Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest

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Abstract

Slope instability problems in the Chilliwack Forest are particularly prominent in areas of sedimentary rock and where very steep glaciated slopes persist. Increased frequency of slope failures often appears related to recent logging and road construction. Specific factors contributing to instability can be analyzed by interpreting site conditions in relation to soil shear strength and stress equations. Such analysis can be applied in planning roads and harvesting to minimize stability problems.

Introduction

Timber harvesting and associated road construction often initiate or aggravate mass soil movements in the mountainous terrain of western North America. Such mass soil movements may cause erosion, loss of forest productivity, sedimentation of streams, and damage to forest roads.

Although soil mechanics theory can be a powerful tool in predicting and minimizing soil instability, its rigorous application on highly variable forest terrain is often problematic and expensive. In routine forestry practice, it is often useful to adopt a less rigorous approach, supplementing theory by local experience with geologic materials and other site factors. A number of case studies, when viewed as a whole, may yield a broad regional perspective on the forest soil stability problem from Alaska to Oregon (Bishop and Stevens 1964; Barr and Swanston 1970; Fredriksen 1970; Dyrness 1967; Swanston 1967, 1969, 1970, 1971a, 1971b). In British Columbia, O'Loughlin (1972a, 1972b) recently evaluated local problems near Squamish.

This paper briefly discusses slope instability problems in the Chilliwack Provincial Forest in southwestern British Columbia (Fig. 1 and 2). The observations may be applicable in other areas of similar geologic materials and terrain in the province.

Many of the large slope failures on the Chilliwack watershed are characterized by a well-defined shear plane near the top of the failure zone. During failure, much of the material moves as a debris slide, debris

Résumé

Les problèmes de l'instabilité des pentes dans la Forêt de Chilliwack s'avèrent particulièrement importants en ces régions définies par des assises sédimentaires surtout caractérisées par des pentes glacées persistantes. L'augmentation accrue dans le bris des pentes semble être attribuable aux récentes exploitations et aux constructions de route. Cette instabilité due à certains facteurs spécifiques peut être étudiée au moyen de l'interprétation des conditions de stations corrélées aux forces de glissement du sol et aux équations s'y rapportant. Une telle analyse peut être applicable en planifiant la construction des routes de même que l'exploitation afin de diminuer ces problèmes de stabilité des pentes.

avalanche, or debris flow, depending on water content. There is often evidence of an increasing tendency for saturation and debris flow near the bottom of the deposition area.

Slope instability in the Chilliwack Forest is not exclusively associated with timber harvesting. A very old slide scarp on Church Mountain once supported mature timber which has since been harvested (location *h*, Fig. 2). Reduced productivity is evidenced by the low basal area of stumps within the slide area in comparison with stumps on adjacent stable terrain. A slide involving deep-seated bedrock failure, occupying over 80 acres and still evident on aerial photographs, once blocked the Foley Creek drainage and contributed to the damming of Foley Lake (location *x*, Fig. 1). Despite many such examples of the fact that slope failures are common in areas undisturbed by man, it appears that their occurrence can be increased by timber harvesting and associated road construction. Specific effects of such activities can be visualized with reference to an idealized model of slope failure, similar to that described by Swanston (1970).

Interpreting stability equations

A slope becomes unstable when the available shear strength no longer exceeds the applied shear stress. The factor of safety can be calculated as the ratio of available shear strength to applied shear stress. Shear stress can be evaluated in terms of

FIG. 1. Location of the Chilliwack Valley in southwestern British Columbia. Shaded area is shown in Figure 2. X indicates location of the natural slope failure which contributed to the damming of Foley Lake.

FIG. 2. Locations of some of the larger slope failures in a portion of the Chilliwack Forest. **a**, failure in road-fill and side-cast material; **b-i**, failures, mostly involving glacial till or colluvium over bedrock or lodgement till; **j**, failure in glacial outwash at edge of kame terrace; **a-g**, failures associated with timber harvesting and road construction; **h-j**, natural failures, antedating recent disturbance. Numerous additional failures exist within this map area.

of α , the slope of the shear plane, and W , the weight of the total load (soil, trees, water, snow, and structures, if any) over a unit area of the shear plane:

$$\text{Shear stress} = W \sin \alpha \quad (1)$$

Available shear strength can be considered as the sum of three components: cohesive strength of the soil itself, C ; strength contributed by root systems, R ; and the strength contributed by friction. The frictional strength is related to that component of the load exerted perpendicular to the shear plane, $W \cos \alpha$; the upward buoyancy U caused by pore water pressure (which has a lifting effect, tending to reduce friction); and the frictional angle, Φ . In many superficial slope failures, the shear strength is approximated by the relationship

$$\text{Shear strength} \approx C + R + (W - U) \cos \alpha \tan \phi \quad (2)$$

A simplifying assumption, implicit in this model, is that the failure zone may be treated as an infinite plane surface. With such an assumption, the model

cannot accurately quantify the problems in short-radius rotational failures and in very small slides, particularly where toe slopes have been undercut. For accurate quantitative evaluation, some procedures involving refinement of this model or calculation of rotational moments are described by Terzaghi (1950) and Terzaghi and Peck (1967). However, the simpler model described above is adequate for a qualitative evaluation of many stability problems encountered in forestry practice.

In the Chilliwack area, the slope α of the shear plane is commonly defined by the surface of either bedrock or lodgement till (compacted glacial till). For a cohesionless, rootless soil with zero pore water pressure, the frictional angle equals the maximum angle of repose. That is, if α equals Φ , $W \cos \alpha \tan \Phi$ equals $W \sin \alpha$, and hence the shear strength equals the shear stress, for this special case where U , C and R equal zero. At steeper angles, the slope would fail. For several major failures examined in detail in the Chilliwack Forest, the modal value of slope angles adjacent to head scarps is 37° . Failures at lower slope angles are

usually associated with evidence of excess water. Therefore it is assumed that the frictional angle, Φ , for many of the surficial materials is approximately 37° .

Cohesive strength, C , is negligible in many soils. However, it may be appreciable in clay-rich soils at moderately low water content. Changes in water regime are likely to be implicated where timber harvesting affects cohesive strength. Strength contributed by cementation may, for convenience, also be included in the C term. Both physical disturbance and weathering may affect strength contributed by cementation.

In the Chilliwack valley and its subsidiary drainages, recent failures of lodgement till over bedrock on slopes up to 50° have been noted. Presumably, similar slopes have been failing ever since the Vashon stage of glaciation in southwestern British Columbia. Because such slopes are considerably steeper than the angle of repose for noncohesive or noncemented materials, it seems likely that their failure is related to a gradual decline in strength because of weathering. Though the inherent instability of such slopes is not caused by man, failures may be triggered by such activities as harvesting and road building. The failure potential of such slopes should be recognized when road locations and harvesting operations are still in the planning stage.

The shear strength contribution of roots exists only if roots grow through the shear plane. Where shear planes are shallow enough to lie within the root zone, data of Swanston (1970) and O'Loughlin (1972b) suggest magnitudes of R of the order of at least several tens of pounds per square foot. Field observations by Bishop and Stevens (1964) and others, and laboratory testing by O'Loughlin (1972b) indicate that gradual decay of roots may contribute to failures occurring several years after timber harvesting. Also, in some soils, hydrophobic surface horizons or other conditions may divert water to old root channels, by-passing the soil matrix, and contributing to high pore water pressure by saturating the region over the shear plane.

Where sidecast is deposited in an area of cull logs and stumps of standing timber, the woody stems may contribute to shear strength in a manner resembling root effects. For example, non-cohesive road-fill and side-cast material sustained an angle of 45° for more than a decade after road construction (location *a*, Fig. 2). Recent failure of this material is partly attributable to decay of buried tree stems that had previously contributed to the shear strength.

The unloading associated with timber removal reduces W , and this has occasionally been credited with significant alteration of slope stability. However, because W positively affects both shear stress and shear strength, and because timber weight is usually a small fraction of W , the change in W seldom causes more than a trivial change in the ratio of strength to stress. Moreover, depending on the magnitudes of various terms involved in this ratio, the resulting change in stability may be either positive or negative.

So long as the water table does not rise above the soil surface, the upward (buoyant) pressure U has nearly the magnitude of the pore water pressure μ . It can be estimated from the height h of the water table above the shear plane. An adequate approximation for most purposes is

$$U = \mu \cos \alpha = 62.4 h \cos^3 \alpha \quad (3)$$

where U is in units of pounds per square foot and h is measured in feet. The " $\cos^3 \alpha$ " factor, which accounts for the water potential field where water flows downslope over the shear plane, is often neglected. The third " $\cos \alpha$ " is needed to express the vertical pressure in terms of a unit area of shear plane.

Logging may cause the water table to rise because of reduced evapotranspiration. (A similar effect may be implicated in some cases of increased slope failure after fire.) The most significant harvesting effect on the water table, however, is the localized effect associated with channeling of runoff by roads, culverts, and yarding pathways, that causes saturation of portions of the slope that have never before been so wet. A slope previously at repose may quickly become unstable, particularly during winter rains or spring runoff. Evidence that this soil saturation effect has played a significant role in shear failure appears in numerous areas where surface water can be seen flowing in head scarp areas.

If the shear plane is below an impermeable layer (within lodgement till, clay, or bedrock, for example) a more familiar form of the available shear strength equation (Swanton 1974) may be applicable:

$$\text{available shear strength} = (W \cos \alpha - \mu) \tan \phi \quad (4)$$

In this case, the pore water pressure acts like a hydraulic jack, and pressure may amount to several thousands of pounds per square foot, because the water column under the impermeable layer may extend tens or even hundreds of feet upslope (See Terzaghi 1950). The uncertainty in predicting deep-seated failures often arises because we cannot readily evaluate pore water pressures below impermeable layers.

Though most failures observed in the Chilliwack Forest are relatively superficial and in moderately porous material, some are deep-seated and may well have resulted from extremely high pore water pressures, far in excess of what would be calculated from $h \cos^2 \alpha$ at the point where the failure originated.

Failures observed in the Chilliwack drainage range from small slumps of back-slope material, which are significant in that they block roads and ditches, to major mass movements of an acre or more in extent. Density of the recent major failures now reaches three per square mile in some harvested areas, and may continue to increase. So far, the largest single failure associated with timber harvesting and roads covers about 15 acres (location *b*, Fig. 2).

Some specific problems

Most of the slope failures, both major and minor, are concentrated in the western half of the Chilliwack Forest area. This geographical distribution is evidently associated with a complex of conditions:

1. Poorly consolidated geologic materials of the Cultus formation and certain other sediments (Monger 1966).

2. Steep slopes of weathered bedrock, colluvium, and glacial till, and steeply sloping planes of weakness along bedrock and till.

3. Decay of root systems after logging, and delayed development of new root systems from forest regeneration in certain areas.

4. Removal of toe-slope support by road cuts.

5. Changes in hydrologic regime, resulting from clearcutting and road construction practices. Specific problems include:

- a. In-sloping of roads where little or no drainage system is provided, leading to water-saturation of the roadbed during the wet season.
- b. Bulldozing of debris into channels of ephemeral streams which frequently pass unnoticed during road construction in the dry season.
- c. Capture of slope drainage by road systems, discharging large amounts of water on portions of the slope which have never before been receiving areas. On abandoned or seldom-used roads where closely-spaced drainage bars are lacking, gullies sometimes develop in wheel ruts for distances of several hundred yards before spilling water from the road system.

Areas such as these should be subject to special care in the planning of road systems and timber harvesting, based on site-specific assessments of geologic materials, topography, and other factors. In some cases, main haul roads could economically be located on alternative slopes or materials. Unless a consistent program of maintenance can be followed, reliance on ditches and culverts should give way to out-sloping of roads and (or) frequent construction of drainage bars.

Though natural slope failures may not be wholly predictable, the risk of natural slope failure can often be evaluated by applying the considerations outlined above, without necessarily using more sophisticated treatments of soil mechanics theory. Timely recognition and avoidance of potential slope failure areas can reduce the cost of constructing and maintaining forest roads. Appropriate road design and harvesting plans can minimize aggravation of potentially unstable conditions. Especially where operating costs are high and important non-timber values are at stake, there is ample reason for designating potentially unstable sites as "protection fo-

rest", removing them from sustained yield calculations and harvesting plans.

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