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THE EFFECT OF TIMBER REMOVAL ON THE STABILITY OF FOREST SOILS

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ABSTRACT

The principle ways in which the removal of a forest cover influences the stability of sloping soils are briefly described. In order to review the cause-and-effect relationships between deforestation and mass soil movements, particularly landslides, simple slope stability analyses are applied to an infinite slope under dry and saturated conditions. The methods by which relevant soil physical data can be obtained for use in stability analyses are outlined.

INTRODUCTION

In recent years the adverse effects of deforestation on the stability of steep slopes have caused some concern among forest managers in various parts of New Zealand. Commonly, removal of a forest cover from hill or mountain country accompanied by the construction of logging roads accelerates mass wasting – that is, the downslope movement of soil and rock materials *en masse* under the influence of gravity. Fine examples of this exist in north Westland on steep dissected hill country underlain by podsolized forest soils over impermeable sandstone and cemented gravels, and on topographically similar dissected hill country on the Coromandel Peninsula where clay loam soils are developed on andesite. Other better known examples of landsliding after removal of a forest cover are widespread in the mountains of inland Canterbury and Marlborough and in the East Coast - Poverty Bay area of the North Island. The aim of this paper is to review the cause-and-effect relationships between deforestation and mass soil movements, particularly various forms of landslides. It will emphasize the importance of soil water conditions to the stability of steep slopes with the aid of simple slope stability models.

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FOREST COVER INFLUENCES ON SLOPE STABILITY

A forest cover appears to affect the stability of slopes in a number of ways:

(a) *by wind throwing and root wedging.* Although trees may be frequently overturned on steep slopes exposed to strong winds and to heavy snowfalls, thereby creating considerable disturbance to the soil mantle and initiating landslides (Schiedigger, 1961; Swanston, 1969), generally the beneficial effects of tree roots greatly outweigh the adverse effects. Exceptions are reported by Schweinfurth (1967) and White (1949).

(b) *by increasing surcharge on a sloping soil mantle.* Calculations by Bishop and Stevens (1964) show that the shear stress produced by the weight of a mature forest crop may be negated by the increased soil shear strength due to the surcharge. Moreover, in most mature forest situations, the total weight of the soil and parent materials overlying a potential failure plane far exceeds the weight of the forest crop (Fig. 1). For instance, the surcharge due to the weight of a mature West Coast podocarp/beech/mixed-hardwood forest is unlikely to exceed 2.50 kPa, which is equivalent to a layer of stony forest subsoil approximately 15 cm thick.

(c) *by mechanically reinforcing the soil with tree roots.* There is no doubt that the stabilizing functions of root systems are very important on steep slopes, particularly where soil mantles are shallow and mass wasting occurs within the rooting zone as is the case in many New Zealand hill and mountain environments. Presumably, root systems contribute significantly to the stability of many forested slopes by binding the soil mass together and by helping to anchor the soil mantle to the substratum.

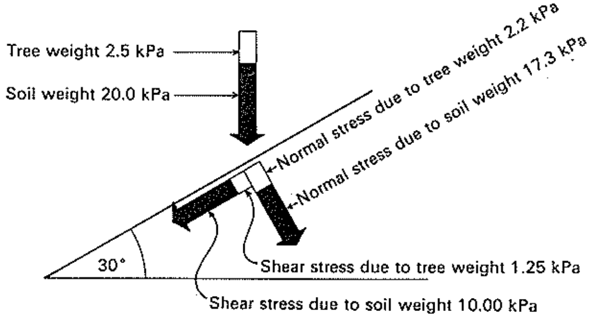


FIG. 1 — Shear and normal stresses resulting from the weight of a tree crop and a soil overburden on a 30° slope. Assumptions: 50 trees per hectare; 70 m^3 (timber volume) per hectare; green wood density 1500 kg/m^3; weight of each tree is distributed over 8 m^2 of slope surface; saturated soil unit weight 20 kN/m^3; soil depth 1 m.

(d) *by modifying soil moisture distribution and soil pore water pressure*. Forests deplete soil moisture to considerable depth through evapotranspiration (Hoover, 1953; Douglas, 1967) and may maintain a depressed groundwater table which sometimes rises dramatically if the forest cover is removed (Heikurainen, 1967). A forest can also intercept precipitation, either in the crowns of trees or in the forest litter layers at the soil surface (Jeffrey, 1970). The combination of transpiration and interception may tend to delay or mitigate saturation of the soil mantle on steep slopes (Bethlahmy, 1962; Hallin, 1967), while tree root channels provide low-resistance pathways for rapid transmittance of water (Aubertin, 1971).

Bishop and Stevens (1964), Swanston (1967, 1970) and Fujiwara (1970) have provided considerable evidence that the deterioration of tree roots and the changes which occur in the subsurface hydrological status of soils are the most significant tree-crop-related factors involved in accelerated mass wasting on recently deforested slopes. The relative importance of tree roots as opposed to the soil water conditions as factors influencing soil stability has been a subject of debate for many years although, historically, increased pore water pressure associated with saturated soil mantles has been shown to be a primary factor in the initiation of landslides on many types of slopes (Terzaghi, 1950; Taylor, 1948). Because of their importance to the future management of steep-slope forests in New Zealand, it is worth detailing the available information on the relationships between tree roots, soil water conditions and slope stability.

INFINITE-SLOPE MODELS

In order to examine the various movement-promoting and movement-resisting forces operating on a steep slope, it is convenient to construct simple slope models and apply stability analyses based on theoretical soil mechanics. However, it must be appreciated that the use of hypothetical stability models greatly oversimplifies what are really highly complex situations. In real landslide situations it is normally impossible to define accurately the stress field and subsurface water conditions at the time of failure.

According to Taylor (1948), an infinite slope designates " . . . a constant slope of unlimited extent which has constant conditions and constant soil properties at any given distance below the surface of the slope". Such ideal conditions never apply to natural slopes, but if the thickness of the soil mantle is small compared to the height of the slope, then the slope may be termed infinite. Under the infinite slope conditions the failure plane is parallel to the slope.

A soil's strength or resistance to failure is described by Coulomb's law (Terzaghi, 1950; Sowers and Sowers, 1970; Lambe and Whitman, 1969) which can be written as:

$$s = c' + \varsigma' \tan \varphi' \tag{1}$$

where s = soil shear strength (in Pa);
c' = effective soil cohesion (in Pa);
ς' = effective normal stress (in Pa);
φ' = effective internal friction angle (in degrees). For sandy-gravelly forest subsoils values range between 28° and 40°.

Although the mineral portions of many hill and mountain forest soils are predominantly cohesionless, for practical purposes these soils can be considered cohesive because of the effects imparted by the tree root network. An apparent cohesion (c_a) due to roots can be recognized as a component of the soil strength. In the analyses of infinite slopes outlined below the soils are assumed to possess no true cohesion (c') but possess only an apparent cohesion causing c' to be replaced by c_a in equations (4), (6), (10), (11) and (12).

Analysis of Unsaturated Infinite Slopes with No Seepage

In Fig. 2, representing part of a dry, infinite slope, the stress components per unit width on the base plane at depth z are:

$$T = \gamma_d z \sin \alpha \cos \alpha \tag{2}$$

$$\varsigma' = \gamma_d z \cos^2 \alpha \tag{3}$$

where T = tangential stress (in Pa);
γ_d = dry unit weight of soil (in kN/m^3);
α = slope angle.

It is assumed that the normal forces f_i and f_{i+1} and the shear forces t_i and t_{i+1} acting on the vertical faces of the free body (width a and weight W) cut in the soil are equal and balance each other ($f_i = f_{i+1}$ and $t_i = t_{i+1}$).

The factor of safety, which is a commonly used index of stability, in the case of a dry forest soil with roots is:

$$\frac{\text{available shear strength}}{\text{shear stress required for equilibrium}}$$

$$= \frac{c_a + (\gamma_d z \cos^2 \alpha) \tan \varphi'}{\gamma_d z \sin \alpha \cos \alpha} \tag{4}$$

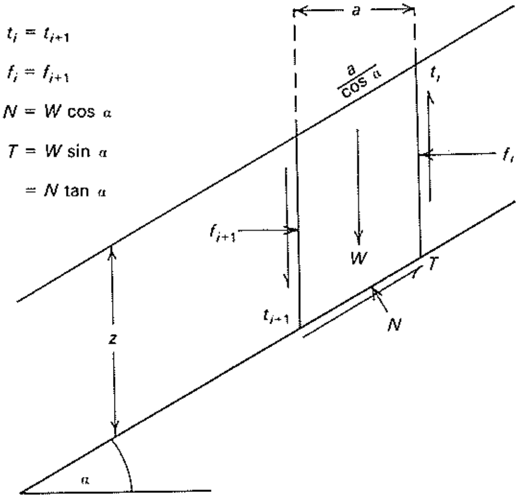


FIG. 2 — Portion of an unsaturated infinite slope with no seepage.

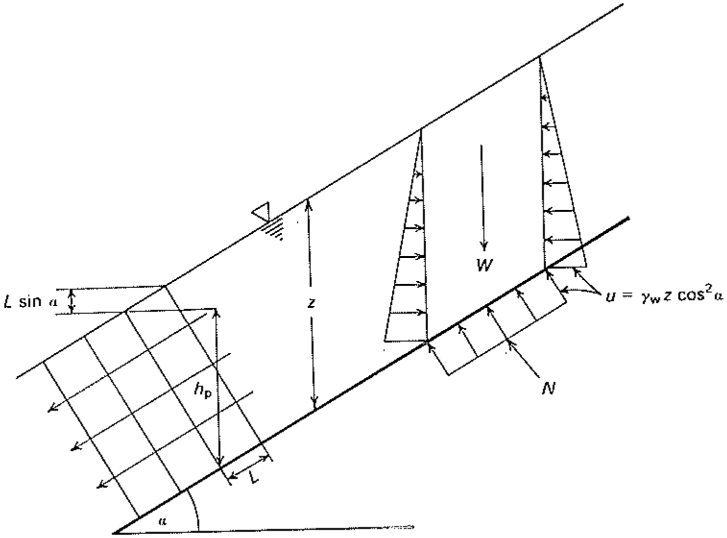


FIG. 3 — Portion of a saturated infinite slope with seepage.

This simplifies to $$\frac{\tan \varphi'}{\tan \alpha} \tag{5}$$
if there is no cohesion.

Theoretically, if the factor of safety is greater than 1.0, then the slope is stable, but if it approaches 1.0 or drops below 1.0 then failure becomes imminent. By substituting expressions (2) and (3) into the failure law ($T = c_a + s' \tan \varphi'$) the apparent cohesion c_a required for stability can be derived:

$$c_a = \gamma_d z \cos^2\alpha(\tan \alpha - \tan \varphi') \tag{6}$$

Analysis of a Saturated Infinite Slope with Seepage

Fig. 3 shows a sloping saturated soil through which water is seeping downslope. The free water surface coincides with the soil surface while the soil rests on an impermeable substratum, the surface of which represents a potential failure plane. It is assumed that the soil is isotropic, or that the maximum soil permeability is in the direction parallel to the slope, thereby permitting construction of a simple orthogonal flow net of equipotential lines and flow lines. In contrast to the relatively simple dry soil condition, the saturated condition introduces important pore water pressures into the analysis. These greatly influence the normal stress acting on the failure plane because they produce an uplift force. At depth z the pore water pressure u is:

$$\begin{aligned} u &= h_p \gamma_w \\ &= \gamma_w z \cos^2\alpha \end{aligned} \tag{7}$$

where h_p = pressure head of water (in m);
γ_w = unit weight of water (in kN/m^3).

The normal effective stress and the tangential stress acting on the basal plane are respectively:

$$\begin{aligned} s' &= (\gamma_s - \gamma_w) z \cos^2\alpha \\ &= \gamma_b z \cos^2\alpha \end{aligned} \tag{8}$$

$$\text{and } T = \gamma_s z \cos \alpha \sin \alpha \tag{9}$$

where γ_s = saturated soil unit weight (in kN/m^3);
γ_b = buoyant soil unit weight (in kN/m^3).

The effect of seepage forces applied by the moving water to the soil skeleton through frictional drag are included in the computation of the tangential stress T. The seepage forces cause the tangential stress to be proportional to the saturated unit weight of the soil whereas the effective normal stress ς' is proportional to the buoyant unit weight. Typically, γ_b is about half γ_s for many soil materials.

The factor of safety for an infinite saturated slope with seepage parallel to the slope is:

$$\frac{c_a + \gamma_b z \cos^2\alpha \tan\varphi'}{\gamma_s z \sin\alpha \cos\alpha} \tag{10}$$

substituting expressions (8) and (9) into the failure law $T = c_a + \varsigma' \tan\varphi'$ gives:

$$c_a/(\gamma_s z) = \cos^2\alpha[\tan\alpha - (\gamma_b/\gamma_s)\tan\varphi'] \tag{11}$$

and the cohesion required for stability is:

$$c_a = \gamma_s z \cos^2\alpha[\tan\alpha - (\gamma_b/\gamma_s)\tan\varphi'] \tag{12}$$

It is noteworthy that the factor for a saturated cohesionless soil mantle which does not derive support or shear strength from an interlocking root system is approximately half that for a similar soil mantle in an unsaturated condition with no downslope seepage.

ASSESSMENT OF SOIL STRENGTH PARAMETERS AND PORE WATER PRESSURES

A crucial problem in applying slope stability analyses of the type described above is the determination of meaningful soil strength parameters (c_a and φ'). In addition, as the assumptions of soil isotropy and downslope seepage parallel to the slope are unlikely to apply in field situations, field assessments of pore water pressures are required before reliable analyses can be made.

Determination of the Root Strength Factor c_a

The contribution that tree roots make to the shearing strength of soil has been measured directly with shear-strength-testing equipment by Japanese experimentors (Endo and Tsuruta, 1968; Takahasi, 1968) and by O'Loughlin (1972). Indirect assessments of c_a have been made by Swanston (1970), who performed stability analyses on failed slopes in Alaska. Using a simple form of the 'method of slices' (Lambe and Whitman, 1969) he assumed a safety factor of 1.0 at failure, and by back-calculation derived values for c_a. Table 1 summarizes some of the results of these studies, providing an idea of the magnitude of reinforcement tree roots impart to soils.

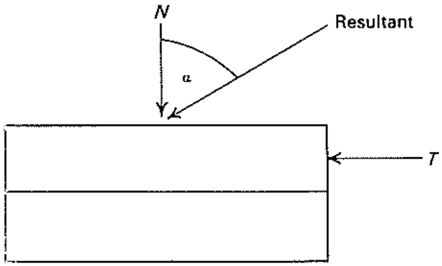
TABLE 1 — Results of studies of root strength factor c_a.

Investigator	*Soil-vegetation situation*	*Increased soil shear strength due to tree roots (kPa)*
Swanston	Mountain till soils under conifers	3.35– 4.35
Endo & Tsuruta	Silt loam soils under alder	2.00–12.00
Takahasi	Silt loam soils under birch	1.50– 9.00
O'Loughlin	Mountain till soils under conifers	1.00– 3.00

The large range in the strengthening effect of roots 'within' investigators as well as 'between' investigators is mainly due to vastly different tree-root network densities in terms of root weight per unit volume of soil.

Determination of the Friction Angle φ'

The friction angle or angle of shearing resistance is a rather complex soil strength parameter which depends not only on the frictional resistances developed between individual soil particles but also on the degree of interlocking of soil particles. To fully understand the meaning of φ' requires an understanding of Mohr-Coulomb failure theory (Lambe and Whitman, 1969). The oldest and possibly simplest method of determining φ' is by direct shear testing. The soil to be tested is held in a split box, a confining force (N) is applied and then a shear stress (T) is applied to cause a relative displacement between the two parts of the box (Fig. 4).



$\alpha = \phi$ at slippage

FIG. 4 — Forces acting on soil in a direct shear test.

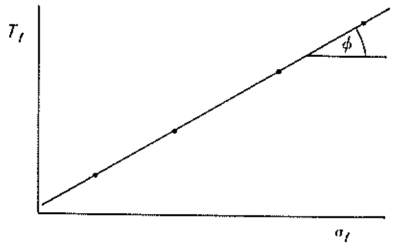


FIG. 5 — Shear stress at failure (T_f) vs normal stress at failure (s_f) for several direct shear tests.

Several individual tests, each with a different confining stress, permit the construction of a plot of T_f versus s_f (where T_f is the maximum measured shear stress and s_f is the corresponding normal stress), the slope of which provides an estimate of φ' (Fig. 5). In other words, for cohesionless soils, the measured stresses at failure are in the ratio:

$$T/s' = \tan \varphi' \tag{13}$$

It is possible to conduct direct shear tests in the field using a large steel shear box. The shearing force can be provided by a small portable winch, while the magnitude of the force applied can be measured with either a set of accurate scales or an automatically recording stress gauge (Fig. 6). Such equipment has been used in the United States, Canada and Japan to assess φ' and the apparent cohesion due to root networks.

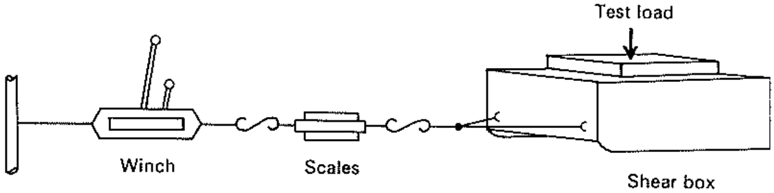


FIG. 6 — Soil shear testing equipment for use in field situations.

Depending on soil void ratios, particle size distributions, angularity of soil particles and mineral composition of the grains, φ' may range from 28° to 50°, but for dominantly stony, sandy or silt loam forest soils φ' will fall between 30° and 40°.

Determination of Pore Water Pressures

In order to determine accurately the magnitude of the effective normal stress s' operating on a potential failure plane, the pore water pressures u, if any, must be known ($s' = s - u$ where s is the total normal stress in Pa). Positive pore water pressures are generally measured with piezometers or certain types of tensiometers which are capable of measuring into the positive pressure range. Piezometer designs range from sophisticated instruments equipped with pressure transducers and recorders, to simple pipes. For slope stability work, simple piezometers which record maximum piezometric head rise are very useful (Fig. 7). In situations where the soil mantle rests on an impermeable substratum, the piezometer intake should be positioned as closely as possible to the subsoil–substratum interface. Piezometric measurements on steep forest slopes in Canada (O'Loughlin, 1972) and Alaska (Swanston, 1967) have indicated that pore water pressures may rise to values greater than those predicted by equation (7) during storm periods when shallow soil mantles saturate. Generally, however, equation (7) provides an acceptable estimate of u under saturated shallow soil conditions on steep slopes.

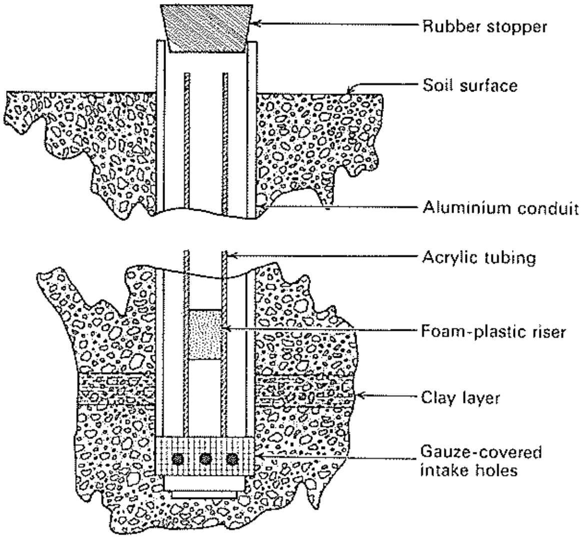


FIG. 7 — Simple piezometer for measuring maximum piezometric head. Rising water level in inner tube carries buoyant, foam plastic riser upwards. The water film between float and acrylic tube permits riser to remain at point of maximum water rise, which is measured by removing inner tube.

Determination of Soil Unit Weights

Piston samplers or Shelby tubes can be used to provide intact bulk samples for unit weight determinations. If soils are coarse-grained cohesionless types, then other techniques such as sand replacement methods or balloon densometer methods can be employed. Table 2 provides a broad indication of the magnitudes of forest subsoil unit weights.

TABLE 2 — Typical unit weights in (kN/m^3) of gravelly-sandy forest subsoils.

Dry unit weight	11–13
Saturated unit weight	16–18
Buoyant unit weight	6– 8
Unit weight water	10

APPLICATION OF INFINITE-SLOPE MODELS

In the absence of relevant New Zealand data the following analysis uses soil strength, soil unit weight and soil pore water pressure data collected from a steep clearfelled slope in southwest British Columbia, Canada. The forest soil under consideration was a stony, podsolized sandy loam developed over an impermeable till substratum. Several debris slides had occurred in shallow depressions on the clearfelled slope since the original conifer forest cover had been removed in 1968. Table 3 presents the slope data used in the analysis.

TABLE 3 — Physical soil data for natural slope, southwest British Columbia.

Mean soil depth (cm)	80
Mean moist soil unit weight (kN/m^3)	15.5
Mean saturated unit weight (kN/m^3)	17.9
Mean slope of ground surface (deg.)	30
Internal friction angle (deg.)	36

Piezometers indicated that the soil mantle attained saturation during peak storm periods within drainage depressions on the slope. In order to illustrate the effects of changes in the internal friction angle as well as changes in the soil water conditions on slope stability, several analyses were made for a moist soil condition with no seepage and for a saturated soil condition with downslope seepage using a range of values of φ'. Root reinforcement effects were neglected in the computation of factors of safety in the first part of the analysis. The results are shown in Table 4.

TABLE 4 — Factors of safety and the apparent cohesion required for stability for a natural slope, southwest British Columbia.

Seepage condition	*35°*	*36°*	*37°*	*38°*	*39°*	*40°*
	Factor of safety:					
Moist, no seepage	1.21	1.26	1.31	1.35	1.40	1.45
Saturated, seepage parallel to slope	0.53	0.56	0.58	0.60	0.62	0.64
	Apparent cohesion for stability (kPa):					
Saturated, seepage parallel to slope	2.16	2.06	1.97	1.87	1.77	1.67

These results indicate that, even without the benefit of a stabilizing root system, the slope would – theoretically – not have failed as long as the soil remained in an unsaturated condition. However, it is apparent from the very low calculated factors of safety that the stability of the slope depended heavily on the additional strength imparted by the tree root network during storm periods when the slope was saturated. Under these circumstances, measured and calculated pore water pressures (equation 7) attained approximately 6.00 kPa at the base of the soil mantle, which resulted in a reduction of the effective normal stress at the potential sliding plane to approximately 4.50 kPa – which is only 50 percent of the effective normal stress when the soil was moist. Variations in the magnitude of φ' caused relatively minor changes in the stability condition.

In the case of the slope under analysis it is not known whether or not removal of the timber affected the degree or rate at which the soil saturated during storms. It is probable that deterioration of the root system after cutting was the main causative factor in landsliding. Measurements of the decline of the tensile strength of small tree roots in coastal British Columbia after death of the parent tree indicate that over half the strength is lost within 3 to 5 years after cutting.

The obvious importance of pore water pressures to soil stability suggests that any changes which induce saturation of steep slopes should be avoided. Too often the surface drainage from logging roads is diverted into sensitive gully heads or on to steep slopes, causing soil saturation and resulting in accelerated mass wasting.

CONCLUDING REMARKS

Although the analyses described in the preceding passages are fraught with uncertainties, they nevertheless illustrate how deforestation may effect changes in the stability of steep slopes. In New Zealand, where an expanding timber industry has its eye on large tracts of commercially valuable forests established on steep hill country, the need for soil physical data of the type mentioned above should be obvious. On landslide-susceptible terrain, soil-water information is most urgently required so that slopes or parts of slopes with high susceptibilities can be recognized. Slope stability analysis has reached a high degree of sophistication in engineering situations such as earthfill dam slopes and embankments, but quantitative analyses of forested slopes have not generally been attempted – principally because of the large number of unknown factors operating and the heterogeneities existing in forest soil physical properties. However, computers make it possible to analyse the large amounts of input data associated with complex slope conditions using complicated stability models, and there is little doubt that, in the future, stability models will be useful tools in the study of slope behaviour on forest lands.

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