Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publ. no. 209, 1992.

289

Shallow landslide analysis in terrain with managed vegetation

R. C. SIDLE & P. K. K. TERRY

Intermountain Research Station, 860 North 1200 East, Logan, Utah 84321, USA

Abstract Shallow landslides triggered by rainfall are common erosion phenomena in steep forested terrain. Vegetation management on such slopes can influence site stability by modifying rooting strength — an important component of cohesion. An infinite-slope landslide model is presented that incorporates changes in rooting strength and vegetation surcharge through several simulated vegetation management cycles. Impacts of a prior vegetation removal are overlain upon a more recent removal to generate a long-term simulation of probability of slope failure. For each year the model calculates the groundwater-soil depth ratio (M_{crit}) that would induce slope failure. Rainfall data are used to estimate groundwater response by either: (a) a regression model or (b) a steady-state solution to the Dupuit-Forchheimer equation. An extreme value distribution of groundwater values is then generated. Calculated M_{crit} values are compared to this extreme value distribution to establish a probability of occurrence for a landslide in any year.

INTRODUCTION

Shallow rapid landslides, such as debris avalanches and slides, are important erosion processes in steep terrain. These failures are frequently initiated far up on the hillslope in slightly concave depressions (Temple & Rapp, 1972; Johnson & Sitar, 1990). It is believed that these depressions were former landslide scars which have gradually filled with soil and organic material through time (Shimokawa, 1984; Reneau *et al.*, 1989). As soil depth in these depressions increases with time, the stability of the site decreases. This coupled with the occurrence of an episodic storm or snowmelt event can sufficiently decrease soil strength resulting in another slope failure.

Another factor influencing slope stability, especially in forested areas, is the effect of changing root strength caused by vegetation management. When trees are cut, live roots begin to decay and there is generally a lag time before the root systems of newly planted or invading trees contribute substantial root strength to the site. Field studies in many parts of the world have shown that sites are most susceptible to landsliding about 2 to 12 years after forest cutting (Endo & Tsuruta, 1969; Megahan *et al.*, 1978). This period corresponds to the time of minimum rooting strength as determined in several independent studies (Ziemer & Swanston, 1977; O'Loughlin & Watson, 1979).

This paper presents an overview of a conceptual model of slope stability applicable to managed forest sites and other landslide-prone areas where vegetation contributes significant strength to the soil mantle. Detailed root strength, groundwater, and tree surcharge aspects of the model have been published elsewhere (Sidle, 1987, 1991, 1992). Examples are presented comparing effects of different vegetation management strategies on slope stability with an emphasis on minimizing potentially harmful effects of vegetation removal.

DESCRIPTION OF THE MODEL

The model is based on the infinite slope equation which is applicable to shallow, rapid failures with a shear plane approximately parallel to the soil surface, uniform soil depth, and failure length much greater than failure width or soil depth. Many sliding failures of this type occur high on hillslopes; thus, groundwater models used to predict shallow groundwater response in larger basins are often not applicable (Johnson & Sitar, 1990).

Parameters in the model are either static, deterministic, or stochastic. Soil and site properties such as soil depth (Z), angle of internal friction (ϕ), cohesion (C), unit soil weights (γ_m, γ_{sat}), and slope gradient (α) are treated as static parameters. During the length of typical vegetation management simulations (100-300 years), these parameters should change very little. Deterministic parameters include rooting strength (ΔC) and tree surcharge (W_T, weight per unit area). Rainfall and the resulting influence on groundwater are treated as stochastic variables.

The effects of long-term vegetation management on the probability of landslide occurrence are simulated by overlaying the impacts of a prior vegetation removal on a more recent removal. For each year, the model calculates the groundwater-soil depth ratio (M_{crit}) that would induce slope failure (Fig. 1). The factor of safety equation for infinite slopes is set equal to 1 (critical equilibrium state) and is solved for M to yield

$$M_{crit} = \frac{C + \Delta C + \cos\alpha(\tan\phi - \tan\alpha)(\gamma_m Z\cos\alpha + W_T)}{[(\gamma_{sat} - \gamma_m)\tan\alpha - (\gamma_{sat} - \gamma_m - \gamma_w)\tan\phi]Z\cos^2\alpha} \qquad (1)$$

where γ_m, γ_{sat}, and γ_w are the unit weights of moist soil, saturated soil and water, respectively. Equation (1) assumes slope parallel flow in the soil mantle.

Long-term rainfall data for a given site are fitted to an extreme value distribution (e.g. Gumbel). Rainfall data are used to calculate maximum groundwater response using one of two models: (a) an empirical function relating relative piezometric response to antecedent rainfall, storm intensity, and total storm precipitation; and (b) a linearized, steady-state solution to the Dupuit-Forchheimer equation. An extreme value distribution of groundwater values can be generated for either case. The calculated M_{crit} values are then
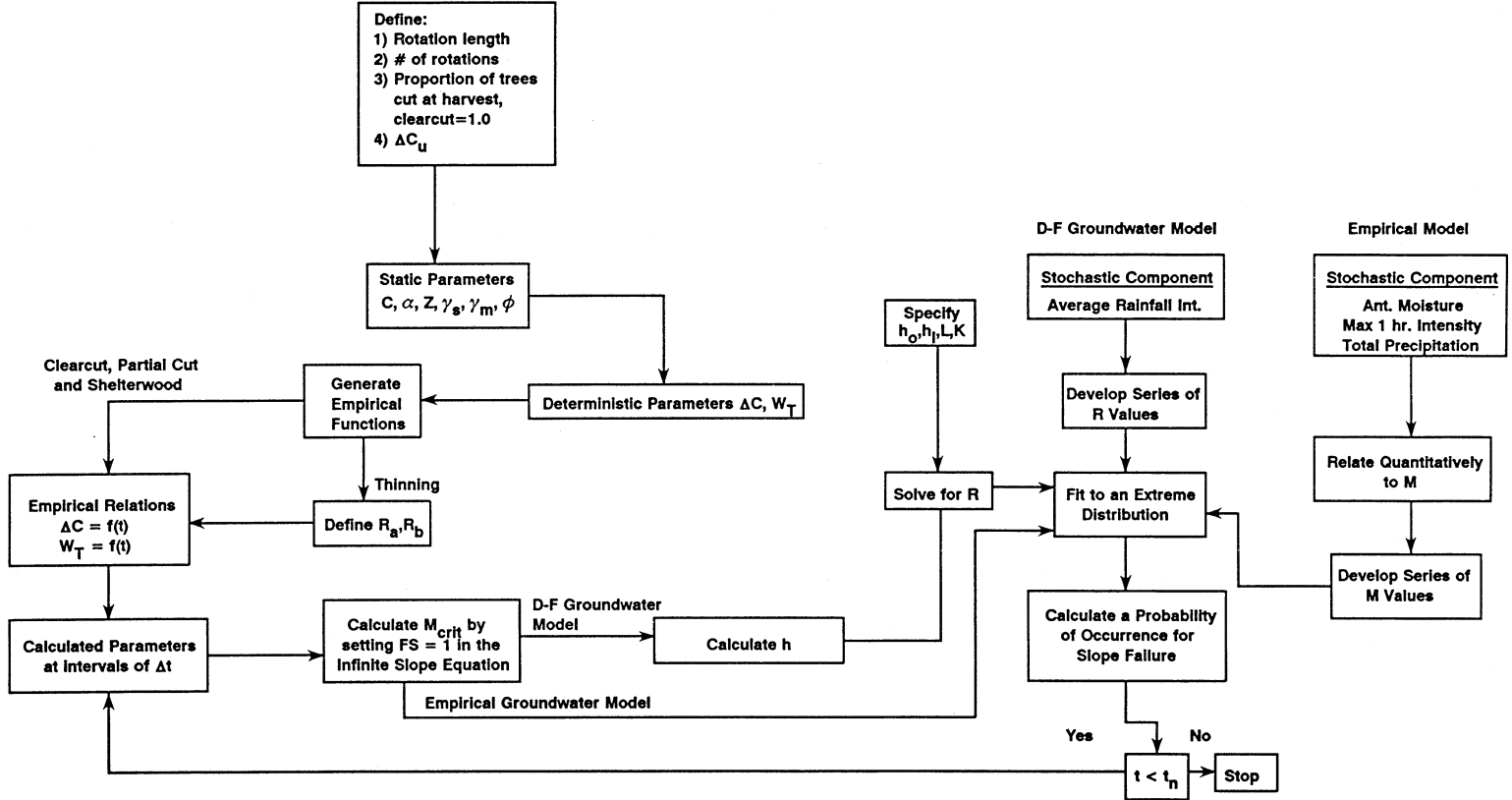
Fig. 1 Operational flow chart for the landslide model.

compared to the extreme value distribution for groundwater in order to establish a probability of occurrence for M_{crit} (and thus a landslide) in any given year.

VEGETATION

Root strength can be viewed as an additive component to soil shear strength (O'Loughlin & Ziemer, 1982). In the model, root strength is treated as a dimensionless parameter, $\Delta \check{C}$, calculated as $\Delta C / \Delta C_\infty$, where ΔC_∞ is the maximum root strength for a given vegetation type. Decline of rooting strength following the removal of vegetation has been described by a negative exponential relationship (Sidle, 1991):

$$D = \exp(-kt^n) \tag{2}$$

where D is "dimensionless" root strength $(0 < D \leq 1)$, k and n are empirical constants, and t is the time (in years) since vegetation removal. Values of D must be multiplied by the maximum root strength for a given vegetation type (ΔC_∞) to convert them to actual cohesion values. Root strength decay data for several vegetation types worldwide are given in Fig. 2. The solid line on each graph represents the best fit of equation (2). Root systems of radiata pine decay the most rapidly after timber harvesting, while those of Sitka spruce-western hemlock forests decay the slowest. Sugi (Japanese cedar) root systems initially decay more rapidly than roots of spruce-hemlock forests; however, after 25 years the relative root cohesion of the two forest types is similar. Varieties of individual species can have different root decay characteristics. Five years following timber harvest, root systems of dead coastal Douglas fir lost 80% of their initial strength, while root strength of Rocky Mountain Douglas fir declined by only about 60%. However, maximum root strength of coastal Douglas fir is almost twice that of Rocky Mountain fir (Burroughs & Thomas, 1977). Decay coefficients (k and n) for the six vegetation types are given in Fig. 2. Root strength of a site is also affected by the regeneration of new vegetation following harvesting. A conceptual model of root strength regrowth is given by Sidle (1991) as:

$$R = [a + b \exp(-kt)]^{-1} + c \tag{3}$$

where R is dimensionless root strength, t is the time in years since vegetation removal, and a, b, c and k are empirical constants. Although few data are available on root strength recovery, this conceptual relationship is based on estimates of root strength and uprooting resistance in different aged stands (Kitamura & Namba, 1981; Ziemer, 1981; Abe & Iwamoto, 1987). Coefficients in equation (3) are evaluated by the model by specifying the inflection point of the root regrowth curve (t_i), the percentage of maximum root
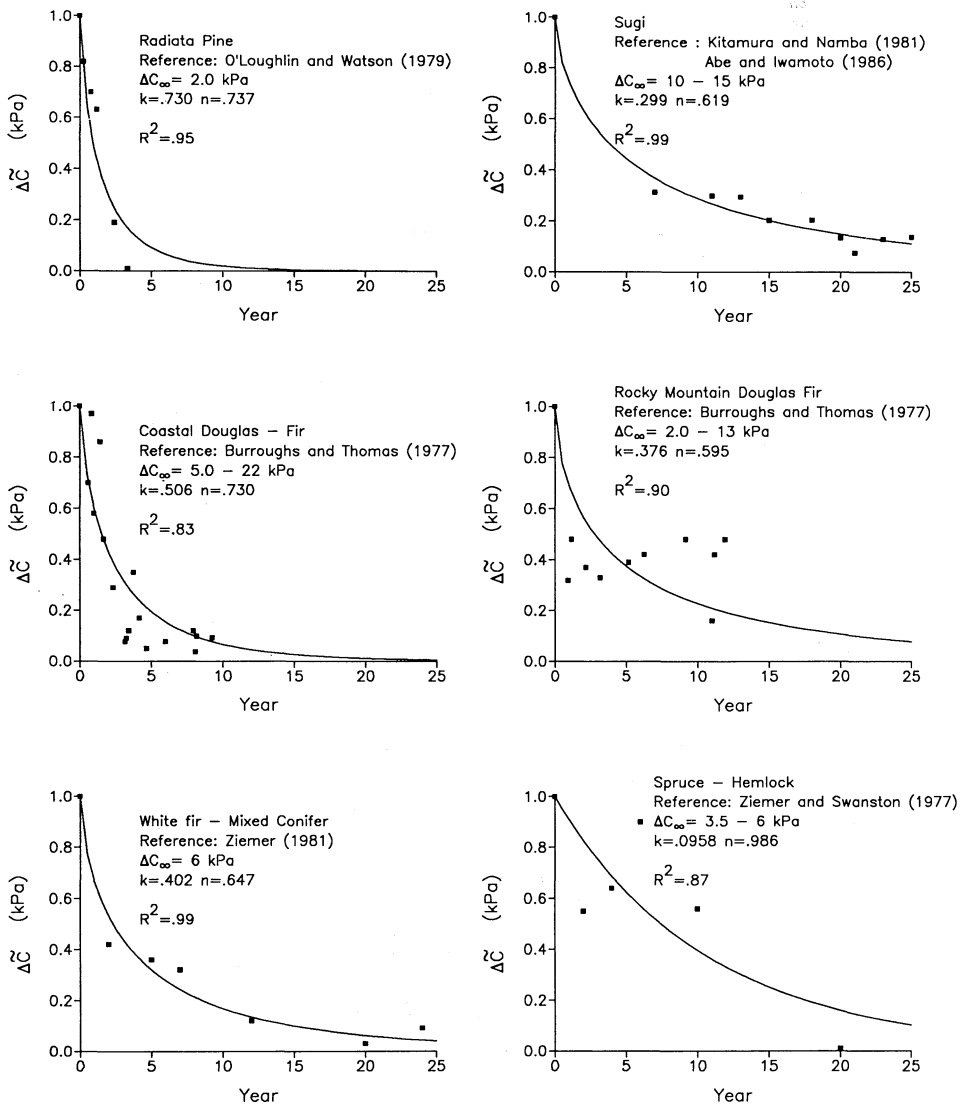
Fig. 2 Root strength decay following clearcutting for six vegetation types.

strength recovery at $2t_i$, the maximum root strength (ΔC_∞), and the initial conditions.

Relative net rooting strength at any time during the simulation [$\Delta \tilde{C}(t)$] is equal to the sum of R and D. However, if this sum ever exceeds 1, the model restricts the upper limit of $\Delta \tilde{C}(t)$ to 1. The infinite slope model assumes that vegetation roots intersect the potential failure plane. In the case of deep soils or shallow-rooted vegetation where this is not true, the values of rooting strength should be multiplied by 0.1 to 0.5 to represent the reinforcement of the soil around the perimeter of the failure zone only (Hammond *et al.*, 1992).

A deterministic parameter of less importance in the model is the

surcharge due to tree weight (W_T). At the time of timber harvest, the surcharge attributed to the removed trees is set to zero. In the case of a clearcut, the entire surcharge is set to zero; for a partial cut, surcharge is reduced proportionally to the percentage of trees removed. Recovery of tree surcharge following harvesting can be explained by the same sigmoid relationship used to describe root strength recovery:

$$W = [a + b\exp(-kt)]^{-1} + c \tag{4}$$

where W is the surcharge recovery function and a, b, c, and k are empirical constants evaluated by methods outlined by Sidle (1991). Estimates of W can be obtained from timber inventory data; the weight of understory or brush vegetation can be ignored in the analysis.

GROUNDWATER

The empirical model used to predict piezometric head (p) was derived from data collected in unstable hillslope sites in coastal Alaska (Sidle, 1984a). The regression equation is:

$$p = 0.149\ln(TOTPPT) + 0.0398(ANT2)^{1/3} + 0.0668\ln(INT1) \tag{5}$$

where $TOTPPT$ is total storm precipitation (mm), $ANT2$ is antecedent two-day precipitation (mm), and $INT1$ is maximum 1-h rainfall intensity. Piezometric head (p) is expressed in metres. Equation (5) explained 99% of the variation in maximum piezometric response. As with other empirical models, equation (5) can only be reliably applied in the area in which it was developed. However, piezometric levels in shallow hillslope soils in other areas seem to respond to similar rainfall and antecedent conditions (Johnson & Sitar, 1990; Sidle *et al.*, 1991).

Rainstorms that produce a maximum annual value of p (as determined by equation (5)) are then compiled into an annual series for the area of interest. For the examples presented in this paper, 27 years of climatic data from Juneau, Alaska, were compiled for the three independent variables in equation (5) that yielded maximum annual p values. The value of M_{crit} at each time step in the landslide model (equation (1)) is multiplied by $Z\cos^2\alpha$ to convert it to p. This conversion assumes slope parallel flow conditions. The p value at each time step is then compared to an extreme value distribution (e.g. Gumbel) based on the historical rainfall record to determine the probability of a landslide occurring at any time.

Another option for analysing maximum groundwater response during rainstorms is a linearized, steady-state solution to the Dupuit-Forchheimer equation (Yates *et al.*, 1985). This equation predicts vertical groundwater

height (h) along a two-dimensional slope. Because groundwater table varies in the x-direction, inherent assumptions in the infinite slope model are violated. However, for steep slopes, if hydraulic conductivity is high (>0.04 m h^{-1}), the phreatic surface approximately parallels the slope for short slope distances (i.e. 6 to 30 m). The steeper the slope, the shorter the slope distance over which a parallel phreatic surface occurs. Thus, the user must be very careful that the conditions are applicable to the site being analysed before the groundwater model is applied. The driving climatological factor in the model is average rainfall intensity during the storm (R'). The Dupuit-Forchheimer equation can be solved for R' in terms of M ($M = h/Z$):

$$R' = \frac{KI[h_L - MZ + (MZ - h_o)\exp(-IL/\bar{h}) - (h_L - h_o)\exp(-Ix/\bar{h})]}{L[\exp(-Ix/h) - 1] - x[\exp(-IL/h) - 1]} \qquad (6)$$

where I is the slope gradient (rise/run), h_o and h_L are the downslope and upslope initial vertical water table heights, x is the distance upslope of $h(0,0)$, and $\bar{h}$ is the average water table height, $(h_{max} + h_{min})/2$.

In the model, R' is calculated for each year and represents the average rainfall intensity (in one event) required during that year to generate M_{crit}, and thus a landslide. An annual series of R values is then fitted to an extreme value distribution (e.g. Gumbel) to calculate the probability of occurrence of such a landslide-producing rainfall event.

STABILITY SIMULATIONS

The slope stability model allows land managers to make qualitative comparisons of different vegetation management strategies in potentially unstable terrain. The number of years between individual vegetation removals (e.g. clearcuts, brush burning) and the extent of each removal can be dictated by the user. In the case of forest vegetation, the relative importance of understory rooting strength can be specified. The model will also allow for regeneration of different vegetation types (e.g. as in the case of direct planting) after any removal interval. Effects of removing tree surcharge can be quantified.

Five clearcut and partial-cut rotations in a western hemlock-Sitka spruce forest were simulated (Fig. 3). Rotation length was constant at 60 years. Site and soil properties were within ranges reported for the Karta soil mapping unit in coastal Alaska (Sidle, 1984b): $C = 4$ kPa; $\phi = 36°$; $\alpha = 38°$; $W = 2.5$ kPa; $Z = 1.2$ m; $\gamma_{sat} = 11.3$ kN m^{-3}; $\gamma_m = 13.8$ kN m^{-3}; $\Delta C_u = 0.5$ kPa; and $\Delta C_\infty = 5$ kPa. Root strength regrowth and decay parameters given by Sidle (1991) for spruce-hemlock forests were used. For the steady-state Dupuit-Forchheimer model, the following assumptions were made: $L = 10$ m; $h_o = 0.5$ m; $h_L = 0.1$ m; and $K = 0.022$ m h^{-1}. Probability of failure predictions were consistently higher using the empirical groundwater
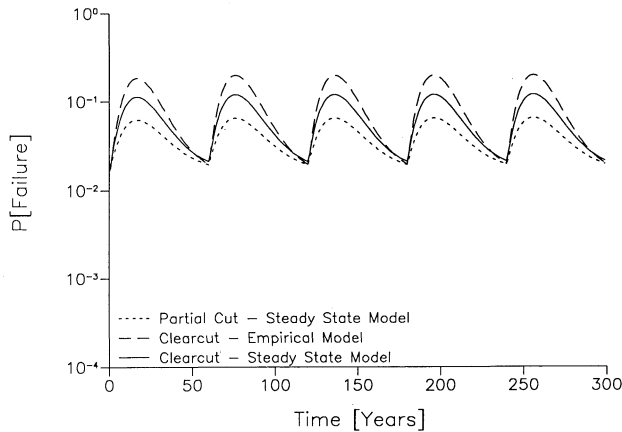
Fig. 3 Simulations of probability of failure in a steep western hemlock-Sitka spruce forest site subject to five clearcuts and partial cuts.

model compared with the Dupuit-Forchheimer model for this site. Peak values of probability of failure occurred 16 years after clearcutting and were 0.12 and 0.2 for simulations using the Dupuit-Forchheimer and the empirical groundwater models, respectively (Fig. 3). These simulations indicate that the site is at a high risk for landslides during the period from about 11 to 21 years following each clearcut. Retaining just 30% of the forest stand in each cutting cycle (i.e. 70% partial-cut) decreases the probability of failure almost two-fold compared with the clearcut simulation (Fig. 3). The 60-year rotation period used in Fig. 3 allowed sufficient time for root strength recovery to preclude any cumulative effects of sequential timber harvests.

Vegetation conversion and range improvement practices on steep slopes can have a profound impact on site stability. In many areas, brush species are periodically eradicated by fire, herbicide or mechanical means to promote increased productivity of grasses. While more dense grass cover offers protection from surface erosion, the rooting strength of the grasses is negligible compared to most shrub or tree species.

An example is presented for periodic removal of brush by prescribed fire. Four cycles of 35, 25, 15, and 10 years are simulated. Maximum rooting strength was assumed to be 2.5 k Pa and root decay coefficients were $k = 0.55$ and $n = 0.75$. Root strength regrowth for each cycle was based on equation (3), assuming that 90% of the maximum rooting strength was recovered 26 years after burning. Site and soil conditions were as follows: $C = 3$ kPa; $\phi = 36°$; $\gamma_{sat} = 11.3$ kN m^{-3}; $\gamma_m = 13.8$ kN m^{-3}; and $Z = 1.8$ m. Hypothetical simulations were run to establish acceptable slope gradients for this brush control strategy. On steep slopes ($\alpha \geq 32°$) brush clearing increased the probability of failure to > 0.1 for more than half of the time even during the longest burning interval (Fig. 4). Following the shorter burning intervals (10 and 15 years), probability of failure was in excess of 0.16 at all times. For these site conditions, this would not be an acceptable management alternative.

On moderately steep slopes ($\alpha = 29°$), probability of failure remained < 0.085 for the longer burning intervals. For the shorter burning intervals, maximum probability of failure increased above 0.1 (Fig. 4). Longer burning intervals would be marginally acceptable for such site conditions; however, intervals < 20 years should probably be avoided. Finally, the same simulation was run for moderate slopes ($\alpha = 26°$). Although probability of failure increased with decreasing burning intervals, values were always ≤ 0.02 (Fig. 4). Similar cumulative effects of progressively shorter intervals for removal of vegetation have been simulated for various forest stands (Sidle, 1991).
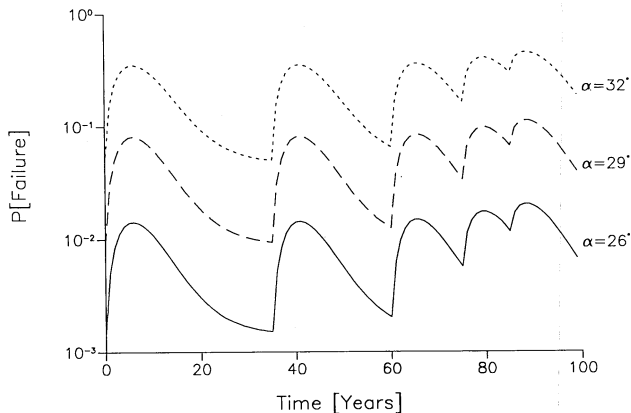

Fig. 4 Simulations of the effects of decreasing cycles of probability of slope failure for gradients of 26°, 29°, and 32°.

Although these site stability simulations are rather simplistic, they provide the land manager with a tool for comparing various vegetation manipulation options in unstable terrain. Actual values of probability of failure generated by the model should be viewed with caution; however, relative values for given site conditions can be compared and used to assist in management decisions. In all simulations, the weight of vegetation had virtually no effect on stability calculations.

REFERENCES

Abe, K. & Iwamoto, M. (1987) Soil mechanical role of tree roots in preventing landslides. In: *Proceedings of the VIth International Conference and Field Workshop on Landslides*, Christchurch, New Zealand, 1-9.

Burroughs, E. R. & Thomas, B. R. (1977) Declining root strength in Douglas-fir after falling as a factor in slope stability. *Res. Pap. INT-190, For. Serv. US Dept of Agric.*, Ogden, Utah.

Endo, T. & Tsuruta, T. (1969) The effect of the tree's roots on the strength of soil. In: *Ann. Report, 1968, Hokkaio Branch For. Experimental Station, Sapporo, Japan*, 167-182.

Hammond, C., Hall, D., Miller, S. & Swetik, P. (1992) Level I stability analysis (LISA) documentation for version 2.0. *Gen. Tech. Report INT-285, For. Serv., US Dept of Agric.*, Ogden, Utah (in press).

Johnson, K. A. & Sitar, N. (1990) Hydrologic conditions leading to debris-flow initiation. *Can. Geotech. J.* **27**, 789-801.

Kitamura, Y. & Namba, S. (1981) The function of tree roots upon landslide prevention presumed through the uprooting test (in Japanese). *Bull. For. & For. Prod. Res. Inst. no. 313*, 175-208. Ibaraki, Japan.

Megahan, W. F., Day, N. F. & Bliss, T. M. (1978) Landslide occurrence in the western and central Northern Rocky Mountain physiographic province in Idaho. In: *Proceedings of the 5th North American Forest Soils Conference* (Colorado State Univ., Fort Collins), 116-139.

O'Loughlin, C. L. & Watson, A. (1979) Root wood strength deterioration in radiata pine after clearfelling. *NZ J. For. Sci.* **9**(3), 284-293.

O'Loughlin, C. L. & Ziemer, R. R. (1982) The importance of root strength and deterioration rates upon edaphic stability in steepland forest. In: *Carbon Uptake and Allocation in Subalpine Ecosystems as a Key to Management* (Proc. IUFRO Workshop, August 1982), 70-78. Oregon State Univ., Corvallis.

Reneau, S. L., Dietrich, W. E., Rubin, M., Donahue, D. J. & Jull, A. J. T. (1989) Analysis of hillslope erosion rates using data colluvial deposits. *J. Geol.* **97**, 45-63.

Shimokawa, E. (1984) A natural recovery process of vegetation on landslide scars and landslide periodicity in forested drainage basins. In: *Symp. on Effects of Forest Land Use on Erosion and Slope Stability* (East-West Centre, Honolulu, Hawaii), 99-107.

Sidle, R. C. (1984a) Shallow groundwater fluctuations in unstable hillslopes of coastal Alaska. *Z. Gletscherkunde Glazialgeol.* **20**(2), 79-95.

Sidle, R. C. (1984b) Relative importance of factors influencing landsliding in coastal Alaska. In: *Proceedings of 21st Annual Engng Geol. and Soils Engng Symp.* (Univ. of Idaho, Moscow), 311-325.

Sidle, R. C. (1987) A dynamic model of slope stability in zero-order basins. In: *Erosion and Sedimentation in the Pacific Rim* (ed. by R. L. Beschta *et al.*) (Proc. Corvallis Symp., August 1987), 101-110. IAHS Publ. no. 165.

Sidle, R. C. (1991) A conceptual model of changes in root cohesion in response to vegetation management. *J. Environ. Qual.* **20**(1), 43-52.

Sidle, R. C. (1992) A theoretical model of the effects of timber harvesting on slope stability. *Wat. Resour. Res.* (in press).

Sidle, R. C., Tsuboyama, Y., Sammori, T. & Noguchi, S. (1991) Shallow groundwater response to summer rainstorms in a zero-order basin, Hitachi Ohta, Japan. *EOS Trans. Am. Geophys. Union* **72**(44), 215 (abstract).

Temple, P. H. & Rapp, A. (1972) Landslides in the Mgeta area, western Uluguru mountains, Tanzania. *Geogr. Ann.* **54A**, 157-193.

Yates, S. R., Warrick, A. W. & Lomen, D. O. (1985) Hillside seepage: an analytical solution to a nonlinear Dupuit-Forchheimer problem. *Wat. Resour. Res.* **21**(3), 331-336.

Ziemer, R. R. (1981) Roots and the stability of forested slopes. In: *Erosion and Sediment Transport in Pacific Rim Steeplands* (Proc. Christchurch Symp., January 1981), 343-361. IAHS Publ. no. 132.

Ziemer, R. R. & Swanston, D. N. (1977) Root strength changes after logging in southeast Alaska. *Res. Note PNW-306, For. Serv., US Dept of Agric., Portland, Oregon.*