occurrences. Current investigations have been directed more toward avoidance of damaging disturbances and reduction of landslide incidence after disturbance. Avoidance can best be accomplished by reduction in forest road construction in unstable areas and substantial reduction of slope disturbance by logging. A number of promising new timber harvesting methods to reduce the environmental impact of logging in unstable areas are being investigated, including balloon logging and helicopter transport.

Reduction in landslide incidence is best approached through improved road design and construction and planting vegetation to stabilize disturbed areas. Some effective road design and construction techniques are already available to the engineer and land manager; it is their successful application which will determine the final impact. ☐