A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest

Second Edition

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A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest

Second Edition

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FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes. many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining and improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests (Research Branch), and the B.C. Ministry of Environment (Fisheries Branch). Participating agencies include Forestry Canada (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests, Research Branch, 31 Bastion Square, Victoria, B.C. V8W 3E7.

PREFACE TO THE SECOND EDITION

A decision was made to reissue Land Management Handbook Number 18 - A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest, due to the considerable demand for copies. It is not the intent of this second edition to reflect substantial revision of the contents of Handbook Number 18; however, some minor changes reflect suggestions expressed by users. These have been incorporated into this edition. Changes have been made to Chapters 1, 2, 3 and 4, along with the addition of three new appendices following Chapter 2.

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INTRODUCTION

A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest has been prepared for agency and industry personnel who are operating in areas with existing or potential stability problems. The document is intended for use in the coastal areas of the Pacific Northwest, even though the principles may be applicable to other locations in North America. The guide addresses four topics:

- Slope movement processes and characteristics.
- An office/field technique for recognizing landslide-prone terrain.
- Measures to manage unstable terrain during forestry activities.
- Road deactivation and revegetation of unstable terrain.

The guide is designed to be carried in field staff vehicles. A "condensed" version of the book will be available in the form of field cards that can be more easily carried in field note books. They will provide some of the basic information contained in this larger document.

Physical Setting

The region referred to as the Pacific Northwest extends from southern Alaska to northern California, and includes the province of British Columbia, and the states of Washington and Oregon. It is an area of high relief and varied bedrock comprised of several mountain systems fronting the Pacific Ocean.

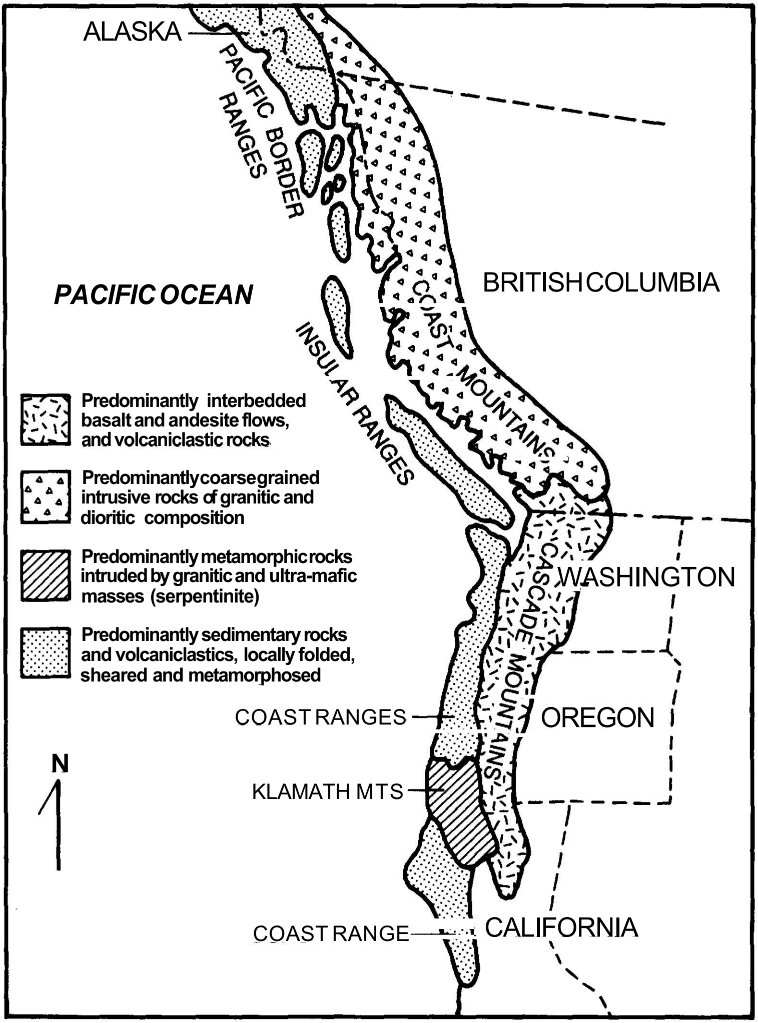
Region	Mountain system	Dominant bedrock
Alaska	Pacific Border Ranges	Sedimentary+volcaniclastic rocks
British Columbia	Insular Mountains	Sedimentary+volcaniclastic rocks
	Coast Mountains	Granitic and dioritic intrusives
Washington/Oregon	Coast Ranges	Sedimentary+volcaniclastic rocks
	Cascade Range	Volcanic flow and clastic rocks
	Klamath Mountains	Metamorphic with intrusions
Northern California	Klamath Mountains	Metamorphic with intrusions
	Cascade Range	Volcanic flow and clastic rocks
	Coast Ranges	Sedimentary+volcaniclastic rocks

The present-day landscape of the Pacific Northwest has been shaped by a variety of geological processes during the past 10 million years:

- uplift
- glaciation
- fluvial dissection
- mass wastage

It is therefore a region of diverse geology, topography and climate.

The high relief of the various mountain ranges is a product of recent geologic uplift that began about 10 million years ago. The Coast Mountains of British Columbia, for example, have risen 2-3 km in the last 10 million years. During the last 1 million years, the mountain ranges extending from northern Washington to Alaska have been extensively modified and sculptured by repeated glaciations during the Pleistocene (1 million to 10 000



Mountain ranges of the coastal Pacific Northwest - dominant bedrock types years ago). The topography of these regions is characterized by rugged, glacier-clad mountains, fiords carved by glaciers, and steep mountain slopes with rounded ridgetops overtopped by glacier ice. Valley profiles are typically U-shaped and have glacially oversteepened sideslopes.

During this glacial interval, the southern Washington, Oregon and northern California landscape was modified by fluvial erosion. This resulted in the incision of valleys and the creation of rugged, mountainous topography. These southern mountain ranges are typically deeply dissected, characterized by incised rivers, steep slopes and narrow sinuous ridgetops. Valley profiles are V-shaped.

The coastal Pacific Northwest is characterized by a temperate rainy climate with warm to cool summers (maritime west coast climate – Alaska and British Columbia) or warm to hot summers (Mediterranean climate – Washington, Oregon, and northern California). Average precipitation ranges from 100 to more than 500 cm per year; most of the rainfall occurs during winter storms between October and April.

Tectonic activity, intense precipitation (especially during the winter months), and steep slopes all combine to make the Pacific Northwest a landscape where denudation of slopes is dominated by **mass movement processes.** These processes and their impacts, in turn, have been altered by human activities such as forest harvesting and construction of resource roads. Minimizing the effects of mass movements in such landslide-prone terrain –or preventing them altogether–requires the consolidated effort of all resource managers.

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CHAPTER 1
SLOPE MOVEMENT PROCESSES AND CHARACTERISTICS

by

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1.1 SLOPE MOVEMENT TYPES AND PROCESSES

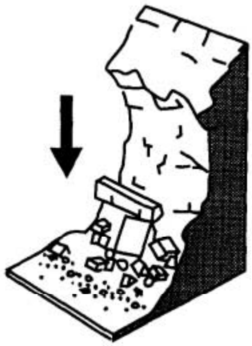
The mechanics and rates of slope movement are controlled by many factors: slope gradients, overburden depth, structural rock properties, water content and soil pore water pressure, and certain engineering properties of overburden and weathered rock, such as cohesion and coefficient of friction. Geomorphic, hydrologic, and vegetative factors determine the occurrence, frequency, and relative importance of such processes in an area.

1.1.1 Classification

Six dominant groups of landslide processes are encountered on steep forested terrain in the Pacific Northwest: falls, creep, slumps and earthflows, debris avalanches and debris flows, debris torrents and bedrock failures. These groups have been categorized according to depth of movement, rate of initial failure, failure mechanics, and water content of the moving material. As well, each category is distinguished by zone of initiation (slope source) rather than by transportation and deposition zones, and by composition of its material.

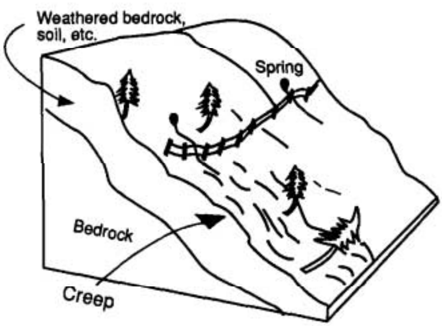
The terms "soil" and "overburden" refer to any surficial material overlying bedrock, and include alluvial/fluvial sands and gravels, marine and lacustrine silts and clays, colluvium and rock fragments, weathered bedrock, and glacial till. The term "debris" refers to any mixture of soil, rock and organic material incorporated into a landslide mass. "Debris flows" are rapid downslope movements of a mass of predominantly soil and organic debris mixed with water. Within the Pacific Northwest the rapid downslope movement of channelized floods of water with high concentrations of soil, rock and organic debris are called "debris torrents."

1.1.2 Description of Forest-Landslide Categories



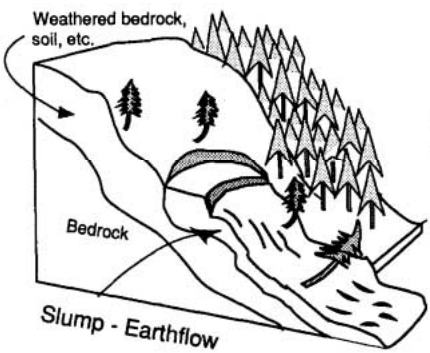
Falls

Movement takes place mainly through the air by free-fall, leaping, bounding, or rolling. Falls are very rapid to extremely rapid mass movements (from meters/minute to meters/second).



Creep

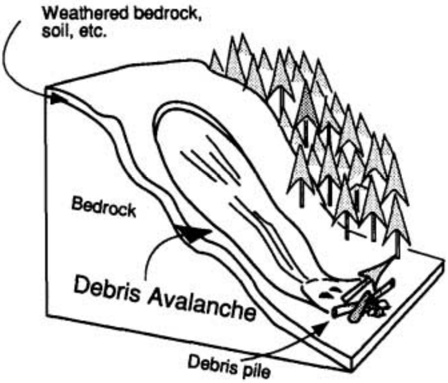
The slow downslope movement of overburden. Rates of movement are very slow (centimeters/year) to extremely slow (millimeters/year).



Slumps and Earthflows

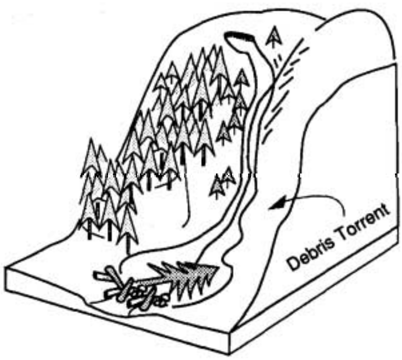
These often involve combined processes of earth movement (rotation of a block of overburden over a broadly concave slip surface, or slump), and result in the downslope transport of the resulting mass, either by a flow or a gliding displacement of a series of blocks (earthflow). Creep activity is a common precursor to slumps and earthflows. Rates of movement range from extremely slow (millimeters/year) to rapid (meters/second).

Debris Avalanches and Debris Flows



Debris avalanches are rapid, shallow landslides from steep hillslopes. Movement begins when overburden slides along bedrock or along other layers within the overburden having higher strength and lower permeability. If enough water is present, debris avalanches become debris flows. This results in the rapid downslope transport of a slurry of soil, rocks, and organic material (collectively called debris) directly to the valley floor and occasionally to stream channels. Debris avalanches typically begin on open slopes or within shallow hillslope depressions where groundwater is concentrated. Debris flows commonly follow existing drainageways or linear slope depressions created by past landslide activity, although not necessarily. Debris flows tend to increase in volume downstream. Rates of movement range from rapid (meters/minute) to extremely rapid (meters/second).

Debris Torrents



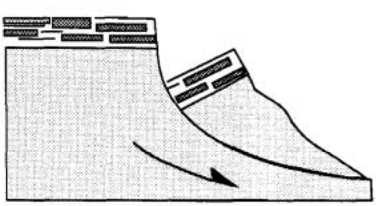
Where debris avalanches and debris flows enter steep gullies and canyons during high flow periods, debris torrents or debris floods occur. These torrents involve the rapid movement of large volumes of water-charged soil, rock, and debris. Rates of movement are very high (meters/second) and damage can be extensive.

Bedrock Failures

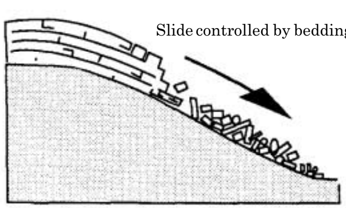
Bedrock slumps typically occur as a displacement of one or more blocks, which rotate backward along a curved basal shear surface which may cross several rock units. Movement rates are extremely slow (millimeters/year) to moderate (meters/day) and take place well beneath the surface of the earth.

Bedrock slides typically occur as movements along a planar or nearly straight basal shear surface which follows a structural discontinuity within or at the boundary of rock units. Movement rates of bedrock slides range from rapid (meters/minute) to extremely rapid (meters/second) and are usually initiated below the surface.

Bedrock Slumps



Bedrock Slides



1.2 THE GENERAL DYNAMICS OF LANDSLIDES

1.2.1 Mechanics of Movement

The infinite slope model is a common framework for discussing the mechanisms and complex relationships between the factors active in development of landslides on steep forested slopes. Although this model applies predominantly to shallow planar slides, it is useful in illustrating the mechanics of more complex failures. It describes the stability of a block of material in terms of the ratio between its shear strength, or resistance to sliding along a surface of failure, and the downslope gravity or shear force. This ratio defines the "Factor of Safety" of the block. As long as the shear strength exceeds the pull of gravity, the Factor of Safety is greater than 1 and the block of material will remain in place. By analogy, the block becomes a surrogate of the material and terrain conditions prevailing in an area. Landslides result from changes in the "Factor of Safety" of a block of overburden in the vicinity of failure.

The geometrical relationship of the forces acting on a small block are shown below.

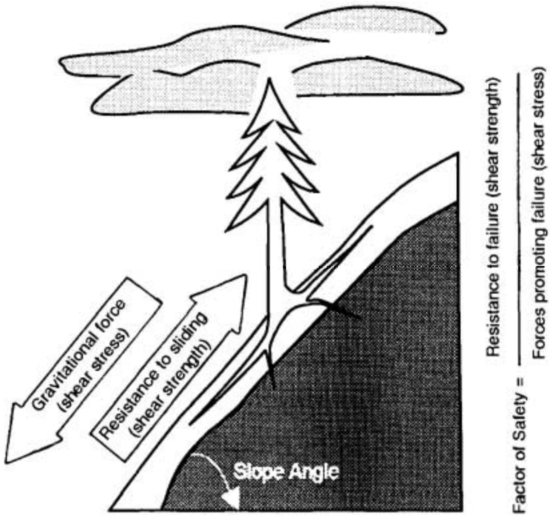


Diagram of force acting on a vegetated slope

Increases in shear force or the pull of gravity on a block result from increased sliding surface inclinations, such as those produced by undercutting slope, or from increased weight of the block of rock or overburden. Shear force can also be influenced by:

WIND FORCES transferred to the surface through the stems and root systems of trees
HORIZONTAL ACCELERATIONS produced by earthquakes and blasting

Three principal forces are active in maintaining shear strength. These are:

COHESION or the capacity of particles to stick or adhere together
FRICTIONAL RESISTANCE between individual particles and between the overburden mass and the sliding surface
RESISTING FORCE generated by the anchoring and reinforcing effect of tree roots, provided the failure surface is within the rooting depth of vegetation

Shear strength can be significantly reduced by:

- **presence of zones of weakness** in overburden or underlying bedrock produced by bedding surfaces, fractures and joints, and local layers of silt and clay;
- **removal of downslope support** of the mass, as a result of undercutting, commonly by stream cutting or roads;
- **development of a temporary water table** above a potential failure surface; and
- **progressive creep** producing a strain-dependent drop in strength.

1.2.2 Factors Affecting Slope Stability

Undisturbed, steep mountain slopes have adjusted to the various forces acting on them and have developed a delicate "static equilibrium" between gravitational forces tending to pull the overburden materials downslope and the various resisting forces comprising shear strength. Slopes in such a state are highly sensitive to modifying factors which change the developed strength/stress relationships over geologic time. The table below lists these modifying factors for both shear strength and gravitational force in terms of their influence on the Factor of Safety at a site. Road construction and logging activities strongly influence these factors by undercutting of hillslopes, increasing surface weight, altering surface and subsurface drainage, and reducing short-term anchoring and reinforcing effects of tree roots.

Texture and mineralogy (both of which govern cohesion), angle of internal friction, water content of overburden, pore water pressure, and gradient of the potential sliding surface are controlling factors in determining the stability of a steep forested slope. These controlling factors are interactive, and the importance or effectiveness of each in controlling the type and degree of instability is dependent on local geologic, vegetative, and hydrologic conditions.

Factors modifying slope stability

Increasing Gravitational Force (Shear Stress)		**Reducing Shear Strength**	
Inherent (internal)	**External** (variable)	**Inherent** (internal)	**External** (variable)
1. composition (increased weight)	**1.** undercutting (increases local gradient, removes lateral support)	**1.** composition (reduce cohesion, reduce internal friction angle)	**1.** weathering (disintegration, clay alteration, permeability)
2. structure (downslope dip of fractures and beds)	**2.** surcharging (increased surface load)	**2.** structure (downslope dip of beds and joints)	**2.** intergranular forces (pore water pressure)
3. slope geometry (increased gradient)	**3.** shocks and tilting (earthquakes, blasting)	**3.** slope geometry (increase gradient, concave slopes, slope depressions)	**3.** vegetation removal (loss of anchor and reinforcing effects of roots)
	4. lateral pressure (frost wedging, heaving)	**4.** creep deformation (reduces cohesion)	
	5. wind stress (prying, loosening, lateral pressure from swaying trees)		

Influence of Geologic Conditions

1) Overburden Materials

Non-cohesive (coarse-textured materials low In clay-sized particles)

- **Colluvium**
- **Sands**
- **Gravels**
- **Weathered surface of most tills**
- **Residual soils**

Debris avalanches and debris flows dominate in non-cohesive materials. Slope angle is a major indicator of the stability of these sites. Slopes at or above the angle of internal friction of the overburden material indicate a highly unstable natural state even in the absence of excess water. The development of a temporary perched water table or the disturbances produced by timber harvest and road construction greatly increase the probability of failure of such slopes.

Cohesive (fine-textured materials)

- **Lake silt/clay**
- **Marine silt/clay**
- **Some residual soils and tills**

Stability in cohesive materials is controlled largely by clay mineralogy and moisture content of overburden. When they are dry, clayey materials have high shear strength with high cohesion and angle of internal friction (>30 degrees or >58%). Increased water content mobilizes the clay as it is absorbed into the clay structure. Thus, clay-rich materials have a high potential for accelerated deformation and ultimate failure in the presence of excess water. Under these conditions, failures do not depend directly on sliding surface gradient as in shallow, cohesionless materials, but may develop in slopes with gradients as low as 2-3 degrees (about 5%), with creep, slump and earthflows being the dominant processes.

2) Bedrock

- **Silt/claystones**
- **Mudstones**
- **Soft shales**
- **Graywacke**
- **Sandstone**
- **Welded ash-tuff**
- **Serpentine-rich rocks**

Under moist upper mid-latitude climatic conditions, many materials are susceptible to rapid weathering: medium- to fine-grained sedimentary rocks (siltstones, mudstones, claystones, poorly indurated shales, sandstone, graywacke); welded ash and tuff; and serpentine-rich rocks. Such materials develop a high degree of cohesion and mobility. They are prone to slope movements of the creep, slump and earthflow types.

- **Granite/diorite**
- **Hard sedimentary**
- **Metamorphic rocks**

On slopes underlain by more resistant coarse-grained intrusives (granites and diorites), hard and dense sedimentary and metamorphic rocks (massive shale, graywacke, sandstone and conglomerate, greenstone and limestone/marble), shallow overburden derived from these rock types are usually coarse grained and low in clay-sized particles. Such materials have low cohesion and are most likely to develop slope movements of the debris avalanche and debris flow types.

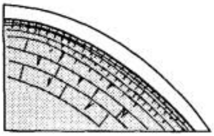
- **Andesite and basalt**

Fine-grained andesite and basalt flow rock also develop thin, coarse-textured overburden on steep surfaces, with resultant debris avalanche and debris flow failures. On flat-lying surfaces underlain by such rocks, deep weathering is common due to retained water, and slumps and earthflows are the dominant types of slope movements. On near-vertical outcrops of this rock, rockfalls are most common.

3) Structure and Stratigraphy

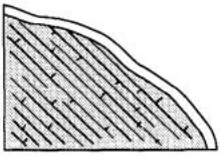
(internal character of the rock)

- **Highly jointed or fractured bedrock slopes**

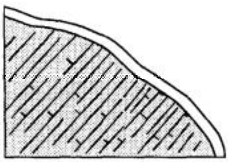


Highly jointed or fractured bedrock slopes with principal joints and fracture surfaces parallel to or dipping with the slope provide little mechanical support to overlying materials and create avenues for concentrated subsurface water movement. Jointing also provides avenues for deep penetration of surface and ground water. This results in the development of springs at remote sites on the slope, and of excess hydrostatic pressures locally because of confining rock and overburden layers. At near-surface locations, joint and fracture planes are ready-made zones of weakness that provide potential failure surfaces along which overlying materials can slide.

- **Dipping bedding surfaces**



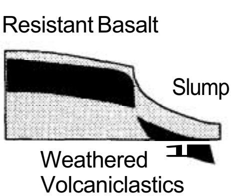
Parallel (less stable)



Perpendicular (more stable)

Downslope dipping surfaces between units with different composition, permeability, or degree of alteration serve as boundaries to subsurface water movement, as layers restricting penetration and development of root systems, and as potential surfaces of failure. Conversely, horizontal bedding surfaces and those dipping into the slope frequently produce natural buttresses that may actually increase stability of slopes locally. Care must be taken in assessing the stabilizing influence of horizontal and in-dipping bedding surfaces, however, because jointing, which is always present to some degree, frequently cross-cuts the bedding planes. When this happens, it becomes the major determinant of a slope's ultimate stability.

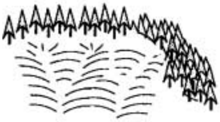
- **Alternating bedrock units (Stratigraphy)**



Flat-lying, resistant rock units capping incompetent rock, commonly play an important role in shaping complex slump and earthflow features. Steep headwall scarps of slumps and earthflows usually occur at these contacts. Water is frequently trapped and transported laterally along bedding surfaces and joints or within more permeable rock units and fed directly into more incompetent materials, where failures occur.

4)Topography

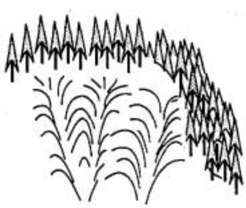
- **Shallow, linear depressions or "swales"**



Shallow, linear depressions or "swales" on hillslopes are common points of origin for debris avalanches and debris flows. Such linear depressions are created by the weathering of bedrock along zones of weakness. Subsequent and recurring slope processes result in periodic stripping and in-filling of these swales. Converging flows of groundwater into these depressions during periods of storm precipitation or rapid snowmelt cause the buildup of temporary perched water tables. Later generation of pore-water pressures in the in-fillings of the depressions reduces the strength of the material and greatly increases the instability of the site.

In local areas, subsurface water accumulation in these depressions may be substantially augmented by seepage from downslope-dipping bedrock units and joint systems. Midslope springs are indicative of this type of augmented flow and may be important indicators of potential failure sites. Jointing also conducts surface water considerable distances downslope under confined conditions, resulting in the local buildup of excess hydraulic head and the explosive failure of overburden.

- **Deep gullies and canyons**



Deep gullies and canyons (V-notch drainages) dissecting the slope frequently serve as collectors of debris avalanche and debris flow material from adjacent hillslopes. They also tend to have very steep, unstable side slopes with frequent rockslides and small debris avalanches that dump additional soil, rock and organic debris directly into these confined channels. If the quantities of debris are large enough, or if flows are too small to mobilize debris initially, temporary dams may develop. During major storms, these dams may fail, producing large volume, high velocity debris torrents. Torrents may also be produced during high-flow periods by the mobilization of stored channel materials. In general, debris torrent activity increases with increasing gully density.

Influence of Vegetation

Tree cover influences the amount and intensity of rainfall reaching the surface, the amount of water stored in the overburden, and the strength developed along a potential failure surface.

- **Interception**

  The direct effect of interception on the water budget in the overburden material is probably not large, especially in areas of high total rainfall or during large storms, when most slope movements occur. Small storms, where interception is effective, probably have little influence on total subsurface water available for activating slope movements.

- **Evapotranspiration**

  In areas of low rainfall (<750 mm), the effect of evapotranspiration is much more pronounced, but it is particularly dependent on region and rainfall. For example, in areas characterized by warm, dry summers, evapotranspiration significantly reduces the degree of saturation resulting from the first storms of the fall recharge period. This effect diminishes as subsurface water deficit is satisfied. Once the overburden material is recharged, the effects of previous evapotranspirational losses become negligible. Conversely, in areas of continuous high rainfall or those with arid or semi-arid climates, evapotranspirational withdrawals are probably negligible during the time period when most landslides occur.

- **Depth of evapotranspirational withdrawals**

  Depth of evapotranspirational withdrawals is important, also. Deep materials may require substantial recharge of the groundwater deficit, delaying or reducing the possibility of saturated conditions necessary for major landslide-producing events. Shallow materials, however, recharge rapidly, possibly becoming saturated and reaching an unstable state during the first major storm.

- **Root systems**

Root systems of trees and other vegetation may increase the shear strength of unstable overburden by anchoring through the mass into fractures in bedrock, providing continuous long-fiber binders within the overburden (a fiber reinforcing effect) and tying the slope together across zones of weakness or instability. In shallow materials, all three effects may be important. In deep materials, the anchoring effect of roots becomes negligible, but pore water pressures and soil strength parameters remain important. In some extremely steep areas, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area.

Influence of Hydrologic Conditions

- **Recharge of subsurface water**

Recharge of subsurface water is the result of water entering the overburden materials. It is influenced by vegetation cover, management practices, and shape of terrain, as well as by soil physical processes affecting water movement.

- **Discharge rate of water**

The discharge rate of water from unstable overburden is probably the most significant hydrologic factor affecting slope movement. If subsurface flow rate is less than infiltrating rates (from rainfall and/or snowmelt) for extended periods of time, a perched groundwater table will form within the overburden. The height and persistence of the perched water table above an impermeable layer depends largely on rainfall or snowmelt intensity, duration, and antecedent conditions, infiltration rate at the site, slope gradient, subsurface configuration of the bedrock, and flow rate within the overburden. Because the infiltration rate often does not limit recharge of unstable slopes (infiltration rate is more than able to absorb incident rainfall), the subsurface flow rate becomes the controlling hydrologic variable during most rainfall and snowmelt periods.

1.2.3 Factors Affecting Downslope Transport

Once failure occurs, movement of materials downslope is determined largely by the morphology of the hillslope and associated flow path.

- **Open slope (debris avalanches and debris flows)**

On the **open slope (outside of a confining drainage),** large failure volumes, steep hillslope gradients, and unobstructed flow paths generally encourage greater transport distances and greater impact in the deposition zone. Sharp reductions in gradient caused by intervening bedrock benches, valley floor interception, or the buttressing effect of trees standing within the flow path can cause rapid deposition and significantly limit landslide runout.

- **Channelized (debris torrents)**

The channelization of landslide materials, such as in a gully, provides an established, less obstructed flow path and may significantly increase velocity of movement, distances traveled, and volumes of debris delivered to the valley floor and associated channel systems. Once landslide debris becomes channelized, fluidity increases due to converging groundwater and surface water flows. The volume of materials transported also increases as a result of increased channel erosion and mobilization of debris temporarily stored on and adjacent to the channel banks. Much of this stored debris is the direct result of local slumping of channel banks and deposition from earlier landslide activity.

The gradient of the channel controls the rate at which landslide debris is transported and the dominance of erosion or deposition processes during a particular flow event. Scouring and mobilization of debris in and adjacent to the channel generally occur at gradients above 10 degrees (about 18%). Major velocity reductions and significant deposition of materials occur when channel gradients drop below 7 or 8 degrees (12 to 16%).

Preliminary research on landslide transport distances suggests that behavior of **channelized landslides** is determined by a combination of geomorphic and hydrologic factors, including junction angle, channel gradient, and magnitude of stream discharge. Channelized landslides that reach tributaries at a low angle of incidence (70-90 degrees) tend to deposit debris at the tributary junction. At this point, channel gradients are decreasing, channel widths are increasing, and an abrupt change in flow direction occurs. How long this deposit remains in place is a function of the drainage area above the deposit and the volume of flow in the tributary at the time of deposition. It is possible that during major storm flows, the deposit may be almost immediately remobilized. Channelized landslides that enter tributaries at a high angle of incidence tend to travel farther initially and may pass through several tributary systems before final deposition occurs. In small first- and second-order channels with gradients greater than 10 degrees (about 18%), scouring and lateral erosion dominate, resulting in a major portion of the mobilized material originating in this portion of the flow path. Below that gradient, erosion rates are reduced. Significant deposition begins below 8 degrees (14%). As debris flows into larger, higher-order channels, deposition and erosion are reduced as magnitude of the streamflow increases.

Further Reading for Chapter 1

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CHAPTER 2
A TECHNIQUE FOR STABILITY HAZARD ASSESSMENT

by

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2.1 GENERAL PROCEDURE FOR RECOGNIZING UNSTABLE TERRAIN AND IDENTIFYING AREAS AFFECTED BY LANDSLIDES

Steps for identifying both potential and existing landslide areas are outlined on page 24. After following these steps, the user should be able to recognize that a landslide problem may exist within a specific development area. Having recognized the problem, the user should seek the expertise of a specialist for further analysis of the problem, assessment of risk, and recommendations for control and correction.

The procedure for recognizing unstable terrain involves:

Part A: an office evaluation of existing information
Part B: a field evaluation
Part C: a simple method of assessing stability hazard

2.2 PART A: OFFICE EVALUATION OF EXISTING DATA

Information used in a landslide evaluation may come from single or multiple sources including maps, reports, and aerial photographs. The table below identifies the kinds of information one can expect to obtain from these various sources. A data card for this exercise is presented on pages 22 and 23.

TOPOGRAPHIC MAP indicates slope gradient, terrain configuration, drainage pattern.

TERRAIN MAP identifies material, depth, geological processes, terrain configuration, surface and subsurface drainage, slope gradient (also called surficial geology or Quaternary geology maps).

BEDROCK MAP/REPORT identifies bedrock type, surface and subsurface structure, surficial cover (overburden), age.

SOIL MAP identifies surficial material (overburden) type, drainage, limited engineering characteristics, soils characteristics, vegetation cover.

FOREST COVER MAP identifies surface vegetation, topographic features, surface drainage pattern, soil drainage character.

AIR PHOTO REVIEW identifies vegetation cover, topography, drainage pattern, soil drainage character, bedrock geology, surficial geology, landslide type and relationship to other factors.

RESEARCH STUDIES may provide information on all of the above, plus quantitative data on controlling factors and possibly local stability risk assessment.

Site Name:____________________ Date:____________

Map Sheet Number: ____________ Map Scale 1: ________

Reviewed By: ____________________

Slope Stability Map Data ❑ No Data Available

Rating on Slope Stability Map ____________________

Recommended Land Use ____________________

Landslide Data Derived from Resource Maps/Air Photos

1. **Identify if Landslides Present** (check box)
   - ❑ Landslide(s) occur in area/ similar terrain nearby
   - ❑ Landslide(s) impacted a stream
2. **Identify source of data** (check box)
   - Forest Inventory Map ❑ — ❑ Air Photos
   - Terrain Map ❑ — Air Photo Year ________
   - Soil Map ❑ — Air Photo Number ________
   - Landslide Inventory Map ❑
   - Bedrock Geology Map ❑
3. **identify Type of Landslide** (check box) Fall ❑ Creep ❑ Slump ❑
   Earthflow ❑ Debris Avalanche/Flow ❑ Debris Torrent ❑
4. **Describe Character of Landslide initlation Site**
   Slope Angle: _____ (°) _____ (%) Location: Gully ❑ Open Slope ❑

Material Type: Till ❑ Colluvium ❑ Fluvial ❑ Fluvial/glaciofluvial ❑

Weathered rock (residual soil) ❑ Marine/Lacustrine ❑ Bedrock ❑

Other: ____________________

Drainage: Rapid/Well ❑ Moderately Well-Imperfect ❑ Poor ❑

Land use: Natural ❑ Clearcut ❑ Road ❑

Physical Character of Study Area

1. **Identify Source of Data** (check box)
   - Forest Inventory Map ❑ — ❑ Air Photos
   - Terrain Map ❑ — Air Photo Year ________
   - Soil Map ❑ — Air Photo Number ________
   - Landslide Inventory Map ❑
   - Bedrock Geology Map ❑ — Topography Map ❑
2. **Slope Angle** _____(°)_____ (%)
   Shape: Concave ❑ Convex ❑ Straight ❑
3. **Overburden**
   Type: Till ❑ Colluvium ❑ Fluvial/Glaciofluvial ❑
   Weathered Rock (Residual Soil) ❑ Marine/Lacustrine ❑
   Other ____________________
   Depth: Shallow (<3 m) ❑ Deep(>3 m) ❑
   Texture: Coarse-Grained ❑ Fine-Grained ❑
   Drainage: Rapid/Well ❑ Moderately Well-Imperfect ❑ Poor ❑
   Dissected by Gullies ❑ (check if yes)
4. **Bedrock** Exposed ❑ Subsurface ❑
   Type: Intrusive ❑ Volcanic ❑ Sedimentary ❑ Metamorphic ❑
   Specific Type: ____________________
   Structure: Bedded ❑ Dip Parallel to Slope ❑ Joints, Fractures ❑
   Dip Perpendicular to Slope ❑ Massive (few beds) ❑
   Stratigraphy: Massive, hard beds overlying softer rock ❑
   Steep outcrops present ❑

Summary ____________________

____

____________________ Field Check Required ❑ (Yes)

Office data card (information derived from existing sources)

Site Information

Site Name: Identify the site by geographic name, drainage basin, cut block number, etc.
Map Sheet Number: Indicate topographic number and name
Map Sheet Scale: Enter map scale

Slope Stability Map Data

If no slope stability map is available – check box [✔]
Slope stability rating: Enter rating of the area from the map
Recommended land use: Many slope stability maps are accompanied by legends that detail different land use practices in landslide prone terrain; note any of these recommendations made for the area of concern.

Landslide Data from Resource Maps/Air Photos

1. **Indicate** if landslides have occurred in area/near the area after review of all resource maps and air photos - check box [✔]; also indicate if these landslides have entered a creek - check box [✔]
2. **Source of Data:** check box(es) [✔] to indicate source of information used to determine landslide activity.
3. **Check box(es)** [✔] to indicate type of landslides in area; use definitions provided In Section 1.1.2 (p. 3-5).
4. **Describe the Character** of Landslide Initiation Site (where the landslide started):
   Slope Angle: enter slope angle in degrees or percent
   Location: check box [✔]; use definitions provided in Section 1.2.2 (p. 12 and 15)
   Material Type: check box [✔]; use definitions provided in Section 2.3 (p. 50-51)
   Drainage: check box [✔]; use definitions provided in Section 2.3 (p. 68)
   Land Use: check box [✔]; natural refers to forested

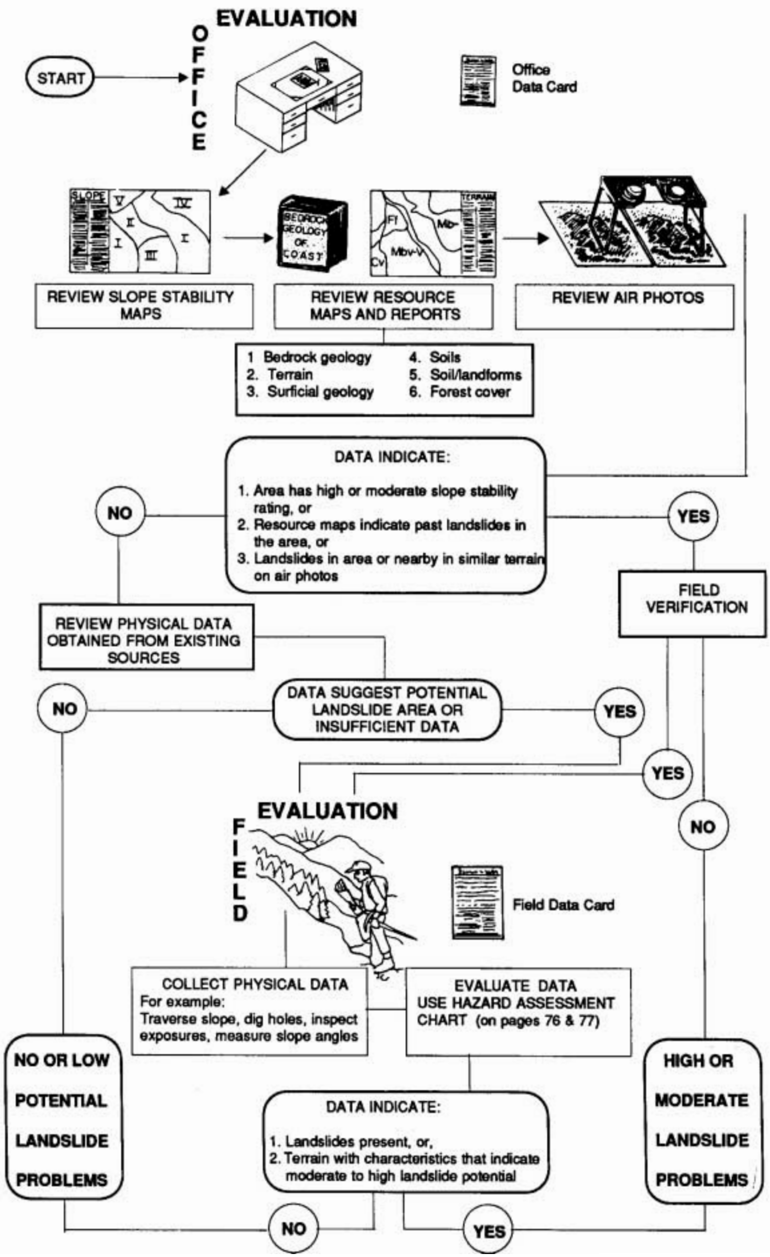
Physical Character of the Study Area

1. **Source of Data:** Check box(es) [✔] to indicate source of information used to determine character of area
2. **Slope angle:** enter slope angle in degrees or percent
3. Overburden:
   Material Type: check box [✔]; use definitions provided in Section 2.3 (p. 50-51)
   Depth: check box [✔]
   Texture: check box [✔]; use definitions provided in Section 2.4.2 (p. 75)
   Drainage: check box [✔]; use definitions provided in Section 2.3 (p. 68)
4. **Bedrock:**
   Type: for specific types use rock classification chart in Section 2.3 (p. 63)
   Structure: check box(es) [✔]; use definitions provided in Section 2.3 (p. 64)
   Stratigraphy: check box(es) [✔]; use definitions provided in Section 2.3 (p. 65)
   Steep Outcrops: check box [✔] if these are present

Summary

Summarize the information available; indicate if a field check is required.

Explanation notes of office data card



Flow diagram of procedures for recognizing unstable terrain

2.2.1 Maps and Reports

There are several types of geological, geotechnical, and biophysical maps and reports from which data can be extracted for a landslide evaluation. These include topographical maps, terrain (surficial geology) and soil maps and reports, slope stability maps, landslide inventory maps, forest cover maps, and bedrock maps and reports. The maps vary from large to small scale (e.g., 1:10 000 to 1:100 000) and the reports, which may accompany these maps, can be regional or site specific.

In British Columbia, information from terrain classification (Appendix 2) and mapping is used as a basis for deriving slope stability classes (Appendix 3) with regards to forest activity. These classes are portrayed on stability maps (e.g., page 96).

The types of information available from maps and reports listed in the table below and on page 27 note the various agencies or locations where the maps and reports may be obtained.

Information Available from Maps and Reports

Information type		Topo	Terrain	Soil/ landform	Soils	Slide inventory	Bedrock	Forest cover
SLOPE	: angle	•	•	•	•	•		
	: configuration	•	•	•	•	•		
MATERIAL	: type		•••	•	•••			
	: texture		•••	•	•••			
	: landform		•••	•	•••			
	: drainage		•••	•	•••			
LANDSLIDE	: areas		•				••[1]	
	: specific sites		•			•		•
	: character		••			•		
BEDROCK	: type		••		••		•••	
	: character		••		••		•••	
GEOLOGIC HISTORY			••				••	

• Data may be obtained from a map.
•• Data may be obtained from a report (if available).
••• Data may be obtained from a map and a report (if available).
1 These reports only discuss large rock failures.

2.2.2 Limitation of Map and Report Data

QUALITY AND SCALE of photographs and experience of the mapper strongly influence the reliability of data. An experienced mapper and good quality photographs result in a more accurate map.

A FIELD CHECK is a prerequisite for final judgment, no matter how detailed a photo interpretation may be. Areas mapped strictly from air photographs are generally less reliable than those that have been field checked.

INFORMATION that can be obtained from these sources is presented at a regional scale (e.g., 1:100 000) and should not be used inappropriately in a detailed landslide evaluation study (e.g., at a scale of 1:20 000). For example, a 1:50 000 terrain map may indicate that a certain type of material occurs on a particular slope (e.g., till). At this scale of data presentation, however, local variations in material type may occur on this slope (e.g., 15% of the slope may be made up of lacustrine silt).

FINITE BOUNDARIES in mapping terrain, soils, and bedrock conditions must be drawn for some conditions that do not have finite boundaries. Thus, there is a certain degree of error built into these maps, even the most detailed. For example, groundwater levels can transgress different types of material.

Sources of Maps/Reports

Source of data	Topo	Terrain	Soil/ landform	Soils	Slide inventory	Bedrock	Forest cover
Maps B.C. (Ministry of Environment)	•	•	•	•	•		
U.S. Geol. Survey	•	•			•	•	
Geol. Survey of Canada		•				•	
B.C. Min. of Energy, Mines & Pet. Res.					•		
B.C. Min. of Forests	•	•		•	•		•
U.S. Forest Service		•		•	•		•
U.S. Bureau of L. Mgmt.				•		•	
Forest Companies	•	•		•	•		
Agriculture Canada				•			
U.S. Soil Cons. Serv.				•			

• Map/report available

2.2.3 Air Photograph Analysis

Careful study of a given area of terrain with the aid of oblique photographs and vertical stereo pairs can yield significant information on landslide type and frequency, and the effects of management practices. A review of recent and past air photographs of the area should be undertaken whenever possible, as older slides may not be evident on more recent photographs. The table on page 28 outlines the various agencies or locations where aerial photographs and other remote imagery can be obtained.

Features discernible on air photographs can help users identify landslide type and develop a reasonable assessment of overburden characteristics. These, in turn, provide a means for estimating the landslide hazard at a site.

Sources of Remote Imagery

Source of data	Imagery: Aerial Photos	EOSAT (LANDSAT)	SLR
Canada, Department of Energy Mines and Resources		•	•
Maps B.C., Ministry of Environment	•		
B.C. Ministry of Forests	•		
U.S. Forest Service	•		
U.S. Geological Survey			
EROS Data Center, Sioux Falls, SD			•
Earth Observation Satellite Co. Landau, MD		•	
Washington State, Department of Natural Resources (Photo Sales Division)	•	•	•
Oregon State, Department Natural Resources	•	•	•

Air photographs can also be a valuable aid in identifying "potential" landslide terrain. A skilled air photograph interpreter can identify numerous ground conditions (type of material, drainage, and so forth) indicative of potential or developing hazards by observing various elements on the photograph.

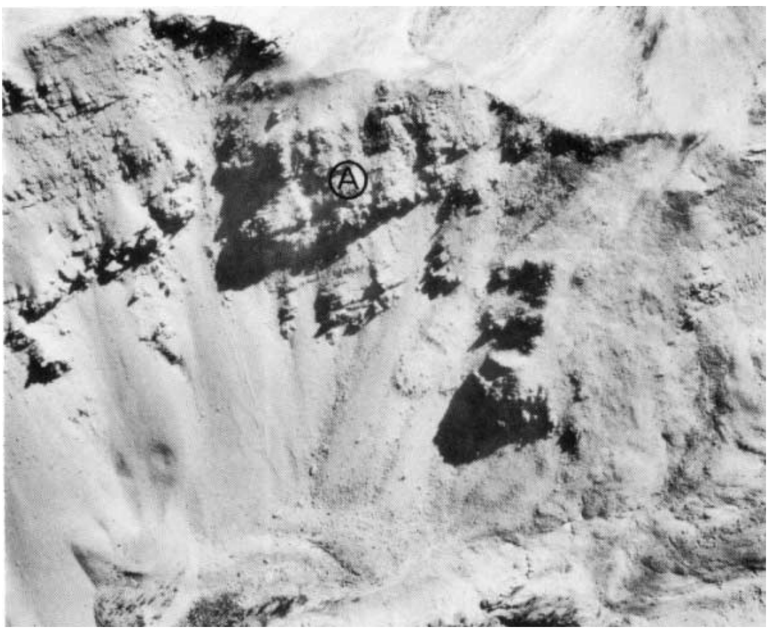
A number of features discernible on air photos also aid in the identification and interpretation of landslide processes. Some of these are: scarps, irregular or hummocky topography below scarps, bare linear tracks oriented downslope, fresh rock exposures, and fresh rock accumulations at the slope base. Air photograph examples and a list of basic features useful for identifying landslide types and terrain that may be potentially unstable are outlined on the following pages.

Features of rockfalls or sediment falls

AREAS of steep rock outcrop with large blocks or boulders, or of talus deposits (fans or cones) resting at the foot of the slope.

RECENT rockfall at the above sites may be indicated by fresh rock accumulations at the base of the slope or exposed rock on the rock face (both would have a light tone on the photo).

ESCARPMENTS of unconsolidated sediments with large coherent blocks of sediment at the base of the escarpment.



Rock cliffs (A) subject to rockfall processes. Note fresh accumulation of large rock blocks at the base of the slope (talus deposit).

Features of bedrock landslides

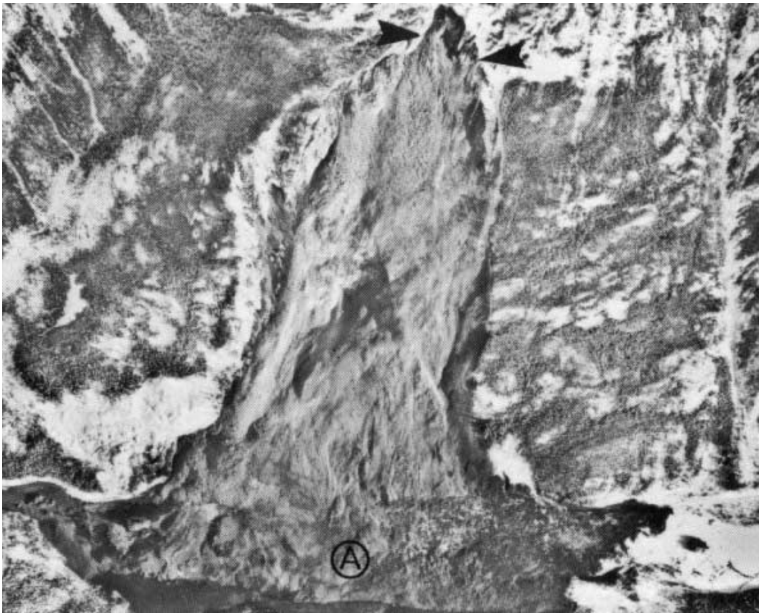
HEADWALL and sidewall scarps that are straight or concave.

TOPOGRAPHY below scarp may consist of large blocks of bedrock, or irregular mounds made up of large bedrock fragments.

SURFACES may display tension fractures, benches and ponded water.

STREAMS at base of landslide may be displaced laterally towards opposite valley sidewall.

OLDER bedrock landslides may display some of the above features, but they are not as sharply defined.



Hope landslide, B.C. Note well-defined headwall scarp (arrows) and irregular topography on the valley floor (A).

Terrain susceptible to bedrock instability

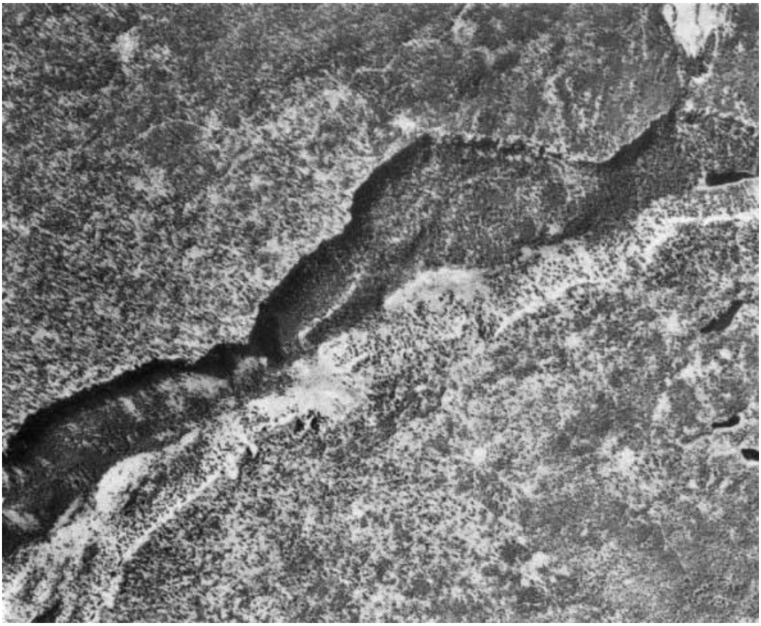
Steep bedrock slopes (cliffs or escarpments) that exhibit the following features are common sites of rockfall or deep-seated bedrock landslides. Wet sites are particularly prone to failure.

ALTERNATING parallel dark and light bands on hillslopes and straight, nearly parallel ridges or escarpments usually indicate the presence of tilted, interbedded sedimentary and volcanic rocks.

NARROW, linear, intersecting features (joints) highlighted by darker photo tones than surrounding areas.

DARK-TONED, narrow linear or curvilinear lines (faults, scarps) interrupted by standing water (ponds, lakes); or curvilinear lines creating a banded pattern on the photograph (folds or benches).

NARROW linear features on cliffs or steep hillslopes with a distinct tonal difference from the surrounding area (tension fractures).



Escarpment consisting of volcanic flow rocks

Features of slumps and earthflows in overburden

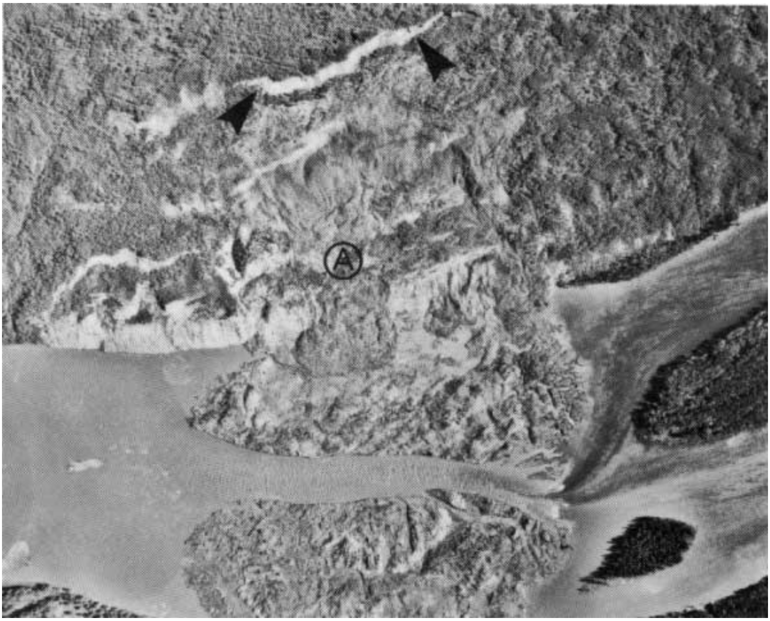
HEADWALL and sidewall scarps that are straight or concave. Scarps may be rectangular or horseshoe-shaped.

TOPOGRAPHY below scarp may consist of a large intact block or series of blocks with scarps, or chaotic irregular-shaped mounds and hummocks, or mixes of both.

SURFACES of slumps and earthflows may display tension fractures, benches and small scarps, and ponded water (sag ponds).

STREAMS along the base of these landslides may be diverted laterally towards the opposite site of the valley.

OLDER landslides may display some of the above features but they are not as sharply defined.



Slump in glaciolacustrine materials, Fraser River, B.C. Note headwall scarp (arrows) and bench-like topography downslope Ⓐ.

Terrain susceptible to slumps and earthflows

Slumps and earthflows commonly occur in exposed lake and ocean bottom sediments (silt, clay); in wind-blown deposits of silt and fine sand (loess), and fine-textured till; and in residual overburden derived from fine-grained sedimentary or volcanic rocks. Features that aid in the identification of these materials are outlined below.

Slumps and earthflows typically occur at escarpments undercut by streams and ocean waves, and in moderate to steep slopes. Wet or poorly drained locations on these slopes are particularly sensitive to these processes. Shallow drainage channels appear as narrow, linear features above steep pitches, whereas seepage sites tend to be irregularly shaped patches. The photo tones of both features contrast sharply with the surrounding area.

- **FINE-TEXTURED LAKE, OCEAN BOTTOM, AND WIND-BLOWN SEDIMENTS**

FLAT or undulating surface topography.

GENERAL absence of surface drainage and local ponded water with associated organic deposits (bogs).

SMALL STREAMS or gullies with steep sideslopes and flat bottoms (U-shaped profiles).

DISSECTED AREAS, with connected gullies forming intricate feather-like (pinnate) drainage patterns.

UNIFORM, drab, dark gray photo tones over broad areas.

- **FINE-TEXTURED RESIDUAL OVERBURDEN**

REGIONAL TOPOGRAPHY of low, softly rounded hills and rounded ridge tops.

TREE-LIKE DENDRITIC drainage patterns with local springs and ponds.

HILLSLOPES with lobate bulges, terracettes, swales and short, shallow, intermittent gullies.

VEGETATION cover of trees interspaced by open prairies indicating local surface disruption.

Raised marine silts, northern Vancouver Island, B.C. Note flat topography (A), absence of surface drainage and escarpment along shoreline (potential site for failure).

Features of debris avalanches, debris flows and debris torrents

BARE, narrow, linear tracks in forested terrain oriented downslope; denuded gullies and canyons.

DEPOSITION of material at slope toe, or some distance downslope in fan-shaped or hummocky forms.

OLDER TRACKS indicated by vegetation differences (species type or age – see page 71).

SNOW AVALANCHES and debris flow tracks may be separated by their point of origin (alpine zone vs below treeline).

ORIGINATE in gullies and canyons displaying steep, unstable side slopes and steep channel gradients or steep open slopes.

Oblique photo of debris avalanches, Vancouver Island, B.C. Note bare linear tracks in contrast to an older revegetated track (arrow).

Terrain susceptible to debris avalanches, debris flows, or debris torrents

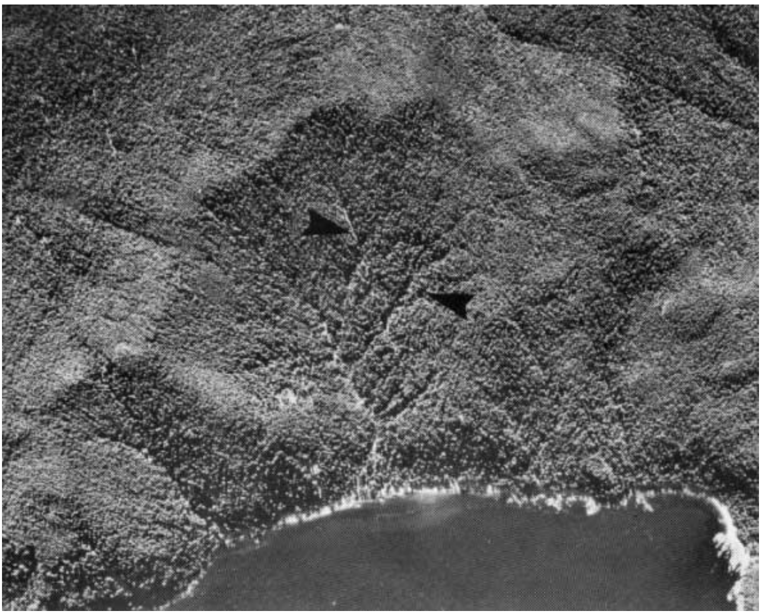
Debris avalanches and flows develop on steep slopes and in coarse-grained, low cohesion overburden. Debris torrents (debris floods) result from rapid discharge of debris-laden water from confining gullies during high-flow periods. Failures that indicate terrain susceptible to these processes are:

STEEP, smooth, slopes (>26°); lighter tone, irregular or narrow linear patches indicate wet sites and are prone to failure.

SHALLOW OVERBURDEN indicated by frequent bedrock outcrops and minor surface irregularities.

SLOPES DISSECTED by gullies or canyons; usually indicated by linear features whose tone contrasts with the nearby area.

DEBRIS FANS and cones at foot of the slope.



Forested, steep, gullied (arrows) slopes overlain by shallow overburden

2.2.4 Sources of Support Research

Published reports from various public and private research organizations charged with developing knowledge of landslide processes and the influence of management practices on them are excellent sources of technical information. The output of public agencies is generally available through government publications or as reprints from professional journals obtained from the particular agency involved. The output from universities, government departments and private organizations may appear as internal reports, or consultation reports, or in professional journals available from departments, companies or authors. Several federal agencies in British Columbia and the U.S. Pacific Northwest have active slope stability research programs and are primary sources for most available research information.

2.2.5 Office Assessment

A preliminary slope stability assessment may be made on the basis of the information collected on the office data card.

STEP ONE: Review slope stability map data

If the area in question has a **moderate** to **high** slope stability rating:

- Seek outside expertise of a specialist; or
- Proceed to Section 2.3 (field evaluation).

If no stability maps exist for the area, proceed to Step 2.

STEP TWO: Review resource map/air photo data for landslides

If the resource data indicate that landslides have occurred in or near the area of concern in similar terrain:

- Seek outside expertise of a specialist; or
- Proceed to Section 2.3 (field evaluation).

If the resource data indicate no landslides have occurred in or near the area of concern, proceed to Step 3.

STEP THREE: Review physical character of the area as established from the resource map/air photo data

If there is sufficient information available, review the physical character of the area for the **presence of indicator factors,** (as reviewed in Section I), such as slope angle, character of overburden, moisture status, and presence of geological processes that can influence slope stability. A simple guide is presented below, although it can and should be adjusted according to the various regions in the Pacific Northwest.

If the area consists of non-cohesive[1], shallow (<3 m in depth), coarse-textured materials on slopes >33 degrees (>65%), or on slopes >20 degrees (>36%) that are wet[2] or dissected by gullies:

- Proceed to Section 2.3 (field evaluation).

[1,2] For definitions of these terms, refer to Section 2.4.1, pages 75 and 80.

If the area consists of cohesive,[3] deep (>3 m), fine-textured materials on slopes >30 degrees (about >58%), or on slopes >10 degrees (18%) that are wet or exhibit progressive deformation:

- Proceed to Section 2.3 (field evaluation).

If there is insufficient resource data available to assess the site:

- Proceed to Section 2.3 (field evaluation).

[3] For a definition of this term, refer to Section 2.4.1, page 75.

2.3 PART B : FIELD EVALUATION

An integral part of the procedure for recognizing unstable terrain is being able to identify and interpret certain "indicators" of controlling and contributing factors in the slope stability model described in Chapter 1. This requires a working knowledge of how these factors operate and interact, and sufficient knowledge at the site to discover what kinds of indicators of instability are present. The resulting information can be integrated with support data to provide a final stability assessment. Some of the field information can be obtained from air photo analysis. This may be all that is required for general planning.

2.3.1 General Procedure

Six major groups of known characteristics should be investigated to supply information adequate to characterize unstable conditions on forested watersheds. These are:

1) **Landform**
2) **Overburden**
3) **Geological Processes on the Slope**
4) **Bedrock Lithology and Structure**
5) **Hydrology**
6) **Vegetation**

For each of these groups, there are diagnostic indicators which identify factors controlling stability. A data card has been developed for compiling information according to these six topics (pages 42-43). The information provided on the data card, in turn, can be used for the stability hazard assessment outlined on pages 74-83.

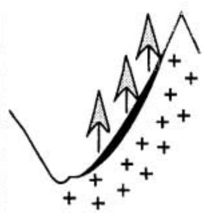
Click here for next page

1) Landform

Regional landscape

Landscapes are qualitative indicators of unstable terrain that may be obtained from air photos, topographic maps, and limited field reconnaissance.

Landscapes Prone to Rockfall, Rockslides, Debris Avalanches, Flows, and Torrents

<table>
<tr>
<td>Landscapes modified by glaciers
• U-shaped valleys
• steep, glacially scoured side slopes
• shallow overburden (mantles) of colluvium and till
• extensive outcrops of bedrock</td>
<td></td>
</tr>
<tr>
<td>Non-glacial landscapes
• V-shaped valleys
• steep planar side slopes due to
-joints, fracturing, faults
-resistant hard bedrock
• shallow overburden of locally derived coarse-textured materials
• benches and escarpments of bedrock</td>
<td></td>
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</table>

Site Name: ______________________ Date: ______________
Map Sheet: ____________________ Photo Number: ______________

1) Landform/Slope Data (Section 2.3.1, p. 41-48)

Slope Shape: Concave ❑ Convex ❑ Straight ❑
Surface Configuration: Uniform/smooth ❑ Irregular/benchy ❑
Slope Angle: __________ (degrees) __________ (percent)

Hillslope Profile

2) Overburden Characteristics (Section 2.3.1, p. 48-58

Material Type: Till ❑ Colluvium ❑ Fluvial/Glaciofluvial ❑
Lacustrine/Marine ❑ Weathered rock (Residual Soil) ❑
Other: ______________________________

Texture: Estimate % Gravel/rubble ____________________
% Sand ____________________
% Fines (silt/clay) ____________________

Coarse Fragment Shape: Rounded ❑ Angular ❑
Impermeable Layer: Yes ❑ Depth Below Surface ________ (meters)
Overburden Profile: **Comments:**

(Note different layers and depth to bedrock and impermeable layer, seepage zones, etc.)

3) Geological Process Data (Section 2.3.1, p. 59-62)

Landslides:
Evidence of Past Landslides: Yes ❑ No ❑
Type: Fall ❑ Creep ❑ Slump ❑ Earthflow ❑ Debris Torrent ❑
Bedrock Slide/Slump ❑ Debris Avalanche/Flow ❑
Downslope Impact: Entered Stream Yes ❑ No ❑
Dimensions: Depth: ______ (m) Width: ______ (m) Length: ______ (m)
Character of landslide initiation (starting) zone:
Material Type: Till ❑ Colluvium ❑ Fluvial/glaciofluvial ❑
Lacustrine/Marine ❑ Weathered Rock (residual soil) ❑
Other: ______________________________
Texture: %Gravel/Rubble _____ %Sand _____ %Fine (silt/clay) _____
Slope angle: __________ (degrees) __________ %
Slope Shape: Concave ❑ Convex ❑ Straight ❑
Surface Configuration: Uniform, Smooth ❑ Irregular, Benchy ❑
Drainage Features: Evidence of seepage ❑ (Yes)
Overall Drainage: Rapid-well ❑ Mod. well-Imperfect ❑ Poor-v. poor ❑
Landuse: Clearcut ❑ Natural ❑ Road ❑
Location: Open slope ❑ Gully ❑

Continued on next page

Field data card

Box 3 continued

Other Features that Indicate Instability

Gully Erosion

Area Dissected by Gullies: ❑ Yes ❑ No

Number of Gullies in Area: ______________

Landslide Evidence on Gully Slopes: ❑ Yes ❑ No

Termination Point of Gully: (describe)____________________

Tension Fractures

Tension Fractures Evident in: Roadbed ❑ Overburden ❑

Landslide Deposits (indicate upslope landslide activity)

Debris Piles/Irregular Mounds at Base of Slope : ❑ Yes ❑ No

Upslope Location of Landslide: ____________________

Fans/Cones at Base of Slope: ❑ Yes ❑ No

Lobes/Levees on Fan Surface: ❑ Yes ❑ No

Buried Landslide Deposits: ❑ Yes ❑ No

Upslope Location of Landslide: ______________________

4) Bedrock characteristics (Section 2.3.1, p. 62-66)

Bedrock: Exposed (outcrops) ❑ Subsurface (buried) ❑

Bedrock Type: Volcanic ❑ Intrusive ❑ Sedimentary ❑

Metamorphic ❑ Specific Type: ____________________

Structure: Massive (nonbedded) ❑

Bedded ❑ Dip Downslope (parallel to slope) ❑

Jointed/Fractured ❑ Dip Downslope (parallel to slope) ❑

Stratigraphy that Promotes Landslides:

Massive Beds over Easily Eroded Beds ❑

Local Setting: Tension Fractures: ❑ Yes ❑ No

Cliffs: ❑ Yes ❑ No

Fresh rock exposed on cliff face: ❑ Yes ❑ No

Scattered boulder/blocks at base of cliff: ❑ Yes ❑ No

Talus at base of cliff: ❑ Yes ❑ No

Fresh rocks on talus/fresh blocks at base: ❑ Yes ❑ No

5) Hydrologic Characteristics (Section 2.3.1, p. 67-69)

Evidence of Wet Soils:

Mottles in Upper Meter of Soil: ❑ Yes ❑ No

Gleyed Soils: ❑ Yes ❑ No

Surface "Wet" Indicators:

Springs ❑ Sag Ponds ❑ Seepage/Damp Sites ❑

Shallow Linear Depressions

Drainage of Overburden: Rapid-Well ❑ Mod. Well-Imperfect ❑

Poor-v. Poor ❑

6) Vegetation (Section 2.3.1, p. 70-73)

Water tolerant Vegetation Present: ❑ Yes ❑ No

Identify species ______________________

Movement Indicators: Jackstrawed/Leaning Trees ❑ Split Trees ❑

Curved Trees ❑ Linear patches of uniform age forest oriented downslope that differ from surrounding forest ❑

Evidence of Windthrow: ❑ Yes ❑ No

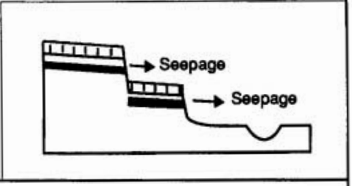
Site Conditions:______________________

Field data card

Landscapes Prone to Slumps and Earthflows

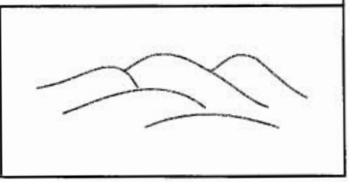
Landscapes modified by glaciers

- dissected valley-fill sediments
- terraces, escarpments of glaciolacustrine silt/clay or ice contact materials with beds of finer sediments
- raised marine terraces, escarpments along the ocean margin
- till from fine-textured bedrock (e.g., shale)



Non-glacial landscapes

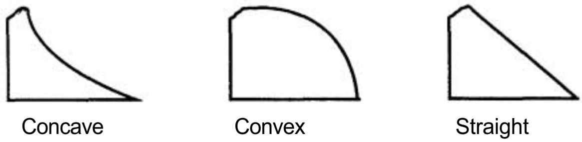
- soft, rounded topography due to weathering of fine-textured bedrock (e.g., mudstone)
- bench-like topography due to resistant bedrock overlying weathered soft rocks



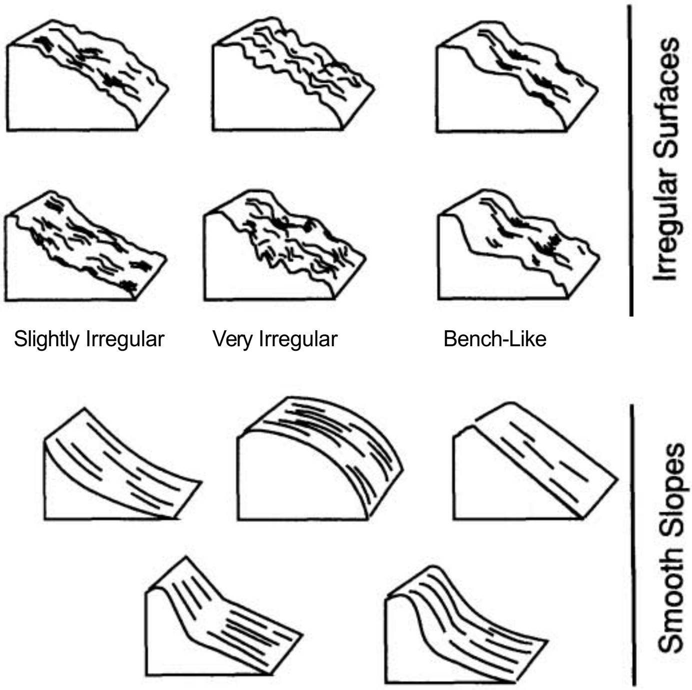
Slope configuration and gradient

Slope configuration refers to the shape of the slope. It is a qualitative indicator of location and extent of most unstable areas that may be obtained from air photos, topographic maps and limited field reconnaissance. Convex slopes have steepest gradients in the mid-lower portions. Concave slopes have steepest gradients in the upper portions. Irregular or broken slopes generally have a reduced potential for stability and off-site hazard because steep sections are short and landslides have limited travel distances. In general, the slope configuration of a site can be defined as **uniform** (smooth with few surface irregularities) or as irregular (broken). Examples of both these forms are illustrated below.

Slope Shape



Surface Configurations



Examples of different slope shapes and configurations

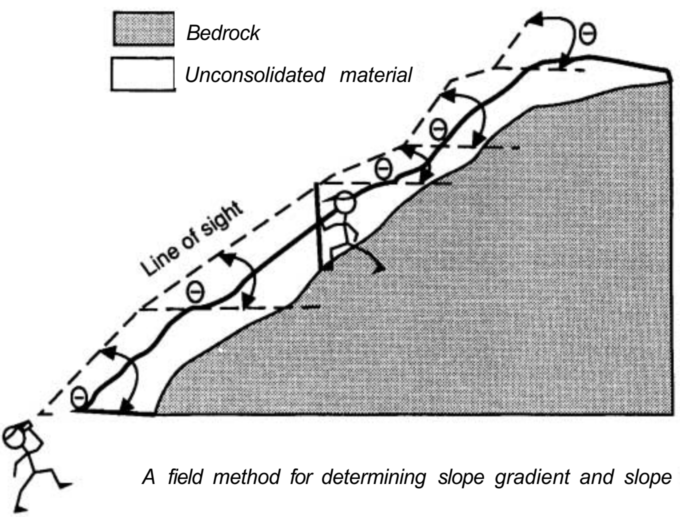
Slope gradient is a key factor in controlling stability in steep mountain watersheds and is a quantitative indicator of relative stability of a site. Slope gradient may be quantified on the ground or from topographic maps. It determines effectiveness of gravity acting to move a soil mass or a block of rock downslope. The gradient of a slope may be expressed in degrees or as a percent. The following table illustrates the relationship between degrees and percentage.

Relationship between degrees, percent and ratio

Degrees	Percent	Ratio
2.5	5.0	
5.7	10.0	10:1
10.0	17.6	
14.0	25.0	4:1
19.3	35.0	
20.0	36.4	
24.2	45.0	
26.1	49.0	
26.6	50.0	2:1
30.0	57.7	
33.0	65.0	
35.0	70.0	
38.6	80.0	
42.0	90.0	
45.0	100.0	1:1
55.0	142.8	
60.0	173.2	

On steep hillslopes with shallow semi-cohesionless overburden, slope gradient is a major indicator of natural landslide hazard. Slopes >36 degrees (>73%) tend to be highly unstable; slopes <26 degrees (<49%) tend to be stable, provided high water table conditions do not prevail. On hillslopes underlain by deep cohesive overburden, slope gradient is not as important since, given the right conditions of moisture content, texture, rock structure, and clay mineral content, failures can occur on slope gradients less than 10 degrees (<18%). Slope gradient also has a major effect on the drainage rate of subsurface water flow and on the susceptibility of water table to build up during high intensity storms.

Slope configuration and gradient are generally considered in profile. To assess overall hazard properly in the assessment area, it is necessary to construct cross-sectional profiles of the entire slope from ridge top to valley floor, depicting both slope angle and shape; make it from topographic map sources (if available). A profile made from field measurements is more accurate, however, and provides a better data base for stability assessments. To do



A field method for determining slope gradient and slope this, the surveyor traverses up or down the slope, recording changes in slope angle and configuration for various distances using an Abney level, rangepole and tape. Estimates of depth to bedrock or water table can also be included during this recording of the slope profile.

2) Overburden

Many details about the character of the overburden (surficial materials) may be obtained from a preliminary review of air photos and existing geological data sources. The Terrain Classification System for British Columbia is used throughout the province for the classification and mapping of surficial materials (see Appendix 1 and 2). The existence and extent of these overburden features, however, must be verified by field examination, and some characteristics of the overburden can only be established by field examination. Information about the character of the overburden in the field may be determined from:

- **soil pits or tree throws**
- **landslide scars**
- **river or stream escarpments**
- **road cuts**
- **gully sidewall exposures**
- **bore-holes.**

Origin of materials

Origin of materials refers to how the materials were formed. Knowledge of origin is a useful aid in stability assessments because how materials were formed is closely related to what their most important physical properties are. It provides a qualitative indication of the texture, permeability, engineering properties, material strength, and presence or absence of impermeable layers (potential failure or perched water table boundaries) in the subsurface. These suggest types of landslide processes operative within an area. Page 31 shows an example.

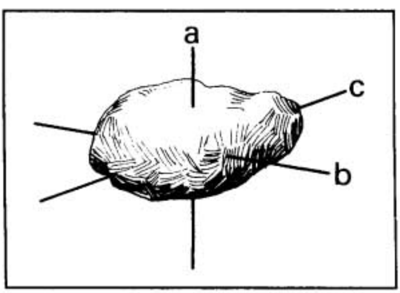
COLLUVIUM, some residual materials, and some tills and pumice on steep slopes commonly possess little or no cohesion. Failures in such materials are usually of the debris avalanche and debris flow types.

WEATHERED fine-grained sedimentary rocks (mudstones, claystones, graywacke, shales), volcaniclastics, or lacustrine or marine clays and silts possess a high degree of cohesion and characteristically develop failures of the slump and earthflow types. Mica content of these materials may also have a major influence on soil strength. Ten to twenty percent mica will produce results similar to high clay content.

The table on pages 50-51 outlines some of the characteristics for various surficial materials that are helpful for their field recognition. These data, used in conjunction with information obtained from air photo analysis, provide a guide to the identification of material origin.

Texture

The texture of material refers to the size of the component particles and can be estimated in the field. It provides information about the sedimentary history of a material and can be used to identify material origin. It also provides qualitative information about important properties such as cohesion, porosity, and permeability, which can be used for slope stability assessment. The size of a particle is determined by its intermediate length (b-axis).



Intermediate length determines texture class

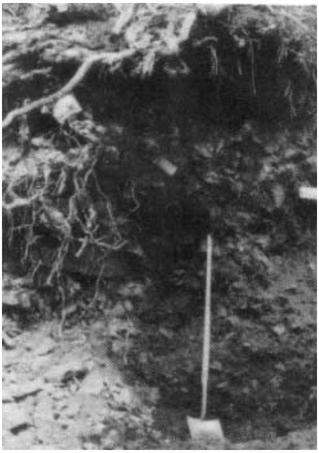
Characteristics of various surficial materials

CHARACTER	MATERIAL

MATERIAL: Till (basal)

Material deposited from glaciers.
- heterogeneous mixture of particle, sizes in a matrix of sand, silt, and clay.
- stones often have different rock types and may be striated.
- non-stratified (no bedding).
- unweathered till is highly consolidated (compact).
- weathered till that overlies unweathered till has most of the above properties; however, the material is loose and often cohesionless.

MATERIAL: Colluvium



Accumulation of material that moves downslope due to gravity.

Group 1: talus deposits, snow avalanche deposits, and colluvial mantles, usually overlying bedrock.
- dominant character and texture consists of angular rock fragments in a heterogeneous mixture;
- fragments derived from local bedrock sources; and
- materials are non-cohesive, loosely packed, and porous (well drained).

Group 2: debris and mudflow fans.
- dominant character and texture consisting of heterogeneous interbedded flow deposits with fluvial gravels; and
- deposits tend to be well drained.

Group 3: slump and earthflow deposits.
- character and texture determined by local geology; and
- materials commonly consist of weathered bedrock blocks, till, or fine-grained lake/marine sediments with high clay contents.

Fluvial/Glaciofluvial

Material deposited by streams and glacial meltwater.

- consists of sand and gravel that is non-cohesive, and highly porous and permeable (rapidly to well drained);
- gravels are typically rounded;
- deposits are commonly well sorted, non-compact, and display well-developed stratification (bedding) although massive, unstratified deposits of gravel may be found.

Lacustrine/Marine

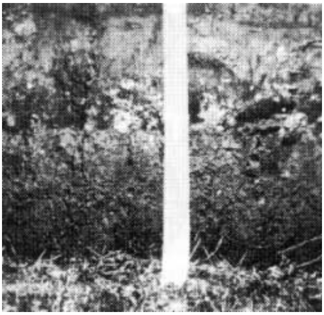
Group 1: (fine-textured deposits) result from settling of particles out of suspension in lakes or oceans.

- consist of sand, silt, and clay that may be bedded to massive, may have high cohesion, and are often poorly drained;
- marine sediments may contain shells;
- include glaciolacustrine and glaciomarine sediments deposited close to glaciers.

Group 2: (coarse-textured deposits) result from wave action along former lake or ocean margins.

- consist of sand and gravel deposits with properties similar to fluvial gravels.

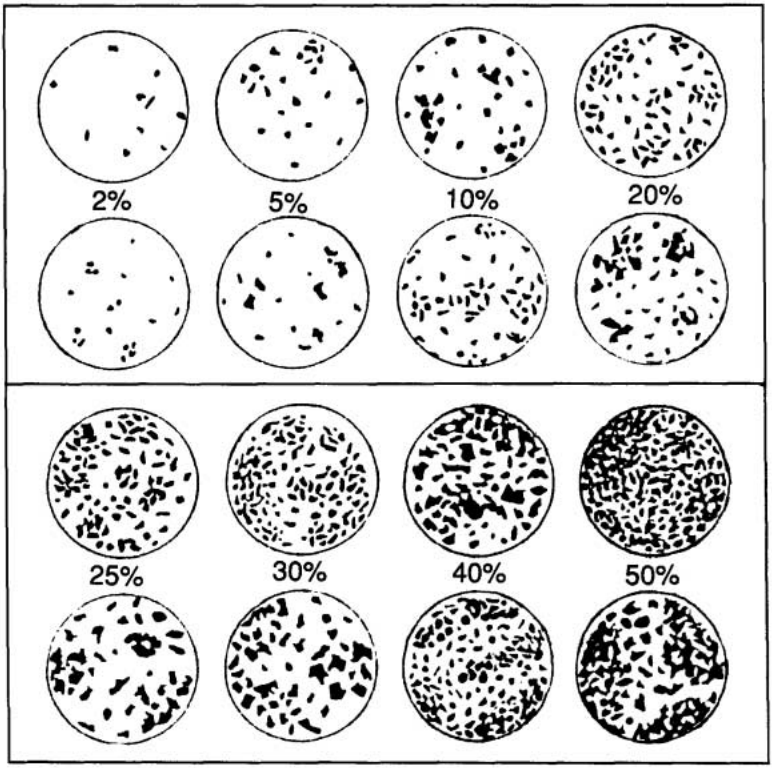
Weathered Bedrock



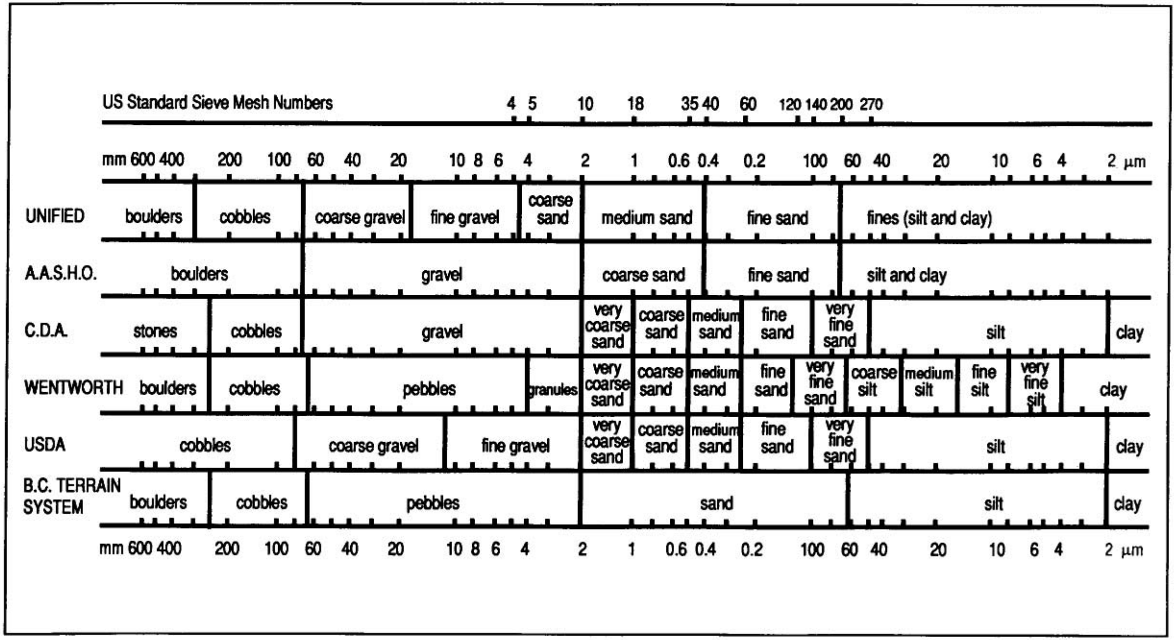
Material derived from mechanical and chemical weathering processes.

- character/texture vary with bedrock, climate, and degree of weathering;
- fine-grained volcaniclastic and sedimentary rocks in a warm, humid climate weather deeply and form clay-rich saprolites with high cohesion;
- granitic rocks under warm, moist climate weather into coarse, sandy materials (gruss) with little or no cohesion;
- hard, dense volcanic flow and granitic rocks under cool, wet or dry conditions produce coarse-grained colluvial and talus deposits with little or no cohesion.

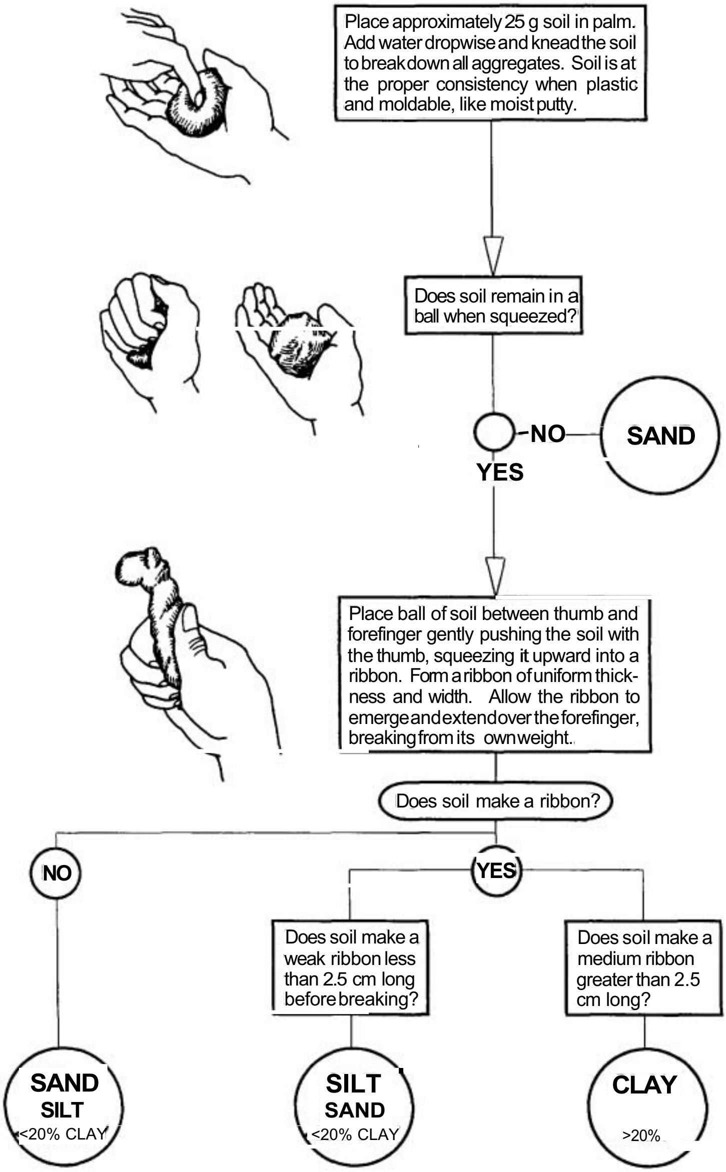
Several classifications of particle size are in common use, depending on discipline. These classifications and their relationship to one another are presented in the chart on page 53. Particles of coarse sand size and larger are easily seen by eye and the percentage (by volume) can be determined by **visual estimation charts.** Medium sand and smaller sized particles can be estimated by hand texturing –feeling the sediment with one's fingers. A guide to hand texturing of particles is presented on page 54. A pinch of silt in the mouth will feel "gritty" between the teeth, whereas clay will not. The estimated percentage of coarse and fine particle sizes of a material in the area in question should be made using these techniques.



Visual estimation chart for estimating percentage volume of material type. (Source: J. Sediment. Petrol., 1955.)



Various textural classifications (Terrain Classification System for British Columbia 1988)



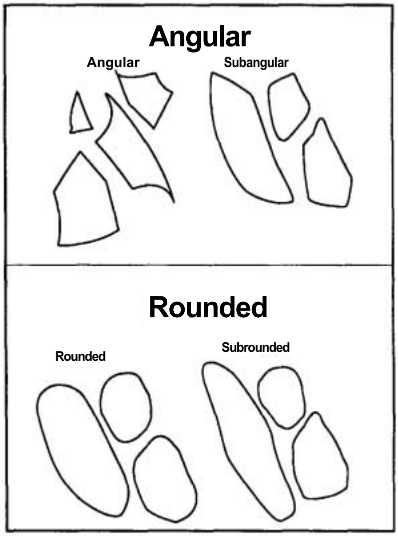
Hand texturing of fine sediments

Particle shape

Particle shape or the shape of fragments in a material is another factor that influences the shear strength of a soil mass. For example:

- Shear strength is lower for rounded particles than for angular particles.

The shape of particles > 2 mm can be simply classified as **rounded** or **angular.**



Different particle shapes

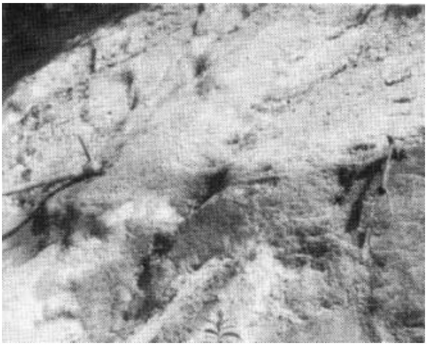
Presence and depth of an impermeable layer

An impermeable layer refers to a layer that restricts the downward passage of water. It can result from:

Compaction

- material closely packed, such as unweathered till or bedrock.

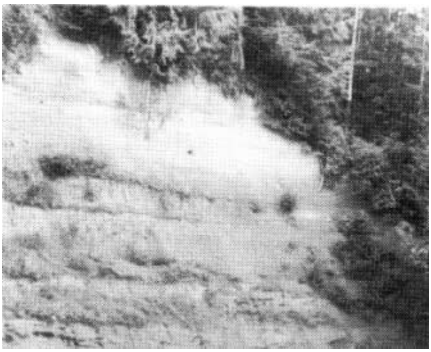
Water movement restricted at the surface of the compact unweathered till (arrow)



Cemented sand layer (arrow) restricting groundwater movement

Cementation

- "pans" or hard, impermeable layers caused by cementing substances such as iron, calcium, or silica.



Groundwater movement restricted by subsurface lacustrine silt (highlighted by vegetation)

Textural change

- such as coarse, loose material like gravel overlying a clay or silt bed that has a lower permeability.

Identification of an impermeable layer and its depth below the surface provides a quantitative indicator of the depth and type of failure that may occur at a site. It also indicates principal paths of subsurface water movement or zones of temporary water table development, probable surfaces of failure on the slope, and, in some instances, the depth of root penetration, which can be important for identifying areas made unstable by windthrow. Such sites on steep hillslopes are potential initiation sites for landslides. Examples are slopes covered with the following material.

LOOSE, PERMEABLE WEATHERED TILL that overlies basal till, the contact between the two materials acts as a barrier to the downward movement of water as well as a failure surface. Pans also commonly develop at this contact, further defining the boundary change. Such conditions favor the generation of debris avalanches and debris flows in the weathered material.
SHALLOW COLLUVIAL MATERIALS (loose, non-compact) that overlie competent bedrock on slopes display conditions similar to those on slopes covered by weathered basal till and also favor the generation of debris avalanches and debris flows.
FLUVIAL AND GLACIOFLUVIAL MATERIALS on slopes may contain beds or layers of fine-textured sediments (silt and/or clay) within the sand and gravel. These finer sediments restrict the downward movement of water, and may develop pans which trap downward draining soil water, in turn causing the development of perched water tables which often serve as failure surfaces. If these restricting layers occur at considerable depth (several meters below the surface), they can promote slumps, particularly on near-vertical slopes of banks and escarpments. Near-surface impermeable layers favor the generation of debris avalanches and debris flows.

Engineering characteristics of materials

Site-specific data on the nature of the overburden can be collected for use in engineering analyses of landslide mechanics, and in assessments of maximum and minimum stable slope gradients for a particular material. These quantitative factors are identifiable by field testing, sampling, and laboratory analysis. While this type of analysis is beyond the scope of this manual, the various factors and their influence on stability (listed on page 59) are useful for more effective hazard assessments.

MATERIAL DEPTH: Principal determinant of the weight of the mass and an important factor in determining strength and gravitational stress acting on an unstable material.

TEXTURE (particle size distribution): The relative proportions of sand (2.0 - 0.05 mm), silt (0.05 - 0.002 mm), and clay (<0.002 mm) in a material.[1] Texture and clay mineral content are important factors in controlling cohesion, angle of internal friction, and hydraulic conductivity of an unstable material.

CLAY MINERALOGY: An indicator of sensitivity to deformation. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas where creep occurs. Expanding lattice or "swelling" clays such as montmorillonite are particularly unstable because they absorb water which decreases their strength.

ANGLE OF INTERNAL FRICTION: An indicator of the frictional resistance of a material caused by the interlocking of individual grains; an important factor in determining shear strength. The tangent of the angle of internal friction times the effective weight of the mass constitutes a mathematical expression of frictional resistance or strength developed along the failure surface. For shallow, cohesionless materials, a slope gradient at or above the angle of internal friction is a good indicator of a highly unstable site.

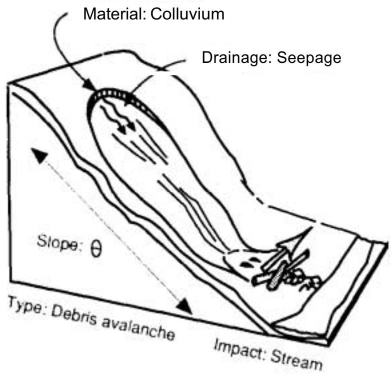
COHESION: The capacity of particles to stick or adhere together. This is a distinct property produced by cementation, capillary tension, and weak electrical bonding of organic colloids and clay particles. Cohesion is usually the direct result of high (20% or greater) clay particle content and is an important contributor to shear strength of a fine-grained material.

[1] USDA Textural Classification p. 53

3) Geological Processes on the Slope

Landslides

Evidence of past landslides is an indicator of potential instability. Historical landslides are usually evident on air photographs; however, they should be reviewed in the field to gain knowledge of the site conditions at their point of origin, the type and size of the landslide, and downslope effects. Information that should be collected at the point of initiation of a landslide includes:



ORIGIN of failed material

TEXTURE of failed material

SLOPE gradient at point of initiation

SLOPE configuration in the zone of failure

TYPE and degree of drainage at site

DEPTH of failure

TYPE of landslide

LAND use at origin (road, clearcut, natural)

LOCATION (gully, open slope).

In addition, the size of the landslide should be estimated and impacts on streams should be noted. Data from all identified landslides in the immediate area should be collected. Knowledge of the site conditions that favor landslide activity on the slope enables one to identify other similar sites on the slope that represent potential landslide initiation sites.

Gully erosion

Till, colluvium, and residual overburden that are dissected by gullies are potential sites of debris torrents. In most instances, the presence of gullies or canyons can be readily identified from air photographs, though the nature and density of gullies in forested terrain are often only known after a field investigation. Data that should be collected about gullies include:

CHARACTER of gully side- and headwalls (rock or material type, slope gradient).
PAST landslide activity in the gullies (many small side-wall failures may not be evident on the photos).
NUMBER of gullies on the slope (density/hectare).
POINT of downslope termination (e.g., does it end in a stream, on a fan?).
QUANTITY of stored debris in the gully channel.

Till slopes undergoing gully erosion. Note difference before logging Ⓐ *and after logging* Ⓑ.

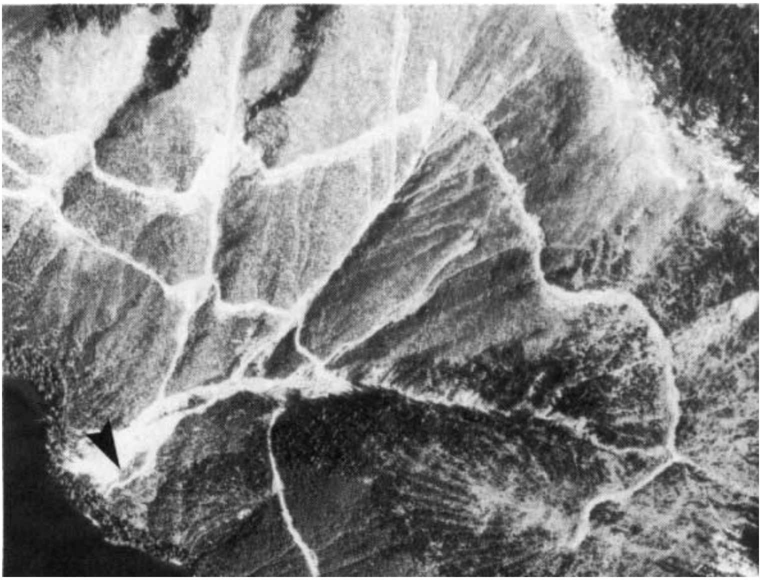
Tension fractures

Field evidence of movement downslope may be indicated by the presence of tension fractures or fissures in the overburden, or a roadbed, or bulges in the road. These features indicate there has been some downslope movement already at this site.

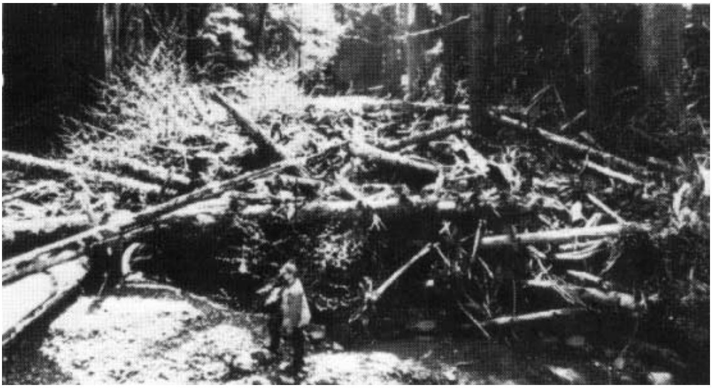
Tension fractures (arrows) in roadbed

Fans/hummocky topography at slope base

Deposits of debris on the ground surface at the slope base, such as hummocky, irregular mounds or cones and fans with lobes or levees of coarse material, often with large logs incorporated in



Debris (light tone) from upslope debris torrent on a fan (arrow) debris on their surface, indicate past debris flow and debris torrent activity upslope.



Debris pile at base of gully

Buried deposits

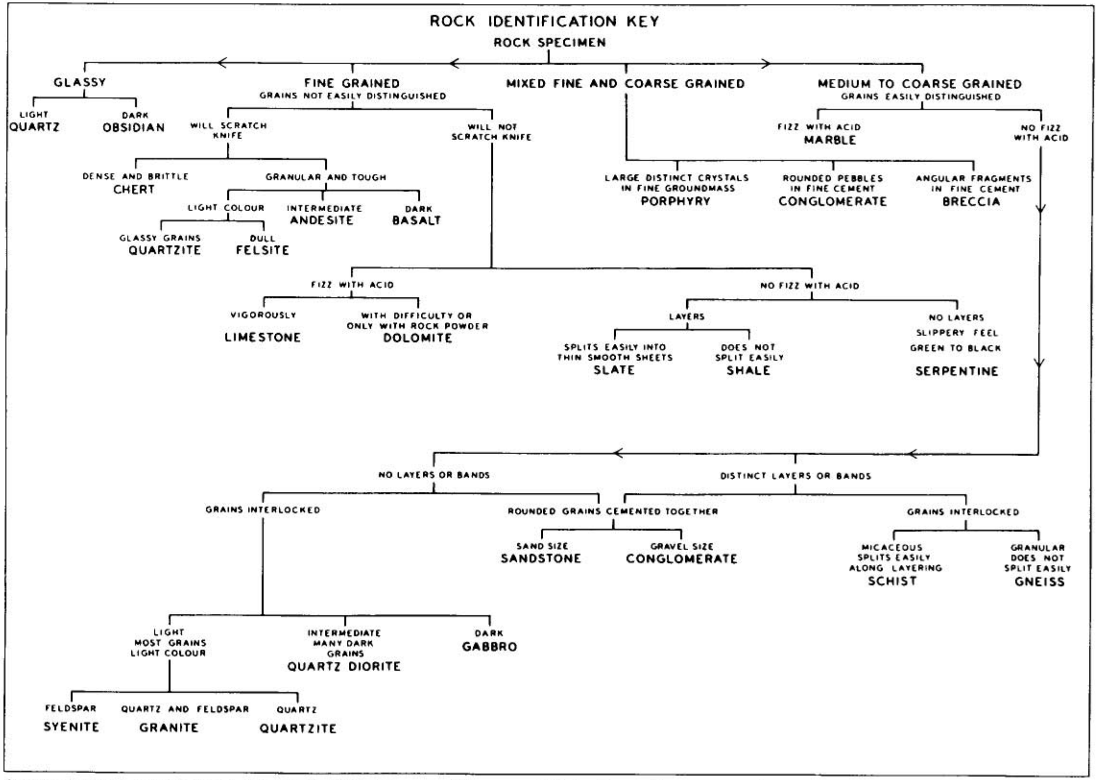
Buried deposits, often with wood layers incorporated in the material, can occur in fans. These layers provide evidence of past upslope landslide activity.

4) Bedrock Lithology and Structure

Rock type

The type of bedrock in an area can provide a qualitative indication of the overburden texture, clay mineral content, and relative cohesiveness. In many cases, the bedrock type is determined from a bedrock map; however, as these maps tend to be small scale and regional, the identification of a specific rock type is usually required in the field.

A simple classification of the common rock types is outlined on page 63. Actual rock identification requires basic knowledge of the differences between igneous, sedimentary, and metamorphic rocks, and some minimum experience with field identification.

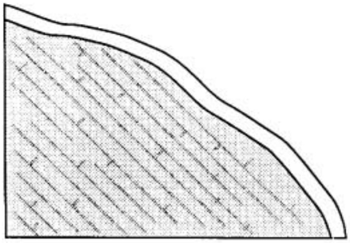


Rock classification chart. (Source: B.C. Energy Mines and Petroleum Resources.)

Structure

There are several structural and stratigraphic features that are useful indicators of potential landslide sites:

Attitude of beds



Beds dipping downslope are less stable

- **Beds of rock** that parallel or dip in the same direction as the slope can be an important contributor to rockfall from cliffs or overhangs, rock slides from steep slopes, or debris avalanches and flows from steep slopes overlain by shallow overburden.
- **Beds that dip** into the slope tend to produce benches and short cliffs which impede the development of large landslides and trap debris and sediment at intermediate locations on the slope.

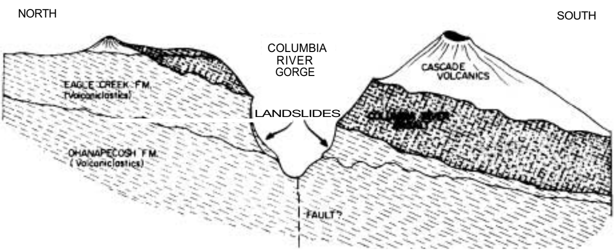
Presence and degree of fractures, joints, and foliation

Rockfall (A) due to joints (arrows)

- **Fractures, joints, and foliation** (planar features associated with metamorphic rocks) refer to cracks in a mass of rock that can be of different intensity (few or numerous). The intensity of these structures can be quantified from measurements of the average spacing between features. Rocks that have numerous cracks (e.g., well-jointed), particularly those that dip downslope, can promote rockfall (from cliffs), rock slides and rock slumps on steep bedrock slopes, and debris avalanches and debris flows on steep slopes covered with thin overburden. The presence of these features in the rock creates local zones of weakness along which failures occur, as well as providing avenues for deep penetration of groundwater, with subsequent active pore-water pressure development along the planes.

Stratigraphy

- Stratigraphy that promotes bedrock failures (rockfalls, rock slides, rock flows) includes massive beds overlying weaker beds, or the alternating of competent and incompetent layers. Examples include volcanic flows (hard, competent, impermeable) that overlie volcaniclastic rock (generally highly weathered, soft, incompetent), or interbedded sandstones (hard, competent) overlying altered shales and mudstone (soft, incompetent).



Differential stratigraphy of Columbia River Gorge, Oregon

Tension Fractures

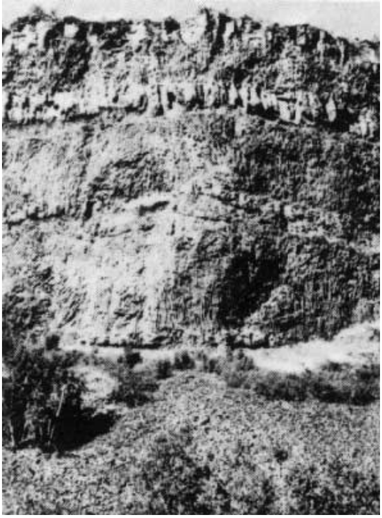
- Tension fractures in rock appear as closely spaced linear cracks or fissures that parallel the rock surface. These fractures are generally caused by incipient slope movements or by expansion of the rock due to

Tension fractures on ridge crest (arrows) removal of surface loads or lateral support (e.g., withdrawal of the weight of overlying glaciers), or differential temperature changes. These features are often difficult to identify on air photographs and their presence and influence on stability must be assessed in the field.

Local terrain characteristics

Local terrain features can also provide clues to potential landslides. Steep rock cliffs represent potential sites for rockfalls and rockslides. Cliffs and steep bedrock outcrops should be inspected for fresh or recent bedrock movement (usually a lighter tone than the surrounding weathered bedrock surface, as illustrated on the right, top). Terrain below and adjacent to the outcrop should be inspected for large isolated boulders or blocks of rock that rest on the overburden, or on talus deposits as illustrated on the right, bottom. Such boulders indicate past rockfall and rockslide activity. Recency of this activity can be judged by the freshness of the blocks and associated rock fragments, impact scars on trees, and relative size of lichens.

Lighter tone on rock face indicates recent activity

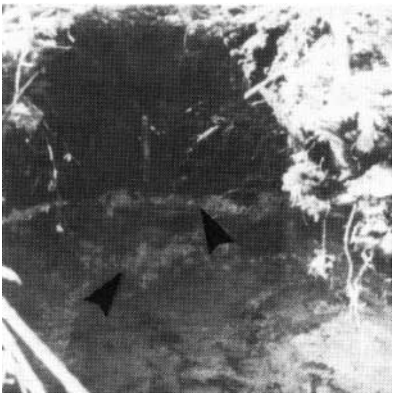


Talus at base of volcanic rock escarpment

5) Hydrology

Because groundwater is a primary factor in slope failures, indicators of wet or poor drainage sites on slopes are important features to note during a field inspection. Evidence of zones of periodic high soil moisture content and potential sites of active pore-water pressures during high rainfall periods may be indicated in the field by subsurface and surface features. These areas, once identified, represent potential areas of slope failure.

Subsurface Features of Poor Drainage Conditions



Mottles (arrow) in soil profiles

- **Mottles** are spots or blotches of different color (primarily reds and yellows) interspersed with the dominant soil color. Mottles (faint or distinct) present in the upper meter of soil generally indicate soil moisture in excess of field capacity for certain periods of the year.

A gleyed soil. Note dull color tones

- **Gleyed soils** (not the parent material) have wet/moist, gray B-horizons (indicating a strong reducing environment) overlain by a black, organic surface layer. Such soils remain wet for extended periods.

Soil drainage for a site can be estimated by the degree of oxidation or reduction evident in the soil profile. This is generally expressed as the relative amount of mottling or gleying indicated in the various soil horizons. The following table lists commonly used drainage classes and defining characteristics.

Class	Soil characteristics
Rapidly drained:	Soils are free from any evidence of gleying or mottling throughout the profile. Common on steep slopes.
Well drained:	Soils are usually free of mottling in the upper 1 m, but may be mottled below this depth.
Moderately well drained:	Soils are faintly mottled in the lower part of the upper 1 m of soil (lower B-horizon).
Imperfectly drained:	Soils are distinctly mottled throughout the B-horizon.
Poor to very poorly drained:	Soils are usually strongly gleyed.

Surface features of poor drainage conditions

- **Vegetation** (see page 70)

- **Seepage** and concentrated subsurface drainage are indicated by springs, sag ponds, or moist areas on open slopes, and seepage sites along road cuts. The locations of these areas of concentrated subsurface flow should be noted on maps and profiles as potential sites of active, unstable ground.

Headwater portion of a shallow linear depression

- **Shallow linear depressions** oriented up- and


Curved depression resulting from slump

downslope represent old landslide scars or surface erosion channels and identify concentrated surface and subsurface flow. Such features are potential sites for debris avalanches and debris flows.

- **Curved depressions** and swales identify local areas of slump and earthflow failure and are sites of deep subsurface water concentration.

Quantitative drainage indicators

Site-specific hydrologic tests that are useful in the identification and analysis of landslide hazards may be available from other sources or may be obtained by specialists with the required expertise and field experience. Such tests and measurements go beyond the objectives of this manual, but are listed below to provide the user with background information on their value and meaning for stability hazard analysis.

HYDRAULIC CONDUCTIVITY The process of water movement in and through slope materials. This is quantifiable in the field and in the laboratory using pumping tests and permeameters. Low hydraulic conductivities mean rapid storm-generated saturation and a high probability of active pore-water pressure, which produces highly unstable conditions on steep slopes.

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

6) Vegetation

The presence of hydrophytes (water-loving plants) is often a reliable indicator of excessive wet areas on hillslopes. Areas undergoing active movement are also frequently indicated by stressed vegetation or by certain types of disturbance vegetation.

Presence of water-loving plants

Water-loving plants indicate high groundwater levels and impeded drainage. In the Pacific Northwest, the presence of these plants on steep slopes overlain by shallow overburden represents sites of potential debris avalanche and debris flow activity. Such plants in hillslope depressions developed in deep soils and weathered bedrock represent areas of potential accelerated creep and earthflow movement. The table on pages 72-73 outlines some of the more common water-loving plants, their major identifying characteristics, and an illustrated example for field identification.

Stressed vegetation indicators of active movement

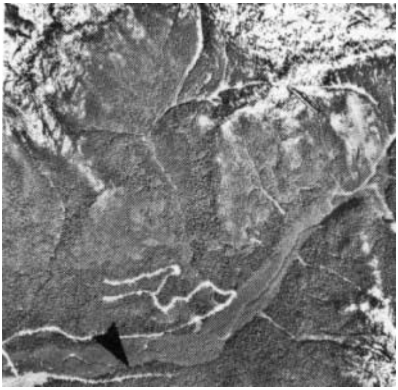
- **Jackstrawed trees** (trees tilted in various directions) and split trees (trees split up the middle) are indicators of active ground movement. They can occur on slump blocks and around headwall sites of newly active slumps and earthflows. The presence of **curved tree trunks** bent downslope may indicate an area undergoing active creep modification, but such an assessment must be used with caution. Snow creep in an area of commonly heavy annual snow accumulation can produce the same type of curvature. Trees tipped downslope on steep gradient sites with shallow soil, may indicate recent mechanical shifting of materials and a

Jackstrawed trees

Recurved trees

potential for slope failure. Past landslides that in many instances have been revegetated can be identified by several factors:

- **Differences** between successional species growing in recent landslide scars (e.g., alder) and species growing in the surrounding forest (e.g., spruce-hemlock).



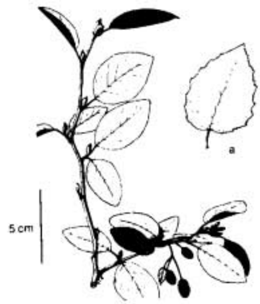
Uniform aged trees delimiting a landslide (arrow); note contrast with surrounding forest

- **Uniform age** of dominant forest cover in old landslide scars, compared to the uneven-age old-growth cover of the surrounding forest. These features are discernible from air photographs and from field traverses.

Patch of windthrown trees

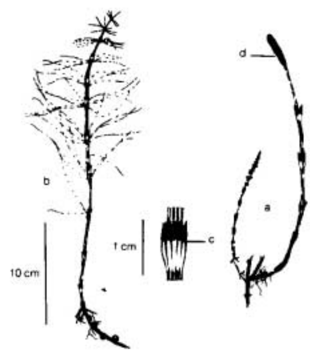
- **Windthrown trees** on hillslope areas commonly indicate poor drainage or shallow soils, or both, and may define sites of actual or potential failure. Windthrown areas are identifiable from air photographs.

- **Shrub,** or rarely, small tree up to 8 m tall.
- **Branches -** twigs hairless to finely hairy, smooth, reddish brown.
- **Leaves,** egg-shaped to elliptic, sharp-pointed at tip (a); finely double toothed, shallowly lobed, leaves yellowish-green on both sides, usually shiny and smooth above, hairy in vein axils below, petioles usually glabrous, young leaves sticky beneath, buds sessile and pointed.
- **Catkins** arising from buds of the current season.

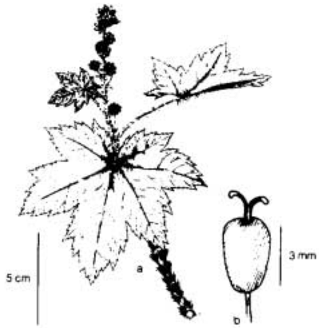


Sitka alder

- **Rhizome,** extensively creeping and branched, dark-felted, tuber-bearing; fertile and sterile stems not alike, annual, erect.
- **Fertile stem -** (a) unbranched, usually thick and succulent, brownish to whitish, soon withering; sheaths with 8-12 large, brown, pointed teeth.
- **Sterile stem -** (b) solitary or clustered, green slender, much branched with about 12 sharp lance-shaped brownish teeth; branch sheaths (c) closest to the stem are large and obvious, while others are slightly flaring, somewhat appressed, and 4-6 toothed; branches numerous in dense, regular shorts, ascending or spreading, mostly unbranched, 3-4 angled; central cavity present.
- **Cones -** (d) long-stalked, blunt-tipped.

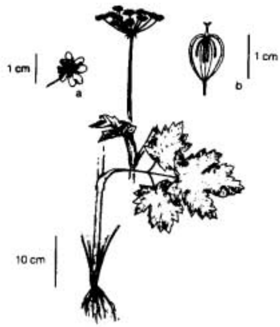


Horsetail



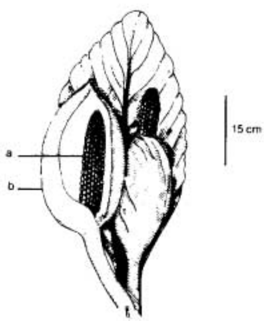
Devil's club

- **Shrub,** deciduous, 1-3 m tall, with thick stems armed with numerous yellowish spines (a).
- **Leaves** shallowly, palmately 7- 9 lobed, broad, twice serrated, "maple leaf" like, with numerous spines present on underside.
- **Flowers** in an elongated cluster to 25 cm long composed of several smaller clusters.
- **Fruit** considerably flattened bright red berries (b); little is known about their edibility, not recommended.



Cow-parsnip

- **Herb,** very large, hairy, single-stemmed perennial from stout taproot or cluster of fibrous roots, 1-3 m tall; stems hollow.
- **Leaves** once ternate, with broad distinctly petiolate, coarsely toothed and palmately lobed leaflets, 10-30 cm long and wide, asymmetrical.
- **Flowers** (a) with 5-10 deciduous narrow bracts beneath compound inflorescence, bractlets below secondary flower stems similar to bracts; flowers white.
- **Fruit** (b) egg-shaped to heart-shaped, with or without hairs.



Skunk cabbage

- **Herb,** perennial with short, fleshy, erect underground stems.
- **Leaves** large, 30-130 cm long and 10-70 cm wide, simple, oblong-oval, glossy green, with a skunk-like odor.
- **Flowers** on spadix (a), yellowish green; spathe (b), large, yellow.

2.4 PART C : STABILITY HAZARD ASSESSMENT

An assessment flow chart is shown on pages 76-77 to guide the quantitative assessment or characterization of unstable or potentially unstable slopes on forested lands. Following the steps in the chart, one can assess the relative potential of landslide initiation (hazard) and the type of landslide that may occur on different types of terrain, based on the data obtained from the review of office sources and field observations. These steps are described below:

Part A: Evidence of past landslide activity

Assess evidence of past landslide activity by reviewing the categories designated in Part A of the assessment chart on page 76.

If YES → the potential landslide hazard is identified on the chart.

In most instances, the user should seek the expertise of a specialist for further analysis of the problem, assessment of risk, and recommendations for control and correction.

If NO → proceed to Part B on page 77.

PART B: No evidence of past landslide activity

DETERMINE THE TYPE OF MATERIAL on the site, unconsolidated or bedrock. If unconsolidated, refer to Section 2.4.1; if bedrock, refer to 2.4.2.

Proceed along the appropiate part of the chart according to the physical characteristics detailed. Most of these variables have been defined in previous sections and sufficient data should be available on the data sheets (pages 22 and 42-43).

2.4.1 Unconsolidated Materials

STEP ONE: Determine material type and texture

Fine-textured materials (cohesive materials)

- **predominantly** made up of sand, silt, and clay;
- **or** made up of more than **20% clay;**
- **or** made up of **clays that swell** upon wetting (e.g., smectite and montmorillonite clays);
- **or** consisting of **layers or lenses** of alternating fine and coarse textured materials.

Include: tills predominantly derived from fine-textured bedrock (e.g., shale) or sediments (e.g., glaciolacustrine silts and clays); windblown silts; colluvium and weathered bedrock (residual over-burden) derived from fine-textured bedrock (e.g., mudstone); silt/clay lake sediments and ocean bottom sediments.

Coarse textured materials (non-cohesive materials)

- made up of sand and/or gravel, rubble and rock fragments with low to moderate amounts of silt (<20%) and little to minor clay (40%).

Include: the weathered surface of most basal tills, ablation tills; mixed sand and gravel fluvial, glaciofluvial and shoreline deposits; colluvium and weathered bedrock (residual soils) derived from medium- to coarse-textured bedrock.

Part A: EVIDENCE OF LANDSLIDES (check appropriate boxes)

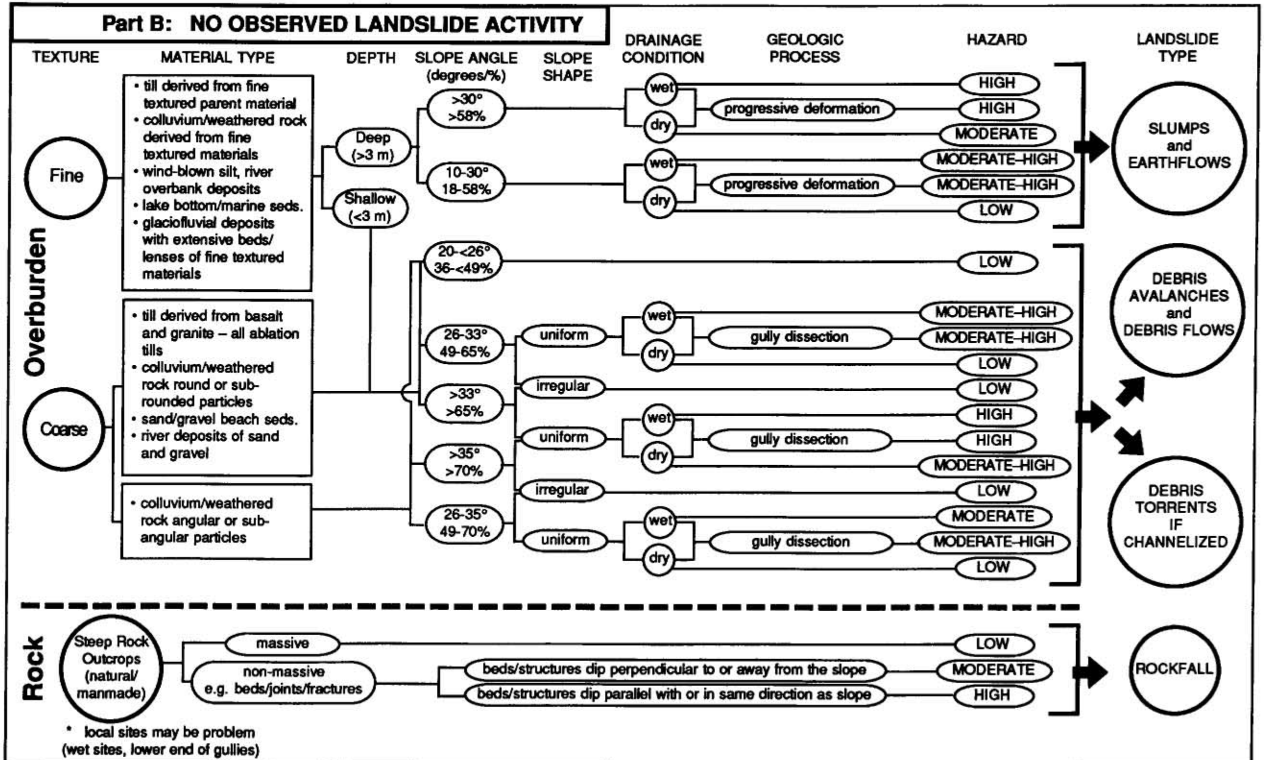
1. Recent landslides occur in the area ❑ → HIGH LANDSLIDE HAZARD →
   - ❑ debris avalanche/flow
   - ❑ debris torrent
   - ❑ slump/earthflow
   - ❑ rockslide/rockfall

2. Tension fractures ❑ arcurate depressions ❑ numerous springs ❑ split trees ❑
   eneschelon benches ❑ bulges in road ❑ sag ponds ❑
   → MODERATE-HIGH HAZARD: active movement, primarily creep, slumping and earthflows

3. Partially vegetated strips ❑ linear patches of even-age timber ❑ buried landslide deposits ❑
   downslope deposits of debris ❑ debris-filled gullies ❑
   → MODERATE-HIGH HAZARD: recent activity, primarily debris avalanches, debris flows, or debris torrents

4. Deep gullies and canyons ❑ gully gradient >22°, >40% ❑ organic/inorganic debris in channels ❑
   debris piles at mouth ❑ raw, exposed gully side-walls ❑
   → MODERATE-HIGH HAZARD: recent and continuing activity, primarily debris flows and debris torrents

5. Talus/scattered boulders at slope base (fresh, recent) ❑
   cliff face with fresh exposed rock ❑
   → MODERATE-HIGH HAZARD: recent and probably continuing rock slide and/or rock fall activity


Part B: NO OBSERVED LANDSLIDE ACTIVITY
TEXTURE
MATERIAL TYPE
DEPTH
SLOPE ANGLE (degrees/%)
SLOPE SHAPE
DRAINAGE CONDITION
GEOLOGIC PROCESS
HAZARD
LANDSLIDE TYPE
Overburden
Fine
• till derived from fine textured parent material
• colluvium/weathered rock derived from fine textured materials
• wind-blown silt, river overbank deposits
• lake bottom/marine seds.
• glaciofluvial deposits with extensive beds/ lenses of fine textured materials
Deep (>3 m)
Shallow (<3 m)
>30° >58%
10-30° 18-58%
wet
dry
progressive deformation
HIGH
HIGH
MODERATE
MODERATE-HIGH
MODERATE-HIGH
LOW
SLUMPS and EARTHFLOWS
Coarse
• till derived from basalt and granite – all ablation tills
• colluvium/weathered rock round or sub-rounded particles
• sand/gravel beach seds.
• river deposits of sand and gravel
• colluvium/weathered rock angular or sub-angular particles
20-<26° 36-<49%
26-33° 49-65%
>33° >65%
>35° >70%
26-35° 49-70%
uniform
irregular
uniform
irregular
uniform
gully dissection
gully dissection
gully dissection
LOW
MODERATE-HIGH
MODERATE-HIGH
LOW
LOW
HIGH
HIGH
MODERATE-HIGH
LOW
MODERATE
MODERATE-HIGH
LOW
DEBRIS AVALANCHES and DEBRIS FLOWS
DEBRIS TORRENTS IF CHANNELIZED
Rock
Steep Rock Outcrops (natural/ manmade)
massive
non-massive e.g. beds/joints/fractures
beds/structures dip perpendicular to or away from the slope
beds/structures dip parallel with or in same direction as slope
LOW
MODERATE
HIGH
ROCKFALL
* local sites may be problem (wet sites, lower end of gullies)

STEP TWO: Determine the shape of coarse particles

Coarse-textured colluvial and residual materials can further be separated by their dominant particle shape into two general categories:

- **Angular**
- **Rounded**

STEP THREE: Determine average depth of materials

Depth refers to the thickness of surficial materials measured perpendicular to the slope and is divided into two categories for purposes of the assessment.

- **Shallow:** <3 m
- **Deep:** >3 m

STEP FOUR: Calculate average gradient of the failure surface in the area of potential initiation

Gradient is measured in degrees or percent.

For shallow, coarse-textured materials, critical gradient can be approximated by the hillslope gradient. Categories for materials with rounded versus angular coarse fragments are:

Rounded		Angular	
20 to <26°	**(36 to 49%)**	**20 to <26°**	**(36 to <49%)**
26-33°	**(49-65%)**	**26-35°**	**(49-70%)**
>33°	**(>65%)**	**>35°**	**(>70%)**

For fine-textured, deep materials,an estimate of the critical failure surface gradient must be made based on apparent size of rotational blocks; "daylighted" failure surfaces in road cuts and along stream channel; other soils or geologic report; and drill log information. Two general categories are recognized:

- **10-30° (18-58%):** low to moderate
- **>30° (>58%):** steep

STEP FIVE: Determine surface configuration

Surface configuration refers to the general shape of the hillslope along the potential path of failure and material transport. Surface configuration is an important indicator of the stability and probable hazard from failures in shallow, coarse-textured materials. Two classes of surface configuration or shape of the slope are recognized:

- **Irregular:** (broken or step-like)
- **Uniform:** (smooth with few surface irregularities)

STEP SIX: Establish drainage conditions

The relative amount of moisture available within the overburden, and the length of time it remains, can have significant influence on hillslope stability in all types of materials.

Two classes of drainage are recognized:

- **Wet:** Materials that have mottled or gleyed profiles in the upper meter and an impervious layer at shallow depth;

  or whose drainage has been classified in soils reports as moderately well, imperfectly, or poorly drained;

  or the presence of water-loving plants at several locations on the slope;

  or of springs;

  or of numerous seepage sites or local ponding;

  or of numerous shallow incipient drainage depressions on the slope.

- **Dry:** Materials that are free from any evidence of mottles or gleying in the upper meter and with no impervious layer at shallow depth;

  or whose drainage has been classified in soils reports as rapidly or well drained;

  or the lack of water-loving plants on the slope;

  or of springs or seepage sites;

  or of incipient drainage depressions on the slope.

Click here for next page

STEP SEVEN: Identify geologic process (presence)

Two classes of drainage are recognized:

- **Progressive deformation (creep):** Subdued, hummocky terrain that may have leaning or tilted trees and is undergoing active creep, but lacks decisive indicators of movement (e.g., tension fractures, headwall scarps, split trees) provides prime sites for future slump and earthflow movement.
- **Dissection by gullies (gully erosion):** Terrain dissected by deeply incised gullies and canyons are, as a general rule, areas prone to debris torrents or debris floods.

FINAL STEP: Determine potential landslide hazard and type from the assessment chart (page 77)

2.4.2 Bedrock

STEP ONE: Identify

Identify sites where there are vertical or steeply sloping outcrops of bedrock or where the activities of man (e.g., road construction) will result in a similar bedrock exposure.

STEP TWO: Determine general character and structure of the bedrock

Two general classes are recognized:

- **Massive:** rocks having a homogeneous texture over wide areas lacking layering (bedding), fractures, and foliation.
- **Non-massive:** rocks having a homogeneous texture and dissected by cracks such as joints and fractures; or rocks made up of layers (beds) that may be dissected by cracks.

STEP THREE: Determine dip of beds, fractures, and joints in the rock

Two categories are recognized:

- **Parallel to slope:** beds, joints, fractures, foliations dip parallel to or at a steep angle in the same direction as the hillslope gradient, providing surfaces of potential failure and open zones for transportation of subsurface water.
- **Perpendicular to slope:** beds, joints, fractures and foliations dip perpendicular to or away from the hillslope gradient, limiting groundwater passage and buttressing the hillslope with benches.

FINAL STEP: Determine potential landslide hazard and type from the assessment chart (page 77)

2.4.3 Analysis Limitations

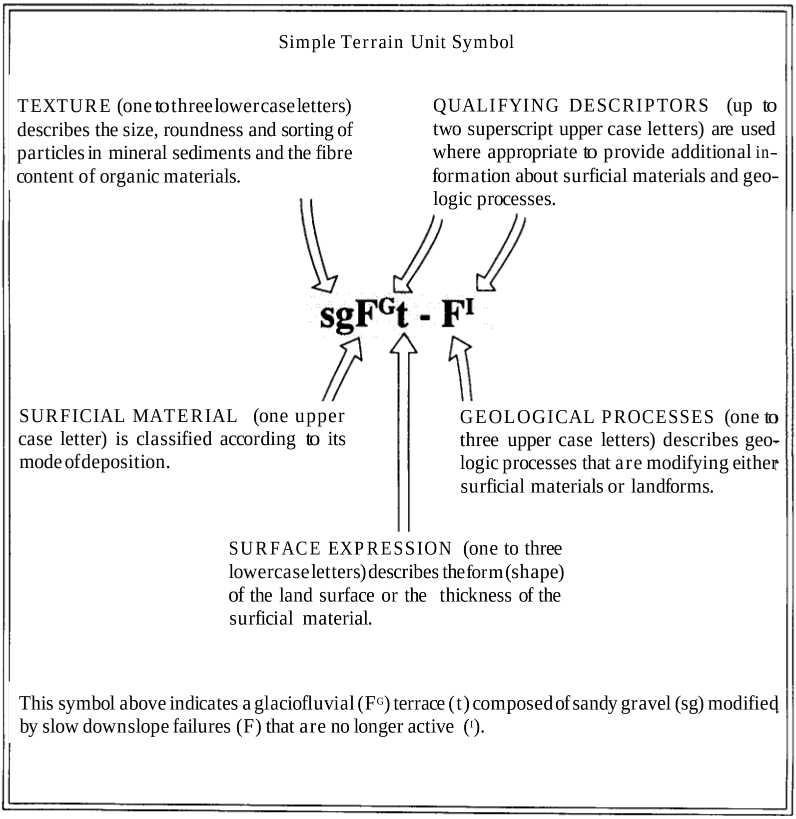
The hazard rating developed using this procedure provides a relative measure of the likelihood of a particular type of landslide occurring following forest harvesting operations. The high, moderate, and low ratings are based on the experience of practicing professionals, as published in the research literature pertaining to slope stability analysis in the Pacific Northwest. The ranges of various factors can vary from site to site and may require adjustment to local conditions. Thus, the hazard rating presented in this flow chart should be used only as a guide to identifying unstable terrain.

A five-class hazard rating system is used for slope stability assessment within coastal forest regions in British Columbia (Appendix 3).

As a general rule, the user should seek outside expertise of a specialist for further analysis of a site if the terrain has a moderately high to high rating, or if the user lacks the knowledge or experience in assessing the various factors influencing slope processes. Potential downslope impacts should also be considered at this time.

APPENDIX 1. Example of terrain unit symbol

Information is portrayed on a terrain map by a terrain unit symbol which is composed of a group of letters. These letters provide information about the character of the terrain and are arranged in a manner such that each letter position represents a particular characteristic of the terrain. Information provided by a terrain unit symbol includes texture and type of surficial material, surface expression, geologic processes, and qualifying descriptors.



Source: Terrain Classification System for British Columbia 1988

APPENDIX 2. Terrain classification system for British Columbia - codes and descriptions

TEXTURE

Symbol	Name	Size (mm)	Other Charateristics
a	blocks	>256	angular particles
b	boulders	>256	rounded & subrounded particles
k	cobbles	64-256	rounded & subrounded particles
p	pebbles	2-64	rounded & subrounded particles
s	sand	.062-2	
[illegible]	silt	.002-.062	
c	clay	<.002	
d	mixed fragments	>2	mix of rounded and angular particles
g	gravel	>2	mix of boulders, cobbles and pebbles
x	angular fragments	>2	mix of rubble and blocks
r	rubble	2-256	angular particles
m	mud	<.062	mix of clay and silt
y	shells		shell or shell fragments
•	fibric		well-preserved fibre; (40%) identified after rubbing
u	mesic		intermediate decomposition between fibric and mesic
h	humic		decomposed organic material; (10%) identified after rubbing

SURFICIAL MATERIALS

Symbol	Name	(Assumed Status of of Formative Process)	Description
A	anthropogenic	(A)	Man-made or man-modified materials
C	colluvial	(A)	Products of mess wastage
D	weathered bedrock	(A)	In situ, decomposed bedrock
E	eolian	(I)	Materials deposited by wind action
F	fluvial	(I)	River deposits
F^G	glaciofluvial	(I)	Ice contact fluvial materials
I	ice	(A)	Permanent snow, glaciers and icefields
L	lacustrine	(I)	Lake sediments; includes wave deposits
L^G	glaciolacustrine	(I)	Ice contact lacustrine materials
M	morainal	(I)	Material deposited directly by glaciers
O	organic	(A)	Accumulation/decay of vegetative matter
R	bedrock	(–)	Outcrops/rock covered by less than 10cm
U	undifferentiated	(–)	Layered sequence; three materials or more
V	volcanic	(I)	Unconsolidated pyroclastic sediments
W	marine	(I)	Marine sediments; includes wave deposits
W^G	glaciomarine	(I)	Ice contact marine sediments

QUALIFYING DESCRIPTORS

Symbol	Name	Description
G	glacial	Used to qualify surficial materials where there is evidence that glacier ice affected the mode of deposition of materials
A	active	Used to qualify surficial materials and geological processes with regard to their current state of activity
I	inactive	

Source: Terrain Classification System for British Columbia 1988

APPENDIX 2 (continued)

SURFACE EXPRESSION

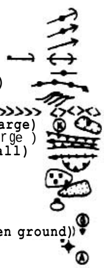
Symbol	Name	Description
a	moderate slope	Unidirectional surface; >15° to ≤26°
b	blanket	A mantle of unconsolidated materials; >1m thick
c	cone	A cone or segment of a cone; >15
d	depression	A lower area enclosed by higher surrounding terrain
f	fan	A segment of a cone; up to 15°
h	hummocky	Hillocks and hollows irregular in plan; 15-35°
j	gentle slope	Unidirectional surface >3° and ≤15°
k	moderately steep	Unidirectional surface; >26° and ≤ 35°
m	rolling	Elongate hillocks 3 to 15° parallel forms in plan
p	plain	Unidirectional surface; up to 3°
r	ridged	Elongate hillocks; 15 to 35°; parallel forms in plan
s	steep	Steep slopes; >35°
t	terraced	Step-like topography
u	undulating	Hillocks and hollows up to ≤15°, irregular in plan
v	veneer	Mantle of unconsolidated material; 10cm to 1m thick

GEOLOGICAL PROCESSES

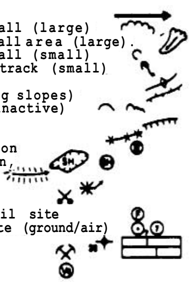
Symbol	Name	(Assumed Process Status)	Description
A	avalanches	(A)	Terrain modified by snow avalanches
B	braiding	(A)	Diverging/converging channels; unvegetated bars
C	cryoturbation	(A)	Sediments modified by frost heaving and churning
D	deflation	(A)	Removal of sand and silt by wind action
E	channelled	(I)	Channel formation by meltwater
F	slow mass movement	(A)	Slow downslope movement of masses of cohesive or non-cohesive material and/or bedrock
H	kettled	(I)	Depressions due to the melting of buried glacier ice
I	irregular channel	(A)	A single, clearly defined main channel displaying irregular turns and bends
J	anastamosing channel	(A)	A channel zone where channels diverge and converge around many vegetated islands
K	karst	(A)	Processes associated with the solution of carbonates
M	meandering channel	(A)	Channel characterized by a regular pattern of bends with uniform amplitude end wave length
N	nivation	(A)	Erosion beneath and along the margin of snow patches
P	piping	(A)	Subterranean erosion by flowing water
R	rapid mass movement	(A)	Rapid downslope movement of dry, moist or saturated debris
S	solifluction	(A)	Slow downslope movement of saturated overburden across a frozen or otherwise impermeable substrate
U	inundation	(A)	Seasonally under water due to high watertable
V	gully erosion	(A)	Parallel/subparallel ravines due to running water
W	washing	(A)	Modification by wave action
X	permafrost	(A)	Processes controlled by the presence of permafrost
Z	periglacial processes	(A)	Solifluction, cryoturbation and nivation processes occurring within a single unit

ON-SITE SYMBOLS

drumlin
crag and tail
roches moutenees
striae
undifferentiated
moraine ridge (major)
moraine ridge (minor)
esker
kettle holes (small/large)
meltwater channel (large)
meltwater channel (small)
cirques
blockfield
rock glaciers
tors
gravel ocurrence
observation site (frozen ground)
stratigraphic site
anthropogenic site



snow avalanches
landslide headwall (large)
landslide headwall area (large).
landslide headwall (small)
landslide scar/track (small)
tension cracks
sackung (sagging slopes)
dunes (active/inactive)
escarpment
strandline
piping depression
karst depression
gully
spring
gravel pit
Quaternary fossil site
Observation site (ground/air)
^{14}C site
mine/quarry
cinder cone



APPENDIX 3. Terrain stability classification used within the Vancouver Forest Region, British Columbia

Introduction

Terrain stability maps are interpretive maps derived from terrain maps. The terrain maps follow conventions and definitions used in the Terrain Classification System for British Columbia (1988). The terrain stability maps are developed from data on surficial materials, landforms, geomorphic processes, slope angle, soil texture, moisture regime, landscape position, vegetation and bedrock types. Most of these data are present on the terrain maps; however, some may come from air photos, bedrock geology maps, vegetation or ecosystem maps and field notes.

Terrain stability rankings provide a relative assessment of mass wasting potential, but give no indication of expected frequency, magnitude or impact. Rankings are intended to identify potential problem areas; actual decisions on logging or road construction should be based on careful field evaluation by appropriate personnel.

The actual criteria that place a given terrain map unit in a specific stability class are usually based on the professional judgement and experience of the terrain mapper and the information contained in the terrain data bank and in the scientific literature. Major management implications expected for operations are included.

Terrain Stability Classes

Class I

- No significant stability problems exist.

Class II

- No significant problems exist.
- Normal road construction and logging practices will not significantly decrease terrain stability.
- Periodic maintenance involving ditch cleaning is expected due to sloughing along road cuts.

Class III

- Minor stability problems can develop.
- Harvesting should not significantly reduce terrain stability; there is a low likelihood of post-logging failure.
- Minor slumping is expected along road cuts on roads crossing areas with slopes greater than 30 degrees, especially for 1 or 2 years following construction.

Class IV

- Expected to contain areas with a moderate to high likelihood of slope failures following conventional road construction. Wet season construction will significantly increase the potential for slope failure.
- There is a moderate likelihood of slope failure in logged areas.
- A field inspection of these areas should be made by a qualified terrain specialist (P.Eng. or P.Geo.) prior to any development in order to assess in detail the stability of the affected area.

Class V

- There is a high likelihood that slope failures will follow logging or conventional road building.
- A field inspection of these areas should be made by a qualified terrain specialist (P.Eng. or P.Geo.) prior to any development in order to assess in detail the stability of the affected area.

Further Reading for Chapter 2

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CHAPTER 3
MEASURES FOR CONTROL AND MANAGEMENT OF UNSTABLE TERRAIN

by

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By now you should be familiar with the many individual factors that can contribute to soil or rock instability. Acting in combination, these factors provide a wide variety of controlling processes and landslide types. There is therefore no single method of managing unstable terrain; instead a variety of techniques are needed by the engineer. In order of priority, the engineer should consider:

AVOIDING the unstable situation
PREVENTING destabilization of marginally stable slopes
STABILIZING unstable slopes
PROTECTING downslope resources when unstable situations cannot be corrected

Avoidance procedures require recognition of unstable terrain, the main subject of Chapter 2. The application of terrain recognition and assessment skills to avoid unstable situations in operational forestry are discussed in this chapter.

Section 3.2 on prevention describes methods of road building and logging that have proven to be successful in reducing the incidence of landslides, and should be standard practices on all steep slopes.

Stabilizing techniques (described in Section 3.3) are specialized construction methods or structures used for crossing obviously unstable terrain. Advice from geotechnical engineers should be sought when most of these methods are used.

The final section (3.4) on protection describes methods of protecting downslope facilities, such as camps or roads, when it is impossible or too expensive to stabilize the upper slope.

3.1 AVOIDANCE

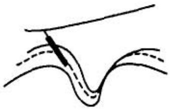
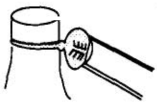
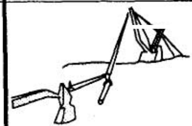
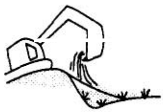
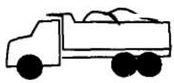
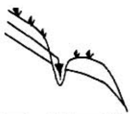
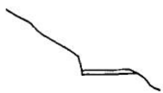
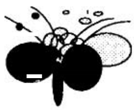
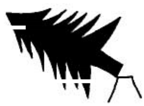
The recognition and avoidance of unstable slopes is without doubt the most effective and cost-efficient method of managing landslide-prone terrain. On extreme slopes, abandonment of the area may be the best environmental and economic solution. In most instances, however, the unstable portion of a slope covers only a small area. Careful field mapping and hazard assessment can locate the boundaries on the unstable area. Often it may be easily avoided during road location or deleted completely from the cutblock. Slight changes in the original road location or changes in road grade are often adequate to bypass the unstable section. Scheduling certain activities to dry periods can also avoid stability problems that might occur during wet months or storms.

Wherever possible, use the avoidance procedures outlined in this section as the first option in dealing with suspect terrain.

3.1.1 Scheduling Harvesting Activities

The vast majority of all landslides occur during the winter, especially during large storms. Soil strengths are low, as moisture is at its highest level, erosion processes are active, and windthrow hazard is high. Additional destabilizing factors such as side casting can increase the seasonal failure rate. **Scheduling road building and yarding activities in steep slope areas for the drier months is an effective landslide control measure.**

Activities that can trigger landslides during very wet weather and activities that are not overly sensitive to weather are listed on page 94. During operations on very unstable slopes, scheduling the activities in column one in drier summer months and those in column two during the wetter period will reduce landslide incidence.

Dry Weather Activities			Wet Weather Activities
Road construction on slopes steeper than 30°			Road construction on slopes flatter than 20°
Cross-stream yarding			Good deflection yarding on open slopes
Pulling on backline or guyline stumps			Mobile backspar yarding
Sidecasting			Endhauling
Deep cuts in soft rock			Road cuts less than 2 m deep
Blasting			Felling

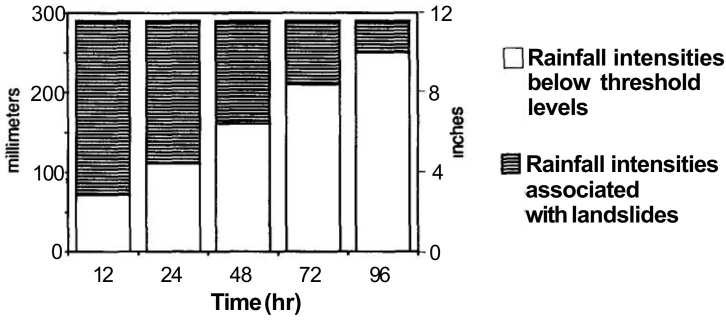
Seasonally dependent logging activities on potentially unstable slopes

3.1.2 Avoiding Activities During Intense Storms

Avoiding logging activities during particularly intense single storms can also reduce landslide risk. Inventories have shown that hundreds of slides in a region may occur during an intense storm. Shallow debris slides and debris flows often occur once a threshold rainfall intensity has been exceeded.

If the total amount of rainfall over a specific time period (the intensity) exceeds the values shown in the histogram below at any time during the storm, then there is a high probability of failure. For example, if the rainfall intensity exceeds 10 cm in 24 hours, **at any time during the storm** the risk of landslides is high.

These values are the minimum intensities needed to trigger slides, assuming previously saturated soils (i.e., from winter storms) and vegetated slopes. Less intense storms may trigger slides within clearcuts or along roads, where drainage may be concentrated at a single point.



Rainfall intensities (with wet antecedent conditions) commonly associated with landslide activities

3.1.3 Locating Forest Roads

Road building is the main destabilizing activity carried out in forestry. Avoidance of naturally unstable areas is the most cost-effective means of dealing with unstable terrain. Avoidance procedures can be carried out at any stage of road building, but are most effective at the engineering stage. The following techniques can aid in locating forest roads and dealing more effectively with road problems in unstable terrain.

Airphoto mapping

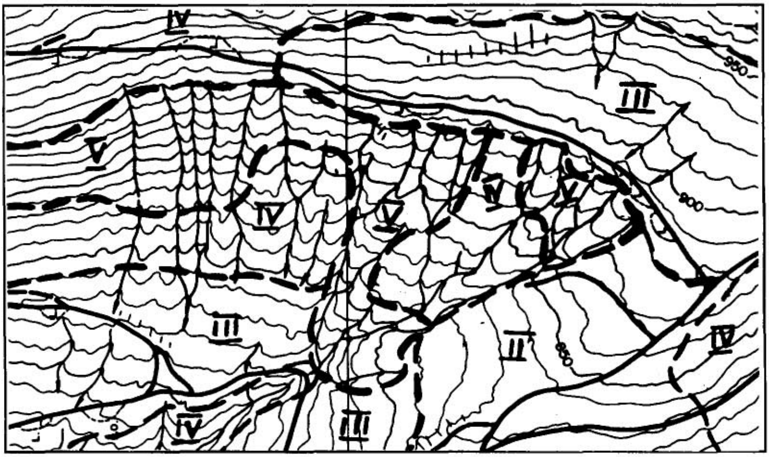
An airphoto reconnaissance of the proposed development area will reveal areas of past landslide activity, an excellent indicator of future landslides. Other more subtle indicators of instability, described in Chapter 2, can also be observed on air photos. These areas should be mapped onto the photos or onto 1:20 000 maps and used during the initial layout to avoid any areas of concentrated instability.

Field investigations

Field investigations must be made of any areas considered to have at least a moderate potential for landsliding. Use Chapter 2 on “field recognition of unstable terrain” to map these areas. It is most convenient to map features of instability directly onto a contoured cutting permit map (1: 5 000 scale). This map should be made before any road locations are established.

Avoidance of unstable sites

Avoid the unstable areas delineated on your map by linking up the stable zones. Treat unstable areas as control points, just as you would a topographic control point such as a rock cliff. In most cases it is possible to avoid all of the unstable areas and still provide adequate access and deflection. The road location in the following map illustrates effective avoidance of unstable areas.



Contoured cutting permit map (1:5000) showing stability class areas (dashed dark lines) and proposed road locations (solid dark lines)

Grade changes

Grade changes can be used to avoid many instability problems. An adjustment of the original grade can be made at any stage of engineering or construction to avoid or minimize the effect of a potentially unstable area, even after landslides have occurred. Examples are avoiding sidecasting onto the head of an incipient slide by moving further upslope, or moving the road alignment away from the toe of a slide to prevent removal of the toe support. Many landslides will progress upslope by headwall ravelling, so give a wide berth if the operation is going above potential landslide sites. The cost effectiveness of grade changes is greatest in the engineering stage. Having to adjust grade abruptly during construction can result in very poor adverse grade as well as the possibility of remedial slope stabilization work.

Abandonment of the road location

Abandonment of the proposed road location may be the best option if there are extensive areas of unavoidable unstable terrain. There are many examples of logging roads that have cost more than the value of the harvested wood. A decision to abandon the area should also be based on a consideration of the other resources that may be damaged by landslides, and the possibility of having to provide expensive protection works farther downslope.

3.1.4 Yarding System Options

Harvesting plans should consider a variety of yarding systems to match terrain conditions to feasible road and landing locations. Switching from one proposed system to another may avoid the need to traverse as much sensitive terrain. Two alternative road locations are shown on the map below for a skyline system

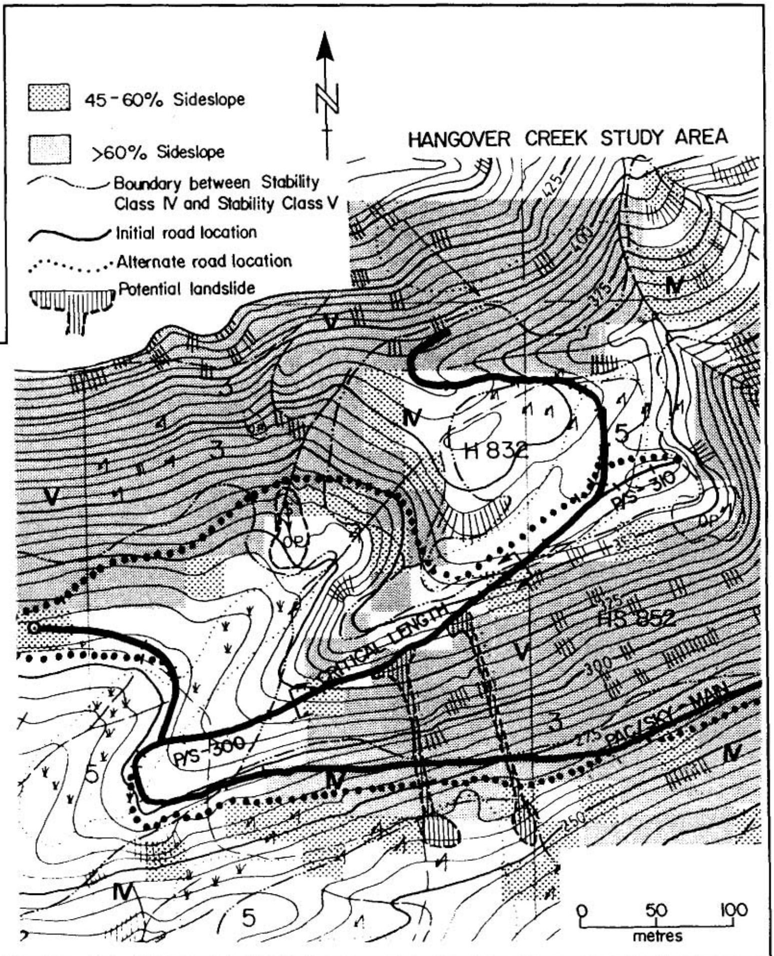
Original Location:

- climbing road at 15-1 8%; cannot get onto stable ridge location.
- if a slide should occur, there is a good chance it would travel to or past the main road below.
- increasing grade on road would not help.

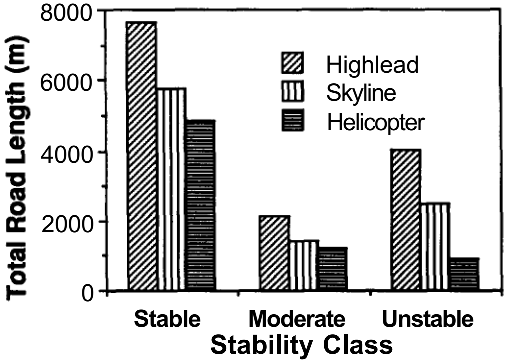
Alternative Location:

- portion of road through Class IV requires careful construction; less Class V than original.
- potential for a slide where one has already occurred; however, debris would not travel very far (if there was flat terrain 25 m below).
- also potential for a short debris torrent if culvert or fill material is improperly placed as road crosses intermittent streams; requires careful placement of fill (Class IV terrain).
- longer route location; could be more expensive to construct, but easier.
- care required around the top of the headwall area of low gradient streams.

(alternative road location) and for a highlead system (initial road location). Skyline systems usually have less total road development. Therefore, more area of unstable terrain may have to be traversed to reach the landing location. Access roads for a helicopter logging option (not shown on the map) could reduce the impact on sensitive terrain even further.

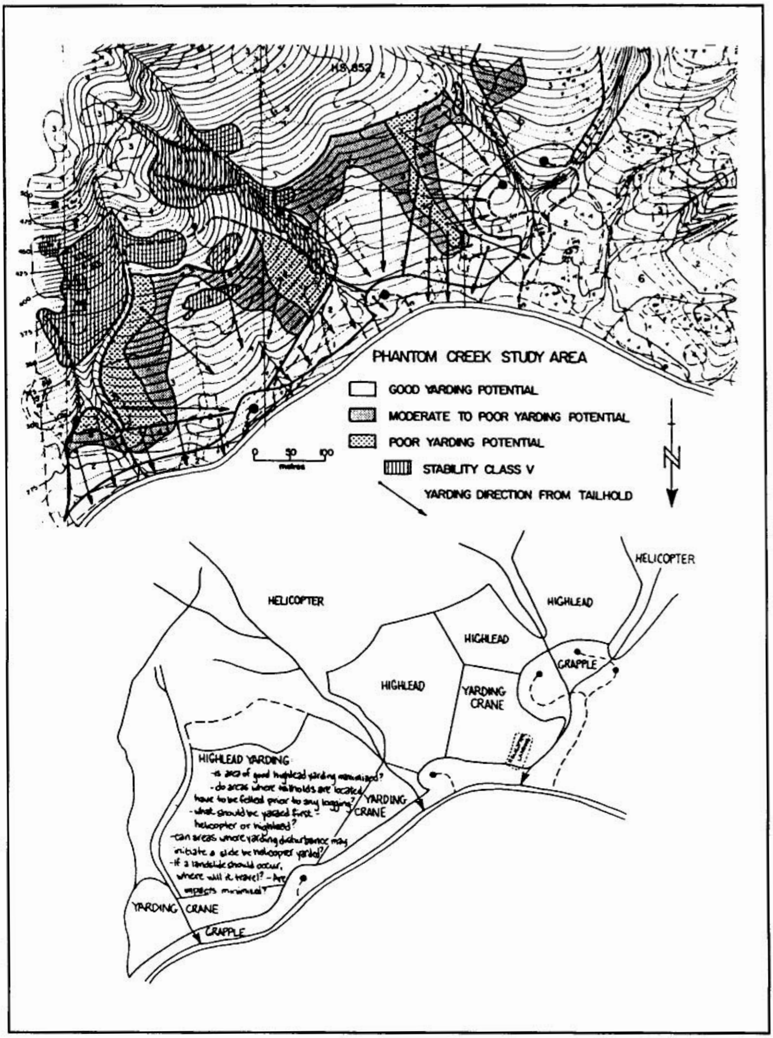


The histogram below shows the total length of road development in various terrain sensitivity classes. The skyline system has 2.3 km less road (40% less) in sensitive class IV and V stability zones than the highlead system. Helicopter yarding would save another 1.5 km of development in the class V stability zone.



Relative lengths of road in various terrain sensitivity classes, under three yarding systems

On most unstable terrain, a mix of yarding systems will allow maximum harvest with least environmental impact from road construction. An optimal mix of highlead, grapple, yarding crane, and helicopter systems is illustrated on page 101. Maximum low-cost conventional harvesting is combined with more expensive partial cut helicopter harvesting in the unstable stability class V areas. The combination of systems fully uses the entire area, protects unstable areas, and is still profitable to harvest.



A mix of yarding systems provides "total chance" harvesting and least environmental impact (FERIC, Land Management Report 59).

3.1.5 Landing Locations

Failure of the soil or rock beneath a landing can be disastrous, so careful consideration must be given in selecting suitable sites. Landing platform failures are not common, as landings are usually located on natural benches or ridge tops. More common are failures of accumulated landing debris, which can oversteepen and overload the slope below the landing. Landing site selection requires that the site stability, as well as the capacity for retaining debris, be considered.

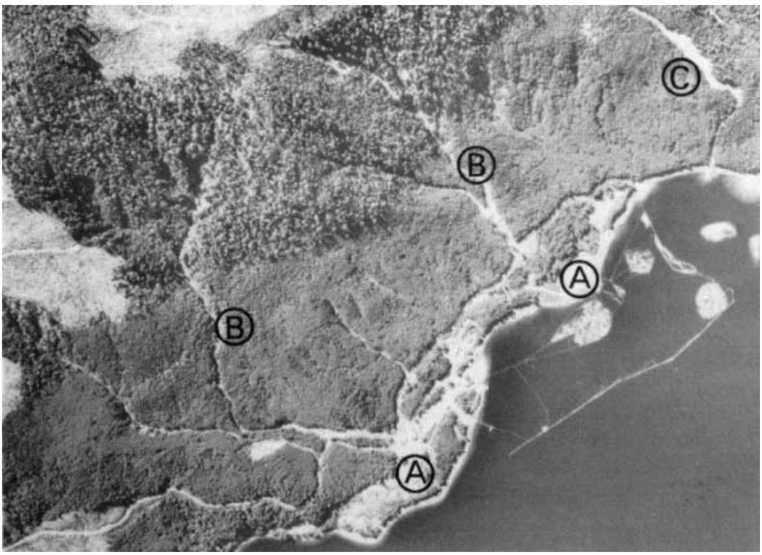
The following terrain conditions should be avoided when sites for landings are selected:

OBVIOUSLY UNSTABLE SITES. These are made even more unstable by landing or road construction.
OPEN SLOPES IN EXCESS OF 30 DEGREES with no natural benches. Full benches are necessary for all landings to withstand the machine vibration and weight loads. Full benching these sites involves tremendous amounts of excavation. The material is often disposed of as sidecast, destabilizing the slope below. Also, open slopes usually have very little room for landing debris, which can accumulate, oversteepen the slope, and eventually lead to failure.
GULLY HEADWALLS. Apart from being naturally unstable sites, there is usually little room to accumulate landing debris safely. Stumps and debris are often cast downslope into the gullies, where they can initiate debris flows.
NARROW RIDGES BETWEEN GULLY HEADWALLS. These sites are attractive for their excellent deflection. The ridges are commonly unstable sites, however, as they develop by retrogressive slumping of the headwalls.
AREAS UNDERLAIN BY STEEPLY DIPPING SEDIMENTARY ROCK OR FRACTURED ROCK. Where the underlying bedrock occurs in layers that are steeply inclined out of the hillslope, machine vibration and blasting can initiate a rockslide.

3.1.6 Locating Camps

A thorough slope stability investigation must be made of any proposed logging camp location. The potential for loss of life and the high capital costs require a more detailed analysis than would normally be used for roads. As camps can be used for many years, the probability of failure at some time during the life of the camp can be high.

The main hazard is from landslides or debris flows initiating upslope and scouring through or depositing material on the camp. The site characteristics ideally suited to camp location–gentle slopes, well-drained soils and available water–are often found on fluvial fans at the mouths of steep gullies. Unfortunately, many of these fans have been built up by repeated debris flows. Camps sited on fans often sit directly astride the runout paths of these landslides.



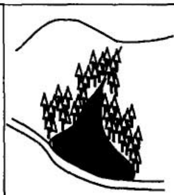
Logging camp located on debris flow fans Ⓐ. Note light-colored track of active debris flow channels Ⓑ and open slope debris slides Ⓒ.

SITE CHARACTERISTICS USED TO IDENTIFY DEBRIS TORRENT RUNOUT ZONES

ALLUVIAL FANS

Fans formed by debris flows often have steeper slopes (6-15 degrees) than true fluvial fans (3-5 degrees).

The fans are composed of unsorted coarse rubble rather than well-sorted stream gravels and sands.



LOBES OR LEVEES

Lobes or levees of coarse rubble, often with large logs lying incorporated in the debris, can be found on the fan surface or in the gully immediately above the fan. Look for old logging machinery, cables, water lines and the like, which have been partially buried by debris.

OLD LOG JAMS

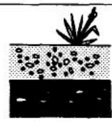
Old log jams may be found lodged in the trees adjacent to the stream channels on the fan or in the gullies above.

ABANDONED CHANNELS

Inspection of older air photos will often show clear unvegetated landslide tracks on the fans and may give an idea of how far down the fan these events have travelled. Abandoned channels can often be observed on the fan surface. These channel changes are frequently the result of debris flows.

BURIED DEPOSITS

Buried soils of older flow material, often with woody layers separating the deposits.



EVIDENCE OF UPSLOPE INSTABILITY

Evidence of slope instability in the gullies above the fan.

Avoid locating camps on fans or any other areas where there is clear evidence of past landslides. A terrain specialist should be consulted where no alternative sites are available. Locating the camp as far down the fan as possible (e.g., beyond the zone of obvious large debris deposition) and building deflection channels and dykes (Section 3.4.1) may be an option. A float camp may also prove to be a viable alternative.

3.1.7 Clearcut Location and Backline Boundaries

Landslides are rarely triggered during the actual logging operation. Rather, they occur on sites that are naturally moderately stable, but become unstable following tree root deterioration. One of the objectives of locating cutblocks is to be able to predict the area that will become unstable over time and adjust the opening boundary accordingly.

Terrain characteristics that are associated with potentially unstable terrain are discussed in detail in Chapter 2. In brief, avoid locating cutblocks:

ON AREAS THAT ARE ACTIVELY SLIDING
ON SLOPES THAT ARE STEEPER THAN 70% and show signs of active soil movement or seepage
IN GULLY HEADWALLS
OVER GULLY SIDESLOPES that have a significant soil cover and that are higher than 15 m and steeper than 75%

Click here for next page

To avoid areas more susceptible to failure, slight changes in clearcut boundary locations can often be made:

ON CONVEX SLOPES, most open slope landslides occur in or near zones of change in slope angle. The slope break can range from sharp to gradual, but most landslides occur where the increase in gradient is 20% or more. With sharp slope breaks, the edge of the slope break is the most common initiation point. With more gradual slope changes, the landslides tend to initiate below the slope break.
ON CONCAVE SLOPES, landslides usually initiate just above the slope break, where seepage is common.

These subtle changes in slope shape are often only apparent after deflection lines are run. Locating the falling boundary inside these trigger points can reduce the incidence of sliding.

3.1.8 Windthrow Boundaries

Landslides along clearcut boundaries are sometimes triggered as a direct result of exposure of standing timber to storm winds. Windthrow-initiated landslides may be reduced by locating windfirm boundaries on stable soils. These boundaries must be run parallel to storm winds. They should not be located on shallow organic soils or on slopes in excess of 40 degrees. Boundaries should not be located along gully head walls. They should be located well above or a good distance below gully head walls, on stable soil (refer Section 3.2.3, Gully Management).

3.2 PREVENTION

Preventative measures are necessary to compensate for changes brought about in slope stability by road construction or clearcutting. Road construction can increase landslide risk by:

OVERSTEEPENING the slope with bermed side cast material
OVERLOADING slopes by adding sidecast material
ALTERING drainage by blocking or redirecting surface or subsurface drainage
REMOVING MATERIAL from the toe of the slope

Yarding operations contribute to slope instability by:

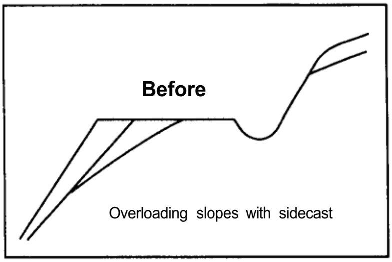
OVERLOADING gullies with debris and soil
INCREASING surface erosion rates which in time may lead to landslides
DISRUPTING drainage

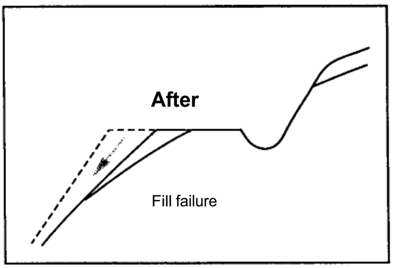
The preventative measures described in this section should be routine operating procedures on all slopes in excess of 60%, and may be necessary on some soil types at even lesser slope angles. Refer back to the “slope stability model” (Chapter 1) to see how changes in the driving and resisting forces can reduce the Factor of Safety to less than 1, often changing a formally stable slope to a potentially unstable site. By implementing the procedures outlined in this section, one can keep the changes in hill slope stability to a minimum.

3.2.1 Road Construction Techniques

Sidecast

Overloading and oversteepening already steep slopes with sidecast material during road construction is the single largest cause of landslides.





Sidecast failures are usually associated with ground slopes steeper than 70%. They are most common on:

- convex slopes
- mid- to upper-slopes
- colluvial soils

Slight regional differences in critical slope angles for different terrain types occur, but 70% is a good "rule of thumb." However, care should be taken to recognize those soil types where the failure angle can be much less, as shown in the table on page 110.

Geographic area	Morainal soils	Colluvial soils	Broken rock
SE Vancouver Island	80% (dry) 65% (wet)	75%	78%
NE Vancouver Island	70% (dry) 65% (wet)	75%	78%
Queen Charlotte Islands	70% (dry) 45% (wet)	70%	75%
Vancouver Island West Coast	70% (dry) 50% (wet)	75%	78% range: 68-100%
Cascades	75% (dry) 65% (wet)	75%	80%

Critical gradients of hillside on which sidecast failures typically occur

To avoid surface ravelling on "sliverfills", 55-60% is maximum ground slope for stable sidecasting. Side slope failures on lesser slopes occur mainly where breakdowns in the road drainage redirect ditch water onto fill slopes. The main contributing factors are:

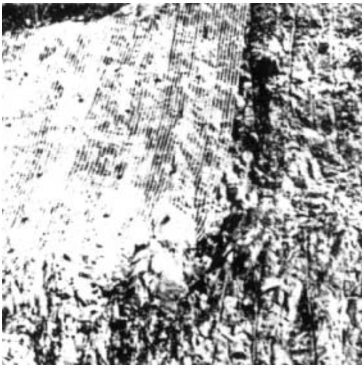
- lack of ditches
- blockage in ditches or culverts by logging debris or cut bank failures
- culverts too far apart or poorly located
- culverts that are too small

Incorporating logs into the fill material only stabilizes the slope in the short term. After 5-7 years, the logs rot and the sidecast failure rate increases drastically. It is not possible to "seal off" a buried stump and prevent rot.

Controlled blasting

Heavy blasting during road construction or quarry excavation is a common cause of landslides. Debris avalanches can be triggered on nearby slopes by ground motion from large blasts, especially during wet conditions. On large cuts, excessive blasting is often used to throw the rock down the slope, often overloading the soil and initiating a debris slide. As well, the rock face itself can be made unstable through heavy blasts that increase rock shattering.

"Presplitting" or "smooth wall blasting" minimizes rock shattering and rock overbreak, and controls the volume and travel distance of blown rock. On unstable sites, excavated rock can be end hauled to more stable disposal sites. A clean rock face needing minimal scaling is created, which is less susceptible to weathering or water percolation and improves long-term stability.



A presplit rock face with partial wire mesh protection

The techniques for controlled blasting cannot be standardized because of the importance of the local rock type, and are beyond the scope of this manual. Basically, however, light charges with millisecond delays are used in closely spaced holes along the fracture face. The cumulative shock from the millisecond blast is less than the shock resulting from an instantaneous blast using the same amount of explosive. The full cut is excavated in a number of separate blasts. The cost of presplitting is little more than controlled blasting, but the extra expense is easily recovered in reduced scaling and maintenance costs.

Recent research has found that the shock wave from blasting is transmitted into wet soils very effectively. In dry soils, there is much less transmission of the energy. This suggests that the potential for initiating a landslide in soil in the vicinity of a blast is much higher in winter than in summer.

Road length reduction

Studies have shown direct correlations between the number of landslides and the total road mileage in an area. Reducing the total road length, and particularly, reducing the road length on steep slopes, will reduce the opportunities for landslides.

Section 3.1.4 describes advantages and disadvantages of various yarding methods and their associated road systems. Reductions in amounts of unstable hillslope construction can, in some situations, be reduced by up to 50% using longline or helicopter yarding systems.

Steep road gradients also provide an efficient means of reducing total road mileage and may be a more cost-effective alternative than full bench, end-haul construction in reducing slide volumes. Steep grades have three advantages in that they reduce:

- amount of road constructed across steep slopes;
- total road mileage;
- road maintenance costs, as a greater percentage of the road is on low maintenance ridge tops.

Disadvantages are road surface drainage problems and increased water erosion. Better ditching, crown surfaces, and frequent culvert spacing are required.

Road width reduction

Most road-related landslides are the result of excessive sidecasting of excavated material. Narrow roads can reduce road surface drainage problems and the amount of excavated material and sidecast dramatically, as shown in the example below.

Road width (full bench)	Hillslope (percent)	Excavated volume (m^3/m)
5.5m	50	31
7.3m	50	47
5.5m	70	69
7.3m	70	107

Excavated soil volume with various road widths and hillslopes; assumes a 1:1 cut slope and a 0.5 meter ditch.

In the 50 and 70 percent slope examples, there is approximately a 35% decrease in the volume of sidecast material with the narrower road. Cut bank stability is also less affected by the smaller cut. This is particularly important where excavations cut through soft, inclined sedimentary rock or clay soils.

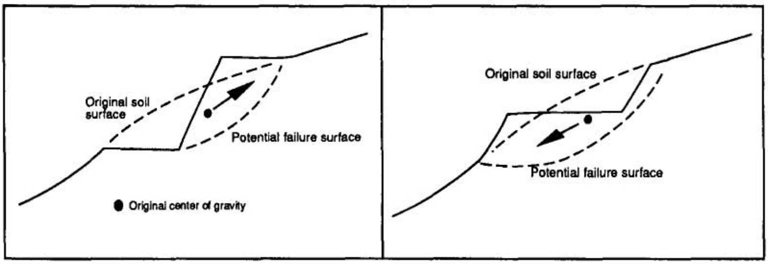
Use of cuts and fills

On most slopes it is difficult to predict exactly where a slide may occur. In these circumstances, the general road construction guidelines outlined in the previous section should be followed.

When the boundaries of an incipient slide are apparent (tension cracks, depressional areas, tilted trees, etc.), the best action is to avoid crossing the area. When this is impossible, knowledge of the boundaries of the incipient slide can be used to advantage. In some cases, correct location of cuts and fills across the landslide can have little effect on the slide stability or may even increase the stability.

The following guidelines are mostly applicable to rotational slides, where the head, toe and side boundaries are apparent.

1. In general, the toe of an actual or potential landslide should be loaded and its head unloaded.
2. Landslides should not be crossed in the middle zone. Both cuts and fills carried out in intermediate positions on the slide can have a conflicting effect on stability. It is therefore best to avoid cuts or fills in intermediate positions and to locate them at the head and extreme toe of the slide, respectively.



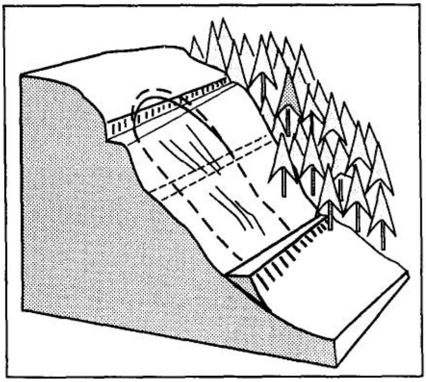
Loading the head and/or unloading the toe shifts the center of gravity upward and increases the potential for slumping.

Loading the toe and/or unloading the head shifts the centre of gravity downward and decreases the potential for slumping.

3. Roads built at the head of the slide should be full- benched and the material end-hauled. No sidecasting should take place.
4. Roads built across the toe of the slide should be built, as much as possible, with end-hauled fill material and cuts made as small as possible. Fill construction is possible only where slope angles decrease downslope, otherwise there is a danger of fill slope failure.

Corrective fills at the toe of the slide are generally preferable to corrective cuts at its head for several reasons:

1. The increase in the "Factor of Safety" is greater with fills.
2. Fill stability improves with time, whereas cut slope stability decreases with time. Cuts in clay soils may take years before failing.
3. In complex slides with more than one potential failure surface, toe loading will protect against all failures, but a cut may destabilize some failure surfaces.



Either:
- Ensure full-bench construction at the head of the slide.

Or:
- Fill construction at toe.

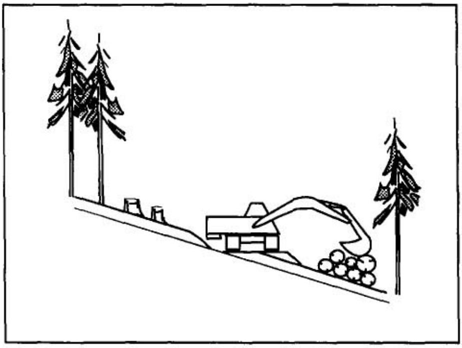
Never:
- Cross middle of the slide.

Backhoe construction

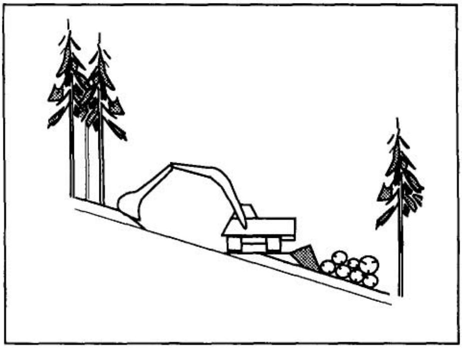
Backhoes have distinct advantages over bulldozers or excavators for road construction on steep slopes. They can:

SORT MATERIALS
DECREASE GROUND DISTURBANCE, especially in wet soils
SELECTIVELY HANDLE material and logs because of long reach and mobility
PRODUCE WELL-CONSTRUCTED DITCHES

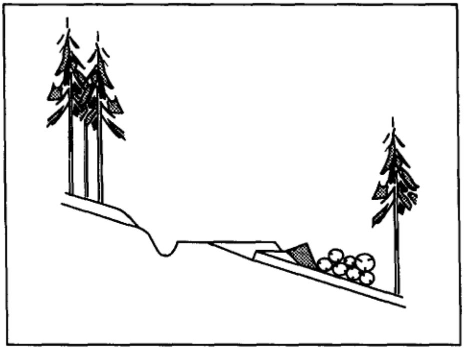
"Clean Up buckets" are recommended to sort materials and leave a smoother, more stable cut bank or ditch line. Balanced cut and fill with the backhoe 3-pass technique excavates the minimum amount of material for a given road width and therefore reduces the volume of sidecast material. In the first pass, log and stump removal take place over a "pioneered" track and logs are stacked crosswise behind. The second pass consists of stripping the overburden from above the "pioneered" track and placing it on the downslope. The logs across the pioneer road are then picked up and placed on and below the wasted overburden. The third pass consists of using the uncovered, unweathered material to construct the bearing surface of the road. Ditch material is also utilized.



First Pass *- Log and stump removal*



Second Pass *- Overburden removal*



Third Pass *- Completed subgrade*

This method minimizes the amount of sidecast material created, and maintains maximum soil strength within the road prism by using only unweathered material.

Compaction

Compaction is the most important aspect of road fill strength. A well-compacted road fill has many times more strength than a loosely placed fill, and should be used in any potentially unstable zone.

Proper compaction depends on soil type, moisture content, and equipment used. Optimum moisture content for various soil types is shown in the following table.

Soil	Optimum moisture
Sand or crushed rock	Bone-dry or saturated. Anything between compacts less.
Clay	Can roll a "worm" 3-6 mm diameter. Smaller, and it is too wet. If it crumbles it is too dry.
Silt	Can't roll to a thread. Can form a ball.

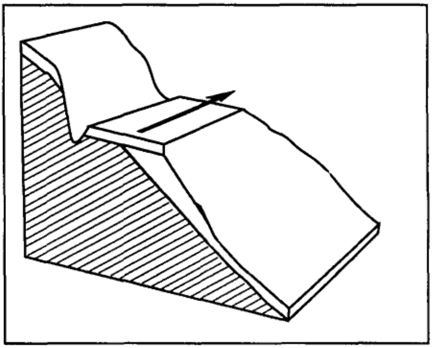
If optimum moisture conditions do not exist, wait for drier weather or sprinkle the fill with water. Aerating with ripper teeth can speed drying. Soil modifiers or cement can aid compaction, especially in silt soils. Place fills in layers of 20-30 cm depending on compactor. Remember bulldozers and loaders are **not** efficient compactors. For logging roads, a grid roller is an inexpensive compactor that works on most soil types.

Road benching techniques

Fill slope failures are the most common type of road-related landslide. Correct handling of fill material during construction of the road bench is the most important fact in the long-term stability of the road. Each of the five methods outlined below and described in the following text is best in specific soil types and should not be attempted in other types of soils. Generally, the methods are listed in order of use for "increasing slope instability." In all instances, care must be taken to ensure that fill does not interfere or block downslope (and subsurface drainage.

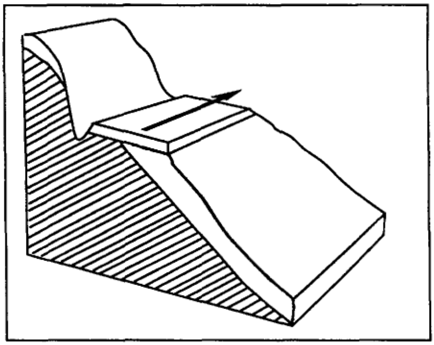
Balanced benching

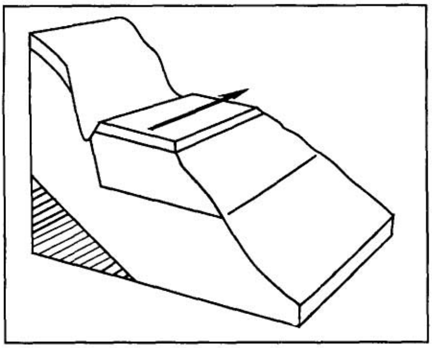
- 3-pass backhoe system
- Balance cut and fill



Sliverfills

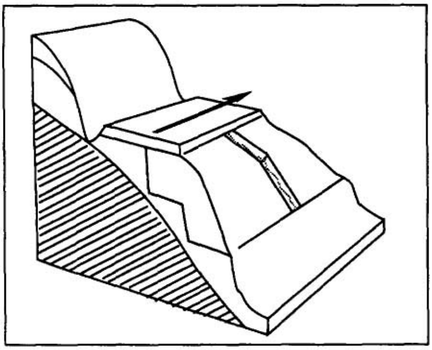
- 3/4 to full-bench construction
- Rubbly material is draped far down hillslope with backhoe
- Use only with rock or coarse colluvium
- Do not use in silts or clays
- Do not place material over organic soils, slash, logs, or brush





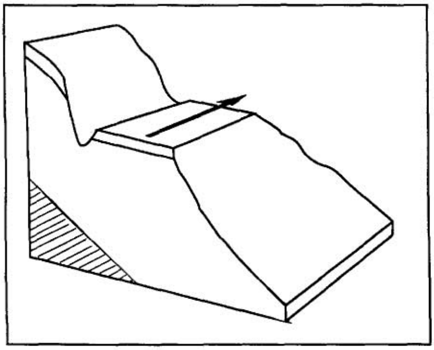
Backcasting

- A wide bench cut 3 m below center line
- Excavated soil backcast on bench behind the backhoe, forming subgrade
- Complete ditch and culvert installation after settling is complete



Multi-benching

- A small bench excavated below grade
- A second, higher bench excavated, with sidecast supported on lower bench
- The road bench then excavated with sidecast supported on the second bench
- Drainage carried over fill slopes in 1/2 culverts or riprap



Full benching / end hauling

- Bench cut equal to road width
- No fill construction
- Excavated soil hauled to stable dump site or, when suitable, used for road ballast

Sliverfills

Sliverfills are thin fills lying parallel to the underlying hillslope rather than as wedges used in normal cut and fill. Controlled sliverfills are built where three-quarters to full- benched roads are constructed through rock or coarse colluvium and there is no-where to dispose of the material. Some level of sliver filling will occur whenever fill material is placed on slopes over 60%. The rationale is to avoid creating an oversteepened slope. This is a method of last resort, as the potential for failure is moderately high and there is a large amount of local forest site loss due to the length of the fill slope. This method can also pose a hazard to fallers working below the roads.

Sliverfills can only be used in specific situations. For example, the excavated material must be free draining: broken rock is ideal; silts and clays are completely unsuitable. Also, the angle of the hillslope cannot exceed the angle of repose of the excavated material.

The material is placed or draped down the hillslope and not cast. The 11-m arm on a backhoe can usually control a 15-m long fill. Care must be taken that material does not hang up on the slope behind stumps or boulders, as locally oversteepened areas can fail. Uncontrolled sliverfills can occur where sidecast material becomes unstable and ravels down the hillslope.

Backcasting

Backcasting is a method used where full-benched roads are necessary and the soil is freedraining. It uses most of the exca-vated material to construct a high subgrade, thereby minimizing the amount of sidecast, and eliminating the need to end haul. The method can only be used where the native materials are suitable for subgrade (medium to coarse textured and well drained) and where side slopes are less than about 80%. The operation consists of the following steps:

Click here for next page

SIDECAST only stumps, logging slash and brush
CUT a deep full bench about 9 m in width and 2.5 - 3.0 m in depth at the center line with the backhoe. The excavated material is then backcast and piled on the subgrade behind the hoe.
LEVEL AND DITCH the backcast material to make the subgrade
ALLOW BACKCAST material to sit and drain. If not, the attendant settling will block culverts and change direction of flow in ditches.
BALLAST the subgrade

In deep soils, this technique also provides toe support to the cut slope, thereby reducing the occurrence of rotational cut bank slumps.

Multi-bench system

Multi-benching is a seldom used, but effective technique for providing stable footings for fill material with only minimal side-cast. It is best used with soils that have a high *in situ* strength, like till. The operation begins with the excavation of a small full bench, below the elevation of the planned road location. The excavated material is normally sidecast, as the small volume does not usually create an unstable situation, but it can be end hauled. After completing the first cut bench, the operator moves upslope and builds a slightly larger bench, casting the excavated material onto the lower bench. After the second bench is completed, the process is repeated upslope, which is the road elevation. The result is a fill-slope keyed into the hillslope on three or more small benches and only a relatively small amount of oversteepened sidecast. Water control is key. Drainage from culverts and waterbars must be carried over the fill-slopes by half culverts, to avoid saturating the fill.

Full-benching/end-hauling

Full-benching is a construction method which should be used in conjunction with end-hauling. A bench is cut into the rock or soil equal to the width of the road. None of the road surface is built on the fill. Where the soils are unsuitable for backcasting or where slopes are extremely steep, then end-hauling of the excavated material must be done.

End-hauling is trucking the excavated material to a more stable dump site. It is a very expensive option, costing on average four to seven times the cost of normal road construction, and therefore it should be used judiciously. However, full-benching, without end-hauling on steep slopes, is a sure recipe for sidecast failure.

End-hauling can also result in landslides if disposal sites are not well chosen. Natural benches with shallow soils, saddles, and broad gully sides are suitable. All proposed fill sites must be field examined, especially those near gullies, before construction. Dump sites that are underlain by thick duff layers will often fail at surprisingly low angles once the organic material decomposes and becomes saturated. End-haul material that contains a lot of slash or logs will become progressively more unstable as the wood rots.

There are some situations, however, in which full-benching and end-hauling should **not** be used:

UNSTABLE ROCK, especially soft sedimentary rock, is not suitable for full-bench cuts. The large excavation required for full-benching removes toe support and can result in a landslide initiating above the road.
DEEP SOFT CLAY SOILS, such as lacustrine or marine soils, are also not suitable for full benches and may induce rotational failures.

EXCESSIVE LOADING of clay or silt soils at an end haul dump site could cause a bearing capacity failure in the subsoil.

Balanced benching or backcasting are more suitable techniques for soft clay or rock materials.

Cut bank stability

The optimum cut slope ratio is a matter of tradeoffs:

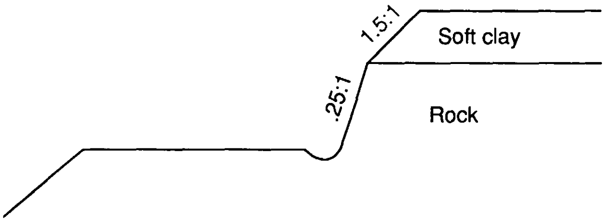
Advantages of steep cut bank	Disadvantages of steep cut bank
1. Less right-of-way	1. Difficult to revegetate
2. Less excavated material	2. Prone to ravel and ditch plugging
3. Less sidecast	3. Prone to tension cracks
4. Shorter slope exposed to erosion	4. Slightly more risk of a rotational failure

Steep cut bank slopes are usually preferable to gently sloping cut banks on temporary roads that will be permanently deactivated after hauling. The disadvantages of steep cut banks can be reduced if high banks are avoided. The maximum cut slope angle and the maximum bank height at that angle is a function of the soil strength and drainage. As soil material type is a good indicator of expected soil strength, it is possible to prescribe typical **cut slope ratios** for each soil type.

Material	Horizontal:vertical cut slope
Till	.25:1 to 1:1
Soft rock	.5:1 (benched)
Sandy or gravel alluvium	1:1 to 1.5:1
Bouldery glaciofluvial	.5:1 to 1.5:1
Lacustrine or marine	1:1 to 2:1
Hard-rock	.25:1 (benched)

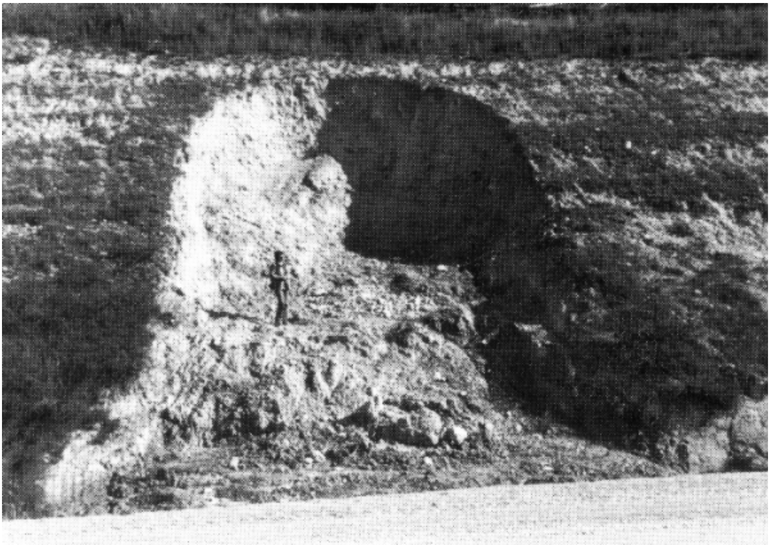
Cut slope ratios

When two different materials are present, one on top of another, the cut slope ratio should be varied, where possible, to take advantage of steeper slopes.



Cut bank stability is not affected by the slope angle of the natural hillslope, provided the soil is free draining. That is, a 3 m high, 0.5:1.0 cut bank is just as stable on a 45% hillslope as it is on a 70% hillslope.

Excavation of cut bank material can, in some instances, cause rotational failures above the road, if toe support is removed. Large rotational failures are most common in deep, poorly consolidated materials such as marine or lacustrine soils or in soft rock. Care should be taken that there are no signs of instability immediately upslope of the road right-of-way.



A rotational slump in lacustrine soils caused by removal of toe support

3.2.2 Road Drainage

Most road-related failures are usually the result of excessive sidecast or problems in the road drainage network. Failures in the road drainage system can lead to saturation of the subgrade of the road or the sidecast material, which reduces effective soil strength and increases the risk of a slope failure. If the ditch flow breaches the road, it can quickly saturate or erode the fill slope, causing a possible slope failure.

Drainage construction practices that are conducive to landslides include:

LACK of ditches, or inadequately sized or poorly maintained ditches
CULVERTS that are spaced too far apart, are poorly located, are not maintained, or are undersized
PROBLEMS associated with discharge points of culverts and ditches

Ditches

Well-constructed and maintained ditches are a real key to long-term stability of a road. Backhoe construction is superior to cat construction in that the ditch can be cut out of the subgrade rather than gouged out of the cut slope. Excavation from the cut slope usually results in an over steepened cut section that subsequently slumps into the ditch. Backhoes can also use the excavated ditch material in the ballast rather than sidecasting it.

The full flow water surface for roadway ditches should be at least 30 cm below the roadway subgrade, plus an allowance for anticipated sediment deposition. This position will prevent ditch water from entering the ballast material, removing the fines and destroying the effectiveness of the ballast. A deep ditch also allows rapid drainage of the subgrade, which reduces the build-up of high water pressures and helps maintain high soil strength. Where ditches are formed from ballast rather than cut into the subgrade, the water can pond in the ditch, saturating rather than draining the subgrade.

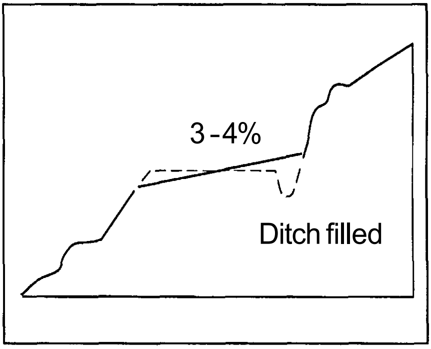
The gradient of ditches is largely determined by the gradient of the road. It should be a minimum 1.5%, to ensure a minimum full-flow velocity of 1 m/sec to permit sediment transport (self-cleaning).

Flat-bottomed ditches are hydraulically superior and less subject to scour than V-shaped ditches. A minimum width of 1 m is recommended.

Ditch maintenance is critical to preventing road failures. Ditches should be inspected after any heavy runoff and pulled if necessary. Relatively minor blockages can lead to spectacular erosion and landslides. Slash that could block culverts should be removed.

Outsloping

In some situations it is very difficult to keep a ditch open. If a cut bank is continually sloughing, or if regular ditch maintenance is not possible, it may be preferrable to outslope the road 3-4%, or place outsloped swales at grade breaks. Unmaintained ditches can pond drainage to over-saturate the soil, causing failure. With outsloping, water ponding is prevented and excessive pore-pressure development at any one point is avoided.



Outsloping road

Culvert management

Culverts are directly or indirectly responsible for a large number of landslides and gully washouts. Problems include:

IMPROPER SPACING
POOR LOCATION
UNDERSIZED
BLOCKAGE
CASCADING DISCHARGE

SPACING AND LOCATION

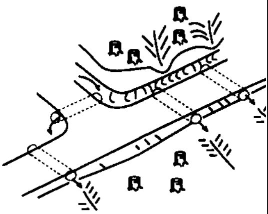
Improper spacing causes concentration of water at a single point, quickly saturating the hillslope.

Place culverts in every natural gully, seepageway, and stream (seasonal and continuous). Put culverts in all dips of the road that will not drain naturally.

Install additional crossdrain culverts to drain ditches and minimize erosion; maximum 150 m apart on grades over 10% and 230 m apart on grades under 10%.

Install additional culverts at road junctions to avoid concentrating drainage in a single ditch system. Do not divert drainage from one watershed into another!

Avoid culvert discharges onto a deep soil or fractured rock that shows any signs of instability. Extend the ditchline to a natural channel.

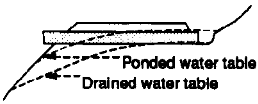


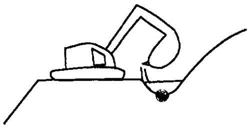
CULVERT SIZE

Undersized culverts can cause water ponding and fill-slope saturation.

Culverts must be able to pass the 50-year flood on mainlines and the 25-year flood on secondary roads.

Metal culverts must be a minimum of 50 cm and wooden culverts no smaller than 100 x 50 cm.

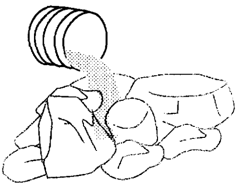




CULVERT MAINTENANCE

Blocked culverts can cause ponding, saturation of the fill-slope, and breaching of the road.

Blocked culverts are more often a problem than are undersized culverts and must be regularly cleaned. Trash racks can reduce maintenance in chronic debris streams.

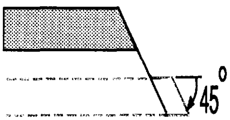


OUTFALL

Cascading outfall can erode and undermine the fill-slope.

An apron of coarse rock or riprap installed over the fill-slope can prevent erosion and undercutting. Cull logs or stumps are also useful.

Sloping half-round culverts or neoprene "socks" reduce outfall velocity, although the socks can become flattened in snow areas.

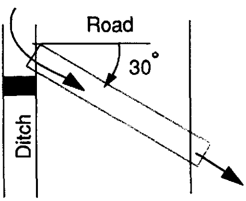


INTAKE

Catch basins constructed at and immediately upstream of culvert openings will reduce turbulence. A basin should be 75-100 cm wider than the ditch and three ditch widths long.

Boulders in the basin will reduce velocity.

Mitred (45°) inlets are less prone to damage and have greater capacity.



STEEP DITCH CULVERTS (>10% GRADIENT)

Maximum spacing = 150 m.

Skew culvert to reduce turbulence and erosion. Angle of intercept between culvert and ditch should be 30° from perpendicular and angled downslope.

Place boulders at and upstream of culvert entrance to slow water velocity.

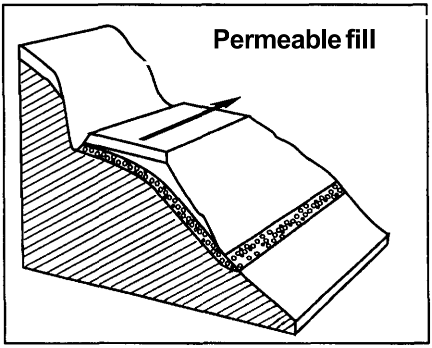
Culvert gradient should not exceed 10%. Use a larger pipe than normal at 10% and flume down the hill.

Install a ditch block.

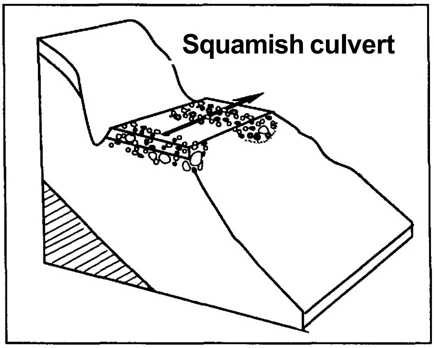
Permeable fills

Embankments built against toe slopes to stabilize a hillslope can impede groundwater flow. Similarly, roads may interfere with natural groundwater paths when a thin permeable soil cover is removed and the road built up onto the rock or impermeable till underneath.

Poor subgrade drainage will also reduce the load-bearing capacity dramatically. Poorly drained, well-graded subgrade will support 50% less weight than well drained soils. In these situations, a drainage path under the embankment for groundwater flow should be constructed. To do so, excavate below the subgrade and use a permeable fill-blanket for the bottom few feet of the embankment. Excavating into the underlying soil "keys" the toe load into the slope as well as ensuring drainage is below the critical failure surface. Use this type of drainage for cut and fill and backcast road construction.

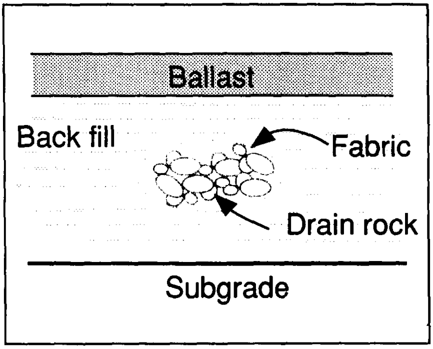


For full-bench road construction requiring a permeable fill subgrade, or where supplies of coarse aggregate are limited, trenches can be cut through the subgrade and backfilled with



gravel (Squamish culverts). The trenches should be about 1 m^2 in cross section and spaced at 5- to 10- m intervals.

A more permanent variant is the “French Drain.” After trenches are excavated, geocloth fabric is laid. The backfill gravel is placed onto fabric and then fabric is folded over top of the drain material. The next step is to backfill and then build a running surface.



French drain

3.2.3 Gully Management

Gullies are particularly susceptible to failure because of their very steep slopes, concentrated seepage, and disturbed vegetative cover. Logging and road building further increase the level of instability; debris flows often initiate where roads cross steep gully headwalls, or from logged gully sidewalls and headwalls.

Road building and yarding activities in gullies that can destabilize the gully include the following:

DEEP ROAD CUTS are often necessary in gullies because of the very steep slope and the deep soils. Sidecasting of the excavated material will oversteepen and overload the lower slope. In soft soils, cut bank failures can also occur.

YARDING can scour gully sidewalls, particularly where cross-gully yarding is practiced. This may destabilize a gully sidewall, initiating a failure or resulting in increased siltation.
LOG BREAKAGE is common during falling along gully sides and during cross-gully yarding. Large amounts of slash can accumulate in the gully bottom. This material increases the volume of any debris flow initiating upslope.

Preventative measures to reduce the incidence of debris flow in gullies can be taken at various stages of harvesting:

Avoidance of unstable gullies

Use the previous sections on site assessment of gully stability to determine the hazard of road building or harvesting. The characteristics of unstable gullies are summarized below:

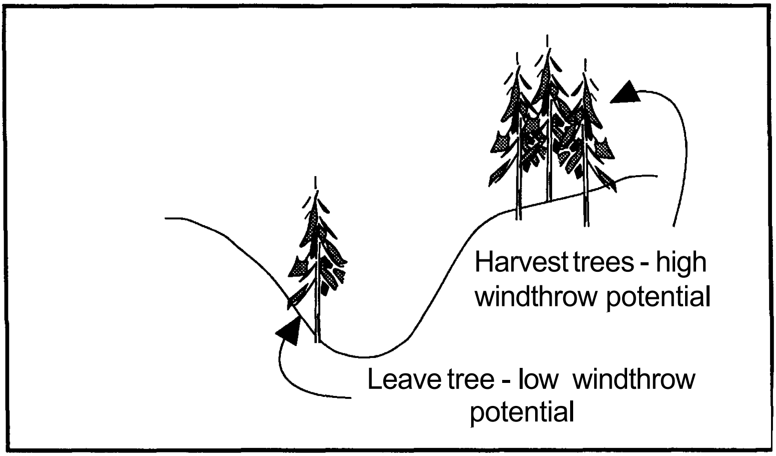
GULLY SIDEWALLS steeper than 70%
GULLY CHANNEL steeper than 45%
DEEP MATERIALS in gully sidewalls
WET SOILS and lots of seepage
SIDEWALL SLUMPS and debris slides
DISTURBED VEGETATION PATTERNS
COMMON WINDTHROW
OVERSIZED FANS at toe of gully

Buffer strips

Buffer strips are areas of intact or selectively cut forest maintained around a gully. Narrow buffer strips around gullies are **only** recommended where the windthrow hazard is not high. Windthrow occurring around an unstable gully will often trigger a landslide and will certainly contribute to the volume of a debris flow. If windthrow is a potential problem either:

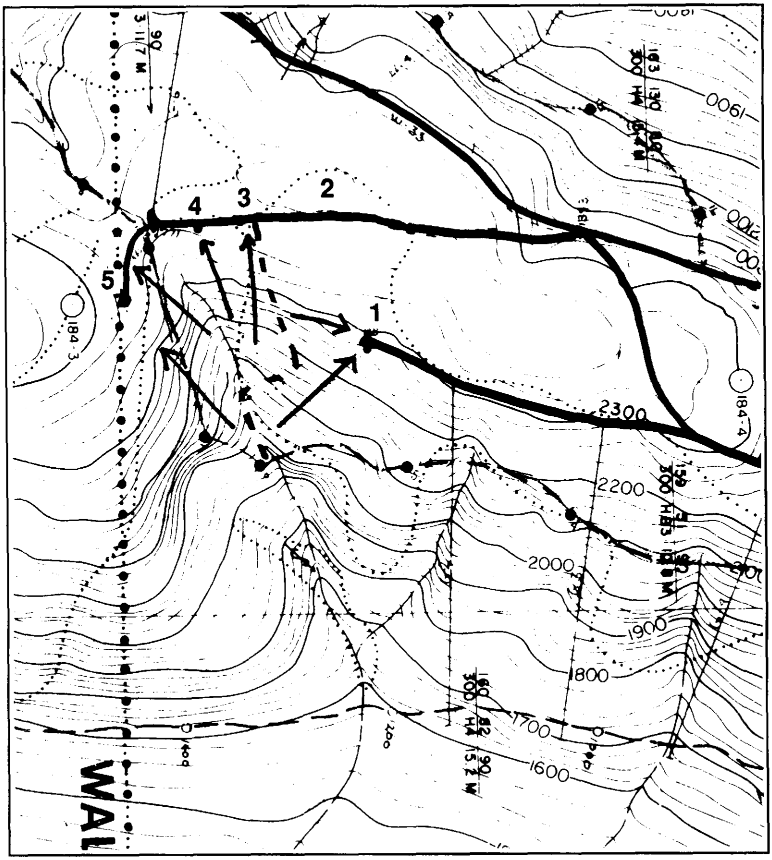
- **leave a large area** around the entire gully complex, or
- **harvest the entire gully** and accept the risk of a possible debris flow, or
- **selectively harvest and leave** those trees that are significantly taller than the topographic break, and hence will have no protection from the wind. Extensive thinning of the buffer stand is not recommended, however, as this can open the entire stand to windthrow.

Buffer strips should be at least the width of the tallest tree in the buffer strip to be effective. It is usually possible to cut a narrow corridor through the buffer strip, for limited yarding of trees on the far side of the gully.



Buffer strip

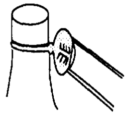
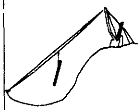
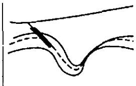
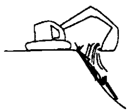
USE DEFLECTION LINES to establish the road and landing location so that maximum deflection will occur over the sensitive sites.
ESTABLISH GULLIES as setting boundaries. Gullies in the middle of the clearcut mean that hundreds of logs are yarded across them. Soil disturbance levels in gullies are directly related to total log traffic over the yarding road.
ESTABLISH LANDING LOCATIONS so that yarding will take place away from the gully. Avoid cross-gully yarding as much as possible.
THE PREFERRED METHOD of logging gullies is to construct a road above the headwaters and to grapple yard straight up the gully to landings along the top road. In the example on the following page, it is possible to highlead the entire headwater area from landing (1), but only by cross-stream yarding. If the road is developed (2), the same area can be logged but wood is yarded up the gullies to landings (3), (4), and (5).



Falling

Directionally fall along the slopes to minimize the accumulation of wood debris in the gullies.

Yarding

Avoid yarding sensitive sites in heavy rainfall months. Yarding disturbance or guyline stress may trigger slides during wet weather.	
For guylines, a minimum stump size of 0.8 m diameter is needed to reduce the incidence of stump pullout. Avoid securing guylines to any stumps located on soils with high water tables. Multiple stumps can be strung together. **Rockbolts may be an option** in rock-lined gullies, where large trees are rare.	
Use full or partial suspension whenever possible. Avoid using two chokers hooked end to end.	
Buck oversized logs, as they are particularly prone to gully disturbance.	
Logs hooked in the centre are unstable and disturb the soil more than logs hooked at one end.	
Do not pull out logs imbedded in the channel. They store considerable amounts of sediment and act to stabilize the channel. Also **leave windthrown trees** in the channel.	
On steep landing locations, clean off debris regularly, but avoid overloading the slopes below with accumulated debris.	

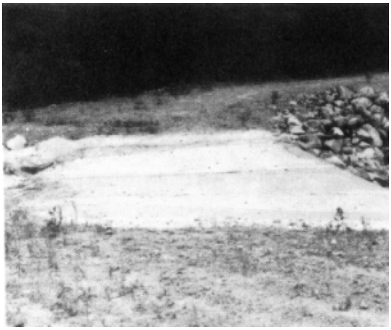
Sacrificial bridges

Bridges across the channel or fan of a gully prone to debris flows should be designed to have either a very high clearance or to be "sacrificial." Most debris flows occur in a series of sediment pulses. Even relatively light bridges are capable of stopping the smaller pulses, causing an in-filling of the channel and a buildup of material behind the bridge. Subsequent pulses will be diverted out of the channel, possibly into buildings or along roads. The bridge may eventually fail under the increasing load, releasing a large destructive volume of material.

Sacrificial bridges should not be designed to be an obstacle to debris flows. Lightweight bridges with at least 4 m clearance will allow minor flows to pass. The more infrequent, large and rapid flows will destroy them without losing momentum. If the bridge stringers are anchored at one abutment by cables, the stringers will be thrown aside but will not become part of the flow.

Fords

Fords are fill or concrete structures built in contact with the creekbed so that vehicles can cross the gully. Examples are the permeable trench drains of coarse cobbles and boulders. Low summer flows seep through the fill; high winter discharges flow over the top. During extreme events or debris flows, the ford will be washed out.



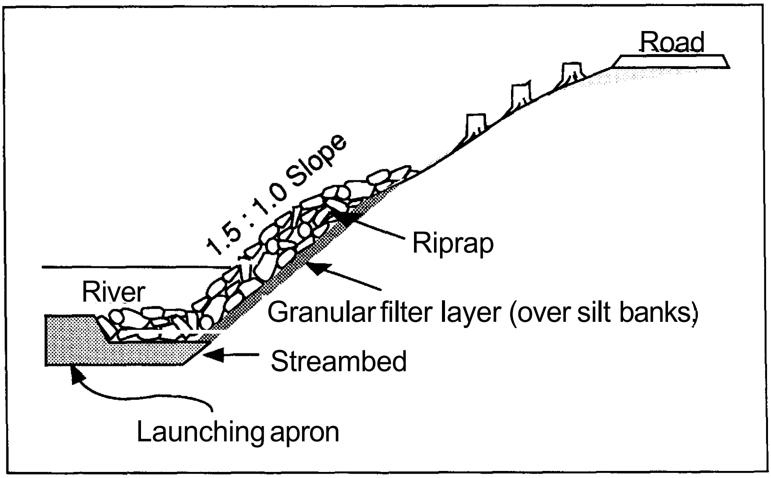
More permanent fords can be made of erosion-resistant concrete dish-shaped structures that will pass both water and debris. Problems can occur with water erosion around the edges of the structure, leaving an impassable elevated ford.

3.2.4 Riprap Revetments

Many valley bottom roads parallel rivers. Where the riverbank sides are steep; or where fill material from the road extends into the river, there is always the danger of material eroding from the toe of the slope. This will reduce the stability of the slope by reducing the resisting forces.

The best method for slope stabilization along rivers is riprapping the toe of the slope. Riprap is relatively easy to construct and is effective on many types of eroding banks. Heavy riprapping keyed into the slope acts as a permeable toe buttress, increasing resistance to failure. Minimum riprap size may be estimated from the largest boulders in the streambed. Where rock of the right size is not available, gabions or wire mesh baskets can be constructed and filled with boulders.

The design recommendations illustrated below and given on the following page should be followed in laying a slope supporting riprap:



Riprap revetment

EXCAVATE into the riverbed to key the riprap into the slope
SLOPES of the riverbank should be cut to a 1.5:1 slope for increased stability before the rock is placed
EXTEND the layer 1 m of elevation above the expected high water level
PLACE riprap, do not just dump it over the bank
INSTALL, where banks are fine textured, a gravel filter before the riprap

3.3 STABILIZATION

The previous sections described the forces that tend to cause failure and those that resist failure. All landslide prevention and slope stabilization methods act on one or more of these forces. There are, in fact, only **four basic methods that can be used to improve slope stability:**

UNLOADING the head of the slope
DRAINING groundwater
LOADING the toe of the slope
SHIFTING the position of the potential failure surface

The stability of any slope will be improved if these actions are carried out. To be effective, however, the most important controlling process must be identified, and the appropriate technique applied to a sufficient level to reduce the influence of that process. There is no point, for example, in installing drainage pipe into a slope which has very little groundwater. The treatment must be designed to fit the condition of the specific slope under study.

Slope stabilization either takes place during construction, when a road must cross an unstable slope, or when stability problems develop unexpectedly following construction. Many slope engineering techniques require a detailed analysis of soil properties and a sound knowledge of soil and rock mechanics. **In any high-risk situation, where a landslide may endanger lives or property, the forest engineer must consult with a geotechnical engineer before any stabilizing work is undertaken.**

Click here for next page

The purpose of this section is to illustrate some of the stabilizing techniques that are available. The emphasis is on simple methods that can be used safely without detailed soil analysis in low-risk situations.

3.3.1 Excavation

Excavation is the removal of soil from the head of a slide to reduce the driving force and thereby improve stability. **This method is only suitable for cuts into deep soil where rotational failures may occur.** It is ineffective on planar failures on "infinite" slopes, or on flow type landslides.

Excavation techniques that can be used to increase slope stability are:

REMOVING the entire slide mass
REDUCING the height of the slope
BACKFILLING with lightweight material
CONSTRUCTING benches
FLATTENING the slope angle

Excavation of slide mass

In some situations, removing the entire slide mass is an effective and economic solution. Generally, however, it is only practical on small slumps or small rotational failures. Large-scale excavation of larger landslide areas is usually not recommended for several reasons:

IT CAN BE INEFFECTIVE on large planar failures
IT MAY TRIGGER A LARGER LANDSLIDE by removing toe support
IT MAY DESTABILIZE the slide further upslope by undercutting
IN DEEPER SOILS, especially soft clays, where there are two potential failure surfaces, one deep and one shallow, excavation down to the first failure surface could trigger a sudden slippage on the deeper failure surface. A stability analysis using soil strength data is necessary for any major excavation project in deep clay.

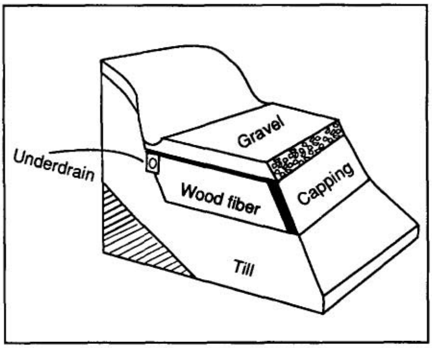
Reducing the height of the slope

Height reduction in a cutbank reduces the driving force on the failure plane by reducing the weight of the soil mass. It usually involves the construction of an access road above the main road and creation of a lower slope by excavation. It is also possible to excavate deeply and lower the main road surface if the right-of-way crosses the upper part of a landslide (see section on Cuts and Fills).

This method is only moderately efficient in increasing stability; it usually increases the Factor of Safety by only 10 or 15%.

Lightweight backfills

A related technique to height reduction is to excavate the upper soil and replace it with a lightweight backfill material such as woodchips, hog fuel, or logging slash. Once blanketed with a thin layer of coarse aggregate, the backfilled material can form a foundation for limited-use traffic.



Lightweight backfills

Benches

Benches are "steps" cut into a deep soil or rock face in an attempt to reduce the driving forces. They can reduce the incidence of shallow failures, but are generally not very efficient in improving the overall slope stability, for which other methods are recommended.

Benches are most useful in providing protection structures beneath rockfall-prone cliffs, controlling surface drainage, or providing a work area for installing drainpipe.

3.3.2 Slope Drainage

Groundwater is probably the most important single contributor to landslide initiation. Not surprisingly, therefore, adequate drainage of water is the most important element of a slope stabilization scheme, for both existing and potential landslides. Drainage is effective because it increases the strength of the soil and reduces the weight of the sliding mass.

Drainage can be either surface or subsurface. Surface drainage measures require minimal design and costs, and have large stability benefits. They are recommended on any potential or existing slide.

The two objectives of surface drainage are to prevent erosion of the face, reducing the potential for surface slumping, and to prevent infiltration of water into the soil, thereby reducing groundwater pressures.

Subsurface drainage is also effective, but can be relatively expensive. It is therefore essential that groundwater be identified as a cause of the slide before subsurface methods are used.

The various methods of drainage include:

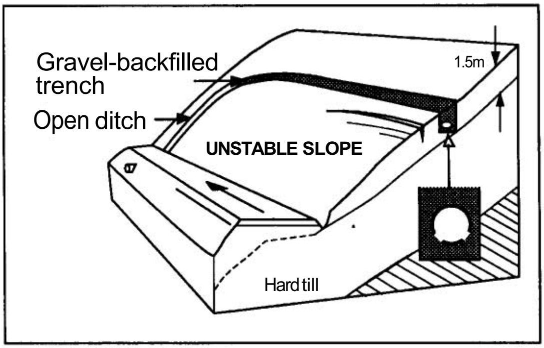
Site leveling

Smoothing the microtopography of the slide surface can prevent surface water from ponding or connecting with the groundwater. Any depressions on the slope that will contain standing water must be removed. Infilling and sealing large cracks in the soil surface by grading the soil mass is beneficial, as it prevents surface water from reaching the failure plane.

Ditches and drains

Surface drainage can be through either surface ditches or shallow subsurface drains. Surface drainage is especially important at the top of the slide, where a system of cutoff ditches across the headwall of the slide, and lateral drains to lead runoff around the edge of the slide, are desirable. Ditch gradient should be at least 2%, to ensure rapid flow away from the unstable area.

The simplest type of subsurface drain is the lateral trench constructed above an unstable slope. Drainage trenches are only economical for shallow soils overlying bedrock or hard impermeable till. The trenches should be excavated to the base of the shallow soil to intercept any groundwater flow along the failure plane. They are backfilled with coarse gravel to prevent sloughing of the ditch sidewalls. An improvement is to use drain pipe, backfilled with coarse gravel.



Drain trenches

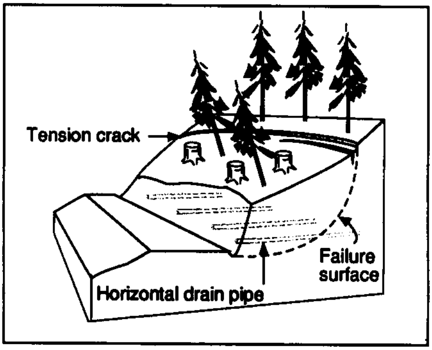
Drainpipe

Horizontal drainpipe is a widely used technique for landslide prevention in highway construction. It is most effective when installed during initial excavation. Because of the long lag-times to lower groundwater tables, the drains are effective only if the pipe is carefully installed, the failure surface is intersected, and the pipe actually drains the soil.

As most slopes have different soil, hydraulic and geometric conditions, drainage systems must be individually designed. The advice of a geotechnical engineer is recommended for any large projects.

The basic approach is to drill holes 5° upward from the horizontal into the slope, using standard drill equipment or continuous flight augers. The holes are drilled near the toe of the cut bank and must be deep enough to intersect the failure surface. A conservative "rule of thumb" in fine-grained soils is to make the length of the drain hole half the height of the slope needing drainage. Spacing and depth of holes depend on individual site conditions and can be determined by trial and error from flow observations. As a rough guide, 5 cm pipe, spaced at 5- to 10-m intervals in clays, or 10- to 15-m intervals in sandy soils, placed in a row as low as possible on the slope, can be effective.

After drilling has been carried out to the desired depth and the casing installed, the latter is cleared of soil and sections of slotted PVC drain pipe are covered with filter cloth, then pushed into the casing and coupled together. The casing is then withdrawn and screen is installed over the end of the drain. Drain holes must be thoroughly cleaned of drill cuttings and mud. Uncleaned holes may be only 25% effective.



Drain pipes

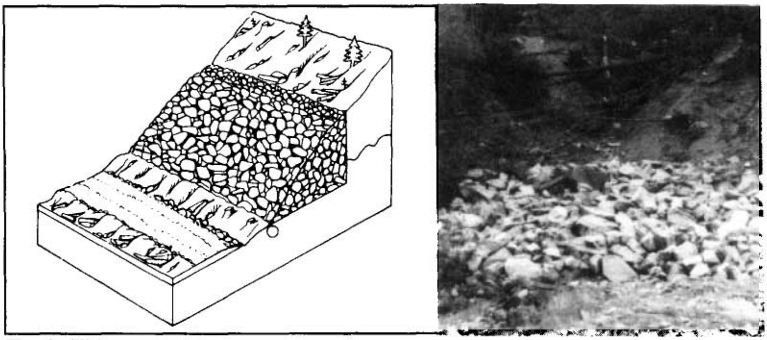
In clay soils, the full change in groundwater tables can take up to 5 years, with 50% of the improvement taking place in the first year. Once water tables are lowered in clay soils, the change is permanent: rainfall events will not alter the groundwater level in the slope provided the drains do not clog. In sandier soils, the groundwater table will lower within a few months but will also fluctuate with rain events.

3.3.3 Rock-fill Buttresses

A simple method to increase slope stability is to increase the weight of the material at the toe, creating a counterforce that resists failure. A berm or buttress of earth fill can simply be dumped onto the toe of the slope. Broken rock or riprap instead of soil is preferable, however, because it has a greater frictional resistance to shear and is also free draining, reducing problems with the plugging of groundwater flow.

Rock-filled buttresses are most effective when the natural soil is excavated below the potential failure surface and the excavation backfilled with the rock. This forces the failure circle to occur either through the stronger rock fill or along a deeper failure surface that is more resistant to failure.

This method requires considerable volumes of fill. The volume of rock-filled berms or buttresses should equal one-quarter to one-third of the unstable soil mass. If earth fills are used, then the volume should be increased to between one-third and one-half of the potential landslide volume.



Rock-fill buttresses

3.3.4 Retaining Walls

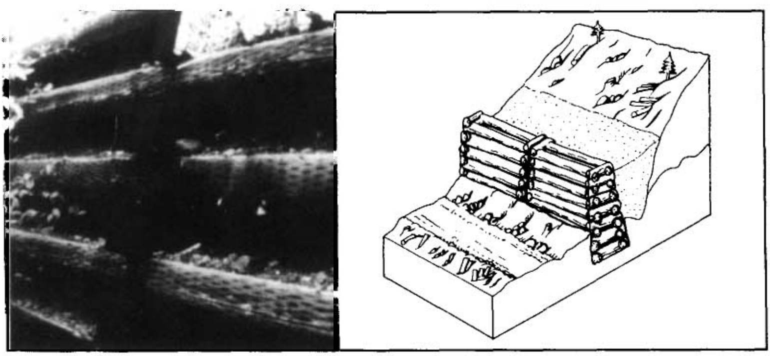
Retaining walls are structures built to support a soil mass permanently. They are used whenever space requirements make it impractical to slope the side of the excavation, or to prevent sloughing of loose hillslope soils onto the road. They are also used to prevent toe erosion by river scour. They **cannot,** however, be used to stop landslides.

There are several basic types of wall: timber crib, steel bin, pile, cantilever, sheet pile, plastic mesh, and reinforced earth. Each has advantages in certain situations, but cost is usually what determines which is used.

For all types of retaining walls, adequate drainage through the structure is essential because very high groundwater pressure can build up behind any retaining wall, leading to its failure. Drainage can be provided simply with a coarse backfill and foundation material.

Timber crib

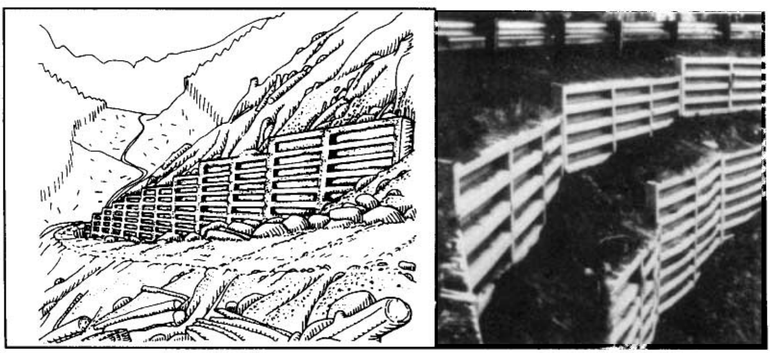
Timber crib walls are box structures built of interlocking logs and backfilled with coarse aggregate. They work by intersecting the critical sliding surface, thus forcing the potential failure surface to a deeper, less critical depth. The structure must be able to withstand: 1) shearing, 2) overturning, and 3) sliding at the base. It must, therefore, be strongly built and buried to sufficient depth, and extend deep enough to intersect the critical failure plane. Crib walls are only effective where the volume of soil to be stabilized is relatively small. They are most efficient where a thin layer of unstable soil overlies a deeper, more stable layer of soil. Crib wall structures should have a volume equal to 10-15% of the volume of the soil to be stabilized. This relatively small volume provides little counterweight support at the toe and, therefore, virtually the entire resistance to failure comes from the strength of the crib.



Timber crib

Steel bin wall

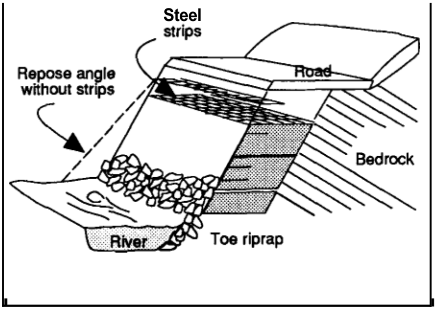
A steel bin wall is formed from corrugated galvanized steel components bolted together to form a box, and then filled with earth. The stability of a gravity wall is due to the weight of the wall itself, perhaps aided by the weight of soil in front of the wall. The bulk of the weight is from the contained soil, not the steel, and this should be kept in mind when the foundation is prepared. Large walls must be individually engineered, with load and foundation requirements calculated. Design charts have been prepared, which provide stringer specifications and height-to-width ratios for typical loading conditions. The widths of walls generally vary from 2-5 m and are one-half to three-fifths the height of the wall. To provide additional sliding resistance, the foot of the wall is usually 0.5-1.0 m below grade, although the design should not rely on the additional toe support, as it can erode or inadvertently be removed. The Factor of Safety is improved if the wall is at a 1:6 slope. Fill material must be well drained and compacted (preferably in 20 cm lifts). Material behind the wall should also be well drained and moderately compacted.



Steel bin wall

Reinforced earth walls

Reinforced Earth is a patented system for constructing fills at very steep to vertical angles without the use of supporting structures at the face of the fill. The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.



Reinforced earth walls

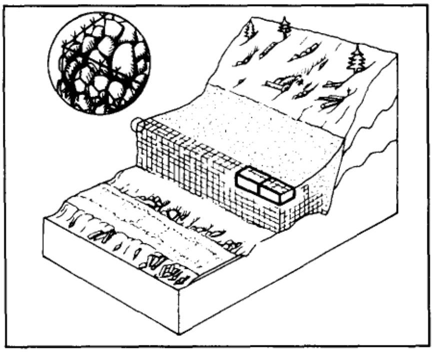
The reinforcing strips are made of galvanized steel. The number and dimensions of the strips are determined by the height of the structure. For routine applications, the length is 80% of the wall height. The strips are attached only to the facing material, which is usually elliptical galvanized steel, concrete panels, or gabions. The backfill material must be granular and well drained, ideally ranging from sand to gravel, 8 cm in size.

Gabion walls

Gabions are wire mesh boxes filled with cobble- sized rock (10-20 cm in size). A gabion retaining wall can be constructed from stacked gabions.

Gabion walls are relatively inexpensive and are easy and quick to construct. Because they are very flexible and can withstand foundation movement, they do not require elaborate foundation preparation; and because of their coarse fill, they are very permeable, providing excellent drainage.

Gabion walls work because the friction between the individual gabion rows is very high, as is the friction between the basal row and the underlying soil. If failure occurs, it is almost always in the foundation soil itself. Three-tiered walls up to 2.5 m high can usually be constructed without the need for any detailed engineering. Higher walls are very heavy and need larger basal foundations and possibly counterforts to brace the wall. Gabion walls built on clay soils require counterforts, which can be constructed as gabion headers extending from the front of the wall to beyond the slip circle. The counterforts serve as both structural members and as drains.



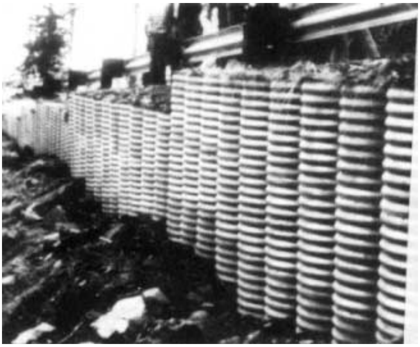
Gabion wall

Design charts are available for various combinations of hillslope angle and retaining wall height. The advice of a civil engineer is needed on any walls higher than 3 m, or those in difficult foundation soils.

3.3.5 Piles

Large diameter piles can be driven into the toe of a slope to form a closely spaced vertical pile wall. Pile walls are normally used as a pre-excavation restraint system, in front of which cut slope excavation takes place.

While large diameter concrete pile and culvert pile walls have been used successfully on highways, small diameter wood or steel piles have not. For most earth or rock movement, wood piles are incapable of providing adequate shearing resistance. They are only recommended where the volume of soil to be stabilized is small. Roughly, one wood pile is necessary for every 50 m^3 of soil, which is inefficient for large stabilization projects. Fewer piles can result in toppling or breakage by the moving soil mass, as well as soil movement between the piles.



Concrete-filled culvert pile wall

A major limitation with log piles is depth, as many failure surfaces occur below the length of the piles. Wood piles are best suited for shallow soil failures over deeper stable soils. The piles must extend below the potential failure surface and be driven into firm subsoil. If the depth of placement is not sufficient to allow the piles to act as a cantilever system, then the piles must be tied back with an anchor system.

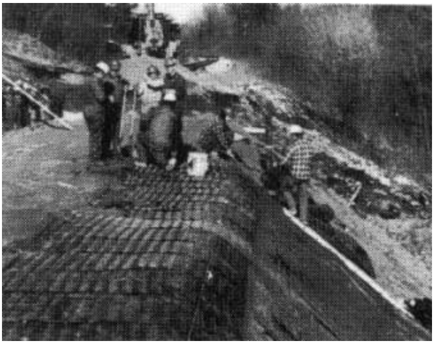
3.3.6 Plastic Mesh Reinforcement (Geogrid)

Geogrid is a synthetic soil reinforcement material, manufactured out of a stretched sheet of polymer plastic to form a lightweight, high tensile strength grid. The grid acts similarly to reinforcing mesh in concrete, adding strength to the shear strength of the soil.

The traditional use of geogrids has been to reduce the amount of ballast needed over soft ground by increasing the bearing capacity of the subsoil. Geogrids also have a number of possible applications in slope stabilization, including:

SOIL STRENGTH reinforcement
SOIL DRAINAGE improvement
RETAINING WALL construction

A fill slope can be constructed at a much steeper angle with geogrid because it increases the overall soil strength. Construction of a reinforced slope requires placing horizontal layers of geogrid on a compacted soil layer, followed by the next layer of fill. The number and spacing of geogrid layers depend on the steepness of the slope and the type of soil. Design charts and emplacement procedures are available from the manufacturers. On average, a layer is used about every 0.5-0.75 m, with short intermediate layers used in certain situations.



Geogrid mesh reinforcement

Geogrid emplacement is difficult in normal cut and fill road construction on steep ground. Apart from the construction difficulties, geogrids may not always work because the failure plane for sidecast slides is often in the intact soil beneath the fill. A "three bench construction" method (Section 3.2.1), backed up by geogrid reinforcement, will work under exceptional circumstances.

A more useful application may be for valley bottom roads pinched between a stream and a rock bluff. The geogrid allows a very steep fill slope to be constructed, preventing sidecast ravelling into the stream. The cost of the geogrid and the specialized construction will be partly offset by reduced end haul costs.

3.3.7 Check Dams

Check dams are small sediment storage dams built in the channels of steep gullies to stabilize the channel bed. They are commonly used in Europe and Japan to control channelized debris flow frequency and volume. A less common use of check dams is to control ravelling and shallow slides in the source area of debris slides. Check dams are expensive to construct and therefore are usually only built where important installations, such as a camp or unique spawning area, lie downslope.

Channelized debris flows are associated with channel gradients over 25 degrees and obtain most of their volume by scouring the channel bed. Check dams serve three purposes when installed in the channels. They:

REDUCE THE INCIDENCE OF FAILURE by reducing the channel gradient in the upper channel.
REDUCE THE VOLUME of channel-stored material by preventing downcutting of the channel with subsequent gully sidewall destabilization, and by providing toe support to the gully slopes.
STORE debris flow sediment, when installed in the lower part of the channel.

When installed on debris slides, the dams store ravelled material which eventually creates small terraces on the slide, reducing the surface slope. Check dams can be constructed of reinforced concrete or log cribs. Concrete mortared rock dams do not usually exceed 8 m in height, while log crib and mortared stone dams must not exceed 2 m. The spacing of dams depends on channel gradient and dam height according to the formula:

$$\text{Spacing} = \frac{\text{dam height}}{\text{tangent (original channel gradient } \phi \text{ - back filled channel gradient } \alpha\square\square}$$

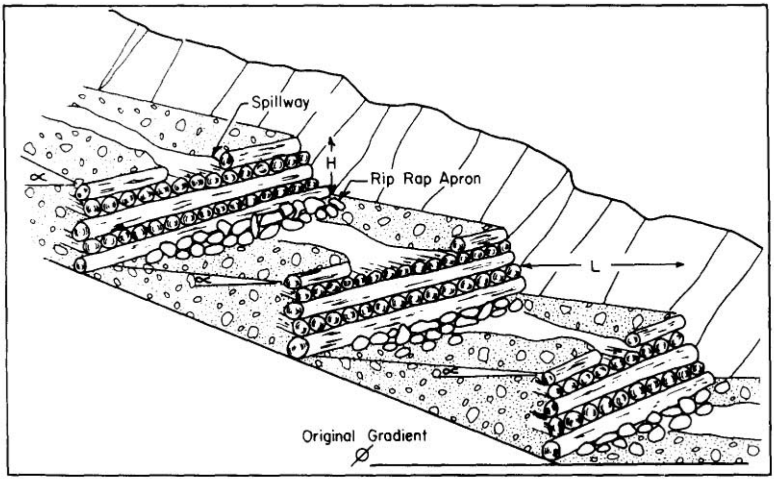
For example, a 2- m high dam in a 20 degree channel with 10 degree sloping channel infill will be spaced every 12 m.

Lateral stream erosion and scour by spillway water are the main causes of check dam failure. During construction, the concrete wing walls and log crib ends must be tied securely into the canyon wall and stream bed to withstand backfill pressures and lateral scour. Wingwalls should slope at about 70% and extend a minimum of 1-2 meters into the banks. The foundation of the dam should have a minimum width of one-third the total height of the dam and be deeper than any scour holes likely to develop.

Concrete check dam in steep stream

Rock and mortar check dams on ravelling debris slide

Every check dam must have a spillway large enough to handle peak flows and robust enough to withstand bed load scour. A spillway width of at least 1.0 m is recommended for most small streams. A riprap layer at the base of the dam prevents scour.



Crib wall check dam

Backfilling the dam, rather than allowing it to fill naturally, reduces the dynamic loading on the structure and results in a more robust design. The slope of the backfill should be less than one-half the channel gradient. Provided the dams have been back-filled, they will survive a debris torrent. The backfill material will not be scoured either during or after a torrent.

3.3.8 Creek Channel Linings

Channel linings are another means of stabilizing the creek channel and sides. The lining is usually slush grouted by high quality concrete, preferably a reinforced steel fiber mat, to resist abrasion. Protruding boulders are set in the concrete to dissipate the energy of water flow.

Channel linings reduce the incidence and volume of debris flows. They are also effective in maintaining channel alignment upstream of a bridge and protecting the abutments. They are most effective if applied over the entire reach of an unstable channel. Linings are usually much less costly than check dams, especially if a long reach is to be stabilized. Check dams are preferable, however, if the banks are very unstable, because they can be keyed into the bank, providing toe support.

Creek channel linings

3.4 PROTECTION

Protection measures are used whenever there is something valuable downstream (such as a camp, mainline road, or important spawning river) and it is either impossible or too expensive to stabilize the slopes above.

The protection measures described are for rockfall and channelized debris flows. Open-slope failures are very difficult to protect against, necessitating an enormous structure if containment is the goal. Also, since the volume of open-slope landslides is unpredictable, the building of protection structures has to assume the worst case–an expensive proposition.

3.4.1 Channelized Debris Flows

Logging camps or mainline roads may inadvertently be located in the runout zone of channelized debris flows.

The options available are to move the facility to a safer location, or to design protection measures. This decision should be based on the anticipated size and frequency of debris flows, as well as the level of development planned in the watershed. Terrain specialists can advise on these considerations.

Before any protection works are built, the upper slopes should be stabilized as much as is practical, thereby reducing the risk of a flow occurring. A sound option is to postpone logging the watershed until the last year of camp use.

The methods available for debris flow protection are debris racks, berms, dykes, and channel excavations and catch basins.

All of these methods require geotechnical expertise to determine size, location, and spacing of the structures. Design should be entrusted to a geotechnical engineer who has modeling facilities.

Runout zone prediction

Channelized debris flows have enormous amounts of energy. It is nearly impossible to try to stop them in the channel. Virtually all debris flows begin to stop flowing naturally when two conditions are met:

1. Flow becomes non-channelized on at least one side.

2. The stream channel gradient is less than 10-15 degrees.

The destructive scouring phase of the flow will not usually extend more than 200 m past this point. Deposition can occur well beyond this point, however, depending on the volume and water content of the flow.

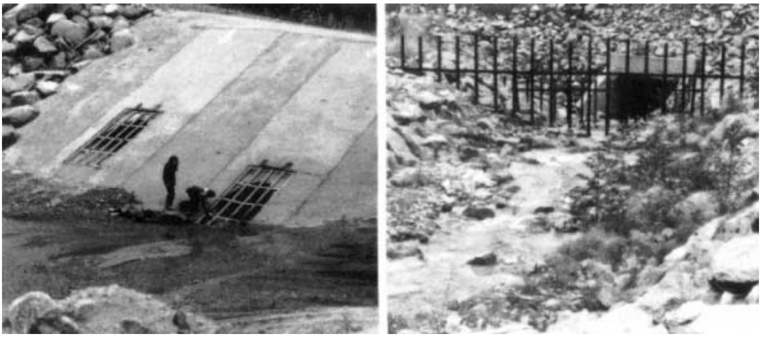
Another method of predicting runout is to look at fan deposits from old debris flows. Debris flows out of the same valley tend to have similar volumes and runout distances. Future debris flows usually will not extend far beyond the old fans.

Debris racks

Debris racks are steel fences built into the bed of steep mountain channels. They are installed immediately upstream of the road and are cemented into the bed and sides of the channel. The racks typically are constructed of welded steel railway rail. Their main function is to catch large pieces of wood that flow down the channel during storms and plug culverts, at the same time allowing the passage of water. When located on the lower part of hillslopes, they can also be surprisingly effective in sieving a lot of woody material out of a debris flow, reducing the magnitude of the flow.

Debris racks should be 1.5-2.0 m high, depending on the size of the channel. They should be grouted into the bed and sides of the channel at an equal depth, and a minimum of 1 m. Debris racks are normally installed 20-50 m upstream of the road; a pair is considerably more effective than one.

Another type of debris rack is a large-mesh steel grate installed over the mouth of the culvert. This is normally used only in conjunction with an upstream rack.



Debris racks require equipment access for cleaning

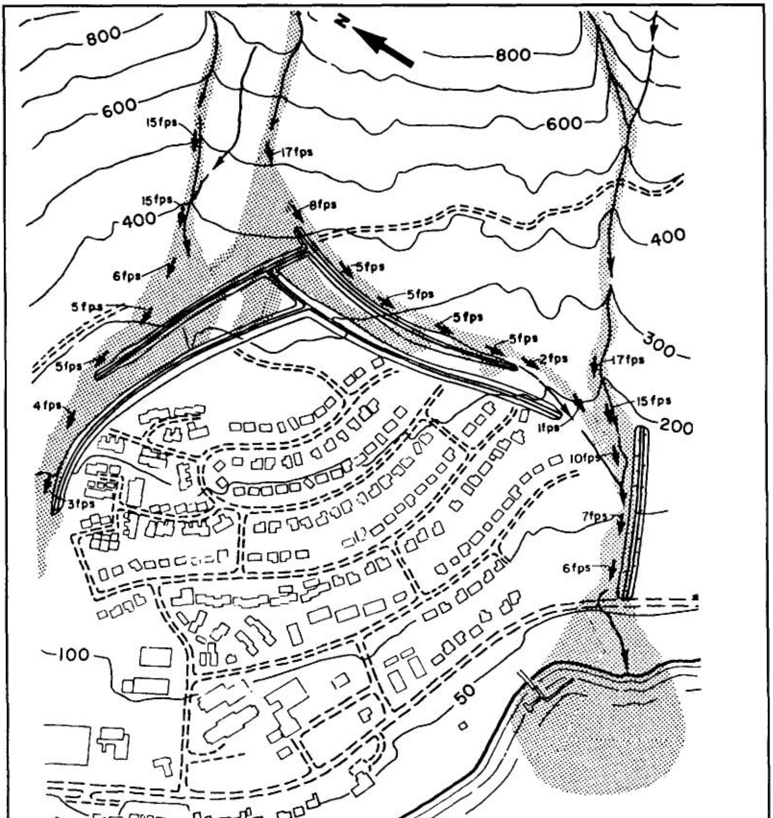
Berms and dykes

Earthfill berms are used to reduce the flow velocity and momentum of a channelized debris flow. A berm is a large deposit of gravel placed below the mouth of a gully. As it is virtually impossible to stop or redirect a channelized flow, the berm should

Earthfill dyke and excavated channel directing flows away from a highway

Click here for next page

be placed beyond the mouth of the gully where flow becomes unconfined on at least one side. The reduced velocity flow should then be guided by earthfill dykes. Earthfill dykes are linear ridges of gravel used to redirect, but not stop, the debris flow. An example of a dyke protection scheme is that developed for the town of Port Alice, B.C. A double system of dykes was used, with the outside set 3 m high and the inside set 1.5 m high to catch any overtopping



Dyking at Port Alice, B.C.
From Canadian Geotechnical Journal 16 (4)

Two parallel systems of dykes deflect debris torrents around the town water or mud. The dyke system was also designed to control flooding, as streams are often diverted from their channel following a debris flow. The tail of the dyke should terminate in a natural drainageway. A layer of riprap along the toe of the dyke will protect against stream bank erosion.

Dyke protection need not be expensive. Material in the fans of former debris torrents make excellent dyke-building material. Plugged channels can be excavated and the material bulldozed up to form dykes.

Channel excavation

Channel excavation is a means of moving the depositional zone further downslope. In the depositional zone, debris flows can blanket a wide area as well as cause flooding, so maintaining the flow around a camp so that the point of deposition is farther downslope can be beneficial.

Deposition of debris flows occurs when the channel becomes unconfined and the gradient drops below about 15 degrees. An excavated channel can therefore maintain confined flow if the channel meets the following requirements:

ITS WIDTH TO DEPTH RATIO is less than approximately 5 for all flows.
IT TAPERS towards the base to allow confinement of smaller flows. Semi-elliptical cross sections are common.
ITS SIDEWALLS are not vertical.
ITS WIDTH IS SUFFICIENT to allow logs to pass without jamming.

ITS SLOPE IS UNIFORM, without sharp bends or sudden changes in cross-section shape.
IT IS LINED with a material such as grouted riprap, or possibly even loose, large size riprap.

Catch basins

A catch basin is a large excavated basin into which a debris flow runs or is directed, and where it quickly dissipates its energy and deposits its load. Abandoned gravel pits or rock quarries can sometimes be used to advantage.

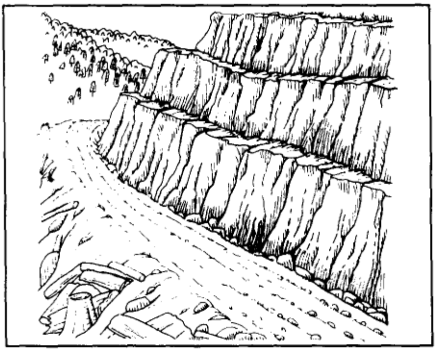
Channel excavation

3.4.2 Rock Slopes

Benches

Horizontal benches excavated into a rock face are the most effective protection from rockfall. Benches not only intercept rockfall, but by reducing tensional forces in the surface rock and reducing surface erosion rates, they also reduce the rate of occurrence of rockfall. However, they have little or no effect on potential deep-seated rock failure.

Individual bench faces can be constructed considerably steeper than the overall slope angle, as any rocks that do fall will remain on the benches. Avoid vertical bench face angles, however, as tension cracks, overhangs and excessive rockfall can result. Bench faces should be terminated at the base of weaker rock layers, fractured rock zones, or water-bearing zones. A minimum width of 4 m is recommended for the benches. All benches should have drainage ditches to divert water away from the rock slope.



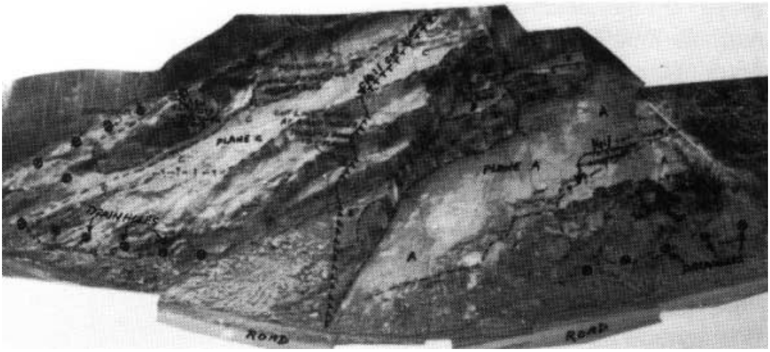
Rock benches

Scaling and trimming

Loose or overhanging blocks of rock, which may endanger passing traffic, can be removed by scaling or trimming. Scaling is the removal of loose blocks by the use of hand pry bars and small explosive charges. Trimming involves drilling and light blasting, followed by scaling, to remove larger areas of overhanging or potentially dangerous rock. The necessity of scaling and trimming can be greatly reduced with the use of controlled blasting.

The adjacent photo shows a typical scaling and trimming plan for a hazardous rock face above a mainline road. Overhanging rock is either removed or trimmed back to a stable face. Note also the large number of drainage drill holes.

Scaling operations are usually carried out by workers on ropes, using pry bars, jacks, and explosives. These operations can be time consuming and expensive (up to \$200/m^3), and on active



A typical scaling and trimming plan for a hazardous rock face

slopes may need to be repeated every few years. For most forest road cuts, a hydraulic boom crane can be used for access to the rock slope, greatly speeding the rate of progress and increasing safety.

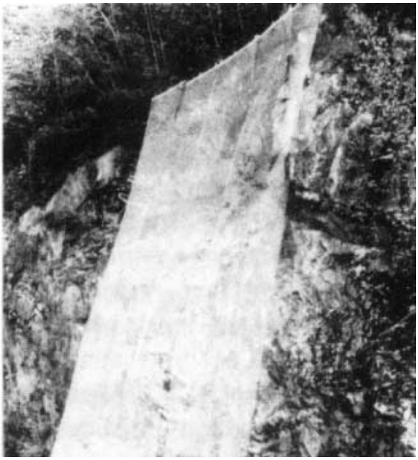
Scaling is dangerous, highly skilled work. Scaling crews should be trained and permanent employees on the road crew, not just casual labourers.

Cable and mesh

Cable lashing and wire nets are simple, economical methods of protecting a road from rockfall.

For large unstable blocks, strands of cable are wrapped around the blocks and anchored to the slope. Where the rock is too fractured to be restrained by individual cables, cable nets or steel ribs can be used to spread the points of contact.

Wire mesh is used to prevent smaller rocks, less than 0.75 m in size, from falling. The standard mesh is double-twisted gabion wire mesh or a heavy gauge chain link. The mesh is either loosely draped over a uniform rock face or bolted where the cliff face is irregular and the mesh can not make close contact with the rock. Bolting the mesh to the rock face often prevents rock from becoming dislodged in the first place, and adds to the overall stability of the slope. Wire mesh is also useful on steep bouldery soil cuts, especially beneath talus slopes.



Mesh over an unstable slope

Catch nets made of cable and wire mesh can be built to catch falling rock at the bottom of gullies and slopes. Suspended from an anchored cable, the mesh forms a flexible barrier to dissipate the energy of the falling rock, and will stop boulders up to 1 m in diameter. Catch nets can also be used in conjunction with roadside catch ditches.

Shotcrete and gunite

Shotcrete and gunite are types of concrete that are applied by air jet directly onto the surface of an unstable rock face. This is a rapid and relatively uncomplicated method commonly used to provide surface reinforcement between blocks of rock and also to reduce weathering and surface scaling. Shotcrete contains aggregate up to 2 cm in size, and is more commonly used than gunite which has smaller aggregate. Both materials can be applied rapidly by air jet, so that large areas can be covered in a short time.

The shotcrete layer bonds with the underlying rock to interlock adjacent loose blocks. The shotcrete envelope itself also has a certain tensile and shear strength, which also reinforces the rock surface. Shotcrete by itself provides no load support, however, so it is not effective against deep-seated rock instability. Structural support can be provided when shotcrete is used in conjunction with rock bolts or wire mesh. It is also useful for providing a more uniform contact surface behind steel straps or anchor beams.

Surface preparation by scaling of all loose rock and cleaning of mud from joints is necessary before the shotcrete is applied. Ideally, the surface should be relatively dry before application, although some mixtures are effective even with wet rock. Shotcrete is usually applied in two layers of 7-10 cm each. The force of the airjet compacts the concrete in place.

Weep holes must be installed at the base of the shotcrete surface to prevent buildup of water pressure in the rock. The holes can be simply drilled after setting, or short sections of plastic pipe can be inserted.

Anchors, bolts, and dowels

Anchors, bolts, and dowels are steel rods or cables that reinforce and tie together a rock face to improve its stability. Anchors are post-tensioned members used to support large blocks of rock, while bolts are shorter and support surface rock. Dowels are similar to bolts but are not post-tensioned.

Reinforcing a rock slope with steel requires specialist knowledge of rock stability analysis, of grouting techniques, and of testing procedures. Determining the orientation of the potential failure surfaces is critical to a successful anchor system. This requires a considerable degree of engineering experience.

Anchors are long pieces of steel rod or cable, grouted into a drilled hole and then tensioned. The reinforcement is therefore from both compressional force on the failure plane, which increases the frictional resistance, and shear force, which resists the downslope movement of the failing block. Anchors are usually used to support an already unstable block of rock, rather than to try to reinforce a slope to prevent instability. Anchors can also be used to reinforce retaining walls, or in some situations, even replace a retaining wall.

Bolts are short pieces of steel, approximately 1 m long, grouted into drilled holes and tensioned. They are used to reinforce the surface rock of an excavated slope. Surface rock failure is usually a result of rock rebound after excavation, or of frost action. By applying a compressive force, bolts stabilize the rock face. The head of the bolt is positioned on either a wide steel plate or a concrete pad. If weathering around the bolt head is a potential problem, then a piece of heavy wire mesh is positioned under the head. Bolts are most effective when installed immediately after excavation, before rebound starts.

Rock bolts on a rock face

Dowels are steel bars that are cemented into bore holes throughout their length. Unlike bolts, they are not post tensioned, and so only the shear resistance is increased across a potential failure plane. Also, dowels reinforce a rock slope only when the slope begins to move. They are most useful on inclined sedimentary beds where interbed sliding may occur. A useful form of dowel, especially in fractured rock, is the perfo-bolt. Perfo-bolts are steel rods encased within a perforated sheet metal liner. The liner is inserted into the hole and, pumped with grout, and then the steel rod is inserted to displace the grout through the perforations, forcing a bond with the rock.

Installation of any steel reinforcement requires good anchorage of the steel beyond the potential failure surface. The steel must have a good bond with the grout and the grout with the rock. The grout pressure must not be so high as to fracture surrounding rock, and probably should not ever exceed 15 pounds per square inch (psi).

Control over the amount of grout spreading is necessary so that it does not impede the natural drainage of the rock slope, particularly along the base of the slope. Adequate anchorage of the steel can be tested during tensioning, but it should also be inspected after installation.

Catch ditches

Falling rock from steep cliffs can endanger passing traffic and block roads. Rock will fall, bounce, or roll down the cliff, depending on the height and shape of the cliff.

Wide catch ditches are effective in containing rockfall, but must be designed in accordance with the cliff geometry. The chart on the next page details the minimum ditch dimensions for various cliff heights and angles.

Rock slope angle	Height (m)	Ditch width (m)	Ditch depth (m)
Near vertical	5-10 10-20 20	3.7 4.6 6.1	1.0 1.2 1.2
0.25 or 0.3:1.0	5-10 10-20 20-30 30	3.7 4.6 6.1 7.6	1.0 1.2 1.8 1.8
0.5:1.0	5-10 10-20 20-30 30	3.7 4.6 6.1 7.6	1.2 1.8 1.8 2.7
0.75:1.0	0-10 10-20 20	3.7 4.6 4.6	1.0 1.2 1.8
1.0:1.0	0-10 10-20 20	3.7 3.7 4.6	1.0 1.5 1.8

Minimum catch ditch dimensions

The bottom of the ditch should be covered with loose earth to prevent falling rock from bouncing or shattering. If there is insufficient space to construct as wide a ditch as is specified, then a combination of a smaller ditch with a gabion or rock wall can be used.

Catch ditch with gabion catch wall

Further Reading for Chapter 3

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CHAPTER 4

EROSION CONTROL: PLANNING, FOREST ROAD DEACTIVATION AND HILLSLOPE REVEGETATION

by

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4.1 EROSION AND SEDIMENT CONTROL PLANNING

Erosion and sediment control problems associated with forest roads and harvesting can often be alleviated or prevented through planning and implementation of an erosion and sediment control plan. Such a plan must be an integral part of forest resource management. There must be a commitment to move erosion and sediment control from a "band-aid" treatment to an active, cost-effective mitigation program.

The time required to prepare an erosion and sediment control plan will depend on the project size, complexity of management concerns and the number of erosion problem sites. A project could cover a short section of road or a complete watershed. Regardless of project size, a plan should include eight components:

Objectives
Inventory of Active and Potential Problem Sites
Priority Assignment
Prescribing Treatment
Cost Estimate and Work Schedule
Training Staff and Operators
Implementing Plan
Monitoring Results

4.1.1 Objectives

Objectives are required prior to embarking on a rehabilitation program. Timber and non-timber resources must be considered. This may require consultation with all interested parties. Some factors to consider are: the risk to human life and property, forest development and management plan for an area, road access requirements, fish habitat protection, water quality concerns, potential slope stability and erosion problems, the integrity and capability of drainage structures, long-term road maintenance requirements, visual impacts and aesthetics, present and future recreational use, and other factors.

4.1.2 Inventory of Active and Potential Problem Sites

An inventory is conducted with the use of air photos and on-site field inspections. All active erosion and potential problem sites are identified, measured, located on a map (1:5000) and catalogued. The source or cause of the erosion problem is located (e.g., water diverted down a road). Also, sediment delivery routes are noted. The information collected during the inventory will help to assign priority ratings and treatment options.

4.1.3 Priority Assignment

A set of criteria should be used to assign priority to sites requiring rehabilitation/mitigative actions. The prioritization criteria must reflect the overall plan objectives, and also the magnitude and immediacy of the problem. Some questions that could be asked to determine high, medium and low priority sites:

- Is an event preventable?
- What is at stake (Consequence): human life, private property, fish habitat, water quality, forest site?
- What is the erosion hazard (High, Moderate, Low)?
- What is the risk (Hazard times Consequences)?
- What is the sediment delivery potential (Sediment Routes, Direct or indirect, Distance)?
- What is the magnitude and potential impact?
- What is the stage of the erosion (Early, Active, Advanced, Revegetated, Stabilized)?

4.1.4 PrescribingTreatment

Some methods and techniques for rehabilitation are presented in sections of Chapter 4. They could be thought of as falling into four categories:

Prevention
Temporary Sediment and Erosion Control
Permanent Sediment and Erosion Control
Biotechnical Slope Protection

Prevention of accelerated erosion in managed watersheds is achieved through the active management of water along forest roads. This is best realized through a planned maintenance program. Intensive maintenance is required before long shutdowns and expected peak flows (i.e., the fall storm season). This will involve road ditch and culvert cleaning and installing of new cross drains on active roads. Roads no longer required for regular use or not maintained will require deactivation (section 4.2). This may involve the removal of bridges and culverts, the construction of fords over seasonal and continuously flowing streams, the placement of water bars and cross ditches, the removal of berms and the re-sloping of the road surface.

Temporary sediment control techniques are used immediately after disturbance to reduce surface erosion and sediment production until permanent control measures are put in place. Temporary techniques often used are silt fences, straw bale barriers, settling ponds, mulches and fast-growing, short-lived cover crops.

Permanent treatments provide long-term sediment and erosion control. Primary consideration is to control surface water flow, create mechanically stable slopes, control surface erosion through the use of grass/legume seeding and promote recolonization of native vegetation. Cover is established through dry seeding or hydroseeding (section 4.3.3). In some situations, re-vegetation mats and netting are used where costs and conditions warrant.

Biotechnical slope stabilization uses woody vegetation and engineering structural support to improve the stability (section 4.3.10). These systems may be simple or complex in design. Experienced personnel are required to design and implement complex systems.

4.1.5 Cost Estimate and Work Schedule

Devising budgets, assigning responsibility and preparing a work schedule is necessary. Some treatment options may routinely be done "in house" whereas other options may require "outside" specialized contractor services. Scheduling will depend on equipment and contractor availability, environmental conditions, treatment options, sequence of treatments and access limitations, operational constraints and budget limitations.

4.1.6 Training Staff and Operators

Training of staff and operators is a must for the successful implementationof a rehabilitation program. Do not leave the implementation of the plan up to untrained staff and equipment operators. Disasters may result in a triggered landslide or ineffective rehabilitation work.

4.1.7 Implementing Plan

Implement the plan as set by project objectives, site priority assignment and work schedule. Flexibility in scheduling must be maintained to ensure optimum conditions at the time of treatment. Clearly indicate to contractors and equipment operators what is required. Provide a sketch of site-specific measures. Mark locations on the ground for rehabilitation works with spray paint or flagging tape. Work site inspections are necessary to ensure that rehabilitation requirements are understood and work specifications met.

4.1.8 Monitoring Results

Monitor the results of a project to ensures success. Determine whether the project has achieved the desired objectives. Check for renewed erosion or instability. Inspect the progress of revegetation. Experience is invaluable for determining what works and what does not work. A successful erosion and sediment control program build on past successes.

4.2 FOREST ROAD DEACTIVATION

Erosion occurs on roads not often used or maintained as a result of water accumulation and diversion onto sensitive slopes. (These roads are referred to as "orphan roads" in Washington State.) A person has only to walk a few inactive roads to discover that culverts and ditches do not maintain themselves. Adequate water dispersal structures designed and constructed when roads are deactivated reduce erosion and prevent the need for large expenditures of funds to rebuild roads for future management use. Water is the critical concern in the design of road drainage structures for active haul roads and in the protection of a deactivated road from surface erosion or mass wasting. Forest engineers must know their areas. The most direct approach is to walk inactive roads assessing erosion and drainage structure adequacy relative to the natural drainage requirements of the watershed. Local experience is invaluable.

4.2.1 Estimating Water Source Area

Knowledge of the water source area (drainage basin) and how roads modify water movement is essential for the design and placement of drainage structures. A drainage basin is a topographically defined area of land draining to a critical point, the basin outlet, which in most cases is a culvert or bridge site. Movement of this critical point up or downstream changes the size of the drainage basin, and hence enlarges or reduces the area draining to the basin outlet. The drainage basin could thus be a few square meters in size, draining to a gully headwall or, farther down the stream channel, it could be a large land area draining many square kilometers.

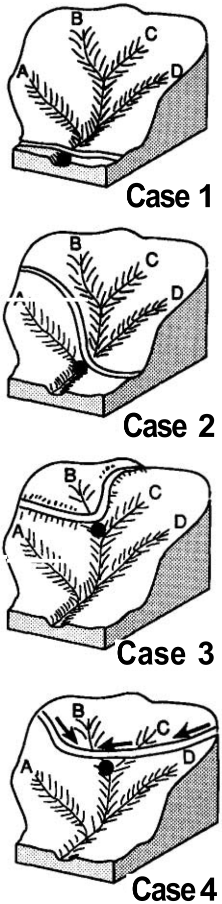
A large drainage basin in mountainous terrain is easily defined topographically, whereas the many small basins 1 ha or less in size may only be identified by an ephemeral stream channel, dips and swales, poorly defined spoon shaped micro-topographic basins, or vegetation changes in ground cover. A road constructed on a hillside intersects many of these poorly defined micro-topographic basins. If cross-drains are not provided, a major redirection of surface and subsurface water runoff down a road to a new critical point could result. This connecting together of many small drainage basins in effect expands the drainage area defined by a single cross-drain. For example, the drainage area to a gully headwall of 0.5 ha in size could be increased to 10 ha by an interconnecting road ditch — a 20-fold increase in drainage basin size.

Calculating the amount of water passing through a single culvert is based on the sum discharges of individual drainage basin areas within the discharge area of the basin outlet.

EXAMPLE:

BASIN	DISCHARGE AREA	DISCHARGE
1.	A+B+C+D	10 m^3
2.	B+C+D	7 m^3
3.	B	2m^3
4.	B+0.7C+0.3D	4.3 m^3

When roads intersect micro-drainages and concentrate discharge into a different drainage, as in Case 4, flow can exceed the normal discharge of the channel and lead to slope failure.



Estimating water source area

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4.2.2 Water Management on Inactive Roads

Roads no longer used for active logging or not regularly maintained require deactivation to provide maintenance-free drainage pathways and slope stabilization. The aim is to reduce erosion and to protect the road investment. The degree of modification to the road prism depends on whether the road will be left open for limited access, (temporary, seasonal deactivation or semi-permanent, rotation deactivation), or whether the road is permanently deactivated (closed permanently). Various techniques are used to deactivate a road: constructing cross-ditches, removing culverts, pulling back unstable fill/sidecast, outsloping roads, removing berms and improving ditches.

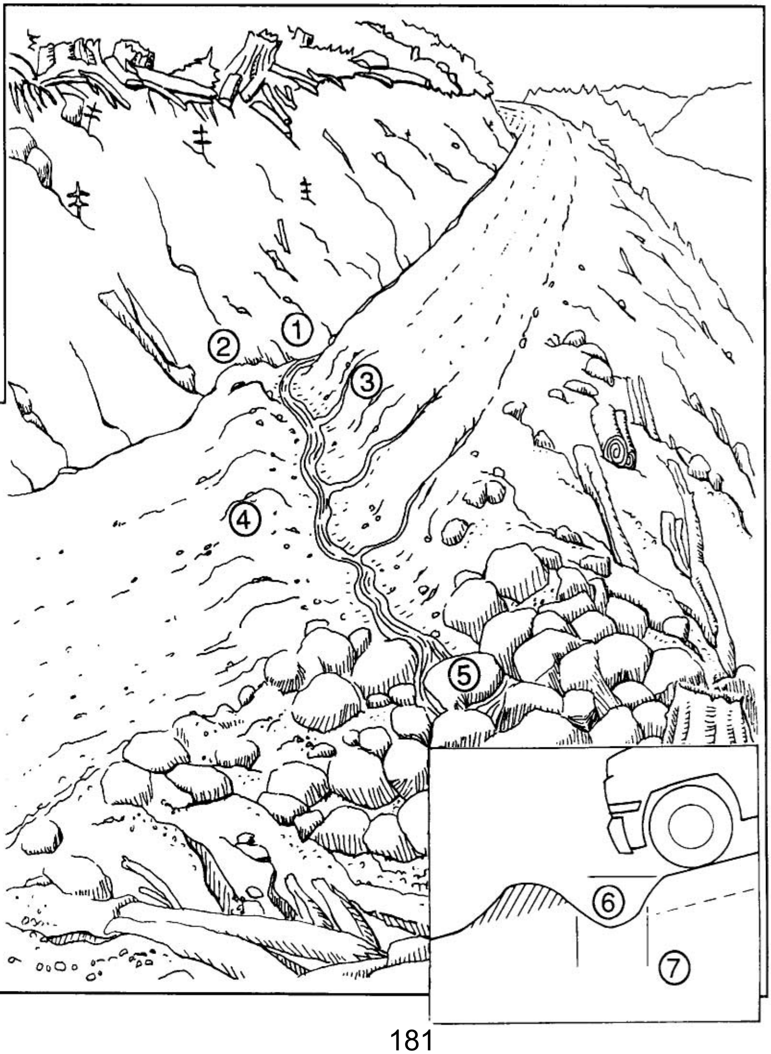
Cross-ditches and water bars

The purpose of a cross-ditch is to intercept, direct and disperse surface water flow off a road and ditch water across a road to a stable site on the downhill side of the road. Very little maintenance is required when cross-ditches are properly constructed, placed in correct locations, spaced closely, or when vehicle traffic is light.

Cross-ditch construction

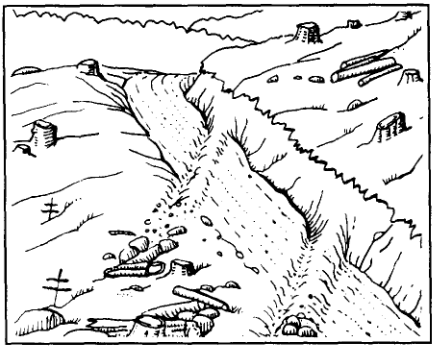
1. The cross-ditch is cut into the road bed from the cut bank or ditch line completely across the road surface, extending beyond the shoulder of the road.
2. Physical blockage of the ditch line down grade from the cross-ditch is required to deflect water flow into the cross-ditch.
3. The cross-ditch should be placed at a minimum skew of 30° to the ditchline – greater on steep road gradients.
4. The excavated material is spread on the downhill grade of the road creating a berm.
5. Water should always be dispersed onto a stable slope with vegetation or rip-rap protection.
6. The cross-ditch berm should dip to allow vehicle cross-over without destroying the ditch.
7. The cross-ditch must be cut to the depth of the ditch line to prevent water ponding and to ensure drainage from the ditch line.
8. Ensure that ditch water is not redirected into different drainage basins.

The purpose of a water bar is to capture and direct road surface water from the road into the ditch line or across the road surface beyond the shoulder of the road. Note: a water bar, unlike a cross-ditch, collects only road surface water and not water flowing down the ditch line.



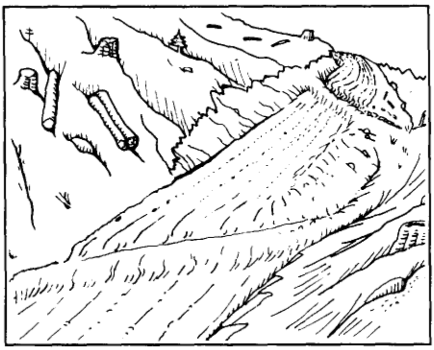
Slope drainage configurations

Various slope drainage configurations exist for cross- ditches. The direction of water flow must conform to the topography or lay of the land.



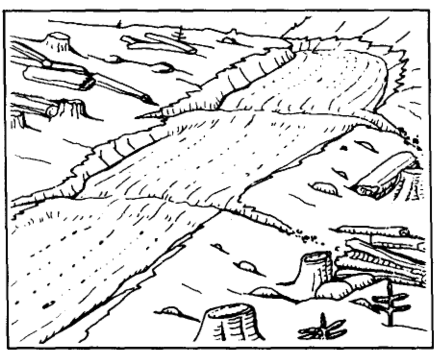
One-way water drainage

- Sidehill or contour cut road.
- Water is drained to one side along the natural hillslope drainage.



Two-way water drainage

- Road constructed in rolling terrain (shifting slope inclination).
- Water is drained to the roadside, dipping to the left or right into sites of natural hillslope drainage.

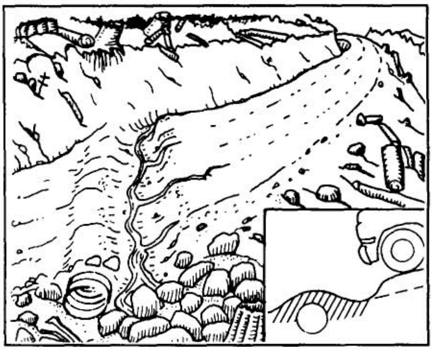


Thru-cut drainage

- Road grade follows the hillslope or cuts through a hillslope. Cut slopes on either side prevent drainage off the road.
- Water run-off on the site can only drain down the ditch line or along the road surface
- Cross-ditches cut in the road and through the cut banks permit water drainage off to either side of the road.

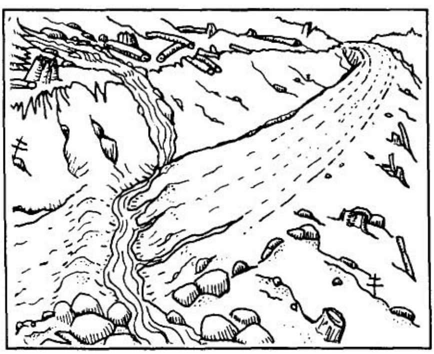
Typical cross-ditch locations

Several locations typically require cross-ditches. These are sites where natural drainage patterns have been disrupted by road construction. The best approach is to simply restore the natural flow patterns and prevent water from entering new channels. Five key locations require cross-ditches: culvert sites, stream crossings, sites where piping is evident, road junctions, and on thru-cuts. Cross-ditch locations should be identified and marked on the ground with flagging tape or, ideally, with spray paint from start to finish. Do not leave cross-ditch locations to the equipment operator's discretion.



Culvert sites

- Construct as a typical cross-ditch.
- Be sure to block culvert.
- Install cross-ditches more frequently than culverts.
- Culvert may be left in if road is to be re-opened shortly, or removed for use at another location.



Subsurface piping or ephemeral streams

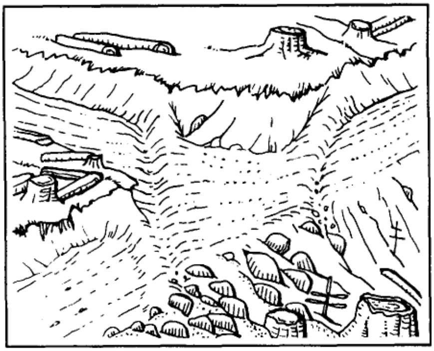
- Locate slightly down grade of a site of subsurface piping or ephemeral stream channel to ensure catchment of flow.
- Ensure that a ditch block is in place.

Thru-cuts and switchbacks

- Design specific drainage solutions for each site.
- Locate cross-ditches on the road grade above the thru-cut.
- General cross-ditch placement in the switchback extends from the lower ditch line at the end of the thru-cut, across the road shoulder.
- Ensure that water is dissipated to a stable site.

Road junctions

- Control drainage from two directions.
- Junctions require specific drainage solutions—several combinations may exist.
- Use typical cross-ditch construction.
- Ensure that drainage is adequate.



Stream fords

- Remove log-bridge or culvert.
- Dig dip to allow vehicle passage (2 WD or 4 WD).
- Riprap stream to reduce erosion.
- Place berm on down-hill side of ford to prevent water jumping the bank.
- Locate a cross-ditch above ford to reduce sediment.

Factors to consider when selecting locations:

LOCATION of natural drainage channels and identifiable water source areas
VOLUME of storm runoff channelized by road: • intercepted ephemeral streams • surface runoff • subsurface seepage and piping • road surface water
DRAINAGE outlets (gullies, streams, depressions)
PREVENT ditchwater redirection into another drainage basin
PRESENCE OF STABLE sites where water can be directed
PRESENCE OF ROLLING dips in road grade already draining water

Cross-ditch spacing

The frequency and spacing of cross-ditches must be matched with the natural drainage requirements of the terrain. There is **no set spacing.** The purpose of a cross-ditch is to prevent channelized water buildup from causing mass wasting or surface erosion. Frequent cross-ditches are optimal since they reduce the volume of water any single ditch must handle and keep the channel's original drainage capacity from being exceeded.

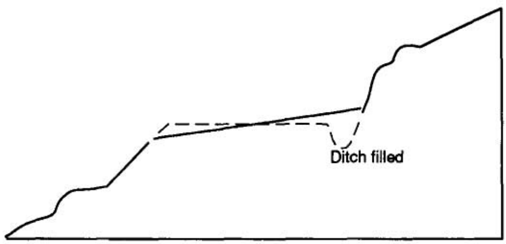
Rule of thumb for cross-ditch spacing

Closer cross-ditch spacing is necessary where: water flow is fastest, as on steeper hillslopes; water volume is greatest, as in mid- to lower positions; and soils are susceptible to erosion. Finer soils are more erodible than coarser, rocky soils.

Controlling water flow by sloping road grades

Outsloped roads

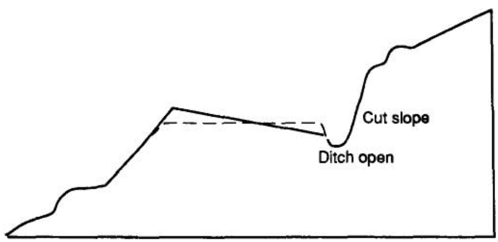
Grading the road surface so it slopes from the cutbank to the road shoulder creates an outsloped surface. Outsloping is effective on road gradients of less than 5% when hillslope gradient is less than 20%. To be effective, the outslope must be sufficient to drain water off the surface, but if visible to the eye, it is too steep for an active road. Outsloping is most effective where cut bank slumping will eventually plug the ditch line. Outsloping reduces the number of cross drains required except where low grades can pond water. Berms must be removed or opened to allow water to flow off the road.



Outsloped road

Insloped roads

Insloping is used along short sections of road to keep road ditch water from flowing onto unstable fill-slopes. The road is sloped inward from the shoulder to the ditch.



Insloped road

Roads permanently closed

Roads constructed for temporary access through unstable terrain are permanently closed after logging. Maintenance costs are too high to keep the road open even for limited access. The conditions where roads normally require permanent deactivation include:

ROADS constructed as spurs
EXTREMELY STEEP SLOPES
INCOMPETENT BEDROCK — no firm bench
EXCESSIVE SIDECAST and fill in unstable positions
POTENTIAL for large fill or sidecast failures
TENSION CRACKS along sections of road
HIGH TO EXTREME landslide or surface erosion hazard
ROAD CONSTRUCTED for temporary access

Before

Note:

- Excessive sidecast
- Incompetent bedrock
- Tension cracks; potential for a large failure
- Lack of adequate drainage
- The presence of seepage water through fill/sidecast
- Organic debris incorporated in fill

After

- Fill and sidecast materials pulled back onto the road surface
- Cutbank overhangs are removed
- Drainage provided to prevent water ponding
- Organic debris removed from fill
- Revegetation undertaken

4.3 SLOPE PROTECTION THROUGH VEGETATION ESTABLISHMENT

Seeding with grasses and legumes reduces surface erosion and helps alleviate site nutritional problems. Planting with shrubs adds vegetative cover and stronger root systems, which in turn enhance slope stability. The prompt reforestation of clearcuts with closely planted vigorous stock assists in the re-establishment of a root network on unstable sites. If not controlled, surface erosion and small shallow slope failures can lead to larger problems which cannot be controlled. Large scale erosion requires applied engineering technology to correct and control. The terms "bioengineering" and "biotechnical slope protection" refer to the use of vegetation and structural slope protection to arrest and prevent slope failure and surface erosion.

4.3.1 Planning

Planning is required for the successful implementation of a revegetation program. Seeding should be an integral part of forestry operations, and not used as an afterthought once soil exposure and erosion occur. Before undertaking seeding ask a person with local experience for advice. Local knowledge based on successes and failures of projects is invaluable.

4.3.2 Site Preparation for Seeding

Seeding is best completed immediately after construction. Rough surface grooves act as miniature checks for seed, fertilizer and rain water, creating a favorable environment for seed germination. However, a slope must be mechanically stable before seeding. This is accomplished by controlling surface water drainage, removing cutbank overhangs, reducing slope angles, and benching.

4.3.3 Seed Application Methods

Two basic methods are used to apply seed:

DRY SEEDING
HYDRAULIC SEEDING

DRY SEEDING is done with rotary disk and air blown seeders. The methods are less costly than hydraulic seeding, but are limited to rough soil surfaces and gentler slopes.

Rotary disk seeders spread seed and fertilizer by centrifugal force. The simplest seeder is a cyclone-type handseeder.

Cyclone handseeder

Larger equipment is adapted for trucks, all-terrain vehicles, and aerial application.

Air blown seeders use air to blow or shoot seed and fertilizer a distance of 5-8 m. Equipment is adapted for trucks and all-terrain vehicles.

Hydraulic seeding

HYDRAULIC SEEDING, or hydroseeding, is the application of seed in a water slurry that contains fertilizer, soil binder, and/

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or mulch. The system requires a mixing tank with mechanical or hydraulic agitation and volume pumping capacity. Hydraulic seeding is effective for seeding slopes 1:1 and steeper, where tacking of the seed to the slope is necessary. Slurry application is from truck-mounted equipment for most applications and helicopters for inaccessible sites. A suspension agent is added to the slurry for helicopter applications that use a conventional dry-seeding bucket. See Appendix 1 for general mixing instructions.

4.3.4 Guidelines for Seeding Method Selection

STEEP SLOPES, high erosion hazard: hydraulic seeding, possibly with a mulch
STEEP SLOPES, medium erosion hazard: hydraulic seeding or dry seeding plus a mulch
GENTLE SLOPES, medium erosion hazard: hydraulic seeding or dry seeding
GENTLE SLOPES, low erosion hazard: dry seeding

4.3.5 Fertilization

Severely disturbed forest soils are generally infertile. Fertilizer applications of nitrogen (N), phosphorous (P), potassium (K), and possibly sulfur (S) are often needed for successful grass-legume establishment and growth.

Fertilization rates vary according to the level of nutrients needed for establishment. Refertilization every 3-5 years may also be needed to maintain plant vigor. A soil test in areas of questionable fertility is recommended before a large rehabilitation program is begun.

GENERAL RULES FOR FERTILIZER USE:
DRY SEED AND FERTILIZER should not be mixed in the same bin: seeds and fertilizer should be separate.
APPLY FERTILIZER at critical locations such as large fills and cut banks, culverts, and bridge sites if supply is limited.
FERTILIZE at the same time as seeding. Cost is minor when compared with total project cost.
USE A COMPLETE FERTILIZER (N-P-K) such as 20-24-15 or 19-19-19 applied at a minimum rate of 200 kg/ha for the initial application.
LEGUMES reduce the need for nitrogen and high nitrogen levels can also inhibit legume establishment.
FERTILIZE every 3-5 years to maintain plant vigor at critical sites and in severely degraded soils.

4.3.6 Seed Mix Criteria

A combination of two to five species is the normal grass-legume mix used for erosion control (sod forming grasses, bunch grasses and legumes). Their suitability depends on soil type, climatic conditions, species compatability, and species replacement. Legumes are always included for nitrogen fixation. Appendix 2 provides examples of a seed mix calculation, calculations for evaluating a seed mixture, and a list of common grasses and legumes used in seed mixes.

Seeding rate

Seeding rate depends on the number of live pure seeds (LPS) per unit weight and not simply on the seed weight. Obtain a seeding rate of 150 - 300 LPS per 1000 cm^2 (35-70 seeds on an area the size of this field guide cover 12.5 x 18.5 cm). This is achieved at a dry seeding rate of about 15-30 kg/ha and seeding rates of 50-80 kg/ha are often used for hydraulic seeding.

Time of seed application

Seed application should begin immediately following disturbance. Seeding should occur a minimum of 6 weeks before periods of drought or damaging frost. Ideal conditions coincide with spring tree planting. Fall seeding is best in areas with summer droughts. Legumes seeded on snow tend to perform poorly. Legumes can take up to 3 years to reach maturity.

ORDERING SEED:
Order percent species by weight (note this is not 100% live seed)
Species certified seed and/or varieties.
Order pre-inoculated coated legume seed to introduce nitrogen-fixing bacteria

DEVELOPING A SEED MIX:
KEEP A MIX SIMPLE: preparing one mix for a specific area is more economical and manageable than attempting to account for all variability in one seed mixture.
GRASS-LEGUME RATIO by live pure seed should be about 70:30 in humid regions and 80:20 in dry regions.

GENERAL MIXES FOR COASTAL ENVIRONMENTS		
Species	**% By weight**	**% Live pure seed**
Creeping red fescue	45	45.4
Annual ryegrass	15	5.9
Orchardgrass	10	8.4
Alsike clover	20	26.9
White clover	10	13.4
Perennial ryegrass	30	8.1
Creeping red fescue	25	16.2
Redtop	5	28.1
Kentucky blue grass	10	21.6
Red clover	20	17.3
Alsike clover	10	8.6
Annual ryegrass	25	6.2
Creeping red fescue	20	13.6
Canada blue grass	10	28.2
Orchard grass	12	6.8
Redtop	3	18.1
Alsike clover	20	18.1
White clover	10	9.0

4.3.7 Soil Binders

Soil binders are made from polymers, seaweed extracts and vegetable gum. They are easily applied by being added to the hydroseeding slurry and are suitable for use in units with hydraulic or mechanical agitation. Binders provide temporary erosion protection by holding seed and surface soil particles together. Application rates are product- and equipment-specific. Refer to specifications before use (range: 10-40 kg of binder per hectare).

4.3.8 Mulch

Mulch is a non-living material spread over the soil surface to provide protection from surface erosion by rain and retention of soil moisture. Various types of mulches are available in the form of straw, grass fibers, wood fibers, seaweed, and paper products. Proper timing of seeding may alleviate the need for mulching.

WOOD-FIBER AND PAPER-FIBER MULCH are used in hydroseeders with mechanical agitation, They provide a relatively inexpensive mulch for critical sites.
SOIL REINFORCEMENT NETTING AND MATTING provide mechanical support to surface soils and may act as a mulch. Various products include jute netting, plastic netting, vexar netting, nylon filament matting, wood fiber matting, and straw matting. Biodegradable mattings break down over a few years adding organic matter to surface soil, while non-biodegradable products do not. Non-biodegradable products remain on and within the soil surface and act as a support matrix for intertwined vegetation roots. Reinforcement materials are most effectively used for specialized erosion control on prepared slopes as a slope blanket or as a ditch liner.

4.3.9 Shrub Establishment

Shrub species selected for use must be indigenous to the area, easily propagated, adaptable to the site, and must be able to produce the desired characteristic (tall or short, browse resistant, deep rooting). Survival rate for planting of unrooted cuttings is 50-70% and rooted cuttings is 90%, provided proper species selection and time of planting are observed.

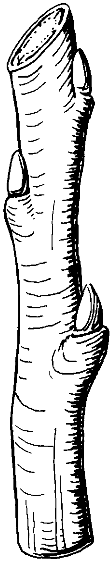
Direct planting of Populus and Salix unrooted cuttings

VEGETATION REQUIREMENTS:

- use dormant native plant's previous season's growth
- must have clean cuts with unsplit ends
- must be straight, healthy and robust

CUTTING PROCEDURES:

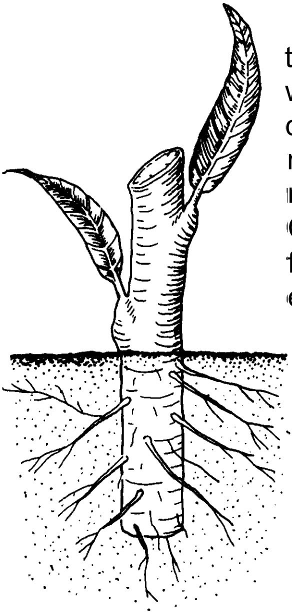
- cut with a sharp knife or good quality shears
- avoid the terminal top 10 cm
- keep length of 15-20 cm or more
- ensure mid-stem diameter is 2 cm minimum
- maintain at least two healthy buds



PLANTING PROCEDURES: Plant in late autumn, in early winter after buds have set (full dormancy), or in spring after snowmelt when moisture stress is low. Planting densities are based on the desired frequency: randomly at selected planting sports; in a grid pattern on a 1 m x 1 m spacing; or with a high plant density in linear rows spaced 2-1 0 m apart.

PLANTING DEPTH: Plant cuttings with as little stem exposed as possible, but still showing at least two buds above ground. A cutting must be firmly planted so that it cannot be readily moved or pulled out. Roots will form along the planted portion of the stem.

Planting of live plants: container or bare-root



LIVE PLANTS propagated from cuttings or seed permit the planting of a wider range of shrub species for erosion control. Plants can be grown by commercial nurseries as container and bare-root stock. The following native British Columbia species have been successfully propagated and are suitable for erosion control:

Rubus spectabilis	*Populus* spp.
Rubus parviflorus	*Cornus sericea*
Vaccinium parvifolium	*Spirea douglasii*
Betula papyrifera	*Symphoricarpos albus*
Holodiscus discolor	*Rosa* spp.
Lonicera involucrata	*Alnus* spp.
Philadelphus lewisii	*Sambucus* spp.
Physocarpus capitatus	*Salix* spp.

PLANTING PROCEDURES: Plant live plants during the **dormant** season, October to March (this may be extended into May-June if moisture stress is not a limiting factor). Frozen ground prevents successful planting in northern latitudes during much of the dormant season.

TAKE PRECAUTIONS to prevent plants from drying out prior to planting.

THE PLANTING SYSTEM will depend on species selection and density desired (random, grid, or linear planting).

4.3.10 Vegetative Methods for Slope Protection and Stabilization

Vegetation protection techniques use live or dead plant parts (stem and branches) which are inserted, driven or buried in the ground to control erosion, minimize shallow sliding, protect erosion control structures, and provide a favorable environment for establishing a permanent vegetative cover. Poplar, willow and red osier dogwood are successfully used. These techniques include:

LIVE STAKING
CONTOUR WATTLING
CONTOUR BRUSH LAYERING

Live staking

PERSISTENT WET AREAS on road cut and fill slopes, and on bare soil surfaces in slumps and earth flows are suitable sites.

FLOORS AND BANKS of small incipient gullies, sediment fill behind check dams, bare gully banks, berms of water bars, and areas just below water-bar outlets.

POROUS REVETMENTS can use live stakes inserted or driven through the interstices or openings in gabions and riprap. This may also help to blend the wall into the landscape.

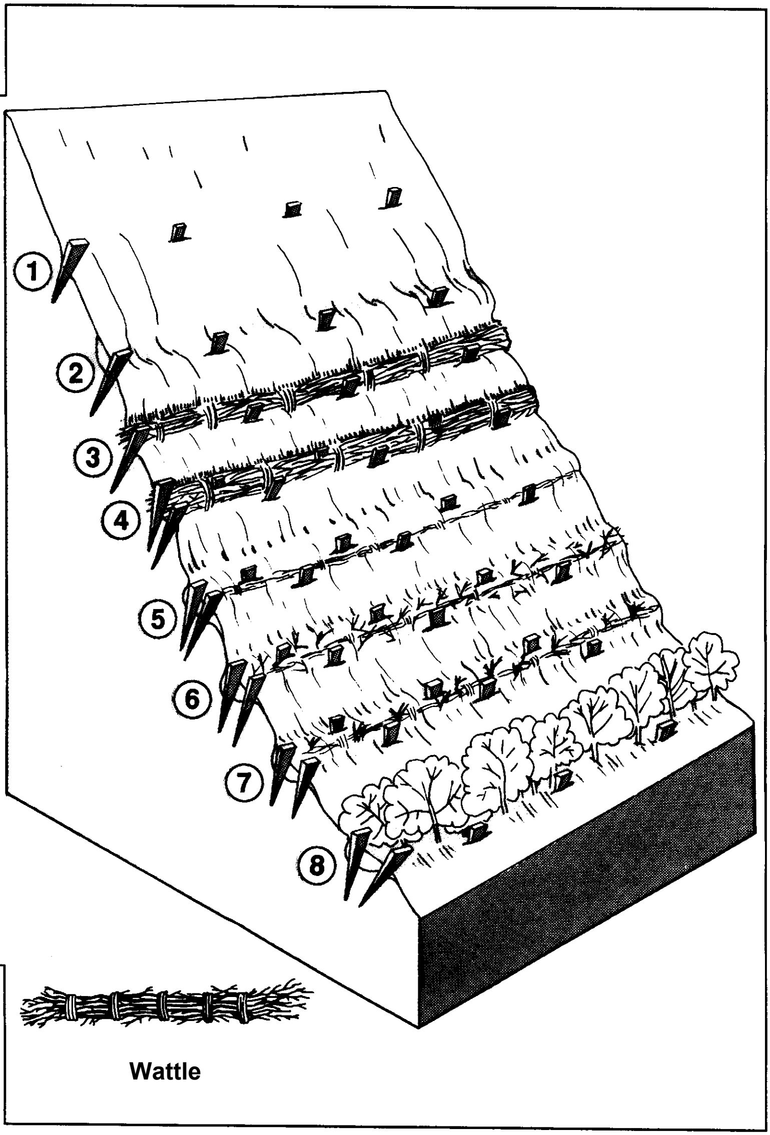
Wattling

Wattling consists of placing bundles of flexible interwoven live branches (the wattle) which root easily, into shallow trenches along consecutive horizontal or diagonal rows on an embankment (cut or fill slope). The wattle stabilizes soil layers (this stabilization effect results from the combined effect of the wattle bundle and stakes), and promotes vegetation establishment. Wattling is most effective on loose surface soil exhibiting sheet or small gully erosion.

WATTLING INSTALLATION

INSTALL WATTLES from the bottom to the top of the slope, spacing them 3-10 m apart. Actual distance apart must be determined on a site-specific basis. The more erodible a slope, the closer the wattles are spaced.

1. **STAKE ON CONTOUR,** using an Abney or Sunto type level. Contour staking is of particular importance on wide slopes with erodible soils. Stakes should be about 40-60 cm long, and driven to a firm hold.
2. **TRENCH ABOVE** the stakes to one-half the diameter of bundles. Material dug from the trench should be wasted downslope to cover lower wattles.
3. **PLACE BUNDLES** in the trench.
4. **STAKE THROUGH THE BUNDLES** close to bundle ties.
5. **COVER THE BUNDLE** with soil and tamp the soil firmly into place. Walk along bundles to add additional tamping.
6. **COMPLETED** wattling resembles a slight terrace with twigs (7-10 cm) protruding along the downslope side.
7. **PARTIALLY BURIED AND STAKED BUNDLES** protect against erosion.
8. **WATTLES ROOT AND SPROUT,** further protecting and stabilizing the slope.



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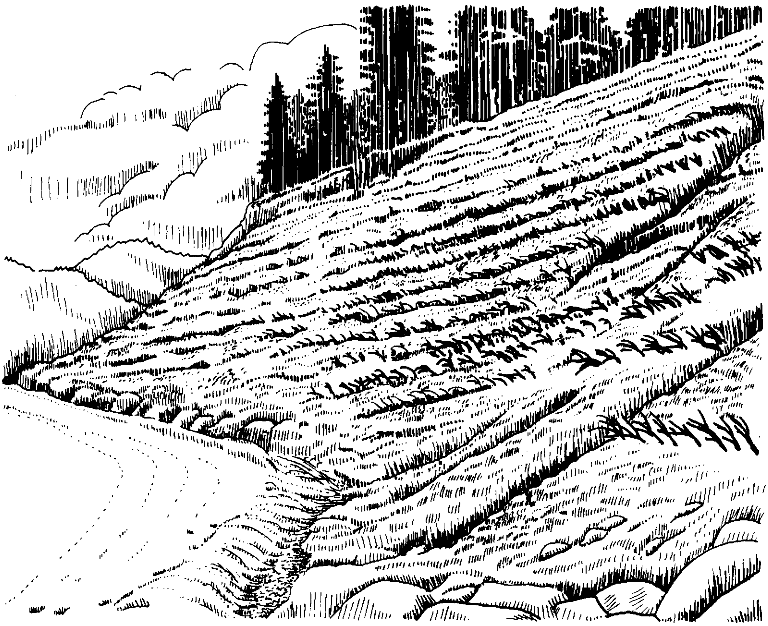
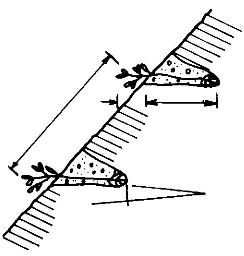
Brush layering construction

Brush layering consists of embedding live branches on successive horizontal rows along contours on the face of a slope. Rooted plants can also be placed among the live branches. The technique is useful for rehabilitating eroded slopes and gullies and for stabilizing fills and embankments during construction.

CONTOUR BRUSH LAYER CONSTRUCTION

- **UNDERTAKE SLOPE PREPARATION,** drainage control and toe wall construction where required.
- **BEGIN WORK** at the bottom of the slope.
- **DIG TERRACES** 50-100 cm wide, manually or with machinery.
- **SPACE TERRACES** about 1 m on steep slopes.
- **ENSURE TERRACES** slope up at least 10°.
- **ENSURE BRANCHES** are at least 1 m long with a mixture of different ages, species thicknesses and length. Branches 2-5 m in length are more effectively used in constructed fills or embankments.
- **PLACE BRANCHES** along the terrace in a crosswise fashion, with only one-quarter to one fifth of their length protruding.
- **PLACE ROOTED PLANTS** 0.5-1.0 m apart among the layer of branches.
- **IN NON-COHESIVE SOILS,** prepare short terrace segments. This helps prevent ditch collapse and soil drying.
- **BACKFILL THE TERRACE DITCH** with material dug for the terrace above.
- **INTERPLANT WITH** shrubs and grass-legume seed.





WATTLE BUNDLE PREPARATION

- **A WATTLE** resembles a cigar-shaped bundle of alternating live branches that root easily, with slender tips extending 40 cm beyond the larger butt ends.
- **BRUSH STEMS** are 5 cm or larger in diameter; 1 m and longer in length (approximately 3 m long is best).
- **THE BUNDLE** is compressed to approximately 20 cm in diameter and tied every 30-40 cm.

SITE SURVEY USE

- **TO DETERMINE** the need for slope preparation.
- **TO DETERMINE** location of suitable plant materials *(Salix* or *Populus* spp.).

SLOPE PREPARATION

- **CONSTRUCT** or repair water drainage structures and ditches.
- **UNDERTAKE** slope rounding or scaling of failing materials.

4.3.11 Gully Stabilization

Gullying is the process of stream downcutting, deepening and widening of the channel, and headcutting or headward extending of the channel. Vegetation removal and increased water flows tend to be major factors contributing to gully destabilization. The main cause for gullying along forest roads can generally be traced back to blocked culverts, inadequate cross drains, or run-off permitted to spill unprotected over cut-banks and fill-slopes. These gully erosion problems, if acted upon immediately, can be stabilized with simple low-cost methods using local materials such as rocks, sandbags, boards, logs and logging slash.

Large V-notch gullies, conduits for debris torrents, become increasingly active after timber removal in headwall areas and along channel sidewalls. Once the triggering effect of debris slide and torrent activity occurs in steep gradient V-notch gullies, the gullies remain destabilized for extended periods of time. Torrent control and vegetation re-establishment in these gullies become sophisticated and costly. Control measures are justified in populated areas, but in the forest environment simple seeding with grasses and legumes is all that can be accomplished to help reduce sedimentation and to aid the natural process of revegetation and eventual pseudo-stabilization.

The goal of gully stabilization is to reduce channel downcutting and headward extension. Vegetation established in the channel and along the sidewalls provides the most permanent control–the long-term solution. Effective gully control is best accomplished using simple "temporary" structures designed for the site, combined with a combination of revegetation techniques.

GULLY STABILIZATION PROCEDURES
ASSESS THE WATER SOURCE. Correct water drainage problems, install adequate road drainage, and redirect water into its natural drainage basin or into stable drainage channels.
DESIGN SIMPLE STRUCTURES. Use local materials, coarse rock, logs, brush, logging slash, sandbags or boards.
CONSULT DESIGN SPECIALISTS for complex problem gullies. Design must consider expected storm flow, slope gradient, and soil erodibility. Designed structures must dissipate energy (water flow), reduce channel downcutting and lateral stream movement, cause suspended material deposition, and permit vegetation re-establishment.
INSTALL A ROCK BLANKET to armor a stream channel and protect the complete wetted perimeter. Rocks must be of sufficient size to stay in place during storm flows.

Simple Gully Stabilization Techniques

Three gully stabilization techniques have been effective in controlling erosion. These include:

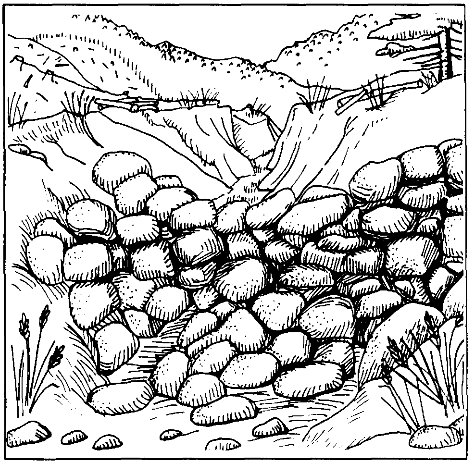
CHECK DAMS
WATER LADDERS
WATER FLUMES

Check Dams

Check dams are most effective on gentle to moderate sloping channels. Considerable design variations do exist, but simple check dam designs with rock, brush and boards should not exceed an effective dam height greater than 1 m.

Rock size in a loose rock check dam must resist displacement from storm flows. In general, large peak flows require large rock. Effective rock gradation at storm flows of less than 1 m^3/sec constitute the following size classes:

- 10-15 cm (25%)
- 15-19 cm (20%)
- 20-30 cm (25%)
- 31-24 cm (30%)



Loose rock check dam

Loose rock can be reinforced with wire, wire mesh, steel posts, and other materials. This reinforcement provides flexibility and strength in the dam to withstand pressures exerted by flows and rocks. Reinforced check dams must follow design specifications. The simple rock structures are not meant for torrent control.

Check dam spacing depends on channel slope gradient. When gully gradient increases, decrease spacing by using additional dams and/or by increasing the height of the dams. (Refer to Chapter 3 for details).

BOARD CHECK DAM INSTALLATION

USE BOARD CHECK DAMS in shallow gullies 1 m or less in depth.

CONSTRUCT DAMS from boards, logs or plywood one or two boards high.

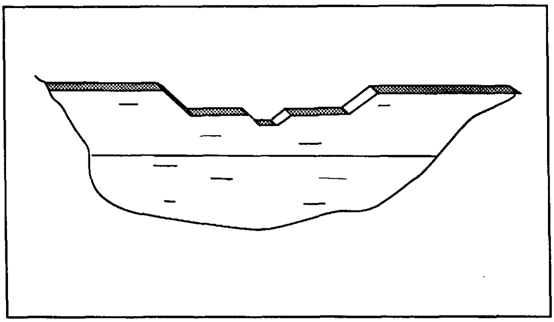
KEY OR INSET the boards or logs in the gully bank and channel a minimum of 25% of the width or depth of the dam to prevent breaching.

STAKE THE BOARDS on the downstream side for additional support.

CUT AN ADEQUATE SPILLWAY NOTCH to accommodate high flows (leave 20 cm minimum distance from the notch to the bank) and low flows (10 cm deep and 15 cm wide).

PLACE ENERGY-DISSIPATING MATERIALS of rock, brush or debris below the spillway and firmly secure to the channel bottom. This apron should extend out from the spillway 30 cm to the next check dam.

REVEGETATE THE SITE with grasses and shrubs.



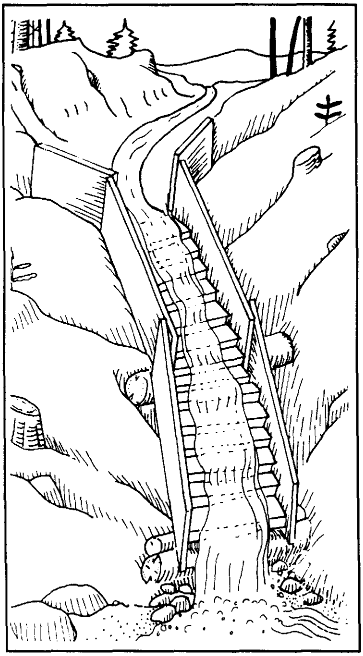
Board check dam

Water Ladder and Water Flumes

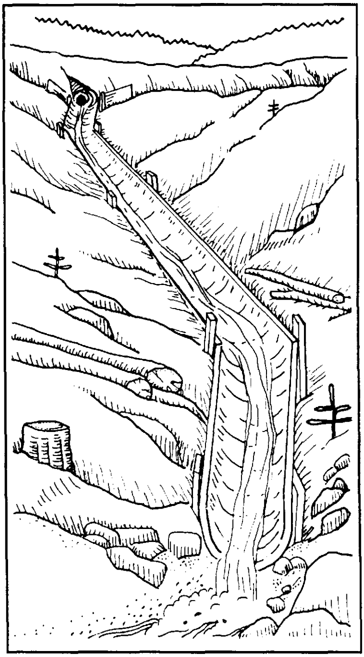
A water ladder is a stair-stepped wooden structure constructed as a staircase flume. A water flume is an analogous structure assembled with half-round metal pipe or half-box to carry water in a chute. Baffles can be added to help dissipate energy.

Water ladders and flumes are most effectively used to direct small volumes of water over steep erodible slopes, to arrest or prevent headward erosion. They are particularly useful when slope gradients are too steep for rock blanket armoring or check dams (cut banks and fill slopes).

When using water ladders or flumes, direct all water into the structure in order for it to function effectively. Wing walls of boards or rock and soil are essential to adequately contain flood flows.



Water ladder



Water flume

When constructing flumes or water ladders, install energy dissipators, such as rock, debris and vegetation, at the flume outlet to prevent channel erosion. Water ladders and flumes can be constructed from locally available materials: boards, logs, flume culverts. It is important to revegetate the site with grass and shrubs following construction.

APPENDIX 1. General hydraulic seeder mixing instructions

1. Mulch must be used only in the proper equipment. Mulch **cannot** be used in hydroseeders providing only hydraulic agitation and should **only** be used in units equipped with strong mechanical agitation. Mulch is applied during the seeding operation or on a second pass, after the seeding operation is completed. Area coverage per tank is reduced by one-half.
2. Mixing requirements and application rates for binders and mulches are product- and equipment-specific. Always refer to the manufacturer's operating instructions.
3. Begin filling the tank with water, under continuous agitation, and add the fertilizer.
4. Start feeding in the soil binder (or mulch). As the tank continues to fill, agitator must be in operation. Slowly add the binder or mulch to avoid lumps.
5. Add the seed last, under continuous agitation.
6. After the tank is full and all materials are added—and before spraying starts—agitation should continue for at least 10 minutes to ensure mixing occurs to a uniform suspension.
7. The nozzle should be operated in a fan-like motion when the slurry is applied, so the material falls gently on the ground surface.
8. Completely flush the tank and pump with clean water after use.

Helicopter hydroseeding application

1. Test-run with water in the seeding bucket to ensure proper application rate. Make sure proper tools are available for adjusting the seed bucket orifice.
2. The hydroseeding slurry should be pre-mixed in a tank with hydraulics or mechanical agitation.
3. General hydraulic seeder mixing instructions apply.
4. Binder or a suspension agent must be added to the slurry if application is to be by conventional dry seeding buckets.
5. Ground coverage is controlled by the helicopter pilot observation of ground wetness.
6. The pre-mix tank should be located a full hose length (30 m) from the helicopter seed bucket filling operation.
7. The helicopter seed bucket is filled from the pre-mixed tank. One large volume hose will make the bucket refill operation fast and efficient.
8. Completely flush tanks and seed bucket with clean water after use.

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APPENDIX 2. Seed mix calculations, mix evaluation and common grasses and legumes

Table 1. An example of a seed mix calculation[a]

(1) Desired species %	(2) kg/ha to yield 300 LPS/ (%÷100)	(3) Seedling rate kg/ha 1000 cm^2	(4) Species by weight (1x2)	(%)
Creeping red fescue	.45	26	11.7	39
Annual rye grass	.15	66	9.9	33
Orchard grass	.10	30	3.0	10
Alsike clover	.20	18	3.6	12
White clover	.10	18	1.8	6
TOTAL	1.0		30.0	100

a

i) Select the species and the desired proportion of the ground cover, Column 1.

ii) Select the yield of live pure seed for Column 2 from Table 1, Column 3 or 4.

iii) Compute seedling rate in Table 2 by multiplying the respective values in Column 1 by Column 2. The summation of Column 3 is the mixture's application rate.

iv) Divide the seeding rate for each species by the total kg/ha (x 100) to obtain the species % by weight, Column 4.

v) Note the difference between the desired species percent, Column 1, and the percentage of various seed by weight in the mixture, Column 4.

Table 2. Evaluating a seed mixture[a]

(1) Mixture[b] % by weight species	(2) LPS/1000 cm² 1 kg/ha + 100 (1x2)	(3) Seed density 1000cm² (Table 1)	(4) LPS at ground 1 kg/ha	(%)
Perennial rye grass	.30	5.1	1.53	8.2
Creeping red fescue	.25	12	3.00	16.2
Redtop[c]	.05	105	5.25	28.3
Kentucky blue grass	.10	40	4.00	21.5
Red clover	.20	16	3.20	17.2
Alsike clover	.10	16	1.60	8.6
TOTAL	1.00		18.58	100.0

a i) Select rate for Column 2 at 1 kg/ha from Table 1.
ii) Obtain seed density (Column 3) by multiplying Column 2 by Column 1.
iii) The percent LPS (Column 4) is obtained by dividing the respective seed density by the total seed density in Column 4.

b Values in Column 1 could use the actual seeding rate kg/ha for each species. Column 1 x Column 2 would thus give the actual seed density (Column 3) for the seed application rate.

c Note for redtop % by weight, Column 1, vs % LPS, Column 4.

Table 3. Some common grasses and legumes used for seeding in British Columbia and the live pure seed ratings

Common Name	Scientific Name	(1) Thousand Seeds/kg	(2) Pure Live Seed per 1 000 cm^2 at 1 kg/ha	(3) Seeding rate to yield 150 PLS/1 000 cm^2 (kg/ha)	(4) Seeding rate to yield 300 PLS/1 000 cm^2 (kg/ha)
Smooth brome	Bromus inermis	275	2.5	60	120
Sainfoin	Onabrychis viciaefolia	40	0.4	375	750
Tall fescue	Festuca arundiunacea	506	5.0	30	60
Birdsfoot trefoil[1]	Lotus corniculatus	1036	10.0	15	30
Perennial lupines[1]	Lupinus corniculatus	48	0.6	250	500
Beardless wheatgrass	Agropyron inerme	297	2.6	58	116
Intermediate wheatgrass	Agropyron intermedium	220	2.2	68	136
Crested wheatgrass	Agropyron cristatum	441	4.2	36	72
Crested wheatgrass	Agropyron desertorum	386	3.7	41	82
Slender wheatgrass	Agropyron trachycaulum	353	3.4	44	88
Streambank wheatgrass	Agropyron riparium	375	3.7	41	82
Siberian wheatgrass	Agropyron sibericum	551	5.2	29	58
Tall wheatgrass	Agropyron elongatum	174	1.7	88	176
Russian wild rye	Elymus junceus	375	3.5	43	86
Alfalfa (Rambler)[1]	Medicago sativa	496	5.3	28	56
Alfalfa (Anik)[1]	Medicago falcata	496	5.3	28	56
Alsike clover[1]	Trifolium repens	1503	16	9	18
Cicer milk vetch	Astragalus cicer	320	3.2	47	94
White clover[1]	Trifolium hybridum	1464	16	9	18
Sweet clover[1]	Melilotus spp.	577	5	30	60
Altai wild rye	Elymus angustus	125	1.2	125	250
Pubescent wheatgrass	Agropyron trichophorum	200	1.9	79	158
Canada bluegrass	Poa compressa	5510	50	3	6
Big bluegrass	Poa ampla	2021	17	9	18
Kentucky bluegrass	Poa pratensis	4752	40	4	8
Redtop	Agrostis alba	11020	105	1	2
Hard fescue	Festuca ovina	1245	11	14	28
Creeping red fescue	Festuca rubra	1355	12	13	26
Meadow foxtail	Alopecurus pratensis	1984	17	9	18
Creeping foxtail	Alopecurus arundinaceus	1984	17	9	18
Orchardgrass	Dactylis glomerata	1190	10	15	30
Annual ryegrass	Lolium multiflorum	478	4.5	33	66
Perennial ryegrass	Lolium perenne	544	5.1	29	78
Reed canarygrass	Phalaris arundinacea	1115	10	15	30
Timothy	Phleum pratense	27	27	6	12

[1] Legume.
[2] Column (3) & (4) The desired number of PLS required per 1000 cm^2 divided by column (1) PLS/1000 cm^2 at 1 kg/ha.

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