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SOIL MASS MOVEMENTS IN THE RENNELL SOUND AREA, QUEEN CHARLOTTE ISLANDS, BRITISH COLUMBIA

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ABSTRACT

Soil mass movements constitute a dominant geomorphic process in Rennell Sound. The area has economically important forest and fisheries resources. Forest harvesting accelerated the natural level of mass wasting. Conflicts between forest and fisheries managers developed. The B.C. Ministry of Forests undertook a research project to provide resource managers with information for decision making. This paper describes the characteristic failure sites and the factors leading to the initiation of mass wasting. Land use practices to reduce the incidence of mass wasting are recommended.

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RESUME

Les déplacements de terrain constituent un processus géomorphologique dominant dans le détroit de Rennell. Les ressources forestières et halieutiques sont économiquement importantes pour la région. La récolte du bois a accéléré le niveau naturel d'érosion en masse. Des conflits sont apparus entre les gestionnaires des pêches et ceux de la forêt. Le Ministry of Forests de la Colombie-Britannique a entrepris un projet de recherche afin de fournir aux gestionnaires des ressources des renseignements permettant de fonder leurs décisions. La présente communicaton décrit les endroits typiques où ont lieu des glissements de terrains et les facteurs menant à l'érosion en masse. On y formule des recommandations pratiques d'utilisation des terres propres à réduire l'incidence de ce type d'érosion de masse.

INTRODUCTION

Mass movements constitute a dominant geomorphic process in areas of steep slopes, high rainfall, strong winds, and seismic activity. They are erosional processes involving the downslope movement of large masses of soil, rock, or debris, primarily under the influence of gravity. The types of mass movement processes described in this report are generally less than 1 meter in depth. Synonyms for these processes are soil mass movements, shallow seated landslides, mass wasting, mass erosion, slides, slope failures, and colloquially, mud slides.

Mass movements are of concern to the forest manager because forest land use practices often accelerate natural levels of instability. Mass movements may result in loss of life, equipment, road investments, and growing sites; degradation of spawning and rearing areas; obstruction to fish passage; and reduction in aesthetic values.

Rennell Sound is located on the west coast of the Queen Charlotte Islands. It is an area with economically important forest and fisheries resources. It is also an area of high natural levels of mass wasting. As forest harvesting progressed to steeper slopes in the late 1960's mass movements became more common in clearcut areas and along forest roads. Forest and fisheries managers were concerned with mass wasting but lacked information for sound decision making. This project was initiated in 1976 to determine characteristic features of failure sites and provide recommendations for forest management.

DESCRIPTION OF THE STUDY AREA

The Rennell Sound study area is located on the west coast of Graham Island, the major northern island of the Queen Charlotte Islands (Figure 1). The area lies along the eastern shores of Rennell Sound and covers 160 square kilometers of forest land.

The study area is located on the western edge of the Skidegate Plateau. The plateau surface is well dissected in the area. Elevation ranges from sea level to 800 meters and hillside slopes range from 20° to 60°. The hillsides are dissected by deep (10-metre plus) V-notch gullies in the bedrock (Figure 2). Gully sidewalls average 45° and headwalls approach 60°.

The general form of the topography was developed prior to the Pleistocene, but it was during the Fraser Glaciation that the bedrock was carved, valleys broadened, slopes steepened, and morainal material spread over much of the area (Sutherland Brown, 1968). Mass movements occur in morainal and colluvial materials, and in bedrock.

Morainal (till) deposits occur as veneers or blankets in valley bottoms, on lower and middle slopes, and along ridges. The till matrix is clay loam to loam. Unweathered till is blue grey in colour, is highly compact and has a low permeability. The contact between weathered and unweathered till is abrupt. Water was observed to flow along this contact. Humic material is

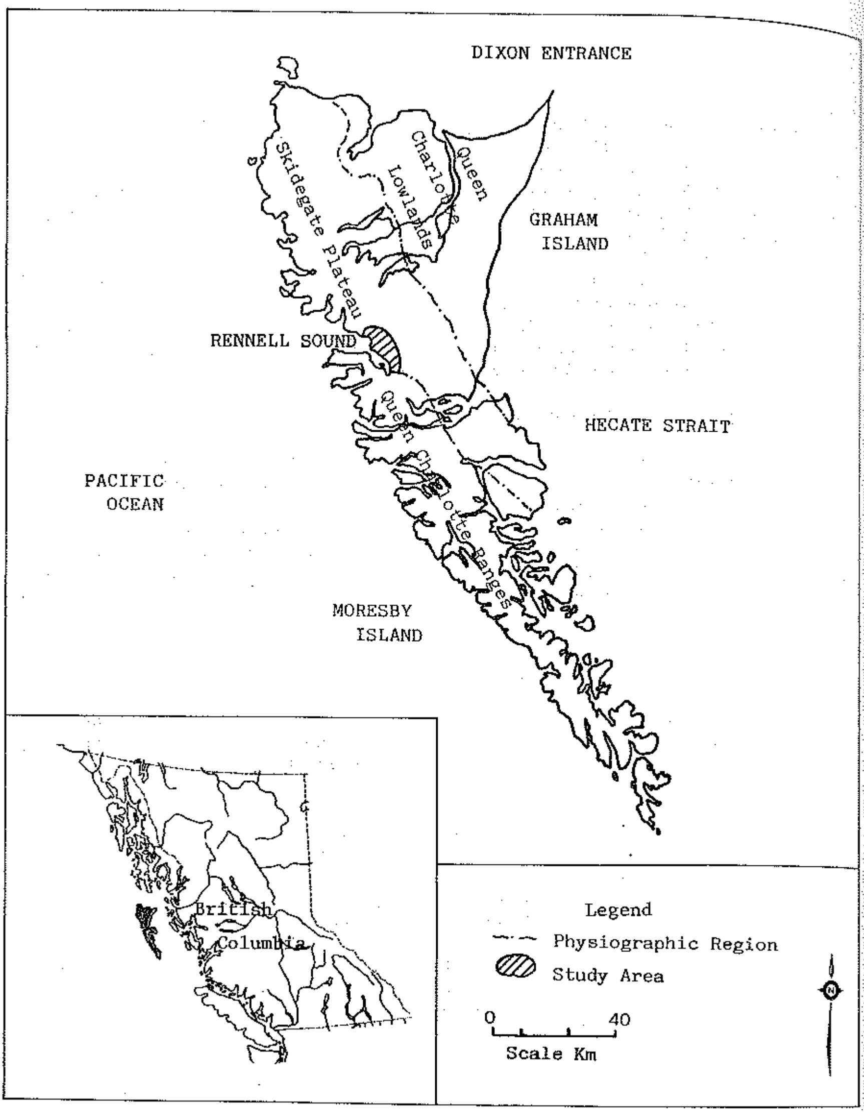

Figure 1: Location map and physiographic regions of the Queen Charlotte Islands

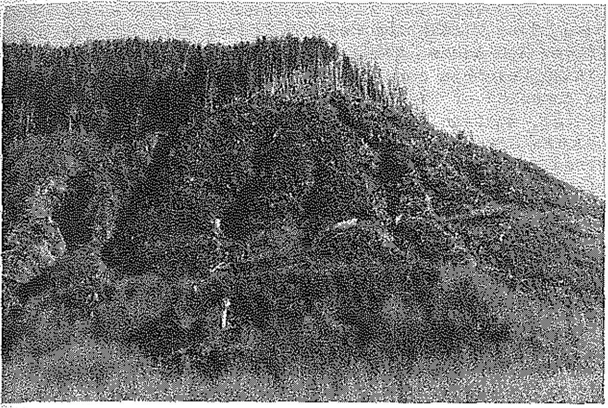

Figure 2. A dissected hillside in the study area. Debris torrents have occurred in the two V-notch gullies (to the left). Debris avalanches have occurred in the depressional channels (center to right).

often found in the contact zone above the unweathered till. Weathered till varies in colour due to pedogenic processes but is generally brown to dark brown. Depth of weathering is variable, but usually exceeds 2 m. on gentle slopes. On steep slopes the depth is less, reflecting the active geomorphic processes.

Colluvium is the dominant surficial material in the study area. The abundance of colluvium and the intense weathering and mass movement processes which generate it serve as a constant reminder of the inherent instability of the terrain (Alley and Thomson, 1978). Colluvium is found as thin veneers on steep slopes and ridges, and as aprons and fans along the base of slopes, where it overlies till or bedrock. Colluvium is derived from bedrock and to a lesser extent till. The matrix has a sandy loam to loamy sand texture. On slopes, weathering and water washing results in coarser textures, higher coarse fragment contents and bands or lenses within the colluvium.

Volcanic, sedimentary, and plutonic bedrock units are present in the study area. The volcanic and sedimentary units have well developed vertical and horizontal joints. These break the rock into small polygonal blocks, permitting moisture percolation to great depths and enhancing weathering. The plutonic rock weathers to form a coarse grained, cohesionless and erodible mantle.

The Queen Charlotte Islands are the most seismically active area in Canada (Sutherland Brown, 1968). The most active movement is along the Queen Charlotte Fault, which is located off the west coast of the islands.

This fault forms part of the circum-Pacific continental margin fault linkage.

The study area lies within the Coastal Cedars Pine Hemlock Biogeoclimatic Zone (Pojar and Annas, 1980). This zone is characteristic of much of the outer British Columbia coast north of Vancouver Island. The commercial forests are composed of Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and yellow cedar (*Chamaecyparis nootkatensis*). Red Alder (*Alnus rubra*) is found on disturbed sites - along streams, on mass movement tracks and on old roads. Unlike most coastal forests, shrubs and herbs in the study area are almost absent. This is attributed to the severe browsing by deer. (Pojar et al., 1980).

Rooting depth is generally less than 30 to 40 cm. There is an abundance of roots in the surface mineral and organic horizons. On the better drained sites, rooting is deeper but seldom extends to the soil-bedrock interface. In Gleysolic soils, rooting depth seldom exceeds 15 to 20 cm.

The west coast of the Queen Charlotte Islands is one of the windiest and wettest regions in Canada. Table 1 represents a climatic summary of data recorded between 1975 and 1978 in Rennell Sound. The maximum hourly wind speed recorded during the period is 54 km/h (gusts are not recorded). The strong winds generally originate in the southwest; however, destructive winds causing trees to blow down occur both up and down valleys. The average annual precipitation in Rennell Sound is 2,300 mm, with October and November being the wettest months. While precipitation amounts recorded during storms are similar to two other stations on the west coast of the Charlottes, average annual precipitation is almost twice as great at the other stations. Tasu has a 17 year average annual precipitation of 4218 mm and Sewell Inlet has a 7 yr. average of 4169 mm. We speculate that the location of the climatological station results in an underestimation of annual precipitation.

The short period of climatological records for Rennell Sound precludes a meaningful determination of extreme storm return periods. Table 2 presents precipitation data for storms known to have initiated mass wasting. These storms are generally greater than 127 mm (5 inches) in a 24 hour period and occur annually. Precipitation events of greater than 250 mm in a 3 day period are estimated to have a 5 to 10 year return interval.

The silvicultural system used is clearcutting with natural regeneration. Recently clearcuts have been planted with Sitka spruce. Clearcut openings range from 100 to 500 acreas. The cable yarding equipment used is highlead with recent modifications to a slackline system.

METHODS

Information on mass movements was collected using 20 and 80 chain aerial photographs, ground inspection, and helicopter reconnaissance. Data cards were used to describe mass movements and failure sites. Site factors included aspect, elevational, slope angle, slope type, slope position, slope length, bedrock, landforms, soil, rooting depth, drainage, vegetation,

Table 1: Climatological information, Rennell Sound, Queen Charlotte Islands

Year / Month	Maximum hourly wind speed (km/h)			Dominant Monthly Wind Direction			Total Precipitation (mm)				Precipitation Extreme 3 day Period (mm)		
	1976	1977	1978	1976	1977	1978	1975	1976	1977	1978	1976	1977	1978
Jan.	*	38	29	*	SW	S	*	*	117	67	*	57	42
Feb.	*	54	35	*	S	E	476	*	340	155	*	98	49
March	*	32	26	*	SW	SW	165	*	260	197	*	71	55
April	*	34	22	*	SW	SW	208	*	160	128	*	66	60
May	39	30	35	SW	W	E	113	103	77	40	46	30	40
June	23	27	23	W	SW	W	192	89	113	19	36	35	9
July	24	30	25	W	SW	SW	136	138	64	30	55	50	15
Aug.	23	21	*	W	SW	*	134	68	49	151	18	42	69
Sept.	42	23	*	S	W	*	149	*	166	264	52	41	80
Oct.	44	44	47	SW	SW	SW	719	*	635	508	98	159	278
Nov.	37	40	36	SW	SW	SW	774	338	299	207	198	59	98
Dec.	35	31	*	W	SW	*	*	380	100	230	84	62	48

Sources: Marsh R.D., pers. comm., 1978, Air Studies Branch, B.C. Ministry of the Environment.
Climate of British Columbia, 1975, B.C. Dept. of Agriculture.

* Climatological station not operating.

Table 2: Storm events known to have initiated mass wasting, 1974-1978
Rennell Sound, Queen Charlotte Islands

Year	Month	Day	Precipitation mm	Extreme Precipitation (mm) 1 Day	2 Day	3 Day	Station
1974	Sept	30	24	95	170	195	AES - Camp Shield Bay[1]
		31	95				
	Oct	1	75				
		2	21				
	Oct.	6	118	193	357	475	AES - Camp Shields Bay
		7	193				
		8	164				
		13	30	163	193		AES - Camp Shields Bay
		14	163				
		21	91	91	165		AES - Camp Shields Bay
		22	75				
1975	Oct	30	162	162	171	243	AES - Camp Shields Bay
		31	9				
	Nov	1	72*				
		2	52*				
1976	Nov	1	20	127	178	198	RAB - Gospel Point[2]
		2	127				
		3	51				
1978	Oct	30	130	130	212	278	RAB - Gospel Point
		31	82				
	Nov	1	66				

* Shields Bay Station closed. Precipitation estimate extrapolated from other west coast stations experiencing the same storm.

[1] "Camp Shields Bay", Atmospheric and Environment Service Canada, Station operated from September 1974 through November 1975. The Station was located 10 kilometers from the present Gospel point Station. The camp location generally experiences higher rainfall during storms than Gospel Point.

[2] Gospel Point climatological station, Air Studies Branch, B.C. Ministry of the Environment. Climatological day extends 9:00 am to 9:00 am the following morning. Station established May 4, 1976, situated 12 m above sea level on a gentle west facing slope.

and mass movement process. Mass movements were classified on the basis of moisture content, rate of movement and type of material. The processes are: debris slides; debris avalanches; debris flows; debris torrents; and slump-earthflows (Varnes, 1958; Swanston, 1976).

Site information on mass movements identified on aerial photographs but not ground inspected, was obtained through air photo interpretation, topographic maps, and helicopter reconnaissance. Measurements were made by transferring identified mass movements from 20 chain photos to a 20 chain topographic map. The measurements included: slope angle, elevation, aspect, slope position, slope length. Other site factors were determined by air photo interpretation.

RESULTS AND DISCUSSION

A total of 435 mass movements were inventoried in Rennell Sound; 322 in the natural forest, 71 in clearcuts, and 42 on forest roads. The average slope at the initiation point is 36 degrees.

A simplistic approach to the identification of slope stability hazard can be made by using an average slope angle. This value can be mapped and logging or forest roads prohibited in the "red area". However, this is not a valid option for forest and fisheries resource managers because mass movements occur over a broad range of slopes. Some of the most damaging can occur on slopes less than 25°. It makes little resource management sense to 'lock up' timber on steep yet stable terrain, or to log on gentle but unstable terrain adjacent to streams.

We found that by identifying mass movement processes, characteristic failure sites can be described. For the Rennell Sound study area, slope, soil moisture, landform, terrain features, land use practices, and in some cases minor vegetation, are the significant site factors in describing potentially unstable sites. The importance of these factors varies for each mass movement process, reflecting the difference in moisture status and level of confinement of the moving material (Tables 3, 4, and 5).

Debris Slides

Debris slides have the lowest mositure content of the mass movement processes. They are shallow (less than 50 cm deep) failures involving the rapid downslope movement of unsaturated soil and forest debris by sliding and rolling. Debris slides start on the shedding position of steep uniform hillsides. Slope angles range from 30 to 40 degrees and most commonly are between 36 and 40 degrees. Soils are shallow; podzols developed in colluvial or morainal veneers, or folisols over bedrock. The failure plane is along a weathering front in the bedrock or at the colluvial/bedrock interface. The bedrock may be smooth or highly jointed. A debris slide track is characteristically a straight swath down the hill, but it may fan out over the slope. Debris slides stop at a reduction in slope angle. However, if the slide becomes confined in a channel or

V-notch gully, debris avalanches or torrents can develop. In these cases movement can continue along slopes lower than 10 degrees.

Table 3: Summary of mass movements in the natural forest

PROCESS	SLOPE RANGE			SOIL	LANDFORM OR TERRAIN FEATURE	MOISTURE	FACTORS
	BROAD	NARROW	MEAN				
Debris slides	31-40	36-40	36	Shallow folisols or podzols	Cv	Shedding	Wind Throw 10-25 year storm
Debris Avalanches	24-42	36-40	35	Podzols	Cv Mv	Receiving or slight depression	Moisture piping, 2-5 year storm
Debris Torrent	Channel Gradient > 30° Sides > 40° Headwalls 40° - 60°			-----	V-notch gully Cr or Cb with organic material in channel	Receiving	3 day, 5 year storm mass movement from adjacent slope into V-notch gully
Slump-Earthflow	60° headwall moderate slope on movement			-----	Mb in a low gradient gully basin	Receiving	Moisture
Debris Flow	not observed						

Debris slides in natural forests occur in thrifty mature stands and there are no indicator plant species. No single triggering agent can be isolated. Based on the age distribution of debris slides the authors speculate that the slides are initiated by rainstorms with a 10 to 25 year return period, combined with wind.

Debris slides in clearcuts occur as a result of yarding disturbance and loss in root strength. Slides initiated by yarding disturbance occur during yarding operations, if soils are wet, or during the first fall rains. More can develop during winter storms. Slides commencing two to five years after logging are attributed to root strength deterioration. The full suspension of logs during yarding operations will reduce failures resulting from yarding disturbance. Debris slides resulting from root strength loss can not be avoided. The maintenance of an organic root web is essential for slope stability on these sites.

Road initiated debris slides have resulted from: 1) sidecasting large and even small amounts of waste material (soil, debris, and rock); 2) by piling large amounts of waste material on the outside edge of the road; and 3) by constructing a road base with fill material (i.e. a road that is not full benched). In these situations the slope is maintained primarily by the frictional resistance to sliding. Some mechanical slope support may be provided by buried stumps and trees. The slope, under these conditions, is said to be overloaded. Failure of overloaded slopes will occur when

Table 4: Summary table of mass movements in clearcuts

	PROCESS	CHARACTERISTIC SLOPE	SOIL	LANDFORM	MOISTURE	FACTORS	RECOMMENDATIONS
Within Clearcuts	Debris Slides	>36°	shallow podzols or folisols	Cv Mv O/R	Shedding	Yarding disturbance Root decay	Full suspension, yarding Rapid Reforestation (but root decay will still occur)
	Debris Avalanches	>30°	poorly drained podzols or gleysols	Cv, Cb, Mv, Mb	Receiving or Depressional	Heavy yarding disturbance. Root decay Increased moisture	Full suspension yarding. Rapid Reforestation (but root decay will still occur)
	Debris Flows	<20°	poorly drained Humic Gleysols or Ferro-Humic Podzols	Mb	Depressional with liverworts and seepage	Logging (no debris flows in the natural forest) Increased moisture	No solutions
	Debris Torrents and Debris slides in V-notch gullies	V-Notch Gullies Channel Gradient > 35° Sides > 45° Headwalls 40° - 60°		Cv, Mv, R, in Gullies	Receiving	Yarding disturbance Root Decay Debris accumulation (slash and soil)	Full suspension
Clearcut Boundaries	Debris Slides - Debris Torrents	> 40°	Shallow Podzols or Folisols	Cv, R, (V)	Shedding	Exposure to storm winds	Avoid locating clearcut boundaries on these sites. Locate upper boundaries above or below gully headwalls. Locate upper boundaries parallel to storm winds.
	Debris Avalanches and Debris Torrents	Gullied, >35°	Gleysols or Podzols	Cv, R, V	Receiving or Depressional	Exposure to storm winds	

Table 5: Summary table of mass movements associated with forest roads

Process	Characteristic Slope	Landform	Moisture	Factors	Recommendations
Debris slides in fill and sidecast material	$>36^\circ$	Cv/R	Shedding	Sidecast fill (road full benched)	Avoid sidecasting Full bench roads.
				Piling waste material on outside of road.	Don't pile waste material on outside of road.
Debris slides, rockfalls, and dry ravel in cutbanks	$>36^\circ$	Cv/R, Mv/R highly jointed bedrock	Shedding	Steep, high cutbanks	Expect erosion on these cutbanks. Roads must be adequately maintained and put to bed following use or ditches become plugged, runoff is concentrated, and debris avalanches result.
Debris avalanches in fill and sidecast material	$20^\circ - 36^\circ$	Cv, Cb, Cv/Cb/Mv	Receiving or depressional with moderate to poor drainage	Sidecasting large amounts of waste material. Piling large amounts of waste on the outside of roads. Inadequate drainage and poor maintenance.	Full bench roads. Endhaul where stability is questionable. Remove Humic Gleysols (black muck). Avoid sidecasting on Humic Gleysols. Avoid large waste piles on outside of roads. Build roads to engineering specifications, especially drainage structures. Maintain roads, put roads to bed.
Debris flows	$<25^\circ$	Mb, Cv/Mb, Cb/Mb	Poorly drained depressional or receiving sites with Humic Gleysols, liverwarts and seepage water.	Overloading soils with low bearing strengths	Avoid loading Humic Gleysols. Excavate Humic Gleysols. Full bench roads. Provide adequate drainage away from the sites. Avoid high cutbanks and expect debris flows or slumps from cutbanks, (maintenance problem site.)
Debris torrents in V-Notch gullies	V-notch gullies. Channel Gradient $>35^\circ$. Headwalls - $40^\circ - 60^\circ$ Sides $>45^\circ$.	Gullied Terrain	Receiving	High cutbanks natural erosion material blocking culverts. Large fills.	Attempt to avoid crossing gullies. Cross gullies where the channel gradient is low, (e.g. on a bench). Avoid headwall areas. Use large bridge type culverts or bridges to avoid blockages by erosional material.

soils are wet; during road construction, during winter storms, or when the mechanical support provided by trees and stumps is lost.

Debris slides, rock falls, and dry ravel from cutbanks are also problematic on slopes greater than 36 degrees. Excavating for a stable road bed removes support for soils and bedrock upslope. Dry ravelling and rockfalls result where the bedrock is weathered and highly jointed. If roads are not maintained or put to bed, blocked ditches and culverts lead to a concentration of runoff. This has lead to debris avalanches.

Long-reach yarding systems are a means to avoid building mid-slope roads. Considerable thought must be given to the practability of mid slope roads and to the problems associated with disposing endhaul and waste material. The following preventive measures should be undertaken to reduce stability problems: 1) design roads to be narrow and full benched; 2) sidecast of waste material should be carefully scrutinized; 3) waste material from road construction and maintenance should not be piled on the outside of the road; 4) adequate road drainage structures should be installed and maintained; inactive roads should be cross ditched and put to bed; 5) rockfalls and ravelling should be expected where road excavation is into deeply weathered volcanic bedrock.

Debris Avalanches

Debris avalanches involve the rapid downslope movement of soil, rocks, and forest debris at or near saturation. Failure initiates in a receiving or depressional landscape position. However, surface features are not always apparent. Frequently subsurface soil drainage features (piping) play a critical role (Chamberlin, 1972). Slopes at the initiation zone range from 24 to 42 degrees. Slopes for debris avalanches are generally less than for debris slides, reflecting the influence of soil water. Soils at the initiation zone are podzols, developed in shallow colluvial or morainal deposits. The initial failure plane is along a weathering front in bedrock or at the soil/bedrock interface. As the avalanche progresses, failure is within unconsolidated material. Downslope movement characteristically is confined to a depressional channel, however, debris avalanches can fan out over a slope. Movement can continue across slopes lower than 10 degrees due to the high moisture content.

Debris avalanches in natural forests appear to be initiated by three day storms with a 2 to 5 year return period (approximately 200-250 mm) (Figure 3).

Debris avalanches in clearcuts characteristically occur on receiving sites with slopes greater than 30 degrees. Debris avalanches commence one to four years after harvesting. The organic root web and evapotranspiration appear to be essential in maintaining slope stability on depressional and receiving sites. Failures resulting from the alteration of surface runoff can be reduced by lifting logs clear off the ground. However, debris avalanches resulting from combined root strength deterioration and increases in soil moisture through reduced evapotranspiration can not be avoided. Rapid reforestation may possibly restore sufficient root strength and evapotranspiration to a site in 15 to 20 years (Harr 1976, after Kovner 1957 and Ziemer, 1964). (Figure 4)

Figure 3. Mass movements constitute a dominant geomorphic process in Rennell Sound.

Debris avalanches associated with forest roads characteristically occur on receiving sites or depressional sites with slopes between 25 and 36 degrees. They are a result of slope overloading and the saturation of fill and sidecast material. Failures are initiated by: 1) sidecasting large amounts of waste material into receiving or depressional sites; 2) piling large amounts of waste material on the outside of a road edge which is built over a depressional or receiving site; 3) inadequate road drainage, and poor ditch and culvert maintenance (Figure 5).

The occurrence of debris avalanches initiated by roads can be reduced by: 1) constructing full bench roads; 2) endhauling waste material from

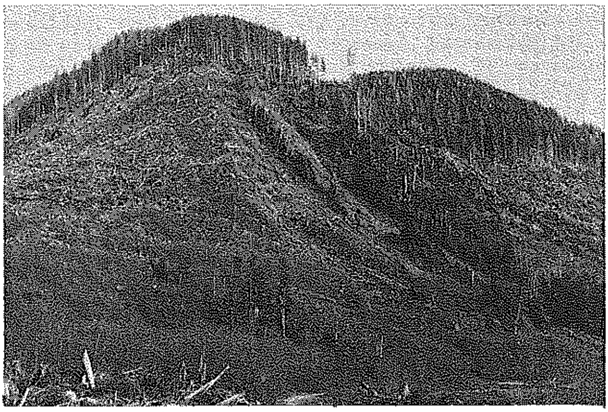

Figure 4. Two major debris avalanches in a clearcut flank a smaller debris avalanche that occurred approximately 40 years before logging.

Figure 5. Debris avalanches occur on roads as a result of excess sidecast piling waste material on the outside of a road edge, and inadequate road drainage.

sites where stability is questionable; 3) excavate material to bedrock when crossing receiving and depressional sites, using coarse shot rock as a road bed to allow subsurface water movement through the fill; 4) not sidecasting waste material into depressional and receiving sites; 5) not piling large amounts of waste material from road construction and maintenance, on the outside edge of a road in a depressional or receiving site, and 6) building roads to the engineered specifications for drainage, and carrying out the necessary culvert and ditch maintenance.

Minor slumping should be expected from cut banks where the soils are imperfectly to moderately well drained.

Debris Flows

Debris flows involve the rapid downslope movement of water saturated soil and debris, by true flow processes. Flows initiate in seepage and depressional positions of fine textured morainal blankets (greater than 1 meter deep). Flows generally initiate on slopes of less than 25^{o}. Movement will continue across level ground as long as the materials are in a liquid state.

Mass movements initiated as debris flows were not observed in the natural forest of the study area. Mass movements were, however, recognized to assume debris flow conditions. The progression of debris slides and avalanches to debris flows, occurs as slope length and complexity tend to confine movement down depressional channels, increasing the water content.

Landscape units with the following characteristics are typical of clearcut sites associated with debris flows: receiving or depressional sites on lower slopes, and at the base of slopes; slope angle of less than 20 degrees; poorly drained soils (Humic Gleysols and Ferro-Humic Podzols); liverworts and seepage water may be present. The landform is a morainal blanket and soils have a clay loam texture. Debris flows occur in the first or second winter following harvesting. Reduced evapotranspiration appears to be the most important causative factor.

Road construction on gentle slopes in the valley bottoms and at higher elevations have initiated debris flows. These sites are characteristically poory drained deep soils in depressional, receiving, and seepage sites, and in the deposition zones of historic debris avalanches. Hillslopes are between 10 and 22 degrees. Liverworts and seepage water are frequently present, along with a thick black mucky organic surface horizon of a Humic Gleysol. The soils have a clay loam texture and a gleyed blue-grey colour. The landform is a morainal blanket, or a morainal blanket/colluvial veneer complex, or a morainal blanket/colluvial blanket complex.

Debris flows initiate on slopes as low as 15 degrees as a result of overloading wet gleysolic soils with large amounts of fill, sidecast and waste material. These failures can initiate during road construction regardless of season, if wet conditions prevail, or following construction during winter storms.

Slumping from cut banks is an additional problem in deep, wet soils. Slumping initiates as a result of basic soil physics. The soil must be at or near saturation before water emerges from the cutbank. This saturated state results in reduced soil cohesion, and increased weight and pore water pressure; factors which lead to reduced cutbank stability.

During field engineering, if gleysolic soils (in depressional of seepage sites, or in the depositional zone of historic debris avalanches) are identified and stability is questionable, the ares should be avoided where practicable by changes in road alignment and by revision of the grade line. During the construction, as soon as a gleyed soil is identified by the operator, construction should stop; and then construction techniques should be altered in order to construct a stable road. A stable road can be constructed by timing construction to avoid wet periods, and 1) not depositing or sidecasting waste material into the depressional area where gleysolic soils have been identified; 2) excavating all the gleyed material to a competent base of unweathered till or bedrock (full benching); 3) placing a blanket of coarse ballast rock into the excavation as the road base and fill. The coarse blanket distributes the weight of the road and provides drainage for ground water under the road; 4) providing adequate drainage away from the area; ensure that road drainage structures do not increase that amount of water in the area, and 5) avoiding high cut banks; minor slumping should be expected to occur.

Debris Torrents

Slopes in the study area are incised by steep V-notch gullies. In the gullies are intermittent to perennial first and second order streams. The gradient of these gullies is generally greater than 35 degrees, with side slopes in excess of 45 degrees, and slopes near gully headwalls approach and exceed 60 degrees. Soils on the steeper portions of side slopes and at gully headwalls are Folosols. On the more gentle upper side slopes Podzolic soils are present, developed in shallow colluvial or morainal deposits.

We think that all steep V-notch gullies are geomorphically active sites for soil mass movement in the Rennell Sound study area. This view is also held by Alley and Thomson (1978). The inherent instability of gullies is a function of climate, and extremely steep slopes in the gullies and on adjacent hillsides. Weathering, of surficial material and bedrock leads to ravelling and debris sliding from side slopes and gully headwalls. Debris accululations in the gully channel are mobilized through debris torrents. Torrents are initiated by concentrated storm runoff or by a mass movement from adjacent hill sides. The gully channel is scoured to bedrock and in many instances debris and sediment is transported to third order streams.

It appears that three-day storm events with a five-year return period (250 mm) are sufficient to initiate debris torrents in natural forests. The frequency of a natural debris torrent occurrence within a given gully is related to the rate of debris accumulation within the gully channel, and to the occurrence of soil mass movements on adjacent hill slopes.

Natural erosion processes are accelerated in V-notch gullies through yarding disturbance, loss in tree root strength, and debris (slash plus soil) accumulation in the gully channel. Yarding disturbance disrupts the soil and root systems, leading to debris sliding from gully side walls. Progressive sliding and ravelling occurs throughout the complete gully system as root strength deteriorates. Debris accumulated in the gully is mobilized as a rapid moving debris torrent through high storm runoff, or through soil mass movements from adjacent hill slopes. Gullies are often scoured to bedrock as the torrent moves down the channel (Figure 6).

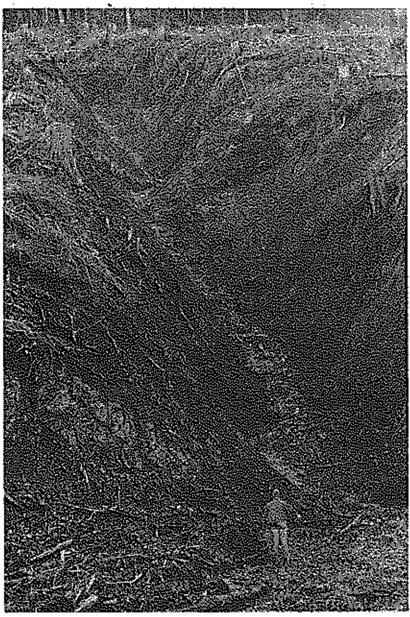

Figure 6. Debris torrents scour V-notch gullies, mobilizing debris and sediments.

Lifting logs clear of the ground will reduce failures initiated by yarding disturbance, but will not reduce slides due to root strength deterioration. Debris torrents may be reduced, but not eliminated, by removing logging debris from gullies, and by lifting logs clear of the ground through full suspension while yarding.

Material is constantly moving down V-notch gully channels. Roads built across gullies with fills rather than with bridges or bridge type culverts, construct the channel, frequently acting as a dam; failing under stress. Debris torrents, avalanches and slides frequently occur in gullies above a road. The road may act as a check dam, reducing the immediate impact of the mass movement. However, the road may fail in time, resulting in an even larger debris torrent. Thus, given that gullies are active mass movement sites, roads should be constructed so that debris, as well as water can flow down the V-notch gullies. This is very important, especially if roads are to be left unmaintained rather than removing the gully crossings.

To reduce the size of roads in gullies, they may be constructed with a rolling dip. This, however, leads to another problem; the gully becomes a low point in the road and thus sediment is transported to the gully, and hence enters the stream system. If it is necessary to cross gullies roads should be located on benches - sites where gullies are not deep.

Debris torrents and slides initiated by roads constructed through gully headwalls are unavoidable. Gullies are characterized by steep headwalls with slopes in excess of 40 degrees and often approaching and exceeding 60 degrees. Soils at the headwall are lithic or nonexistent. The bedrock is highly jointed with the exception of the plutonic rocks. Seepage water is often present, flowing over the bedrock.

The inherent instability of gully headwalls is created by geologic erosion. A situation exists where even a minimal amount of sidecast or waste material overloading the slope will fail. Full bench roads located through gully headwalls may appear to be stable, but it must be recognized that sidecast is unavoidable during construction even with the endhauling of waste material. The extremely high cut banks necessary for construction of full bench road through gully headwalls become a continual problem. The highly jointed, deeply weathered volcanic and sedimentary bedrock of the study area set conditions for rock falls and dry ravel.

The extreme instability of gully headwalls must be recognized. Road construction through gully headwalls must be avoided.

Slump-Earthflows

Slump-earthflows occur in two different landscape positions within the study area. In valley bottoms, slump-earthflows have occurred historically on the edge of deep morainal benches. These movements produced a characteristic slump basin with a scarp five to seven meters in height, and a narrow lower opening through which the soil flow issued. No active slump-earthflows were observed in these deep morainal benches.

On hillslopes, slump-earthflows occur in large, low gradient gully basins. These movements involve the slumping of deep morainal material, exposing a headwall. Below the headwall, there is a ponding of water, and a saturated soil mass. Downslope, the following features are present: tension cracks, tilted and bowed trees, advances of saturated soil tongues and series of smaller slumps. Drainage patterns are poorly developed, but small streams are found, cutting gullies into the slowly moving mass. The slump-earthflow, and all the other active erosional processes associated within it, lead to the formation of a fan at the base of the slope. Even with light storms, the streams draining the slump-earthflow become turbid.

The largest mass movement in the study area is a slump-earthflow. On this movement, the presence of large bowed Sitka spruce suggest that movement, has been active for a period in excess of 250 years. Swanston and Swanson (1976) state that the history of an individual slump-earthflow may extend over thousands of years. This adds to their conclusion that, since slump-earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than the occurrence of the other soil mass movement processes. Forest harvesting has not been conducted on, or adjacent to slump earthflows in the study area. This discussion focuses on the hazards of doing so, emphasizing that the erosional effects could be significant - not only for the slump-earthflow, but for all the other erosional processes occurring on the slowly moving failure.

Forest vegetation reduces surface erosion and appears to be a very important factor controlling movement. Tree roots act as an organic web binding across unstable areas, reducing movement. Evapotranspiration reduces the water content of slump-earthflows. The removal of forest cover reduces evapotranspiration and increases soil moisture levels. Swanston and Swanson (1976) hypothesized that this increase in soil moisture contributes to increased rates of movement.

Acceleration of slump-earthflows and its associated erosional processes in the narrow valleys of the study area will cause major impacts to the stream environments. For this reason, clearcutting the stands on slump-earthflows should not be undertaken. Clearcutting in stands adjacent to slump-earthflows should not be conducted unless windfirm boundaries can be located, and then, only if there will not be an increase in wind exposure to the forest stand on the slump-earthflows.

Road construction has not been undertaken on the natural slump-earthflows in the study area. However, experience with these mass movements has been gained elsewhere. Swanston and Swanson (1976) summarizes: roads result in the routing of additional water onto slump-earthflows, the undercutting of toe slopes, the piling of rock and debris on stump blocks, all which lead to an increase in the movement of slump-earthflows. To these impacts may be added the vibration of traffic and yarding equipment. They noted that once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Clearcut Boundaries

Mass movements along clearcut boundaries initiate as a direct result of exposure of standing timber to storm winds. Windthrow and the stresses caused by dynamic loading reduce shear strength and increase shear stress, and combined with high levels of soil moisture, initiate mass movement events (Swanston, 1969). Debris slides develop on steep shedding sites, and debris avalanches on steep, depressional or receiving sites. Debris torrents develop in gullies as a direct result of windthrow initiated slides at gully headwalls or along gully sidewalls.

Windthrow-initiated soil mass movements can possibly be reduced by locating windfirm boundaries. These boundaries must be 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 headwalls. They should be located well above or a good distance below gully headwalls, on stable soils.

CONCLUSIONS

Mass movements constitute a dominant geomorphic process in the Rennell Sound study area. The mass movements can be classified by process; debris slides; debris avalanches; debris flows; debris torrents; and slump-earthflows. The different processes occur on characteristic sites. A simple description of these sites is adequate for field recognition.

We found that slope, soil moisture, landform, terrain features, and in some cases minor vegetation are the significant site factors in describing a potentially unstable site. The importance of these factors varies for each mass movement process, reflecting the difference in moisture status and level of confinement of the moving material.

The main factors initiating mass movement in the natural forest are heavy precipitation, high winds, and soil moisture (piping). The importance of these factors vary for each mass movement process.

The main factors leading to mass movements in clearcuts are: root decay; debris accumulation in gullies; yarding disturbance; location of felling boundaries, increases in soil moisture; and heavy precipitation. Measures can be taken to reduce some of these factors but root decay, especially on V-notch gully sidewalls, cannot be prevented.

The main factors leading to mass movements on forest roads are: excessive sidecasting; roads built on fill material; roads built through gullies and across gully headwalls; inadequate or lack of drainage structures; inadequate maintenance; failure to put roads to bed; and steep, high cutbanks. Measures can be taken to reduce most of these factors.

Logging planning using terrain maps, adequate fieldwork by staff trained in mass wasting, and scheduling of road construction to avoid operating on sensitive sites during wet weather, are measures that will reduce the occurrence of mass movements. However, some highly unstable sites should be considered as Protection Forests because of their proximity to streams, plantations, or roads, or because of the safety hazards inherent in conducting operations on them.

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