Slope Stability on Forest Land

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Sedimentation of streams resulting from mass soil movement is the most important problem of non-point pollution in the Pacific Northwest, according to state and federal regulatory agencies. Sediment in streams contributes to the deterioration of fisheries habitat and affects downstream water quality. Large mass movements that extend downslope directly into streams can scour channels and alter aquatic ecosystems for decades.

In order to minimize the impacts of forest practices on slope stability, forest and other resource managers must understand the characteristics and causes of various slope failures.

Slope Stability on Forest Land

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The dominant erosional process on forest land in the Pacific Northwest is mass soil movement. Mass soil movements, which commonly occur as landslides, involve the transport of large quantities of soil and debris, primarily by gravity. This is in contrast to the often more visible process of surface erosion, in which individual soil particles are detached and transported downslope by water. While surface erosion may be a significant sediment contributor to streams from localized sites such as cut banks and road surfaces, sedimentation due to various mass wasting processes is much greater on the forested hillslopes of the Pacific Northwest region.

A map showing the extent and severity of road-associated landslides in the Pacific Northwest area illustrates the magnitude of the slope stability problem (Figure 1). The areas of highest land-

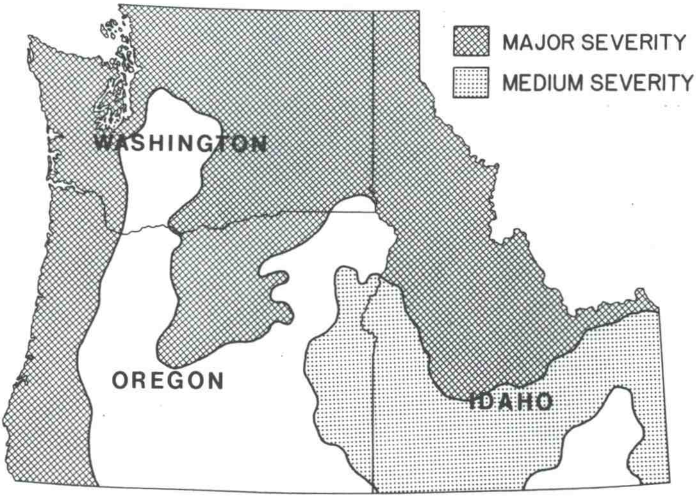

Figure 1. Road-associated landslide hazards extend throughout Pacific Northwest forest lands.

slide potential shown on the map correspond to the steep slopes of Cascade, Coast, and Intermountain Ranges. These low-stability regions frequently experience intense storms and periods of extended rainfall. With increasing demands for timber production and advances in harvesting technology, more of these steep forested slopes are subjected to a variety of forest practices.

This publication deals with basic causes of slope failures, and the impacts of road construction, timber harvesting, and slash burning, with emphasis on control measures to reduce landslide hazards.

Characteristics of Slope Failure

Since it is almost impossible to control mass erosion once it has started, it is important that land managers recognize causes and areas of instability and adjust management plans accordingly to minimize impacts on these potentially erodible areas. Land managers must have a basic understanding of the interacting forces that dictate slope stability, as well as the factors that influence these forces. Generally, three types of mass soil movements occur in the Pacific Northwest: 1) shallow, rapid failures such as debris avalanches, debris flows, and debris torrents; 2) slow, deep-seated mass movements such as soil creep, slumps and earthflows, and 3) single-particle erosion such as dry ravel and rockfall.

Debris Avalanche--Debris Flow

Debris avalanches occur rather spontaneously in shallow soils overlying an impermeable layer such as bedrock (Figure 2). Depending on the water content of the soil mantle at the time of failure, they may be classified as debris slides, avalanches, or flows, in order of increasing water content. In reality, several of these modes may occur in the same landslide, with the failure initiating as a debris slide or avalanche upslope and then breaking up into a more fluid mass as it moves downslope.

Debris avalanches frequently occur on the steep, forested terrain in the Coast Range of Oregon, Washington, and northern California, as well as portions of central Idaho. Relatively hard bedrock, such as Tyee sandstone in the Oregon Coast Range and granitics of the Idaho Batholith, form the lower boundary for these failures. Soils developed on impermeable glacial tills, such as in coastal Alaska, are also subject to debris avalanching.

DEBRIS AVALANCHE- DEBRIS FLOW

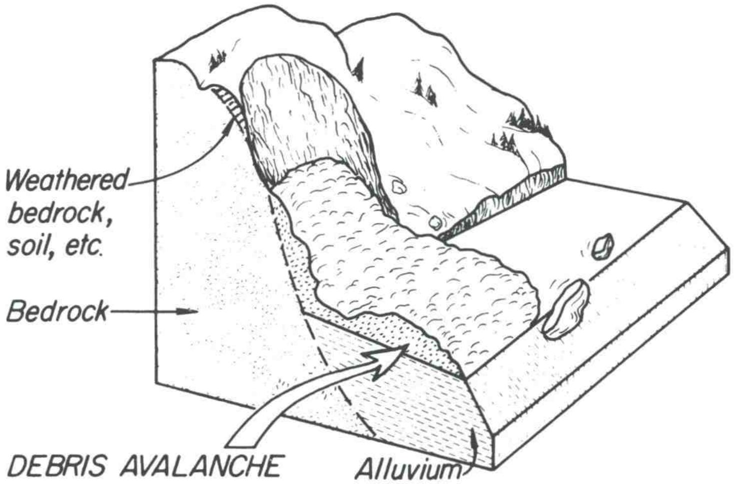

Figure 2. Debris avalanches and flows typically occur on steep slopes with shallow soils overlying an impermeable layer.

Debris avalanches on natural forested hillslopes usually are triggered by large inputs of water into the soil mantle, from either intense storms or rapid snowmelt or a combination of these two. Once the failure is initiated, the relatively thin soil mantle and surficial debris moves downslope at velocities varying from 5 to 15 feet per second, depending on water content and slope gradient. Debris avalanches leave scars in the form of spoon-shaped depressions and their tracks may extend downslope for long distances in steep terrain (Figure 3).

For a sliding-type failure, such as a debris avalanche, the downslope pull of gravity acting on the soil (shear stress) exceeds the ability of the soil to resist sliding (shear strength), causing the slope to fail. As ground water rises in the soil mantle, the interlocking forces among soil particles are reduced, since water exerts a buoyant force on each particle as it becomes submerged. Increased soil water can also create slope instability by increasing the soil weight on an already steep slope, thereby increasing shear stress. The impact of ground water in landslide initiation is especially important in steep, upslope depressions with shallow soils. These steep headwall areas are often points of debris avalanche initiation due to ground water concentration.

Relatively cohesionless soils, which tend to be low in clay content, non-plastic, and granular, are more susceptible to debris ava-

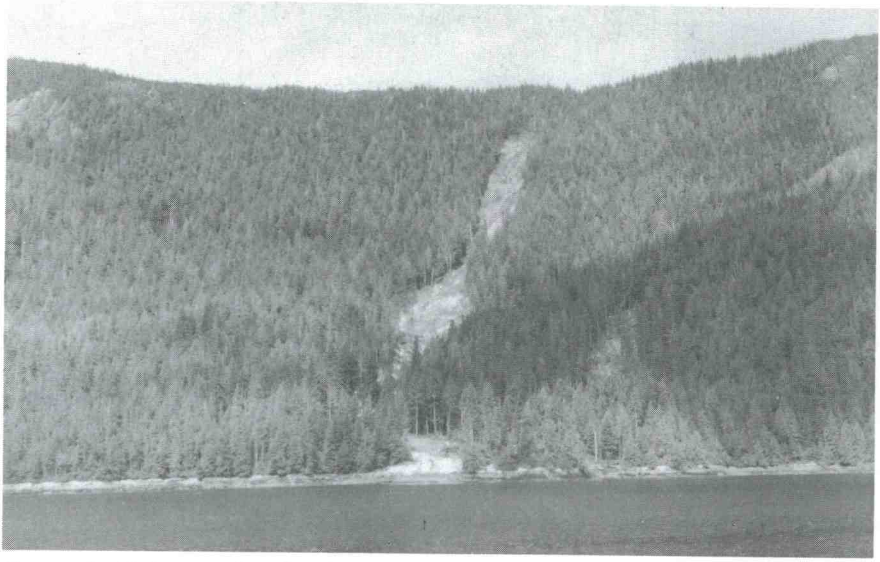

Figure 3. Debris avalanches leave characteristic scars on steep hillslopes.

lanching on steep slopes, since their shear strength is determined primarily by soil particle interlocking. These shallow soils are developed on certain sandstone and granitic bedrock and are basically unstable on slopes greater than 75 percent and may become unstable when disturbed on slopes greater than 53 percent. Living root systems of vegetation contribute substantially to the overall stability of these shallow soils by attaching directly to bedrock and tying the hillslope together across zones of weakness.

Debris Torrents

Debris torrents occur in steep intermittent first-, second-, and third-order stream channels. They are usually triggered by debris avalanches from adjacent land units or by the break-up of debris dams in stream channels. Debris torrents move rapidly down intermittent channels, in a slurry-like state, containing living and dead debris, soil, bedrock, and water. In their progress down channel, debris torrents often scour channels to bedrock and severely erode stream banks, thus inflicting severe damage to downstream fisheries habitat and water quality in general. When debris torrents come to rest downslope there is often a huge deposition of organic debris and sediment covering up to several acres (Figure 4). Although

Figure 4. Debris torrents deposit large quantities of debris and sediment in stream channels.

systematic inventories of debris torrents have not been conducted in the Pacific Northwest, they appear to occur in tandem with debris avalanches, primarily in the steep, dissected terrain of the Coast and Cascade Ranges of Oregon and Washington.

Soil Creep

Although not a slope failure in the technical sense, soil creep involves the slow (usually less than ¼ inch/year) downslope movement of the soil mantle resulting from long-term gravitational influences. Creep rates often increase somewhat during the prolonged wet winter months. In spite of this slow movement, relative to other mass wasting processes, soil creep can contribute sizeable sediment loads to streams. Since the entire hillslope is often in motion in creep-prone areas, stream channels encroached upon by soil creep receive a continuous addition of sediment.

Rapidly creeping hillslopes are characterized by hummocky, rolling topography with poorly formed or immature drainage patterns, sag ponds, springs, and localized slumping below wet areas (Figure 5). Other subtle indicators of soil creep include curved trees, tilted fence posts and telephone poles, differential soil mantle

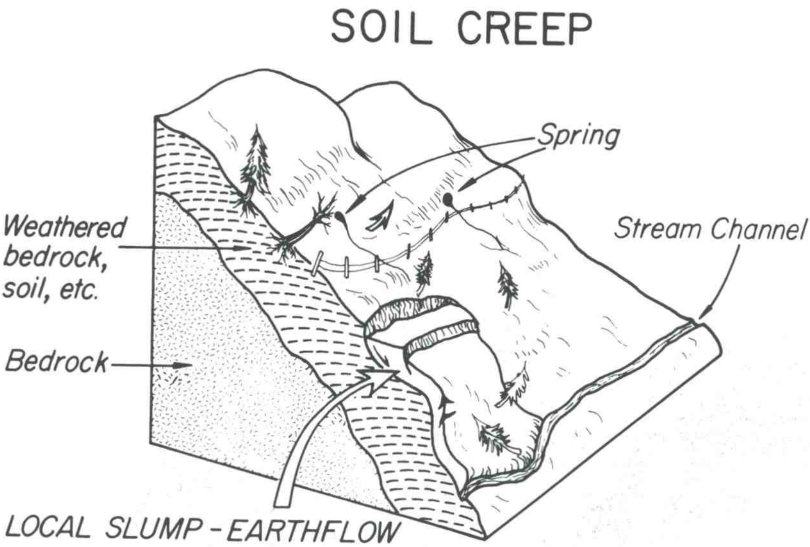

Figure 5. Hummocky topography with springs, curved or tilted trees, and localized slumps characterize land undergoing active soil creep.

movement evidenced by the formation of stone lines along road cuts, and broken or displaced walls or foundations.

Soil creep is also significant because it fills upslope depressions with soil and debris over a period of years. These sites are then subject to future debris avalanching. Creep can also build up stresses in potential slump-earthflows causing them to fail under high soil moisture conditions.

Although creep can occur in shallow coarse-textured and organic soils found in coastal Oregon, Washington, and southeast Alaska, the deep-seated soil creep that often triggers slumps and earthflows usually is found in high rainfall regions with deep, clay-rich soils. Cohesion in these fine-grained soils is a function of moisture content. Cohesive forces are relatively strong in dry soils and tend to increase slightly with increasing water content to a maximum and then decrease rapidly as the moisture content is further increased. The point at which cohesive forces are maximum usually corresponds to the minimum moisture content at which the soil can be deformed without rupture, known as the soils' plastic limit. The type of clay present in cohesive soils can play an important role in determining shear strength. Soils high in expanding clays, such as montmorillonite, experience dramatic losses in shear strength upon wetting near saturated levels due to the extremely large amounts of water absorbed within the clay particles. Non-expanding clays, such as illite and kaolinite, have much lower shrink-swell potentials and thus higher shear strengths when wet. Because of this decrease in soil cohesion on extensive wetting, soil creep rates will accelerate during prolonged wet periods, during which ground water is present in the lower portion of the soil mantle.

The Klamath Mountains of southwest Oregon and northern California have regions of extensive soil creep associated with the highly faulted and sheared metamorphosed sedimentary bedrock known as the Dothan and Franciscan Formations. Also, soil developed on weathered serpentine-rich rocks, and certain interbedded mudstones found in the higher precipitation portions of the Klamath Mountains are conducive to soil creep. Localized areas of deep soil creep are found in the western Cascades in association with soils developed on pyroclastic deposits (tuffs, breccias, and ashes) and in the foothills along the west side of the Willamette Valley of Oregon in conjunction with deeper soils formed on weathered igneous rocks and soft siltstones.

Slump--Earthflow

Although they are technically two distinct modes of slope failure, slumps and earthflows commonly occur together, or one initiates the other. Slumping involves the simple rotation of a solid block of earth over a broad concave failure surface. When the material begins to move downslope, it breaks up and is transported as a disrupted mass known as an earthflow. The earthflow may then incorporate additional masses of soil as it moves downslope through the processes of flowage and progressive slumping. If the blocks of earth are left intact as they move downslope, along the failure plane, the failure is termed a "block glide."

Earthflows typically occur on moderately sloping terrain, often slopes less than 40 percent, in which deep, clay-rich soils have developed. Figure 6 illustrates a typical slump-earthflow with characteristic scarps, slump benches, tension cracks, and sag ponds. Vegetative indicators of slump-earthflow terrain include tipped and jackstrawed trees around the benches and lateral boundaries of the failure. Poor drainage characterizes the hummocky topography of most slump-earthflows. The resulting concentrations of subsurface

SLUMP-EARTH FLOW

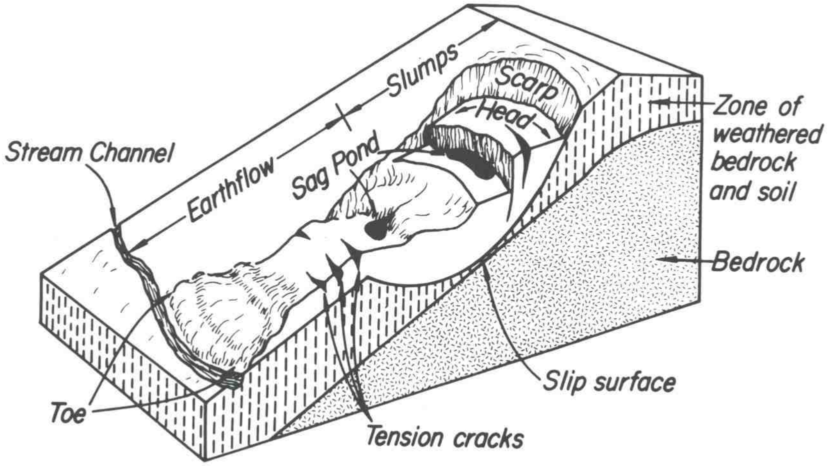

Figure 6. Slumps and earthflows generally occur together, creating such landform features as sag ponds, tension cracks, and headwall scarps.

water during prolonged rainfall develop positive pore water pressures within the earthflow mass that may initiate or accelerate movement. These areas sometimes can be spotted by the hydrophytes or "water-loving vegetation" growing in the vicinity. Movement of earthflows can occur at rates as slow as soil creep and, in extreme cases, as fast as several feet per minute.

Large slump-earthflows are important mass wasting processes in the same areas of northern California and western Oregon and Washington in which deep-seated soil creep occurs. As discussed earlier, deep-seated creep contributes to the initiation and acceleration of slump-earthflows. Geologic and soils conditions conducive to creep likewise promote slump-earthflows. Smaller localized slumping may occur in many areas of the Pacific Northwest in deep clay-rich soils (especially swelling clays) and in highly weathered geologic material interbedded with more resistant strata. Removal of structural support at road cuts or overloading slopes with fill material can initiate localized slumps in cohesive soils. Additional deep-seated slump-earthflows occur in the hillslopes bordering the Columbia Gorge in Oregon and Washington. These failures remain active due to slow, continual geologic and fluvial erosion in the gorge.

Dry Ravel

Dry ravel involves the downslope movement of individual soil grains, aggregates, and coarse fragments by gravitational forces. This mass erosion process is common on steep, denuded, or sparsely vegetated hillslopes with relatively non-cohesive or single-grained surface soils. Dry ravel is caused by the loss of interlocking frictional resistance among soil aggregates or grains, which may be created by freezing-thawing and wetting-drying cycles. Soil and coarse fragments can move by sliding and rolling in thin sheets (known as dry creep) along the surface, making this erosional process almost imperceptible to the casual observer. Dry ravel and creep sometimes are exposed and can be observed when trapped on the upslope side of trees and debris (Figure 7).

Soils most susceptible to dry ravel include those developed on weathered granitic and volcanistic rocks in drier climatic regions where mechanical weathering processes, such as freeze-thaw, dominate. Examples are the single-grained and sandy-textured soils of the Idaho Batholith and portions of southwest and northeast Oregon, as well as certain non-cohesive soils of the Coast and Cascade Ranges. Dry ravel will occur on most hillslopes of the Pacific Northwest following deforestation and litter disturbance as well as slope oversteepening. These effects are described in the section on management related impacts.

Figure 7. Tree stumps trap dry ravel on the upslope side at a burned site.

Much of the dry ravel produced on a hillslope may not directly reach stream channels. However, the potential for reduction in site productivity by the loss of significant quantities of surface soil underlines the importance of dry ravel in susceptible areas. In addition, ravel can contribute to the filling of upslope depressions which are potential debris avalanche sites.

Rockfall

Rockfall is defined as the relatively free falling of newly detached bedrock from a cliff or steep slope (Figure 8). Rockfalls are not a particularly important mass wasting process on undisturbed forested slopes of the Pacific Northwest, largely because exposed rock cliffs or steep rock slopes are rarely present. In localized areas oversteepened by rivers or valley glaciers, rockfalls may occur. Easily weatherable rocks, such as granitics, and highly fractured rocks, such as certain sandstones and jointed igneous rocks, are likely candidates for rockfall. Freeze-thaw action may enlarge joints and help initiate rockfalls. Depending on the competence of the bedrock, distance of fall, and size of the individual rocks, blocks may

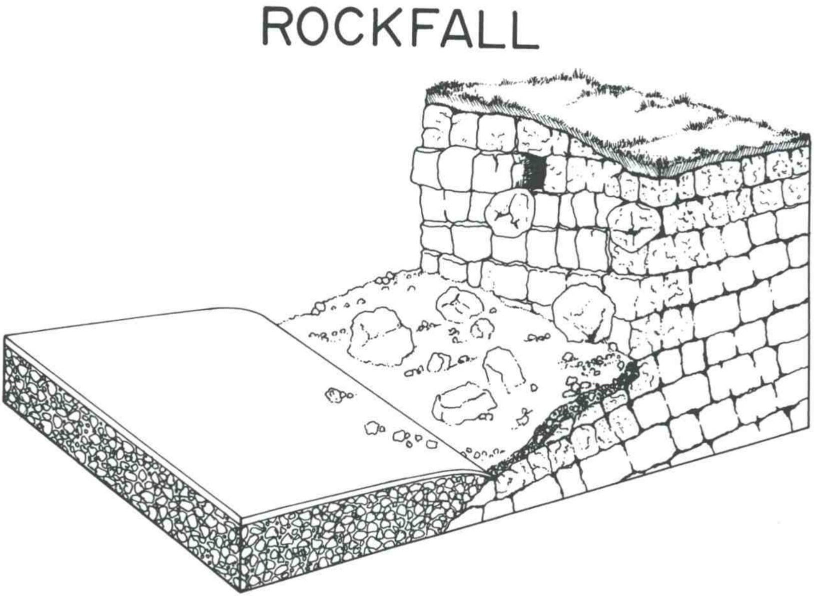

Figure 8. Roadcuts through highly fractured or unstable bedrock contribute to rockfall.

be fractured on impact and move further downslope as a rockslide. As with rockfalls, rockslides are more important erosional processes in rugged alpine areas; however, they may impact upper elevation forested slopes in certain areas of the high Cascade Range and the mountains of coastal Alaska.

One of the most catastrophic landslides ever to occur was the Turtle Mountain rockslide-rockfall of 1903, which carried approximately 40 million cubic yards of rock and killed 70 people in the town of Frank, Alberta. A combination of factors including soft interbedded sedimentary rocks, extensive frost action in well developed joints, previous earthquake-history, and partial mining of a coal seam contributed to this massive failure. The more recent, earthquake-triggered, Madison River rockslide of 1959 killed 28 people and was similar in size to the Turtle Mountain slide. These types of catastrophic rockslide-rockfalls are unlikely to initiate as a result of forest management activities; however, any major excavation into unstable bedrock should be examined by geotechnical specialists who can evaluate the strength of the rock and determine the dip of joints, fractures, and bedding planes. Small rockfalls are common along roadcuts in unstable bedrock, presenting maintenance problems for logging roads.

Impacts of Forest Practices

Certain roadbuilding, timber harvesting, and site preparation practices can have significant impacts on slope stability in the Pacific Northwest. Shallow landslides are caused by improper road location and construction practices in steep terrain, and by clearcutting large blocks of unstable land. Stumps and earthflows can be initiated or accelerated by altering ground water conditions through roadbuilding and clearcutting. Slash burning greatly accelerates dry ravel and dry creep on certain soils. Methods to ameliorate these impacts involve both pre-planning control measures and certain structural measures in critical areas.

Debris Avalanche--Debris Flow

Roadbuilding

With the increasing use of uphill highlead and skyline harvesting systems, timber removal from steep slopes in the Pacific Northwest is becoming commonplace. Although these harvesting methods normally do not require as extensive road systems as ground-based logging, considerable road construction must be done on steep, potentially unstable slopes. These roads must be wide enough to accommodate the large skyline or highlead towers, thus requiring extensive amounts of soil and rock to be excavated.

Roadbuilding is widely recognized as one of the primary causes of debris avalanches in managed forest land. Several studies conducted in the granitic and metamorphic forested hillslopes of central Idaho indicated that road construction was responsible for between 60 and 90 percent of all mass failures. Most of these failures were shallow debris avalanches and debris slides. In a landslide inventory conducted by the U.S. Forest Service in Oregon and Washington following the 1964-1965 winter floods, road related mass failures were involved in approximately 60 percent of the damage reports.

A primary cause of debris avalanches is placing road fill material on steep slopes with shallow, non-cohesive soils. The weight of the fill material acts to upset the balance of forces that determine stability. The stability of fill slopes in steep terrain is further jeopardized by water routed onto these areas from road drainage systems. Poor drainage design and plugged cross-drains can cause saturation of critical areas of the fill slope leading to increased weight and pore water pressures, and the eventual failure of these sites (Figure 9). Roadcuts in steep, unstable terrain may also trigger debris avalanches by removing downslope support.

Timber harvesting

Forest vegetation lends stability to steep hillslopes by providing additional cohesion from root systems and by reducing soil water content through transpiration. When vegetation is removed from these slopes, rooting strength is reduced over a period of time and soil moisture may be increased. The resulting decreases in soil shear strength can increase the probability of debris avalanche occurrence on steep slopes (greater than 53 percent) with relatively non-cohesive soils. A study in southeast Alaska showed greatly increased frequencies of debris avalanches occurring from 3 to 5 years after clearcutting. An analysis of landslide occurrence in central Idaho (largely granitic soils) indicated that slides were most frequent 4 to 10 years after clearcutting. Other studies have shown increased landslide activity up to 16 years after vegetation removal.

Following timber harvest, root systems of trees begin to decay, resulting in the loss of root anchoring into underlying bedrock and the decrease in overall root density of the soil mass. The decay rate of dead roots as well as the amount and type of live vegetation

Figure 9. Poor road drainage can result in catastrophic fill-slope failures.

left on site determine the period of highest landslide susceptibility. This underlines the importance of rapid regeneration on steep harvested hillslopes. Root strength tests indicate that coastal Douglas-fir roots are stronger than western hemlock roots, which in turn are stronger than Sitka spruce roots. Many of the noncommercial trees and brush that are often suppressed or killed by herbicides or slash burning have stronger root systems than fir or spruce.

The reduced transpiration following clearcutting could have an effect on debris avalanche initiation in drier regions, such as eastern Oregon and Washington and southern Idaho. In these areas, soils are rarely at or near saturation, so clearcutting could increase soil moisture levels during storm or spring runoff periods. Coupled with steep slopes, this could initiate debris avalanches.

Although mass erosion from roaded areas is usually more visual and much greater in volume on a per acre basis than failures in clearcuts, the total amount in sediment produced from the two sources often is similar in magnitude. Studies in the western Cascade Range indicated that erosion produced by debris avalanches within a clearcut was almost half as much as the total landslide erosion from road right-of-ways. A survey in the central Oregon Coast Range following the winter storm of 1975 revealed that 77 percent of the landslides occurred in clearcut units, 14 percent in road right-of-ways, and 9 percent in natural forested areas.

Control opportunities

Since forest roads are a major cause of debris avalanches in steep terrain, improved location and construction practices can reduce the magnitudes of these failures greatly. If steep slopes are to be harvested, adequate road systems are a necessary part of the overall operation. Systematic planning of forest roads that tend to minimize mileage and number of steep grades, as well as utilize ridge-top locations whenever possible, reduces the hazards of debris avalanching. Avoid excess excavation in steep terrain. A hydraulic shovel will disturb much less rock and soil and has better control of this waste during road excavation in steep terrain than will a bulldozer. Full-benching of roads and end hauling waste material to stable sites are the most effective means of minimizing debris avalanches on unstable midslopes that must be roaded. Proper road drainage design can substantially reduce fill failures on forest roads.

Adequate sizes and numbers of cross drains are essential on inslope roads to disperse this intercepted water as well as the overland flow from the road surface. Maintenance and cleaning of ditchlines and culverts as well as the installation of debris racks are needed to insure proper functioning of the road drainage system. Culverts and debris racks should be checked and cleaned during major storms. For certain highly erosive soils, such as the coarse-grained granitics, it is desirable to install additional cross drains to prevent excessive scouring and saturation of the road prism. Even well-designed crowned or insloped roads, which utilize cross drains for surface water removal, can create slope stability problems due to the large quantities of water discharged onto slopes at the cross drain outlets. To minimize this problem, road fills should be protected from culvert discharge by extending cross drains beyond the fill and riprapping the outfall. Many of the forest road-related debris avalanches that occur are due to the combination of oversteepening and periodic saturation by culvert discharge on road fills.

Since clearcutting can play a role in initiating debris avalanches on steep hillslopes, certain National Forests are now designating critical head-wall “leave areas” within clearcut units in unstable terrain. These “leave areas” must be properly designed to avoid destruction from windthrow and slash burning from surrounding areas. Alternatives to slash burning as a site preparation procedure may need to be considered on steep unstable sites in order to preserve the rooting strength of the existing vegetation. No information is currently available regarding the impacts of various partial cutting practices on slope stability.

Debris Torrents

Roadbuilding

Since debris torrents are commonly triggered by debris avalanches, roadbuilding practices that cause debris avalanches also initiate torrents in intermittent upland channels. These practices primarily involve oversteepening fill slopes and inadequate road drainage. In addition, debris torrents can be initiated directly by discharging excessive amounts of surface water into steep first-order drainages. Although these drainages are natural waterways, overloading them during storms as a result of poor road drainage can create positive pore water pressures in the thin soil mantle. This, together with accumulations of debris, can cause debris torrents that will scour channels to bedrock and inflict severe damages to downstream water quality and habitat.

Timber harvesting

Loss of rooting strength following clearcutting on steep slopes with relatively non-cohesive soils causes in-unit debris avalanching. As these avalanches move downslope they often enter intermittent first- or second-order upland channels. As the transported soil and debris move through these restricted channels the failure is termed a debris torrent. Residue from timber harvesting can also initiate debris torrents if allowed to accumulate in upland swales. In these cases, the torrent can be initiated by mechanical overloading due to the weight of the debris or by breakup of the debris mass during intense storm flows.

Control opportunities

Road planning and construction practices recommended for reducing the incidence of debris avalanches will also lower the chances of debris torrent occurrence. Adequate numbers of cross drains are especially important on roads located on steep hillslopes to avoid concentrating excessive overland flow into upland swales. Outsloped roads are effective on ridgetop and other stable road-base locations to disperse water more evenly over the hillslope. Isolated areas of instability along forest road right-of-ways may warrant structural support. This is particularly important if the impending failure would directly impact a high value water resource such as a prime fisheries stream or a municipal reservoir. Stabilization structures effective in controlling debris torrents and avalanches caused by fill slope failure include bin walls, gabions, cantilever walls, and tieback walls (Figure 10). Design, selection, and construction of a retaining wall for a given location is an expensive proposition that requires analysis by a qualified design engineer.

The use of remote aids such as aerial photos can be helpful in delineating unstable slopes susceptible to debris avalanches and torrents. Large-scale features such as fault lines, oversteepened slopes, old failure tracks, and poorly drained areas can be spotted using these aids. Once potential problem areas have been designated, an on-the-ground inspection may be necessary to evaluate the potential stability of a site and its probable response to a given management practice.

During this reconnaissance, on-site vegetative, soil, and geologic indicators of slope instability may be useful. Tipped trees and tension cracks in the soil mantle around steep headwall areas indicate imminent slope failure. Areas such as these may best be designated as "leave areas" in the overall harvest plan. Hydrophytes,

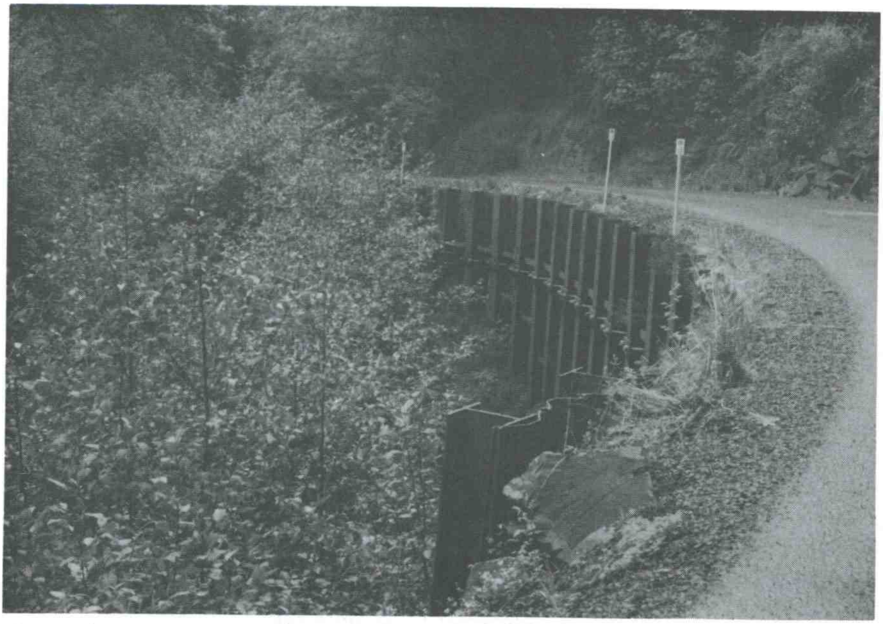

Figure 10. Retaining walls are effective means of controlling debris avalanching from unstable road fills.

such as devils club and skunk cabbage, indicate potentially unstable areas of ground water concentration. The formation of gray or yellow-brown splotches (known as mottles) in the soil profile also indicate periods of saturation. Weak bedrock and bedding planes oriented approximately parallel to the sidehill are geologic characteristics typical of unstable hillslopes. By using these "on-the-ground" indicators together with aerial photos the land manager can designate highly unstable areas in which timber harvesting and road building may be restricted or modified.

Harvesting technology can be applied constructively to minimize the chance of debris torrent occurrence. Cable yarding large logging slash out of upland swales reduces the chance of future sluice-outs. In areas that are too unstable or remote for extensive road systems, new timber harvesting methods, such as balloon and helicopter logging, can be utilized. While these aerial logging techniques offer the potential for resource protection on unstable slopes, their costs are prohibitive in some areas.

Soil Creep

Roadbuilding

Constructing forest roads on creep-prone hillslopes can accelerate the soil creep process largely by diverting road drainage water into the soil mantle. Increased soil moisture conditions downslope of the road drainage outlets will accelerate soil creep and can ultimately result in the initiation of a slump-earthflow failure if pore water presssures are allowed to build up. Road cuts into creeping hillslopes likewise can result in accelerated rates of soil creep or even localized slump-earthflows due to removal of downslope support.

Timber harvesting

When creep-prone sites are clearcut, the resulting reduction of on-site transpirational water losses will affect movement rate in these deep, clay-rich soils. In regions with rain-dominated winters, such as western Oregon and Washington, increased soil moisture levels due to reduced transpiration will occur primarily during fall and spring, thus extending the time period when soils are at or near saturation. This extended time period of high soil moisture could result in a longer period of activity for deep-seated soil creep and slow-moving earthflows. Losses in rooting strength following clearcutting on creep-prone ground are minor in terms of their effects on overall slope stability, since soil mantles usually are deep and root anchoring to bedrock is not an important consideration. On shallow, creeping hillslopes, such as certain soils of coastal Alaska, clearcutting could have a pronounced impact on rate of movement.

Control opportunities

Special road construction practices may be necessary in hummocky terrain undergoing active soil creep. Cutbanks greater than 12 feet in height and deep fills should be avoided in these deep, clayey, unstable soils. Properly place fill material and thoroughly compact to reduce water entry and prevent settling. Remove all debris and other organic material from the fill before placement, since they create zones of weakness upon decomposition. Adequate cross drainage for insloped roads is needed. Avoid discharge onto slump-earthflows lying downslope. Installing perforated horizontal drains into cut and fill slopes can reduce soil creep and the likelihood of possible slope failure by minimizing any build-up of positive pore water pressures (Figure 11).

Skyline and high lead logging systems usually require less extensive road networks than tractor logging, so are more desirable in creep-prone terrain. Avoid road construction in unstable areas of localized water concentration or slumping. These can be spotted by the on-the-ground vegetative and landscape indicators such as

Figure 11. Perforated horizontal drains installed into road cuts and fills can reduce the chance of deep-seated slope failure.

pistol-butted trees, hydrophytes, sag ponds, and springs. Although timber removal may accelerate soil creep on some unstable hillslopes, the land manager must weigh the tradeoffs between timber harvesting benefits and possible resource damages on each individual site.

Slump--Earthflow

Roadbuilding

Roadbuilding can play a major role in initiating slump-earthflows or reactivating old failures. Since slump-earthflows typically occur in deep, clay-rich soils, the removal of downslope support by cutting roads through the toe of old earthflows can reinitiate them or increase their rate of movement. Fill material placed over the top of an old slump block can create an active slump-earthflow that can extend directly down into stream channels. As with most unstable terrain, poor road drainage, together with overloading or undercutting slopes, is a major cause of slump-earthflows. In areas of inadequate drainage, deep, clayey soils develop positive pore water pressures during the wet season. Coupled with loss of cohesion in the wetter soil mantle, this can lead to a rotational slump and subsequent earthflow failure.

Timber harvesting

The impact of clearcutting on slumps and earthflows is primarily to reactivate dormant failures or to accelerate the movement rate of active failures. This is primarily caused by increasing moisture contents in the soil mantle near the failure zone as described for soil creep. The loss of rooting strength following clearcutting is not felt to be an important factor in accelerating slump-earthflow movement, since only minimal root strength contributions may occur in these deep clayey soils by lateral tying of roots across zones of weakness. Since slump-earthflows tend to be large landscape features, it is often difficult to separate management-related causation factors such as poor road drainage and clearcutting. As with shallow failures, no information is currently available regarding the impacts of partial cutting practices on earthflow movement.

Control opportunities

Utilize resources such as aerial photos, soil surveys, and geologic hazard maps to delineate active or dormant slump-earthflows. These can be recognized by such features as slump terraces, sag ponds, and poorly drained soils. An on-the-ground reconnaissance can further reveal unstable land indicators like tension cracks or "catsteps" in the soil around the headwalls of slumps, tipped and jackstrawed trees, and hydrophytes growing in areas of ground water accumulation. Once the most unstable land areas are outlined, make decisions regarding roadbuilding and timber harvesting.

On slump-earthflow terrain use roadbuilding practices recommended for creeping topography, such as limiting the depth of cuts and fills, minimizing road mileage, and thoroughly compacting and removing debris from fills. At slump-prone sites, such as soils overlying weathered siltstones, it is desirable to install additional cross drains on insloped roads to prevent excessive scouring and saturation of the road prism. Drainage systems maintenance is needed to insure optimum handling of surface water. Installing perforated horizontal drains in cut and fill slopes reduces the chance of slope failure at susceptible sites (Figure 11).

Effective road location practices in potentially unstable terrain can reduce the chances of slope failure. Avoid designated unstable areas and select an alternative route if at all possible. If an unstable land mass must be crossed by a road, locate the road so as to minimize the potential for slumping. Loading the toe of an old slump-earthflow by situating the road prism near the bottom of the potential rotational failure will minimize the impact of road construction. Location of the road prism at the head of the potential failure or undercutting the toe of the unstable zone would increase the chance for slope failure. Sag ponds and depressions around unstable land masses can be drained by surface ditches to reduce the chance of slumping.

Structural control of localized slumps along road right-of-ways is sometimes necessary. A relatively low-cost technique for stabilization of existing slumps is to use rock buttresses to provide support for road cut and fill slopes. The weight of the rock provides the structural support that was removed during road excavation (Figure 12).

Timber harvest on slump-earthflow terrain seems to have less impact on slope stability than the associated roadbuilding practices. Pre-planning road systems in conjunction with cable logging operations can reduce overall road mileage and number of steep

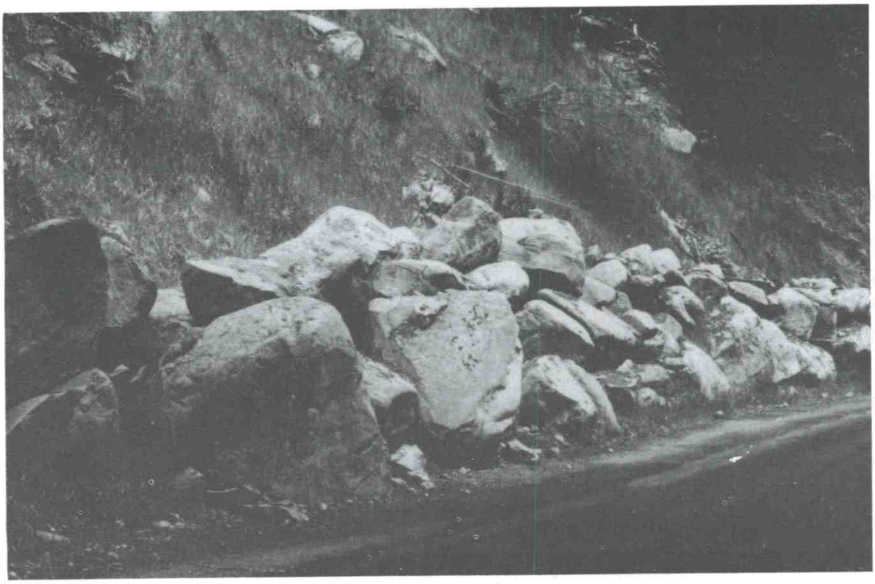

Figure 12. Rock buttresses can control localized slumping along road cuts.

grades. The idea that timber removal from steep unstable sites will increase their stability by decreasing the weight on the soil is faulty. Compared with soil strength losses associated with increased soil moisture directly related to timber removal, the increase in stability gained by removing the weight of trees is trivial. This argument is also invalid for the case of shallow failures such as debris avalanches.

Dry Ravel

Roadbuilding

Exposed soil and parent material on steep cut and fill slopes is subject to dry ravel in areas characterized by long summer droughts, freeze-thaw cycles, and cohesionless or coarse-textured soils. These conditions commonly occur in western Washington and Oregon, northeast Oregon and much of Idaho. Surficial material most susceptible to dry ravel includes sand and gravel-sized particles weathered rather rapidly from underlying parent material. This cohesionless material is easily detached on these steep, exposed slopes by natural weathering processes. Studies of fill slope erosion in the granitic soils of the Idaho Batholith indicate that dry ravel may comprise nearly half of the total fill slope erosion.

Slash burning

In the Douglas-fir region of the Pacific Northwest, logging debris often is consumed on-site by broadcast burning. Although this site preparation technique prepares a clean seedbed for regeneration, it can accelerate certain soil mass movements by removing protective vegetation from the soil surface. Dry ravel from steep hillslopes is increased following slash burning (Figure 7). Most of the ravel is produced immediately following burning, especially if the soil is dry. As the burned site revegetates, dry ravel decreases markedly. The amount of dry ravel produced is directly related to the intensity of the burn with hotter burns creating more erodible conditions. Non-cohesive soils, such as those derived from granitics, pumice, and certain bedded sediments, are most subject to dry ravel.

Control opportunities

Mulching and planting exposed cut and fill slopes with grasses and seedlings can reduce dry ravel significantly. Avoid long fill slopes such as "sliver fills," since the amount of dry ravel produced is proportional to the size of the exposed fill. Since most dry ravel will occur during summer months, clean the ditchlines adjacent to ravel-prone cut slopes before fall and winter rains.

Broadcast slash burning may have to be restricted or modified on ravel-prone sites. If fuel loads are not too high and soils are somewhat moist, the forest litter layer is protected from complete destruction during burning. Preservation of some of the litter layer is critical in controlling dry ravel. Unfortunately, the timing of conventional slash burning normally does not coincide with desirable soil moisture conditions, and management adjustments may be necessary. Consider alternatives to slash burning, such as herbicide application coupled with high utilization of felled timber. Machine piling of debris and mechanical scarification on sites susceptible to dry ravel are not recommended, since they disturb as much surface soil as broadcast burning.

Rockfall

Roadbuilding

Forest roads that require excavation into bedrock have exposed cutslopes subject to rockfall depending on geologic conditions. Geologic materials susceptible to rockfall include "soft" interbedded siltstones and sandstones, schists, and pyroclastics. Fracturing and jointing in igneous rocks, such as granitics, increases their susceptibility to rockfall. Failures are most likely to exist when bedding planes of the rock dip downslope toward the road. Blasting required for road right-of-ways may impart additional stresses in the bedrock. The activity of rockfall along a given road cut can be evaluated by the presence or absence of vegetation on the scarp and the damage done by falling rocks. In active areas, trees are debarked and conifers and other long-lived trees may be absent near road right-of-ways. Ditches are usually dotted with rock fragments produced from cuts undergoing active rock fall.

Control opportunities

In order to minimize the occurrence of rock fall along road cuts, careful road location and planning is required. Avoid making large cuts through unstable rock sequences. Examples include massive lava flows, such as basalt, overlying highly fractured igneous rocks and interbedded sandstone and soft clay or mudstone. Relocate roads to avoid these problem sites if at all possible. Problems associated with bedding planes of rock dipping downslope toward the road sometimes can be solved simply by relocating the road on the other side of the hill, provided that it meets the transportation objectives. Review geological maps before major excavations to determine rock type and orientation of bedding planes.

If roads must be cut through unstable bedrock several construction techniques can be employed to minimize the potential for rock fall. Benching slopes is particularly effective in controlling rock fall in areas with interbedded "hard" and "soft" rock sequences. Construct surface drains around the top of cut slopes to divert water directly into drainage ditches. This reduces freeze-thaw and chemical weathering processes in the exposed bedrock. Use controlled blasting techniques, such as pre-splitting, to minimize the breakage of bedrock and produce a neat, smooth backslope. Consult geotechnical specialists before attempting excavation practices.

Structural methods for controlling rock fall along forest roads can be used in small isolated areas of instability. Rock bolting can be used in blocky, fractured rock to prevent rock fall onto the roadway. Do not use rock bolts in poorly consolidated or highly weatherable materials, such as shales and certain sandstones. Retaining walls are seldom applicable to rock falls. Consult engineering specialists before considering this more expensive method of structural control.

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