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RELATIVE IMPORTANCE OF FACTORS INFLUENCING LANDSLIDING IN COASTAL ALASKA

By

Roy C. Sidle
USDA Forest Service, Pacific Northwest
Forest and Range Experiment Station
Forestry Sciences Laboratory, Juneau, Alaska

ABSTRACT

Shallow, rapid landslides frequently erode the steep, forested hillslopes in coastal Alaska. These unstable slopes have been oversteepened by glaciation and frequently are sites of localized accumulations of groundwater during fall rainstorms. A factor of safety analysis based on an infinite slope model was used in examining the relative influence of soil and site variables on landslides. Stability analyses were performed for several soil types utilizing measured or estimated variabilities of soil and site properties.

Factor of safety values for soils in coastal Alaska are affected to a much greater extent by changes and variability in total cohesion than by changes and variability in angle of internal friction. Of the site factors examined, natural variability of soil depth has the greatest influence on the factor of safety; deeper soils are less stable. The influence of soil depth on slope stability is more important in cohesive soils. Dynamic changes in pore water pressures during storms can influence the factor of safety by similar magnitudes as natural variations in soil depth for essentially cohesionless soils. For a typical Tolstoi soil with overstory vegetation, a groundwater rise from 0.2 m (half-saturated) to 0.5 m (slightly artesian) resulted in a decrease in the factor of safety from 1.49 to 1.23. The relative importance of groundwater is lower for cohesive soils. Wide ranges in calculated factor of safety based on natural variabilities of soil and site parameters indicate that the factor of safety approach for assessing landslide hazard should be used with caution. In simulations of overall effect of forest removal on slope stability, the stabilizing effect of removing tree weight from the site was insignificant compared to the destabilizing effect from the reduction in root strength.

INTRODUCTION

Landslides on steep terrain are a major supplier of sediment to streams in coastal Alaska and the Pacific Northwest in general (Sidle 1980; Swanston 1969). These shallow, rapid soil mass movements typically occur as debris slides, avalanches, and flows that often are initiated in depressions or V-notches on slopes oversteepened by glaciation. Groundwater accumulates in these hillslope depressions during fall storms and causes a buildup of pore water pressure within the soil mantle which may trigger slope failure (Pierson 1980; Sidle and Swanston 1982).

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Sidle, R.C.

Factors determining the stability of slopes include soil strength, soil depth, groundwater accumulation, slope gradient, and vegetative characteristics. Soil strength is influenced by angle of internal friction and cohesion. Geotechnical properties of soils prone to landslides in coastal Alaska, measured by consolidated-undrained triaxial shear tests, are quite variable for certain soil mapping units (Schroeder and Filz 1981; Schroeder 1983). The effective angle of internal friction for these soils tends to increase with increasing bulk density and with decreasing plastic index (Schroeder and Filz 1981). Factor of safety (FS) calculations for shallow soils are greatly affected by small changes in cohesion, especially in the presence of groundwater (Schroeder and Filz 1981; Sidle and Swanston 1982). Piezometer data from unstable hillslope depressions in coastal Alaska indicate that nearly saturated to artesian conditions are often necessary to induce landslides (Sidle and Swanston 1981; 1982). Groundwater levels typically respond to individual storms with maximum rise influenced by rainfall intensity and antecedent moisture (Sidle 1982; Sidle and Swanston 1981; 1982). Slopes steeper than 36° are particularly susceptible to shallow, rapid landslides in coastal Alaska (Swanston 1974). This "critical slope angle" corresponds closely to the angle of internal friction for essentially cohesionless residual and till soils (Swanston 1974).

Although many soils in coastal Alaska are considered cohesionless, root systems of vegetation provide strength by vertically anchoring shallow soils to bedrock and by providing a lateral membrane strength within the soil mantle. Because even small cohesion values can be extremely important to slope stability, the removal of vegetation on potentially unstable slopes can greatly increase their susceptibility to landslides. Studies of root strength loss with time (Burroughs and Thomas 1977; Ziemer and Swanston 1977) indicate a progressive loss of root cohesion after clearcutting. Observations in Maybeso Creek Valley, Alaska (Bishop and Stevens 1964), showed that landsliding increased substantially for 9 years following clearcut logging, and more than half the landslides occurred during a major storm (approximately 6 years after most of the logging was done). Investigations in other areas (Megahan et al. 1978; Fujiwara 1970) showed that landslides were most frequent 4 to 10 years after clearcutting, corresponding to the period of minimum rooting strength of sites.

This study compiles geotechnical, site, and vegetative data for several landslide-prone soils in coastal Alaska and analyzes the relative importance of these factors on calculated FS. In addition, the effects of natural variability of individual factors and the influence of timber harvesting practices are estimated.

FACTOR OF SAFETY ANALYSIS

Slopes fail when shear stress along a potential failure plane exceeds shear strength. An infinite-slope model has been used by numerous investigators (e.g., Gray and Megahan 1981; Sidle and Swanston 1982; Swanston 1970) to analyze the forces contributing to failure (Fig. 1). The analysis applies to the basal shear plane only and is specific to slope failures that are initiated as slides (as opposed to flows); however, since debris avalanches and flows in coastal Alaska often start as debris slides, the use of the model to analyze various shallow, rapid landslides appears appropriate.

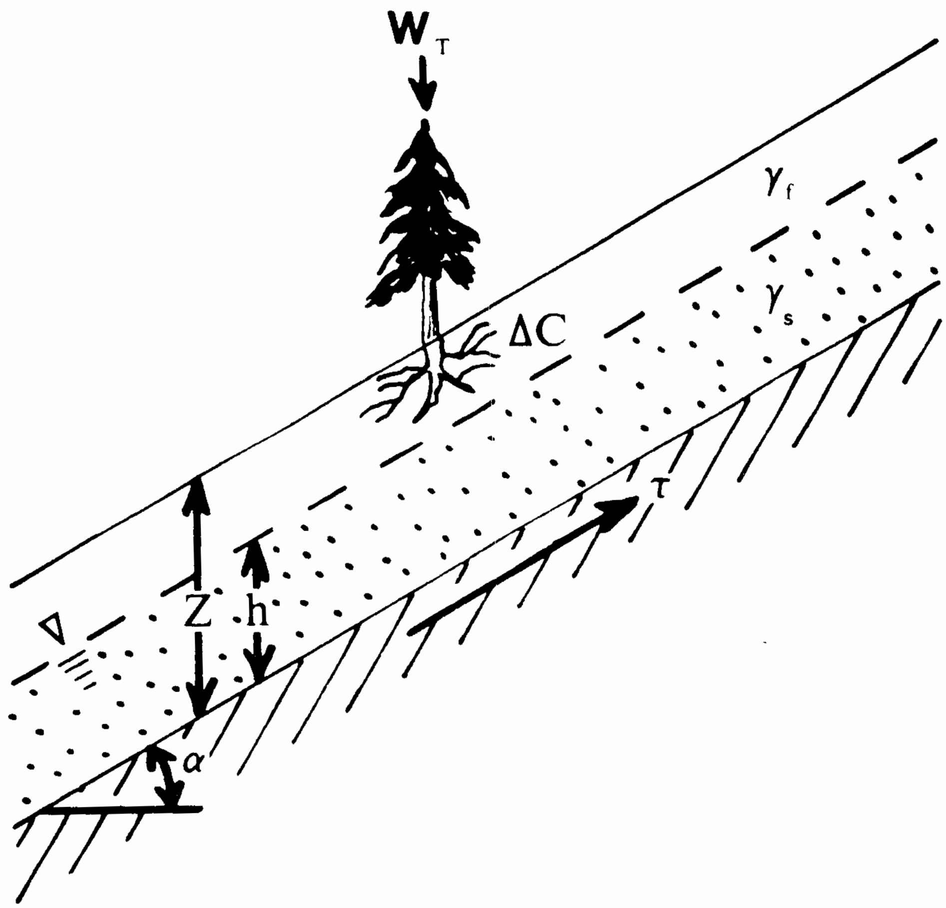


FIGURE 1 - Schematic of the infinite slope model for planar failures.

The shear strength of a soil can be expressed by:

$$S = C + \Delta C + (\sigma - u) \tan \emptyset \tag{1}$$

where S = shear strength; C = effective soil cohesion; ΔC = cohesion from root systems; σ = total normal stress; u = pore water pressure; and $\emptyset$ = effective angle of internal friction. Actual values for C and $\emptyset$ are assumed to be derived from consolidated-undrained triaxial shear tests. For vegetated sites with unsaturated to totally saturated soils, Equation (1) becomes:

$$S = C + \Delta C + \cos^2 \alpha[\gamma_f(z - h) + \gamma_s h + W_t - \gamma_w h] \tan \emptyset \tag{2}$$

where α = slope angle; γ_f = unit weight of soil at unsaturated field moisture; γ_s = saturated soil unit weight; γ_w = water unit weight; z = vertical soil depth; h = vertical height of water table; and W_t = weight of vegetation per unit area. For artesian conditions Equation (2) is simplified as:

$$S = C + \Delta C + \cos^2 \alpha(\gamma_s z + W_t - \gamma_w h) \tan \emptyset \tag{3}$$

Shear stress (τ) for non-artesian groundwater conditions is expressed as:

$$\tau = \cos \alpha \sin \alpha[\gamma_f (z - h) + \gamma_s h + W_t] \tag{4}$$

For artesian conditions Equation (4) can be simplified as follows:

$$\tau = \cos \alpha \sin \alpha(\gamma_s z + W_t) \tag{5}$$

According to the infinite slope model, the FS for slope stability is the ratio of shear strength to shear stress:

$$FS = \frac{S}{\tau} \tag{6}$$

For slope failure FS = 1. Dividing Equation (2) by Equation (4) gives FS for non-artesian groundwater conditions:

$$FS = \frac{C + \Delta C + \cos^2 \alpha[\gamma_f(z - h) + \gamma_s h + W_t - \gamma_w h] \tan \emptyset}{\cos \alpha \sin \alpha(\gamma_f(z - h) + \gamma_s h + W_t)} \tag{7}$$

For artesian conditions:

$$FS = \frac{C + \Delta C + \cos^2 \alpha(\gamma_s z + W_t - \gamma_w h) \tan \emptyset}{\cos \alpha \sin \alpha(\gamma_s z + W_t)} \qquad (8)$$

Factor of safety models (Equations 7 and 8) based on limit equilibrium theory greatly oversimplify the complex field system; however, they provide a framework within which to evaluate the relative contribution of various factors influencing slope stability. The only important factor ignored in these models is the effect of wind shear in trees. Ward et al. (1979) determined wind shear to be insignificant in magnitude in evaluating FS based on the infinite slope model, whereas Brown and Sheu (1975) calculated a short-term decrease in soil creep rates after tree removal because of decreased wind shear in trees.

INFLUENCE OF GEOTECHNICAL PROPERTIES OF SOILS

Geotechnical data for six hillslope soil series from coastal Alaska indicate ranges in mean $\emptyset$ and C of 30.3 to 38.2° and 5.7 to 13.4 kPa, respectively (Schroeder 1983; Schroeder and Filz 1981; Wu et al. 1979). Figure 2 shows the response of FS to changes in $\emptyset$ and C + ΔC for the following soil and site conditions: γ_f = 18.0 kN/m^3; γ_s = 19.0 kN/m^3; W_t = 2.4 kPa (based on calculations by Bishop and Stevens (1969) for hemlock-spruce forests). Because the response surface of the three-dimensional coordinate plots are planar, relative changes in FS are linear with changes in both C + ΔC and $\emptyset$. Factor of safety is much more responsive to changes in C + ΔC within reported ranges than typical changes in $\emptyset$. Cohesion affects FS to the greatest extent (relative to $\emptyset$) for steep, thin, saturated soils (Fig. 2a) and to the least extent for deeper, unsaturated soils on gentler slopes (Fig. 2b). Thus, for typical landslide-prone soils in coastal Alaska, C + ΔC is at least an order of magnitude more important than $\emptyset$ for reported ranges of these geotechnical properties.

The rate of decrease in FS with decreasing $\emptyset$ can be affected by soil depth, water table, and slope gradient. With other site factors constant, the effect of decreasing $\emptyset$ is greater for unsaturated soils than for saturated soils. This effect is greatest for deeper soils on moderate slopes (32°) and lowest for shallow soils on steep slopes (42°). Soil depth has no influence on the effect of $\emptyset$ on FS for unsaturated conditions, whereas for saturated or partially saturated soils, FS decreases to a greater extent with decreasing $\emptyset$ for shallow soil mantles than for deeper soils (compare Fig. 2a and Fig. 2d). Lower values of $\emptyset$ decrease FS to a greater extent for moderate slopes than for steep slopes, although water tables moderate this effect to some extent (compare Fig. 2c and Fig. 2d).

The single most important site factor influencing the decrease in FS with lower values of C + ΔC is soil depth: deeper soils have far less influence than shallow soils. A decrease in C + ΔC from 10 to 6 kPa on a moderate gradient, saturated site ($\emptyset$ = 35°) would decrease FS from 2.91 to 2.02 for a 0.4-m soil

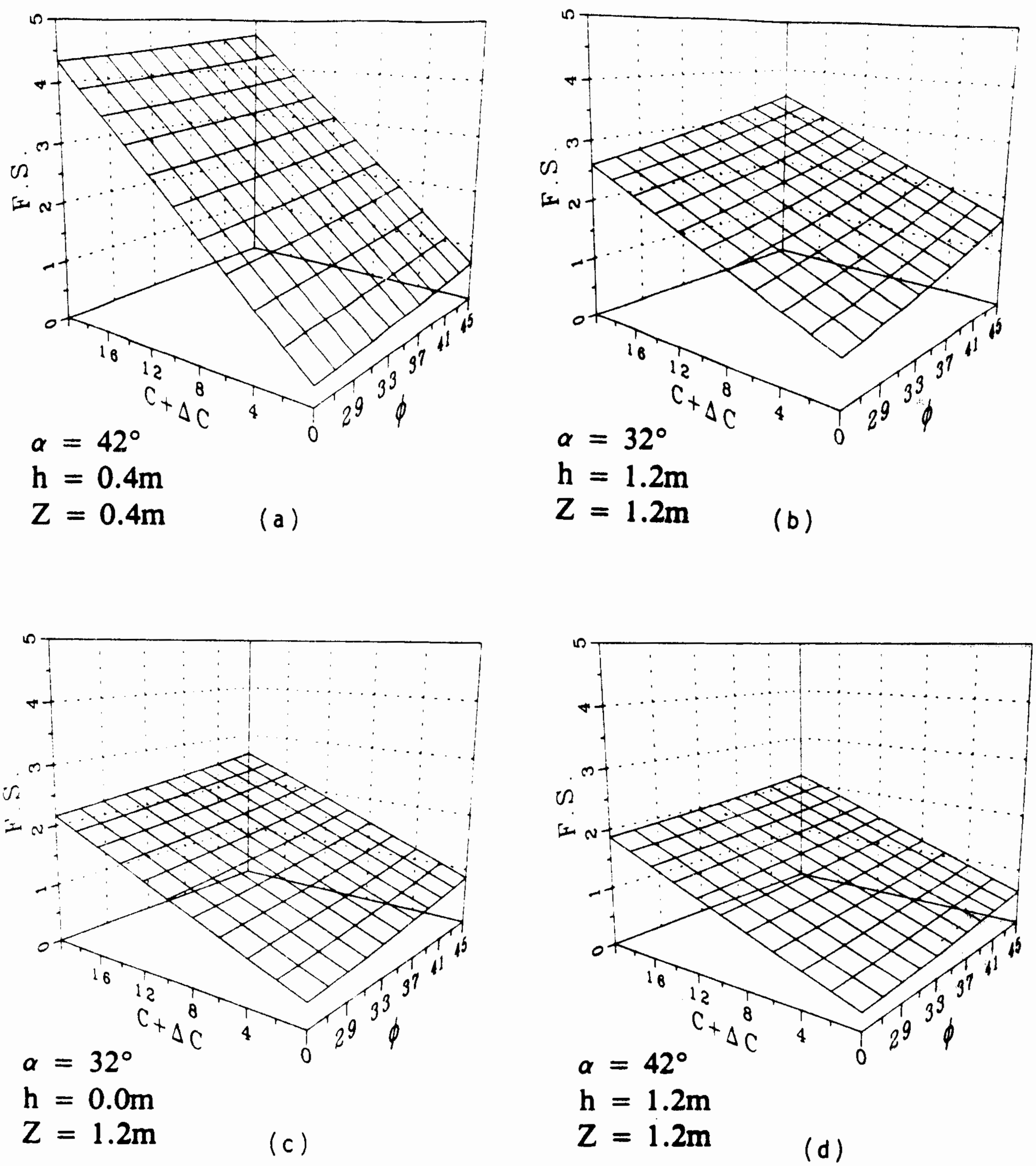
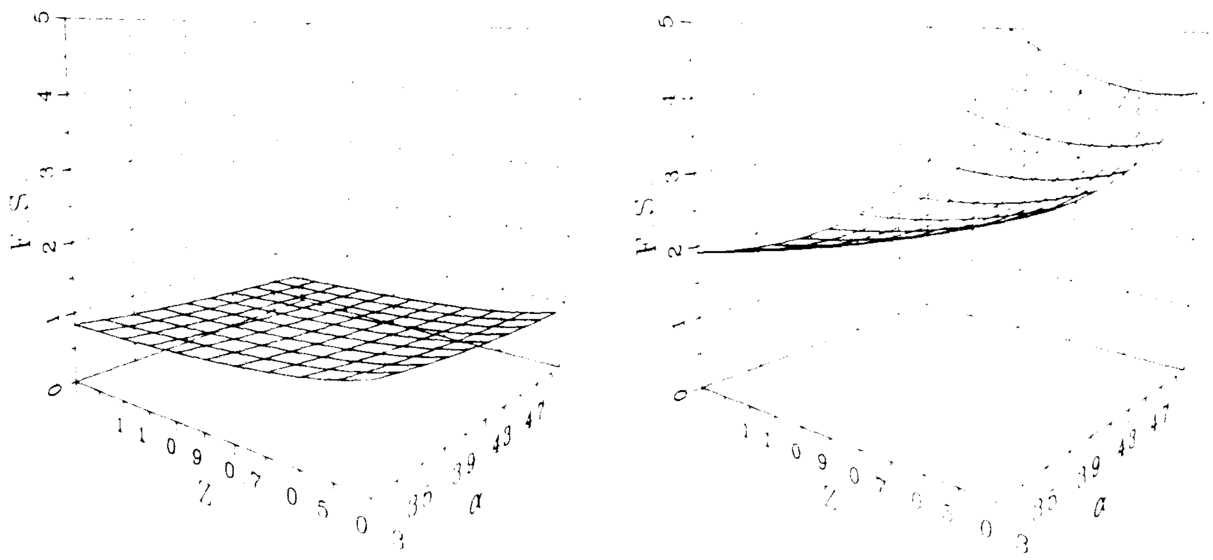


FIGURE 2 - Response of F.S. to changes in Ø (in degrees) and C + ΔC (in kPa) for the following conditions: γ_f = 18.0 kN/m^3, γ_s = 19.0 kN/m^3, W_t = 2.4 kPa.

mantle and from 1.48 to 1.13 for a 1.2-m soil mantle. Under these conditions, slopes with thinner soils are inherently more stable; however, deeper soils are much less affected by changes in $C + \Delta C$. The influence of saturated conditions alone enhances the rate of decline in FS with decreasing $C + \Delta C$ (compare Fig. 2b and Fig. 2c). This influence is much greater for thinner soils and slightly greater for gentler slopes. Decreases in FS associated with decreasing $C + \Delta C$ are greater for moderate slopes than for steeper slopes; saturated conditions slightly enhance this effect (compare Fig. 2c and Fig. 2d).

INFLUENCE OF SITE FACTORS AND GROUNDWATER

Unstable slopes in coastal Alaska may have a variety of combinations of slope gradient and soil depth. All other conditions being similar, deeper soils are less stable than shallow soils. This effect is mainly negated for noncohesive soils. Thus, high natural variation in z for cohesive soils will yield much wider confidence limits for FS than will a similar variation for noncohesive soils. The inverse relationship between α and FS is further amplified by decreasing z, especially for cohesive soils (Figs. 3a and Fig. 3b). The presence of groundwater, however, reduces the influence of α on FS. Typical variation in z for saturated soils results in a wider range in calculated FS than typical variabilty in α, especially for cohesive soils (see "Variability of Natural Factors"). There is a rather narrow range of α for unstable slopes in coastal Alaska.



$C + \Delta C = 2kPa$ $C + \Delta C = 15kPa$

(a) (b)

FIGURE 3 - Reponse of FS to changes in α (in degrees) and z (in m) for totally saturated cohesive (3b) and essentially non-cohesive (3a) soil with $\gamma_f = 18.0$ kN/m^3, $\gamma_s = 19.0\ kN/m^3$, $\phi = 37^o$, and $W_t = 2.4$ kPa.

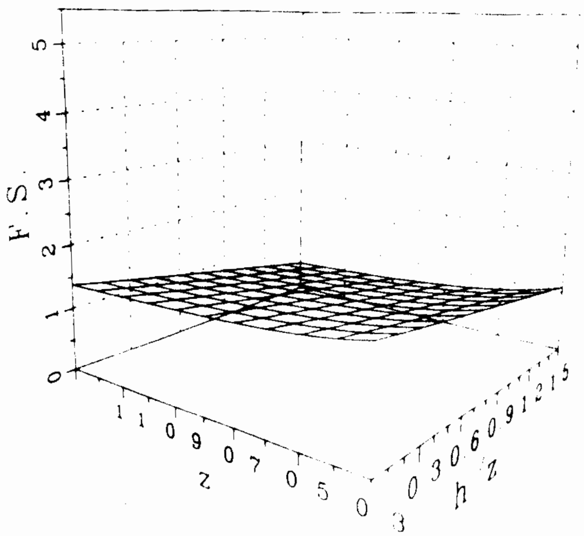
Relative saturation of the soil mantle, expressed as a decimal ratio of groundwater depth to soil depth, directly affects FS by modifying total normal stress to an effective normal stress. Values of h/z measured during major storms in unstable depressions near Kennel Creek, Chichagof Island, Alaska, were 0.94 ($\pm$ 0.18, standard deviation). Factor of safety was slightly more responsive over the range of h/z for the Kennel Creek site (0.75 to 1.15) than over the measured range of z (0.7 m $\pm$ 0.15 m), for essentially cohesionless soils (Figs. 4a and 4c). The reverse situation is true if the soils are cohesive (Figs. 4b and 4d). Factor of safety values decreased to a greater extent in response to increases in z and h/z for gentler slopes, although these slopes are inherently more stable than steeper slopes (Figs. 4a and 4c). The influence of z on FS was not modified to a significant extent by relative saturation of the soil mantle, up to total saturation. As artesian conditions developed (i.e., $h/z > 1.0$), the rate of decrease in FS for deeper soils was slightly enhanced (Figs. 4b and 4d). For essentially noncohesive soils, the rate of change in the FS in response to changes in z increased slightly over the entire range of h/z (Figs. 4a and 4c).

HARVESTING EFFECTS

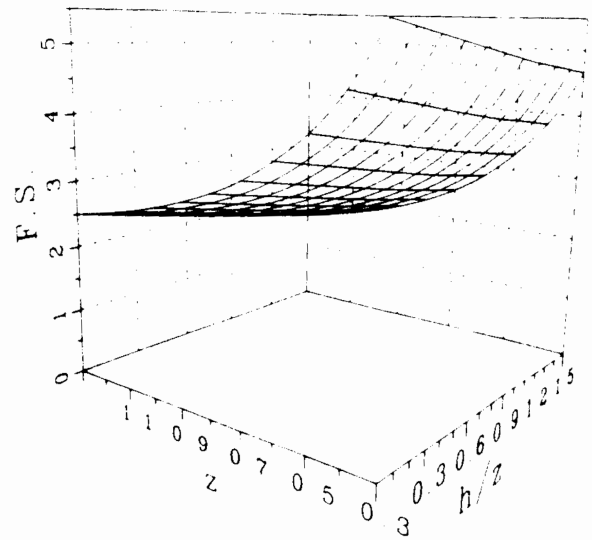
Timber harvesting can decrease the stability of slopes; (1) by reducing root reinforcement because of root-wood deterioration, site disturbance and introduction of different plant species; and (2) by temporarily increasing water inputs and soil moisture because of reduced evapotranspiration and changes in volume and rate of snowmelt. Slope stability after harvesting depends on the number of residual trees and the amount of understory vegetation, rate and type of regeneration, site characteristics, and postharvesting patterns of water inflow. A possible short-term improvement in site stability resulting from the removal of tree weight (i.e., reduced W_t) has been mentioned by Brown and Sheu (1975) and by Gray and Megahan (1981).

The contribution of vegetation roots to soil shear strength has been measured directly (Endo and Tsuruta 1969; O'Loughlin et al. 1982) or estimated by back-calculation of Equation (7) for failed slopes (Sidle and Swanston 1982; Swanston 1970). Swanston (1970) reported a range in ΔC values from 3.3 to 4.3 kPa for hemlock-spruce forests growing on a Karta soil in coastal Alaska, whereas a range in ΔC from 5.0 to 6.6 kPa was calculated by Wu et al. (1979) for a similar site. Sidle and Swanston (1982) calculated $\Delta C = 2.0$ kPa for understory vegetation on a Tolstoi soil at Trap Bay, Alaska. For simulating the effects of timber harvesting on hillslopes of coastal Alaska, the following ΔC values were assumed: 4.0 kPa for hemlock-spruce forests; 2.0 kPa for understory vegetation alone; and 0.0 kPa for denuded conditions. Surcharge because of vegetation weight was estimated at 2.4 kPa for hemlock-spruce forests and was assumed to be negligible for understory species.

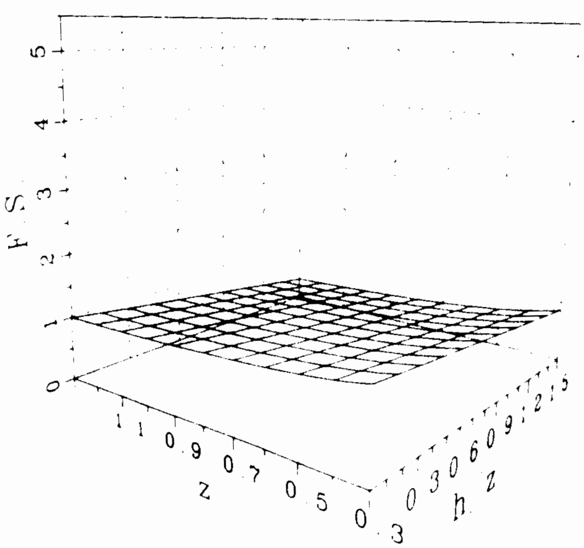
A moderately steep (32°) site with soil properties similar to those of the Tolstoi series ($\phi = 37^{\circ}$, $C = 0$, $\gamma_s = 19$ kN/m^3, $\gamma_f = 18$ kN/m^3, $z = 0.4$m, $h = 0.2$ m) would have a low landslide potential under forested conditions (FS = 2.09),



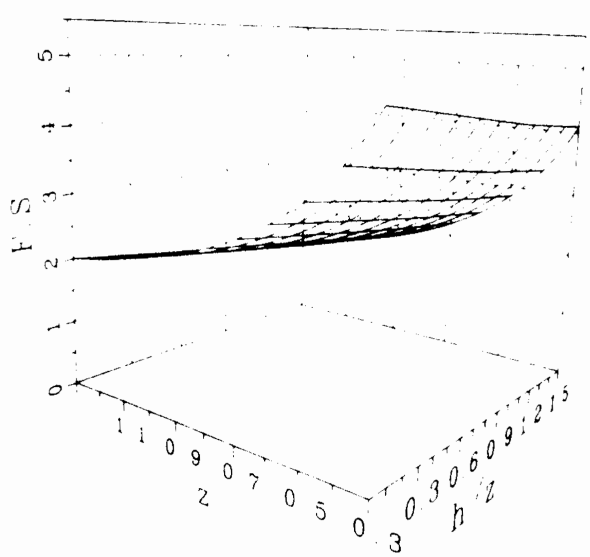
C + ΔC = 2kPa
α = 32°
(a)



C + ΔC = 15kPa
α = 32°
(b)



C + ΔC = 2kPa
α = 42°
(c)



C + ΔC = 15kPa
α = 42°
(d)

FIGURE 4 - Response of FS to changes in h/z and z (in m) for the following conditions: γ_f = 18.0 kN/m^3, γ_s = 19.0 kN/m^3, ø = 37°, and W_t = 2.4 kPa.

a medium potential with understory vegetation alone (FS = 1.49), and failure would be implied if the site were denuded (FS = 0.89). These relative stability values can be related in a general way to various harvesting practices. Clearcut logging by downhill high-lead yarding methods destroys understory vegetation on certain portions of the slope. This temporary reduction in ΔC could provide the critical difference in soil strength that would produce slope failure as outlined in the previous stability calculations. Alternatives to high-lead clearcutting that would provide a viable rooting strength on the site after logging include: (1) skyline logging, where less understory vegetation would be destroyed during yarding; and (various partial cutting practices where a portion of the rooting strength .. the overstory species would be retained. Endo and Tsuruta (1969) have shown that alder has greater rooting strength (ΔC, 2 to 12 kPa) than most conifers. Consideration may be given to encouraging rapid establishment of alder on highly unstable clearcut hillslopes. Although these alternatives are contrary to typical forest management practices, their implementation may be necessary if timber is to be harvested from unstable slopes.

Vegetation weight has only a minor influence on FS compared with ΔC as evidenced in the essentially cohesionless soil examples in Fig. 5. For low rooting strength conditions (low ΔC), increasing W_t had a beneficial effect on slope stability; for soils with higher ΔC values this influence was reversed. The beneficial effect of increasing W_t (for low ΔC values) was greater for steeper slopes, higher groundwater tables, and deeper soils. Slope gradient

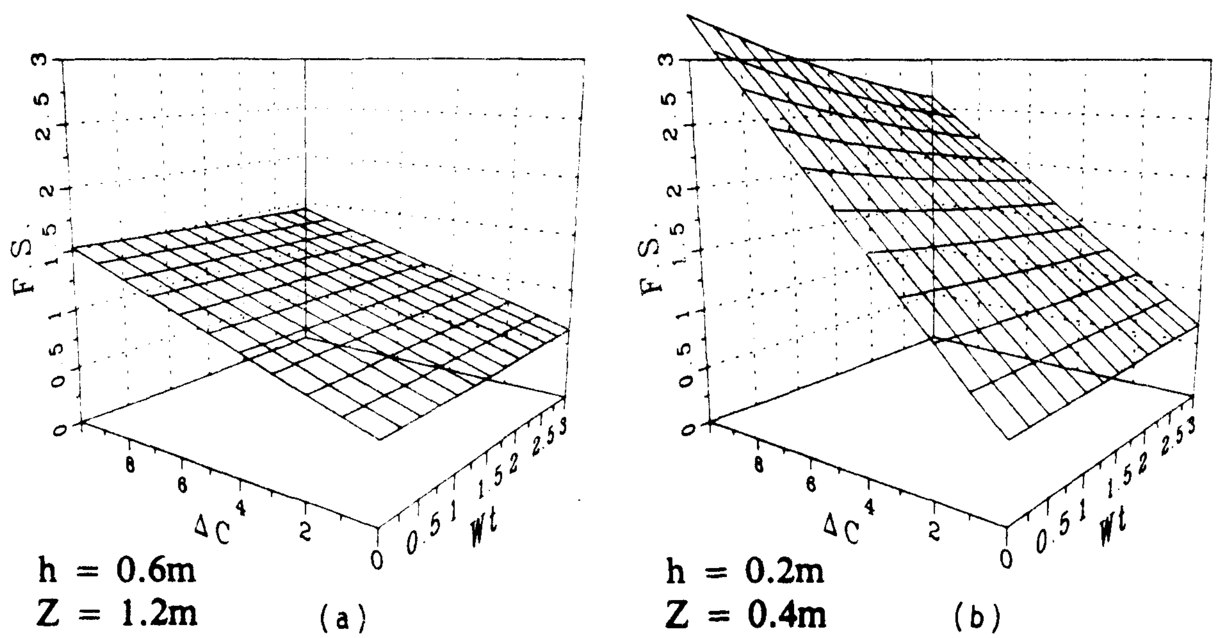


FIGURE 5 - Response of FS to changes in W_t and ΔC (both in kPa) for essentially cohesionless soils (C = 0) with the following properties: $\alpha = 42^{\circ}$, $\gamma_f = 18.0$ kN/m^3, $\gamma_s = 19.0$ kN/m^3, $\phi = 37^{\circ}$.

had little influence on the relationship between FS and ΔC. For gentler slopes the rate of decrease of FS with decreasing ΔC was slightly greater than for steeper slopes. The rate of decrease in FS with decreasing ΔC is about three times greater for shallow soils (z = 0.4 m) than for deeper soils (z = 1.2 m) (compare Fig. 5a and Fig. 5b). The influences of both h and α on the response of FS to changes in ΔC are minimal.

The effect of vegetation removal on shallow groundwater regimes in coastal Alaska hillslopes is probably small during most of the fall storm season because of wet antecedent conditions. Vegetation removal would have the greatest effect on groundwater during a major storm encountered early in the fall when antecedent conditions are generally drier. If timber removal could increase groundwater response in unstable hillslopes by 0.1 m during an episodic storm early in the fall, FS could be reduced an additional 5 to 8% (Table 1). Decreases in FS with changes in groundwater from saturated (h = z) to slightly artesian (h = z + 0.1 m) conditions were greater for shallow soil mantles.

TABLE 1

FACTOR OF SAFETY VALUES FOR VARIOUS GROUNDWATER CONDITIONS[1/]

Groundwater	soil depth = 0.4 m		soil depth = 1.2 m	
height	$\alpha = 32^{\circ}$	$\alpha = 42^{\circ}$	$\alpha = 32^{\circ}$	$\alpha = 42^{\circ}$
h = 0.5 z	1.87	1.49	1.28	0.96
h = z	1.62	1.31	1.00	0.77
h = z + 0.1 m (artesian)	1.50	1.23	0.95	0.73

[1/] Soil and site conditions include: $C + \Delta C = 4$ kPa; $\phi = 37^{\circ}$; $\gamma_s = 19$ kN/m^3; $\gamma_f = 18$ kN/m^3; $W_t = 2.4$ kPa.

VARIABILITY OF NATURAL FACTORS

The natural variabilities of soil and site properties included in Equations 7 and 8 are important considerations in the use of the infinite slope model for slope stability hazard analysis. The literature is replete with applications of the infinite slope model where variability of input factors has not been considered. Table 2 summarizes data for two unstable soil mapping units in coastal Alaska: Kupreanof-Tolstoi and Karta soils. The largest relative variabilities (coefficients of variation 49-55%) are associated with C, one of the most important factors influencing FS. Soil depth measured at specific unstable sites also had large coefficients of variation, 17-37%. Calculated

TABLE 2
ENGINEERING AND SITE PROPERTIES FOR TWO UNSTABLE SOIL MAPPING UNITS

Variable	Kupreanof - Tolstoi mean	Kupreanof - Tolstoi std. dev.	Kupreanof - Tolstoi source	Karta mean	Karta std. dev.	Karta source
C	8.2kPa	4.5kPa	2,3	5.7kPa	2.8kPa	3,7
ϕ	37.1°	3.9°	2,3	35.8°	5.1°	3,7
α	36.0°	6.0°	11	39.5°	5.0°	1
z	0.47m	0.08m	8	0.82	0.31m	10
h/z	0.94	0.18	8	0.94	0.18	9
γ_f	14.0kN/m^3	3.7kN/m^3	4	11.3kN/m^3	1.5kN/m^3	10
γ_s	15.0kN/m^3	4.0kN/m^3	3,4	13.8kN/m^3	1.8kN/m^3	10
ΔC	4.5kPa	1.5kPa	5,6,7	4.5kPa	1.5kPa	5,6,7
W_t	2.5kPa	0.5kPa	1	2.5kPa	0.5kPa	1

<u>Sources</u>

[1]Bishop and Stevens (1964)
[2]Schroeder (1983)
[3]Schroeder and Filz (1981)
[4]Sidle and Shaw (1983)
[5]Sidle and Swanston (1982)
[6]Swanston (1970)
[7]Wu et al. (1979)
[8]unpublished data from Alvin Bay, Kuiu Island, AK
[9]unpublished data from Kennel Creek, Chichagof Island, AK
[10]unpublished data from Prince of Wales Island, AK
[11]unpublished data from Trap Bay, Chichagof Island, AK (Tolstoi soil)

ranges in FS based on one standard deviation of C and z alone were 2.15 to 4.93 for the Kupreanof-Tolstoi complex and 1.21 to 4.93 for the Karta soil. Minimum and maximum values of FS calculated over the range of the nine factors listed in Table 2 were 1.40 to 7.69 for the Kupreanof-Tolstoi soil and 0.81 to 4.59 for the Karta soil.

The wide range of calculated FS based on natural variation of soil and site factors indicates that caution must be exercised when the infinite slope model is used to classify landslide hazards by soil mapping units in coastal Alaska. Site-specific measurements of certain variables are needed to get an accurate FS on a site-by-site basis; however, these site specific data are expensive to collect and for broad planning purposes on unstable forest lands, empirical models relating landslide hazard to important triggering mechanisms (e.g., rainfall intensity and duration) may be more appropriate. The factor of safety approach would still be useful in assessing and comparing management alternatives for unstable landscapes.

SUMMARY

Sensitivity analyses of the infinite slope model revealed that cohesion and soil depth are the two most important variables influencing FS for conditions typical of coastal Alaska. The influence of soil depth on FS is greatly diminished for low-cohesion soils, however. Slope gradient and angle of internal friction affected FS by almost one order of magnitude less than did typical ranges of cohesion and soil depth. Groundwater exerts a dynamic influence on slope stability because water tables can develop in shallow hillslope soils during individual storms and often cause artesian pore water pressures. Removal of vegetation from unstable slopes can substantially reduce site stability primarily through loss of root cohesion. The effects of groundwater fluctuations and loss of root strength would be the most important factors influencing initiation of landslides. Caution should be exercised when the infinite slope model is used to quantitatively predict stability of natural slopes because of the inherent variabiliites of soil and site factors.

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