REFERENCES BY AUTHOR

Abe, K.; Iwamoto, M. 1985. Effect of tree roots on soil shearing strength. In: Proceedings, international symposium on erosion, debris flow and disaster prevention: 1985 September 3–5; Tsukuba, Japan. Tsukuba, Japan: Erosion Control Engineering Society. 341–346.

Abramowitz, M.; Stegun, I. A., eds. 1965. Handbook of mathematical functions with formulas, graphs, and mathematical tables. New York, NY: Dover Publ. 1046 p.

Alexander, E. B. 1989a. Bulk density equations for southern Alaska soils. Canadian Journal of Soil Science. 69: 177–180.

Alexander, E. B. 1989b. Personal communication.

Athanasiou-Grivas, D.; Harrop-Williams, K. 1979. Joint distribution of the components of soil strength. In: Proceedings of ICASP 3, the third international conference on applications of statistics and probability in soil and structural engineering; 1979 January 29–February 2; Sydney, Australia. Kensington, NSW, Australia: Unisearch Ltd. 1: 189–197.

Benjamin, J. R.; Cornell, C. A. 1970. Probability, statistics, and decision for civil engineers. New York: McGraw Hill. 684 p.

Berris, S. N.; Harr, R. D. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. Water Resources Research. 23(1): 135–142.

Bishop, A. W. 1966. The strength of soils as engineering materials. 6th Rankine lecture. Géotechnique. 16(2): 91–128.

Bjerrum, A. W.; Bjerrum, L. 1960. The relevance of the triaxial test to the solution of stability problems. In: Research conference on shear strength of cohesive soils; 1960 June 13–17; Boulder, CO. New York: American Society of Civil Engineers. 437–501.

Bjerrum, L.; Simons, N. E. 1960. Comparison of shear strength characteristics of normally consolidated clays. In: Research conference on shear strength of cohesive soils; 1960 June 13–17; Boulder, CO. New York: American Society of Civil Engineers. 711–726.

Borg, H.; Stoneman, G. L.; Ward, C. G. 1988. The effect of logging and regeneration on groundwater, streamflow and stream salinity in the southern forests of western Australia. Journal of Hydrology. 99: 253–270.

Bowles, J. E. 1968. Foundation analysis and design. New York: McGraw-Hill. 659 p.

Brand, E. W.; Premchitt, J.; Phillipson, H. B. 1984. Relationship between rainfall and landslides in Hong Kong. In: IV international symposium on landslides. 1984 September 16–21; Toronto, ON, Canada. Downsview, ON, Canada: University of Toronto, Canadian Geotechnical Society. 1: 377–384.

Burmister, D. M. 1962. Physical, stress-strain and strength responses of granular soils. In: Field testing of soils, Special technical publication 322. New York: American Society for Testing and Materials. 67–97.

Burroughs, E. R., Jr. 1984. A landslide hazard rating for portions of the Oregon Coast range. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 265–274.

Burroughs, E. R., Jr.; Thomas, B. R. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. Res. Pap. INT-190. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 27 p.

Campbell, R. H. 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. U.S. Geol. Surv. Prof. Pap. 851. Reston, VA: U.S. Geological Survey. 51 p.

Cherubini, C.; Cotechia, V.; Renna, G.; Schiraldi, B. 1983. The use of bivariate probability density functions in Monte Carlo simulation of slope stability in soils. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering; 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1401–1411.

Chowdhury, R. N.; Tang, W. H. 1987. Comparison of risk models for slopes. In: Lind, N.C., ed. Reliability and risk analysis in civil engineering: proceedings of ICASP 5, the fifth international conference on applications of statistics and probability in soil and structural engineering; 1987 May 25–29; Vancouver, BC. Waterloo, ONT: Institute for Risk Research, University of Waterloo. 2: 863–869.

Collotta, T.; Cantoni, R.; Moretti, P. C. 1989. Italian motorway system: experiences with *in situ* tests and inclinometer surveys for urgent remedial works. Transportation Res. Rec. 1235. Washington, DC: Transportation Research Board. 55–59.

DeGraff, J. V.; McKean, J.; Watanabe, P. E.; McCaffrey, W. F. 1984. Landslide activity and groundwater conditions: insights from a road in the central Sierra Nevada, California. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 32–37.

Dunn, I. S.; Anderson, L. R.; Kiefer, F. W. 1980. Fundamentals of geotechnical analysis. New York: John Wiley and Sons. 414 p.

Ellen, S. D.; Wieczorek, G. F., eds. 1988. Landslides, floods, and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay region, California. U.S. Geol. Surv. Prof. Pap. 1434. Washington, DC: U.S. Geological Survey. 14 p.

Endo, T.; Tsuruta, T. 1969a. The effect of the tree's roots upon the shear strength of soil. In: 1968 annual report of the Hokkaido branch, Forest Experiment Station, Sapporo, Japan. 167–182. Translated from Japanese by J. M. Arata and R. R. Ziemer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Station.

Endo, T.; Tsuruta, T. 1969b. A report in regards to the reinforcement action of the vegetational roots upon the tensile strength of the natural soil. In: 1968 annual report of the Hokkaido Branch, Forest Experiment Station, Sapporo, Japan. 183–189. Translated from Japanese by J. M. Arata and R. R. Ziemer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Station.

Fredlund, D. G. 1987. Slope stability analysis incorporating the effect of soil suction. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 113–144.

Gray, D. H.; Leiser, A. T. 1982. Biotechnical slope protection and erosion control. New York: Van Nostrand Reinhold. 279 p.

Gray, D. H.; Megahan, W. F. 1981. Forest vegetation removal and slope stability in the Idaho Batholith. Res. Pap. INT-271. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.

Gray, D. H.; Ohashi, H. 1983. Mechanics of fiber reinforcement in sand. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 109(3). 335–353.

Greenway, D. R. 1987. Vegetation and slope stability. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 187–230.

Hall, D. E.; Kendall, K. S. 1992. Technical documentation for the LISA program. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Hammond, C. J. 1986. Shear strength of the ash cap on the Clearwater National Forest, R1. U.S. Department of Agriculture, Forest Service. Unpublished report on file at Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. Unpaginated.

Hammond, C. J.; Hardcastle, J. H. 1987. Shear strengths and densities of micaceous sands. In: Proceedings, 8th Panamerican conference of soil mechanics and foundation engineering; 1987 August 16–21; Cartagena, Colombia. Bogotá, Colombia: National University of Colombia. 1: 45–56.

Hammond, C. J.; Hardcastle, J. H. 1992. Determination of values for shear strength parameters using improved methodology. Final report for cooperative agreement No. 22-C-4-INT-166, U.S. Department of Agriculture, Forest Service. Unpublished report on file at Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Hammond, C. J.; Miller, S. M.; Prellwitz, R. W. 1988. Estimating the probability of landslide failure using Monte Carlo simulation. In: Proceedings, 24th engineering geology and soils engineering symposium; 1988 February 29–March 2; Coeur d'Alene, ID. Moscow, ID: University of Idaho. 319–331.

Hammond, C. J.; Prellwitz, R. W.; Miller, S. M. 1992. Landslide hazard assessment using Monte Carlo simulation. In: Bell, D., ed. Landslides: proceedings of the 6th international symposium. 1992, February 10–14; Christchurch, New Zealand. Rotterdam, Netherlands: A. A. Balkema Publishers. 959–964.

Hampton, D.; Megahan, W. F.; Clayton, J. L. 1974. Soil and rock properties research in the Idaho Batholith. Report on a cooperative research effort between Howard University, Washington, DC, and U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, Boise, ID. 126 p.

Harr, M. E. 1977. Mechanics of particulate media — a probabilistic approach. New York: McGraw-Hill. 543 p.

Harr, R. D. 1986. Effects of clearcutting in rain-on-snow runoff in western Oregon: a new look at old studies. Water Resources Research. 22(7): 1095–1100.

Hillman, G. R.; Verschuren, J. P. 1988. Simulation of the effects of forest cover, and its removal, on subsurface water. Water Resources Research. 24(2): 305–314.

Hodge, R. A. L.; Freeze, R. A. 1977. Groundwater flow systems and slope stability. Canadian Geotechnical Journal. 14(4): 466–476.

Holstener-Jorgensen, H. 1967. Influences of forest management and drainage on ground-water fluctuations. In: Sopper W. E.; Lull, H. W., eds. International symposium on forest hydrology; 1965 August 29–September 10; University Park, PA. New York, NY: Pergamon Press. 325–333.

Holtz, W. G.; Ellis, W. 1961. Triaxial shear characteristics of clayey gravel soils. In: Proceedings, 5th international conference on soil mechanics and foundation engineering; 1961 July 17–22; Paris, France. Paris, France: Dunod. 1: 143–149.

Holtz, W. G.; Gibbs, H. J. 1956. Triaxial shear tests of pervious gravelly soils. American Society of Civil Engineers, Journal of Soil Mechanics and Foundations Division. 82(SM1): Paper 867. 22 p.

Holtz, W. G.; Krizek, R. J. 1972. Statistical evaluation of soils test data. In: Lumb, P., ed. Proceedings of ICASP 1, the first international conference on applications of statistics and probability to soil and structural engineering; 1971 September 13–16; Hong Kong. Hong Kong: Hong Kong University Press. 230–266.

Hookey, G. R. 1987. Prediction of delays in groundwater response to catchment clearing. Journal of Hydrology. 94: 181–198.

Horn, H. M.; Deere, D. U. 1962. Frictional characteristics of minerals. Géotechnique. 12(4): 319–335.

Hough, B. K. 1957. Basic soils engineering. New York: Ronald Press. 513 p.

Ice, G. G. 1985. Catalog of landslide inventories for the Northwest. NCASI Tech. Bulletin 456. New York, NY: National Council of the Paper Industry for Air and Stream Improvement. 160 p.

Iman, R. L.; Shortencarier, M. J. 1984. A FORTRAN 77 program and user's guide for the generation of Latin hypercube and random samples for use with computer models. Sandia National Laboratories. 67 p.

Iverson, R. M.; Major, J. J. 1986. Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization. Water Resources Research. 22(11): 1543–1548.

Iverson, R. M.; Major, J. J. 1987. Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relations. Geological Society of America Bulletin. 99: 579–594.

Jones, J. A. A. 1988. Modelling pipeflow contributions to stream runoff. Hydrological Processes. 2: 1–17.

Jones, S. 1990. Dark 3 timber sale slope stability assessment. Packwood, WA: U.S. Department of Agriculture, Forest Service, Gifford Pinchot National Forest. Unpublished report.

Keefer, D. K.; Wilson, R. C.; Mark, R. K.; [and others]. 1987. Realtime landslide warning during heavy rainfall. Science. 238(4829). 921–925.

Kenney, T. C. 1959. Discussion of geotechnical properties of glacial lake clays. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division. 85(SM3): 67–79.

Kirkby, M. J., ed. 1978. Hillslope hydrology. New York: John Wiley and Sons. 389 p.

Krahn, J.; Fredlund, D. G. 1983. Variability in the engineering properties of natural deposits. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering; 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1017–1029.

Lambe, T. W.; Whitman, R. V. 1969. Soil mechanics. New York: John Wiley and Sons. 553 p.

Lee, K. L.; Seed, H. B. 1967. Drained strength characteristics of sands. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division. 93(SM6): 117–141.

Leslie, D. D. 1963. Large-scale triaxial tests on gravelly soils. In: Proceedings, 2nd Panamerican conference on soil mechanics and foundation engineering; 1963 July 14–24; São Paulo, SP, Brasil: Associacão Brasileira de Mecânica dos Solos. 1: 181–202.

Lumb, P. 1966. The variability of natural soils. Canadian Geotechnical Journal. 3(2): 74–97.

Lumb, P. 1970. Safety factors and the probability distribution of soil strength. Canadian Geotechnical Journal. 7(3): 225–242.

Lumb, P. 1975. Spatial variability of soil properties. In: Proceedings of ICASP 2, the second international conference on applications of statistics and probability to soil and structural engineering; 1975 September 15–18; Aachen, Germany. Essen, Germany: Deutsche Gesellschaft fuer Erd-und Grundbau. 2: 397–421.

Marachi, N. D.; Chan, C. K.; Seed, H. B.; Duncan, J. M. 1969. Strength and deformation characteristics of rockfill materials. Report TE 69-5, Berkeley, CA: University of California, Berkeley. Pages unknown.

Matsuo, M.; Ueno, M. 1979. Prediction of slope slide by probability of failure. In: Proceedings of ICASP 3, the third international conference in the applications of statistics and probability in soil and structural engineering; 1979 January 29–February 2; Sydney, Australia. Kensington, NSW, Australia: Unisearch Ltd. 2: 449–458.

Megahan, W. F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research. 19(3): 811–819.

Megahan, W. F. 1984. Snow melt and logging influence on piezometric levels in steep forested watersheds in Idaho. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 1–8.

Miller, S. M. 1988. A temporal model for landslide risk based on historical precipitation. Journal of Mathematical Geology. 20(5): 529–542.

Miller, S. M.; Borgman, L. E. 1984. Probabilistic characterization of shear strength using results of direct shear tests. Géotechnique. 34: 273–276.

Negussey, D.; Wijewickreme, W. D.; Vaid, Y. P. 1988. Constant-volume friction angle of granular materials. Canadian Geotechnical Journal. 25: 50–55.

Newendorp, P. D. 1975. Decision analysis for petroleum exploration. Tulsa, OK: PennWell Publishing Co. 668 p.

Oboni, F.; Bourdeau, P. L. 1983. Determination of the critical slip surface in stability problems. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering. 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1413–1424.

Okunishi, K.; Okimura, T. 1987. Groundwater models for mountain slopes. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 265–286.

O'Loughlin, C. L. 1974. A study of tree root strength deterioration following clearfelling. Canadian Journal of Forest Research. 4(1): 107–113.

O'Loughlin, C. L.; Rowe, L. K.; Pearce, A. J. 1982. Exceptional storm influences on slope erosion and sediment yields in small forest catchments, North Westland, New Zealand. National Conference Publication 82/6. Barton, ACT, Australia: Institute of Engineering. 84–91.

O'Loughlin, C. L.; Ziemer, R. R. 1982. The importance of root strength and deterioration rates upon edaphic stability in steepland forests. In: Carbon uptake and allocation in subalpine ecosystems as a key to management: Proceedings of an IUFRO workshop. 1982 August; Corvallis, OR. Corvallis, OR: Oregon State University Forest Research Laboratory. 70–78.

Peck, A. J.; Williamson, D. R. 1987. Effects of forest clearing on groundwater. Journal of Hydrology. 94: 47–65.

Petch, R. A. 1988. Soil saturation patterns in steep, convergent hill slopes under forest and pasture vegetation. Hydrologic Processes. 2: 93–103.

Pierson, T. C. 1980. Piezometric response to rainstorms in forested hillslope drainage depressions. Journal of Hydrology (New Zealand). 19(1): 1–10.

Pierson, T. C. 1983. Soil pipes and slope stability. Quarterly Journal of Engineering Geology, London. 16: 1–11.

Prellwitz, R. W. 1981. Forest Service Handbook 7709.11, Transportation Engineering Handbook, Region 1, Supplement 11, Chapter 60, Foundation Engineering. U.S. Department of Agriculture, Forest Service.

Prellwitz, R. W. 1985. A complete three-level approach for analyzing landslides on forest lands. In: Proceedings: a workshop on slope stability: problems and solutions in forest management. Gen. Tech. Rep. PNW-180. 1984 February 6–8; Seattle, WA. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 94–98.

Prellwitz, R. W. 1988. "SSIS" and "SSCHFS"—preliminary slope stability analysis with the HP41 programmable calculator. EM 7170-9. Washington, DC: U.S. Department of Agriculture, Forest Service. 174 p.

Prellwitz, R. W. 1989. Personal communication.

Prellwitz, R. W.; Hall, D. E. 1992. SARA—Stability Analysis for Road Access (Level II) user documentation. Unpublished peer review draft. Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Prellwitz, R. W.; Howard, T. R.; Wilson, W. D. 1983. Landslide analysis concepts for management of forest lands on residual and colluvial soils. Transportation Res. Rec. 919. Washington, DC: Transportation Research Board. 27–36.

Reid, M. E.; Nielsen, H. P.; Dreiss, S. J. 1988. Hydrologic factors triggering a shallow hillslope failure. Bulletin of the Association of Engineering Geologists. 25(3): 349–361.

Rétháti, L. 1983. Distribution functions of the soil physical characteristics. In: Proceedings, 8th European conference on soil mechanics and foundation engineering; 1983 May 23–26; Helsinki, Finland. Rotterdam, Netherlands: A. A. Balkema. 1: 405–410.

Riestenberg, M.; Sovonick-Dunford, S. 1983. The role of woody vegetation in stabilizing slopes in the Cincinnati area, Ohio. Geological Society of America Bulletin. 94: 506–518.

Ristau, J. M. 1988. Verification of soil slope instability using level one stability analysis. In: Proceedings, 24th engineering geology and soils engineering symposium. 1988 February 29–March 2; Coeur d'Alene, ID. Moscow, ID: University of Idaho. 333–344.

Rowe, P. W. 1962. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. Proceedings of the Royal Society of London. 296(A): 500–527.

Rowe, P. W. 1963. Stress-dilatancy, earth pressures and slopes. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Div. 89(SM3): 37–61.

Rubenstein, R. Y. 1981. Simulation and the Monte Carlo method. New York: John Wiley and Sons. 278 p.

Schroeder, W. L.; Alto, J. V. 1983. Soil properties for slope stability analysis; Oregon and Washington coastal mountains. Forest Science. 29(4): 823–833.

Schroeder, W. L.; Swanston, D. N. 1987. Application of geotechnical data to resource planning in Southeast Alaska. Gen. Tech. Rep. PNW-198. Corvallis, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 22 p.

Schultze, E. 1971. Frequency distributions and correlations of soil properties. In: Lumb, P., ed. Proceedings of ICASP 1, the first international conference on applications of statistics and probability to soil and structural engineering; 1971 September 13–16; Hong Kong. Hong Kong: Hong Kong University Press. 371–387.

Siddiqi, F. H. 1984. Strength evaluation of cohesionless soils with oversize particles. Davis, CA: University of California. 170 p. Dissertation.

Sidle, R. C. 1984a. Relative importance of factors influencing landsliding in Coastal Alaska. In: Proceedings, 21st annual engineering geology and soils engineering symposium; 1984 April 5–6; Moscow, ID. Moscow, ID: Idaho Transportation Department and University of Idaho. 311–324.

Sidle, R. C. 1984b. Shallow groundwater fluctuations in unstable hillslopes of Coastal Alaska. Zeitschrift fur Gletscherkunde und Glazialgeologie. 20(2): 79–95.

Sidle, R. C. 1986. Groundwater accretion in unstable hillslopes of coastal Alaska. In: Conjunctive water use: Proceedings of the symposium; 1986 July; Budapest, Hungary. IAHS Publ. 156. Washington, DC: International Association of Hydrological Sciences Press. 335–343.

Sidle, R. C.; Pearce, A. J.; O'Loughlin, C. L. 1985. Hillslope stability and land use. Water Resources Monogr. Ser. 11. Washington, DC: American Geophysical Union. 140 p.

Simons, D. B.; Li, R. M.; Ward, T. J. 1978. Mapping of potential landslide areas in terms of slope stability. Contract No. 16-712.01-CA, Colorado State University, Fort Collins, CO. Flagstaff, AZ: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 73 p. Draft final report.

Singh, A.; Lee, K. L. 1970. Variability in soil parameters. In: Proceedings, 8th annual engineering geology and soils engineering symposium; 1970 April; Boise, ID. Boise, ID: Boise State University. 159–185.

Skempton, A. W. 1964. Long-term stability of clay slopes. Géotechnique. 14(2): 77–101.

Skempton, A. W. 1985. Residual strength of clays in landslides, folded strata and in the laboratory. Géotechnique. 35(1): 3–18.

Smith, G. N. 1986. Probability and statistics in civil engineering. New York: Nichols Publishing Co. 244 p.

Sturges, H. A. 1926. The choice of a class interval. Journal of the American Statistical Association. 21: 65–66.

Taylor, R. K.; Cripps, J. C. 1987. Weathering effects: slopes in mudrocks and overconsolidated clays. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 405–445.

Toews, D. A. A.; Gluns, D. R. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in Southeastern British Columbia. In: Proceedings, 54th annual meeting, western snow conference; 1986 April 15–17; Phoenix, AZ:. Fort Collins, CO: Colorado State University. 101–111.

Troendle, C. A. 1987. Effect of clearcutting on streamflow generating processes from a subalpine forest slope. In: Forest hydrology and watershed management: Proceedings of the symposium; 1987 August; Vancouver, BC. IAHS Publ. 167. Washington, DC: International Association of Hydrological Sciences Press. 545–552.

Troendle, C. A.; King, R. M. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology. 90: 145–157.

Tsukamoto, Y.; Kusakabe, O. 1984. Vegetation influences on debris slide occurrences on steep slopes in Japan. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 63–72.

Tsukamoto, Y.; Minematsu, H. 1987. Evaluation of the effect of deforestation on slope stability and its application to watershed management. In: Forest hydrology and watershed management: Proceedings of a symposium; 1987 August 9–22; Vancouver, BC. IAHS Publ. 167. Washington, DC: International Association of Hydrological Sciences. 181–189.

U.S. Department of Navy. 1974. Soil mechanics, foundation and earth structures. NAVFAC DM-7.

Waldron, L. J. 1977. Shear resistance of root permeated homogeneous and stratified soil. Journal of the Soil Science Society of America. 41: 843–849.

Waldron, L. J.; Dakessian, S. 1981. Soil reinforcement by roots: Calculation of increased soil shear resistance from root properties. Soil Science. 132(6): 427–435.

Waldron, L. J.; Dakessian, S.; Nemson, J. A. 1983. Shear resistance enhancement of 1.22-meter diameter soil cross sections by pine and alfalfa roots. Journal of the Soil Science Society of America. 47: 9–14.

Williamson, D. 1989. Personal communication.

Wilson, D.; Coyner, J.; Dechert, T. 1983. Land system inventory of the Clearwater National Forest, Region 1 — First Review Draft. Orofino, ID: U.S. Department of Agriculture, Forest Service. 400 p.

Wooten, R. M. 1988. Level I stability analysis validation report. Cook, WA: U.S. Department of Agriculture, Forest Service, Gifford Pinchot National Forest, Zone II Engineering. Unpublished in-service report.

Wu, T. H. 1984. Effect of vegetation on slope stability. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 37–46.

Wu, T. H.; Beal, P. E.; Lan, C. 1988a. *In situ* shear test of soil-root systems. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 114(12): 1376–1394

Wu, T. H.; McKinnell, W. P., III; Swanston, D. N. 1979. Strength of tree roots and landslides of Prince of Wales Island, Alaska. Canadian Geotechnical Journal. 16(1): 19–33.

Wu, T. H.; McOmber, R. M.; Erb, R. T.; Beal, P. E. 1988c. Study of soil–root interaction. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 114(12): 1351–1375.

Wu, T. T. H.; Baladi, G. Y. 1986. The effects of grain characteristics on the limiting densities and angle of repose of cohesionless soils. Preprint, Transportation Research Board annual meeting; 1986 January; Washington, DC.

Ziemer, R. R. 1981a. Roots and the stability of forested slopes. In: Davies, T. R. H. and Pearce, A. J., eds. International symposium on erosion and sediment transport in Pacific rim steeplands; 1981 January 25–31; Christchurch, New Zealand. IAHS Publ. 132. Washington, DC: International Association of Hydrological Sciences Press. 341–361.

Ziemer, R. R. 1981b. The role of vegetation in the stability of forested slopes. In: Proceedings, International Union of Forestry Research Organizations XVII World Conference; 1981 September 6–17; Kyoto, Japan. Ibaraki, Japan: Japanese IUFRO Congress Council. 1: 297–308

Ziemer, R. R. 1984. Response of progressive hillslope deformation to precipitation. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 91–98.

REFERENCES BY SUBJECT

General Slope Stability

Dunn, I. S.; Anderson, L. R.; Kiefer, F. W. 1980. Fundamentals of geotechnical analysis. New York: John Wiley and Sons. 414 p.

Hammond, C. J.; Miller, S. M.; Prellwitz, R. W. 1988. Estimating the probability of landslide failure using Monte Carlo simulation. In: Proceedings, 24th engineering geology and soils engineering symposium; 1988 February 29–March 2; Coeur d'Alene, ID. Moscow, ID: University of Idaho. 319–331.

Hammond, C. J.; Prellwitz, R. W.; Miller, S. M. 1992. Landslide hazard assessment using Monte Carlo simulation. In: Bell, D., ed. Landslides: proceedings of the 6th international symposium. 1992, February 10–14; Christchurch, New Zealand. Rotterdam, Netherlands: A. A. Balkema Publishers. 959–964.

Ice, G. G. 1985. Catalog of landslide inventories for the Northwest. NCASI Tech. Bulletin 456. New York, NY: National Council of the Paper Industry for Air and Stream Improvement. 160 p.

Jones, S. 1990. Dark 3 timber sale slope stability assessment. Packwood, WA: U.S. Department of Agriculture, Forest Service, Gifford Pinchot National Forest. Unpublished report.

Lambe, T. W.; Whitman, R. V. 1969. Soil mechanics. New York: John Wiley and Sons. 553 p.

Prellwitz, R. W. 1985. A complete three-level approach for analyzing landslides on forest lands. In: Proceedings: a workshop on slope stability: problems and solutions in forest management. Gen. Tech. Rep. PNW-180. 1984 February 6–8; Seattle, WA. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 94–98.

Prellwitz, R. W. 1988. "SSIS" and "SSCHFS"—preliminary slope stability analysis with the HP41 programmable calculator. EM 7170-9. Washington, DC: U.S. Department of Agriculture, Forest Service. 174 p.

Prellwitz, R. W.; Hall, D. E. 1992. SARA—Stability Analysis for Road Access (Level II) user documentation. Unpublished peer review draft. Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Prellwitz, R. W.; Howard, T. R.; Wilson, W. D. 1983. Landslide analysis concepts for management of forest lands on residual and colluvial soils. Transportation Res. Rec. 919. Washington, DC: Transportation Research Board. 27–36.

Ristau, J. M. 1988. Verification of soil slope instability using level one stability analysis. In: Proceedings, 24th engineering geology and soils engineering symposium. 1988 February 29–March 2; Coeur d'Alene, ID. Moscow, ID: University of Idaho. 333–344.

Sidle, R. C. 1984a. Relative importance of factors influencing landsliding in Coastal Alaska. In: Proceedings, 21st annual engineering geology and soils engineering symposium; 1984 April 5–6; Moscow, ID. Moscow, ID: Idaho Transportation Department and University of Idaho. 311–324.

Sidle, R. C.; Pearce, A. J.; O'Loughlin, C. L. 1985. Hillslope stability and land use. Water Resources Monogr. Ser. 11. Washington, DC: American Geophysical Union. 140 p.

Wilson, D.; Coyner, J.; Dechert, T. 1983. Land system inventory of the Clearwater National Forest, Region 1 — First Review Draft. Orofino, ID: U.S. Department of Agriculture, Forest Service. 400 p.

Wooten, R. M. 1988. Level I stability analysis validation report. Cook, WA: U.S. Department of Agriculture, Forest Service, Gifford Pinchot National Forest, Zone II Engineering. Unpublished in-service report.

Probability and Monte Carlo Sampling

Abramowitz, M.; Stegun, I. A., eds. 1965. Handbook of mathematical functions with formulas, graphs, and mathematical tables. New York, NY: Dover Publ. 1046 p.

Benjamin, J. R.; Cornell, C. A. 1970. Probability, statistics, and decision for civil engineers. New York: McGraw Hill. 684 p.

Cherubini, C.; Cotechia, V.; Renna, G.; Schiraldi, B. 1983. The use of bivariate probability density functions in Monte Carlo simulation of slope stability in soils. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering; 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1401–1411.

Chowdhury, R. N.; Tang, W. H. 1987. Comparison of risk models for slopes. In: Lind, N.C., ed. Reliability and risk analysis in civil engineering: proceedings of ICASP 5, the fifth international conference on applications of statistics and probability in soil and structural engineering; 1987 May 25–29; Vancouver, BC. Waterloo, ONT: Institute for Risk Research, University of Waterloo. 2: 863–869.

Hall, D. E.; Kendall, K. S. 1992. Technical documentation for the LISA program. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Iman, R. L.; Shortencarier, M. J. 1984. A FORTRAN 77 program and user's guide for the generation of Latin hypercube and random samples for use with computer models. Sandia National Laboratories. 67 p.

Miller, S. M. 1988. A temporal model for landslide risk based on historical precipitation. Journal of Mathematical Geology. 20(5): 529–542.

Newendorp, P. D. 1975. Decision analysis for petroleum exploration. Tulsa, OK: PennWell Publishing Co. 668 p.

Rubenstein, R. Y. 1981. Simulation and the Monte Carlo method. New York: John Wiley and Sons. 278 p.

Smith, G. N. 1986. Probability and statistics in civil engineering. New York: Nichols Publishing Co. 244 p.

Sturges, H. A. 1926. The choice of a class interval. Journal of the American Statistical Association. 21: 65–66.

Root Strength

Burroughs, E. R., Jr. 1984. A landslide hazard rating for portions of the Oregon Coast range. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 265–274.

Burroughs, E. R., Jr.; Thomas, B. R. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. Res. Pap. INT-190. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 27 p.

Endo, T.; Tsuruta, T. 1969a. The effect of the tree's roots upon the shear strength of soil. In: 1968 annual report of the Hokkaido branch, Forest Experiment Station, Sapporo, Japan. 167–182. Translated from Japanese by J. M. Arata and R. R. Ziemer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Station.

Endo, T.; Tsuruta, T. 1969b. A report in regards to the reinforcement action of the vegetational roots upon the tensile strength of the natural soil. In: 1968 annual report of the Hokkaido Branch, Forest Experiment Station, Sapporo, Japan. 183–189. Translated from Japanese by J. M. Arata and R. R. Ziemer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Station.

Gray, D. H.; Leiser, A. T. 1982. Biotechnical slope protection and erosion control. New York: Van Nostrand Reinhold. 279 p.

Gray, D. H.; Megahan, W. F. 1981. Forest vegetation removal and slope stability in the Idaho Batholith. Res. Pap. INT-271. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.

Gray, D. H.; Ohashi, H. 1983. Mechanics of fiber reinforcement in sand. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 109(3). 335–353.

Greenway, D. R. 1987. Vegetation and slope stability. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons: 187–230.

O'Loughlin, C. L. 1974. A study of tree root strength deterioration following clearfelling. Canadian Journal of Forest Research. 4(1): 107–113.

O'Loughlin, C. L.; Rowe, L. K.; Pearce, A. J. 1982. Exceptional storm influences on slope erosion and sediment yields in small forest catchments, North Westland, New Zealand. National Conference Publication 82/6. Barton, ACT, Australia: Institute of Engineering. 84–91.

O'Loughlin, C. L.; Ziemer, R. R. 1982. The importance of root strength and deterioration rates upon edaphic stability in steepland forests. In: Carbon uptake and allocation in subalpine ecosystems as a key to management: Proceedings of an IUFRO workshop. 1982 August; Corvallis, OR. Corvallis, OR: Oregon State University Forest Research Laboratory. 70–78.

Riestenberg, M.; Sovonick-Dunford, S. 1983. The role of woody vegetation in stabilizing slopes in the Cincinnati area, Ohio. Geological Society of America Bulletin. 94: 506–518.

Simons, D. B.; Li, R. M.; Ward, T. J. 1978. Mapping of potential landslide areas in terms of slope stability. Contract No. 16-712.01-CA, Colorado State University, Fort Collins, CO. Flagstaff, AZ: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 73 p. Draft final report.

Tsukamoto, Y.; Kusakabe, O. 1984. Vegetation influences on debris slide occurrences on steep slopes in Japan. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 63–72.

Tsukamoto, Y.; Minematsu, H. 1987. Evaluation of the effect of deforestation on slope stability and its application to watershed management. In: Forest hydrology and watershed management: Proceedings of a symposium; 1987 August 9–22; Vancouver, BC. IAHS Publ. 167. Washington, DC: International Association of Hydrological Sciences. 181–189.

Waldron, L. J. 1977. Shear resistance of root permeated homogeneous and stratified soil. Journal of the Soil Science Society of America. 41: 843–849.

Waldron, L. J.; Dakessian, S. 1981. Soil reinforcement by roots: Calculation of increased soil shear resistance from root properties. Soil Science. 132(6): 427–435.

Waldron, L. J.; Dakessian, S.; Nemson, J. A. 1983. Shear resistance enhancement of 1.22-meter diameter soil cross sections by pine and alfalfa roots. Journal of the Soil Science Society of America. 47: 9–14.

Wu, T. H. 1984. Effect of vegetation on slope stability. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 37–46.

Wu, T. H.; Beal, P. E.; Lan, C. 1988a. *In situ* shear test of soil-root systems. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 114(12): 1376–1394

Wu, T. H.; McKinnell, W. P., III; Swanston, D. N. 1979. Strength of tree roots and landslides of Prince of Wales Island, Alaska. Canadian Geotechnical Journal. 16(1): 19–33.

Wu, T. H.; McOmber, R. M.; Erb, R. T.; Beal, P. E. 1988c. Study of soil–root interaction. American Society of Civil Engineers, Journal of the Geotechnical Engineering Div. 114(12): 1351–1375.

Ziemer, R. R. 1981a. Roots and the stability of forested slopes. In: Davies, T. R. H. and Pearce, A. J., eds. International symposium on erosion and sediment transport in Pacific rim steeplands; 1981 January 25–31; Christchurch, New Zealand. IAHS Publ. 132. Washington, DC: International Association of Hydrological Sciences Press. 341–361.

Ziemer, R. R. 1981b. The role of vegetation in the stability of forested slopes. In: Proceedings, International Union of Forestry Research Organizations XVII World Conference; 1981 September 6–17; Kyoto, Japan. Ibaraki, Japan: Japanese IUFRO Congress Council. 1: 297–308

Soil Shear Strength

Alexander, E. B. 1989a. Bulk density equations for southern Alaska soils. Canadian Journal of Soil Science. 69: 177–180.

Athanasiou-Grivas, D.; Harrop-Williams, K. 1979. Joint distribution of the components of soil strength. In: Proceedings of ICASP 3, the third international conference on applications of statistics and probability in soil and structural engineering; 1979 January 29–February 2; Sydney, Australia. Kensington, NSW, Australia: Unisearch Ltd. 1: 189–197.

Bishop, A. W. 1966. The strength of soils as engineering materials. 6th Rankine lecture. Géotechnique. 16(2): 91–128.

Bjerrum, A. W.; Bjerrum, L. 1960. The relevance of the triaxial test to the solution of stability problems. In: Research conference on shear strength of cohesive soils; 1960 June 13–17; Boulder, CO. New York: American Society of Civil Engineers. 437–501.

Bjerrum, L.; Simons, N. E. 1960. Comparison of shear strength characteristics of normally consolidated clays. In: Research conference on shear strength of cohesive soils; 1960 June 13–17; Boulder, CO. New York: American Society of Civil Engineers. 711–726.

Bowles, J. E. 1968. Foundation analysis and design. New York: McGraw-Hill. 659 p.

Burmister, D. M. 1962. Physical, stress-strain and strength responses of granular soils. In: Field testing of soils, Special technical publication 322. New York: American Society for Testing and Materials. 67–97.

Collotta, T.; Cantoni, R.; Moretti, P. C. 1989. Italian motorway system: experiences with *in situ* tests and inclinometer surveys for urgent remedial works. Transportation Res. Rec. 1235. Washington, DC: Transportation Research Board. 55–59.

Fredlund, D. G. 1987. Slope stability analysis incorporating the effect of soil suction. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 113–144.

Hammond, C. J. 1986. Shear strength of the ash cap on the Clearwater National Forest, R1. U.S. Department of Agriculture, Forest Service. Unpublished report on file at Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. Unpaginated.

Hammond, C. J.; Hardcastle, J. H. 1987. Shear strengths and densities of micaceous sands. In: Proceedings, 8th Panamerican conference of soil mechanics and foundation engineering; 1987 August 16–21; Cartagena, Colombia. Bogotá, Colombia: National University of Colombia. 1: 45–56.

Hammond, C. J.; Hardcastle, J. H. 1992. Determination of values for shear strength parameters using improved methodology. Final report for cooperative agreement No. 22-C-4-INT-166, U.S. Department of Agriculture, Forest Service. Unpublished report on file at Intermountain Res. Sta., Moscow, ID. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, RWU 4702, Moscow, ID. In process.

Hampton, D.; Megahan, W. F.; Clayton, J. L. 1974. Soil and rock properties research in the Idaho Batholith. Report on a cooperative research effort between Howard University, Washington, DC, and U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, Boise, ID. 126 p.

Harr, M. E. 1977. Mechanics of particulate media — a probabilistic approach. New York: McGraw-Hill. 543 p.

Holtz, W. G.; Ellis, W. 1961. Triaxial shear characteristics of clayey gravel soils. In: Proceedings, 5th international conference on soil mechanics and foundation engineering; 1961 July 17–22; Paris, France. Paris, France: Dunod. 1: 143–149.

Holtz, W. G.; Gibbs, H. J. 1956. Triaxial shear tests of pervious gravelly soils. American Society of Civil Engineers, Journal of Soil Mechanics and Foundations Division. 82(SM1): Paper 867. 22 p.

Holtz, W. G.; Krizek, R. J. 1972. Statistical evaluation of soils test data. In: Lumb, P., ed. Proceedings of ICASP 1, the first international conference on applications of statistics and probability to soil and structural engineering; 1971 September 13–16; Hong Kong. Hong Kong: Hong Kong University Press. 230–266.

Horn, H. M.; Deere, D. U. 1962. Frictional characteristics of minerals. Géotechnique. 12(4): 319–335.

Hough, B. K. 1957. Basic soils engineering. New York: Ronald Press. 513 p.

Kenney, T. C. 1959. Discussion of geotechnical properties of glacial lake clays. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division. 85(SM3): 67–79.

Krahn, J.; Fredlund, D. G. 1983. Variability in the engineering properties of natural deposits. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering; 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1017–1029.

Lee, K. L.; Seed, H. B. 1967. Drained strength characteristics of sands. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Division. 93(SM6): 117–141.

Leslie, D. D. 1963. Large-scale triaxial tests on gravelly soils. In: Proceedings, 2nd Panamerican conference on soil mechanics and foundation engineering; 1963 July 14–24; São Paulo, SP, Brasil: Associacão Brasileira de Mecânica dos Solos. 1: 181–202.

Lumb, P. 1966. The variability of natural soils. Canadian Geotechnical Journal. 3(2): 74–97.

Lumb, P. 1970. Safety factors and the probability distribution of soil strength. Canadian Geotechnical Journal. 7(3): 225–242.

Lumb, P. 1975. Spatial variability of soil properties. In: Proceedings of ICASP 2, the second international conference on applications of statistics and probability to soil and structural engineering; 1975 September 15–18; Aachen, Germany. Essen, Germany: Deutsche Gesellschaft fuer Erd-und Grundbau. 2: 397–421.

Marachi, N. D.; Chan, C. K.; Seed, H. B.; Duncan, J. M. 1969. Strength and deformation characteristics of rockfill materials. Report TE 69-5, Berkeley, CA: University of California, Berkeley. Pages unknown.

Matsuo, M.; Ueno, M. 1979. Prediction of slope slide by probability of failure. In: Proceedings of ICASP 3, the third international conference in the applications of statistics and probability in soil and structural engineering; 1979 January 29–February 2; Sydney, Australia. Kensington, NSW, Australia: Unisearch Ltd. 2: 449–458.

Miller, S. M.; Borgman, L. E. 1984. Probabilistic characterization of shear strength using results of direct shear tests. Géotechnique. 34: 273–276.

Negussey, D.; Wijewickreme, W. D.; Vaid, Y. P. 1988. Constant-volume friction angle of granular materials. Canadian Geotechnical Journal. 25: 50–55.

Oboni, F.; Bourdeau, P. L. 1983. Determination of the critical slip surface in stability problems. In: Proceedings of ICASP 4, the fourth international conference on applications of statistics and probability in soil and structural engineering. 1983 June 13–17; Firenze, Italy. Bologna, Italy: Pitagora Editrice. 1413–1424.

Prellwitz, R. W. 1981. Forest Service Handbook 7709.11, Transportation Engineering Handbook, Region 1, Supplement 11, Chapter 60, Foundation Engineering. U.S. Department of Agriculture, Forest Service.

Rétháti, L. 1983. Distribution functions of the soil physical characteristics. In: Proceedings, 8th European conference on soil mechanics and foundation engineering; 1983 May 23–26; Helsinki, Finland. Rotterdam, Netherlands: A. A. Balkema. 1: 405–410.

Rowe, P. W. 1962. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. Proceedings of the Royal Society of London. 296(A): 500–527.

Rowe, P. W. 1963. Stress-dilatancy, earth pressures and slopes. American Society of Civil Engineers, Journal of the Soil Mechanics and Foundations Div. 89(SM3): 37–61.

Schroeder, W. L.; Alto, J. V. 1983. Soil properties for slope stability analysis; Oregon and Washington coastal mountains. Forest Science. 29(4): 823–833.

Schroeder, W. L.; Swanston, D. N. 1987. Application of geotechnical data to resource planning in Southeast Alaska. Gen. Tech. Rep. PNW-198. Corvallis, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 22 p.

Schultze, E. 1971. Frequency distributions and correlations of soil properties. In: Lumb, P., ed. Proceedings of ICASP 1, the first international conference on applications of statistics and probability to soil and structural engineering; 1971 September 13–16; Hong Kong. Hong Kong: Hong Kong University Press. 371–387.

Siddiqi, F. H. 1984. Strength evaluation of cohesionless soils with oversize particles. Davis, CA: University of California. 170 p. Dissertation.

Singh, A.; Lee, K. L. 1970. Variability in soil parameters. In: Proceedings, 8th annual engineering geology and soils engineering symposium; 1970 April; Boise, ID. Boise, ID: Boise State University. 159–185.

Skempton, A. W. 1964. Long-term stability of clay slopes. Géotechnique. 14(2): 77–101.

Skempton, A. W. 1985. Residual strength of clays in landslides, folded strata and in the laboratory. Géotechnique. 35(1): 3–18.

Taylor, R. K.; Cripps, J. C. 1987. Weathering effects: slopes in mudrocks and overconsolidated clays. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 405–445.

U.S. Department of Navy. 1974. Soil mechanics, foundation and earth structures. NAVFAC DM-7.

Wu, T. T. H.; Baladi, G. Y. 1986. The effects of grain characteristics on the limiting densities and angle of repose of cohesionless soils. Preprint, Transportation Research Board annual meeting; 1986 January; Washington, DC. Unpaginated.

Groundwater

Brand, E. W.; Premchitt, J.; Phillipson, H. B. 1984. Relationship between rainfall and landslides in Hong Kong. In: IV international symposium on landslides. 1984 September 16–21; Toronto, ON, Canada. Downsview, ON, Canada: University of Toronto, Canadian Geotechnical Society. 1: 377–384.

Campbell, R. H. 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. U.S. Geol. Surv. Prof. Pap. 851 Reston, VA: U.S. Geological Survey. 51 p.

DeGraff, J. V.; McKean, J.; Watanabe, P. E.; McCaffrey, W. F. 1984. Landslide activity and groundwater conditions: insights from a road in the central Sierra Nevada, California. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 32–37.

Ellen, S. D.; Wieczorek, G. F., eds. 1988. Landslides, floods, and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay region, California. U.S. Geol. Surv. Prof. Pap. 1434. Washington, DC: U.S. Geological Survey. 14 p.

Hodge, R. A. L.; Freeze, R. A. 1977. Groundwater flow systems and slope stability. Canadian Geotechnical Journal. 14(4): 466–476.

Iverson, R. M.; Major, J. J. 1986. Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization. Water Resources Research. 22(11): 1543–1548.

Iverson, R. M.; Major, J. J. 1987. Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relations. Geological Society of America Bulletin. 99: 579–594.

Jones, J. A. A. 1988. Modelling pipeflow contributions to stream runoff. Hydrological Processes. 2: 1–17.

Keefer, D. K.; Wilson, R. C.; Mark, R. K.; [and others]. 1987. Realtime landslide warning during heavy rainfall. Science. 238(4829): 921–925.

Kirkby, M. J., ed. 1978. Hillslope hydrology. New York: John Wiley and Sons. 389 p.

Okunishi, K.; Okimura, T. 1987. Groundwater models for mountain slopes. In: Anderson, M. G.; Richards, K. S., eds. Slope stability. New York: John Wiley and Sons. 265–286.

Pierson, T. C. 1983. Soil pipes and slope stability. Quarterly Journal of Engineering Geology, London. 16: 1–11.

Reid, M. E.; Nielsen, H. P.; Dreiss, S. J. 1988. Hydrologic factors triggering a shallow hillslope failure. Bulletin of the Association of Engineering Geologists. 25(3): 349–361.

Sidle, R. C. 1984b. Shallow groundwater fluctuations in unstable hillslopes of Coastal Alaska. Zeitschrift fur Gletscherkunde und Glazialgeologie. 20(2): 79–95.

Sidle, R. C. 1986. Groundwater accretion in unstable hillslopes of coastal Alaska. In: Conjunctive water use: Proceedings of the symposium; 1986 July; Budapest, Hungary. IAHS Publ. 156. Washington, DC: International Association of Hydrological Sciences Press. 335–343.

Ziemer, R. R. 1984. Response of progressive hillslope deformation to precipitation. In: O'Loughlin, C. L.; Pearce, A. J., eds. Symposium on effects of forest land use on erosion and slope stability; 1984 May 7–11; Honolulu, HI. Honolulu, HI: University of Hawaii, East-West Center, Environment and Policy Institute. 91–98.

Timber Harvest Effects on Groundwater Levels

Berris, S. N.; Harr, R. D. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. Water Resources Research. 23(1): 135–142.

Borg, H.; Stoneman, G. L.; Ward, C. G. 1988. The effect of logging and regeneration on groundwater, streamflow and stream salinity in the southern forests of western Australia. Journal of Hydrology. 99: 253–270.

Gray, D. H.; Megahan, W. F. 1981. Forest vegetation removal and slope stability in the Idaho Batholith. Res. Pap. INT-271. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.

Harr, R. D. 1986. Effects of clearcutting in rain-on-snow runoff in western Oregon: a new look at old studies. Water Resources Research. 22(7): 1095–1100.

Hillman, G. R.; Verschuren, J. P. 1988. Simulation of the effects of forest cover, and its removal, on subsurface water. Water Resources Research. 24(2): 305–314.

Holstener-Jorgensen, H. 1967. Influences of forest management and drainage on ground-water fluctuations. In: Sopper W. E.; Lull, H. W., eds. International symposium on forest hydrology; 1965 August 29–September 10; University Park, PA. New York, NY: Pergamon Press. 325–333.

Hookey, G. R. 1987. Prediction of delays in groundwater response to catchment clearing. Journal of Hydrology. 94: 181–198.

Megahan, W. F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research. 19(3): 811–819.

Megahan, W. F. 1984. Snow melt and logging influence on piezometric levels in steep forested watersheds in Idaho. Transportation Res. Rec. 965. Washington, DC: Transportation Research Board. 1–8.

Peck, A. J.; Williamson, D. R. 1987. Effects of forest clearing on groundwater. Journal of Hydrology. 94: 47–65.

Petch, R. A. 1988. Soil saturation patterns in steep, convergent hill slopes under forest and pasture vegetation. Hydrologic Processes. 2: 93–103.

Pierson, T. C. 1980. Piezometric response to rainstorms in forested hillslope drainage depressions. Journal of Hydrology (New Zealand). 19(1): 1–10.

Toews, D. A. A.; Gluns, D. R. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in Southeastern British Columbia. In: Proceedings, 54th annual meeting, western snow conference; 1986 April 15–17; Phoenix, AZ:. Fort Collins, CO: Colorado State University. 101–111.

Troendle, C. A. 1987. Effect of clearcutting on streamflow generating processes from a subalpine forest slope. In: Forest hydrology and watershed management: Proceedings of the symposium; 1987 August; Vancouver, BC. IAHS Publ. 167. Washington, DC: International Association of Hydrological Sciences Press. 545–552.

Troendle, C. A.; King, R. M. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology. 90: 145–157.

APPENDIX A—DERIVATION OF THE INFINITE SLOPE EQUATION WITH SEEPAGE PARALLEL TO THE SLOPE

Uplift Force on Base

Pore-Water pressure

$$u = \gamma_w h_p = \gamma_w D_w \cos^2 \alpha$$

Uplift Force

$$U = \frac{ub}{\cos \alpha} = \gamma_w D_w b \cos \alpha$$

Other Forces

Total Weight

$$W_T = b(q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w)$$

Normal Force

$$N = W_T \cos \alpha = b \cos \alpha (q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w)$$

Effective Normal Force

$$\begin{aligned} N' &= N - U \\ &= b \cos \alpha (q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w) - \gamma_w D_w b \cos \alpha \\ &= b \cos \alpha [q_0 + \gamma_m D_m + (\gamma_{\text{sat}} - \gamma_w) D_w] \end{aligned}$$

Shear Force

$$T = W_T \sin \alpha = b \sin \alpha (q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w)$$

(Side forces are assumed to be equal and opposite, and therefore cancel out.)

Stresses

Effective Normal Stress

$$\sigma' = \frac{N'}{b/\cos \alpha} = \cos^2 \alpha [q_0 + \gamma_m D_m + (\gamma_{\text{sat}} - \gamma_w) D_w]$$

Shear Stress

$$\tau = \frac{T}{b/\cos \alpha} = \cos \alpha \sin \alpha (q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w)$$

Shear Strength

$$\begin{aligned} S &= C_r + C_s' + \sigma' \tan \phi' \\ &= C_r + C_s' + \cos^2 \alpha [q_0 + \gamma_m D_m + (\gamma_{\text{sat}} - \gamma_w) D_w] \tan \phi' \end{aligned}$$

Factor of Safety

$$FS = \frac{S}{\tau} = \frac{C_r + C_s' + \cos^2 \alpha [q_0 + \gamma_m D_m + (\gamma_{\text{sat}} - \gamma_w) D_w] \tan \phi'}{\cos \alpha \sin \alpha (q_0 + \gamma_m D_m + \gamma_{\text{sat}} D_w)}$$

Substituting $D - D_w$ for D_m and rearranging gives:

$$FS = \frac{C_r + C_s' + [q_0 + \gamma_m D + (\gamma_{\text{sat}} - \gamma_w - \gamma_m) D_w] \cos^2 \alpha \tan \phi'}{[q_0 + \gamma_m D + (\gamma_{\text{sat}} - \gamma_m) D_w] \cos \alpha \sin \alpha}$$

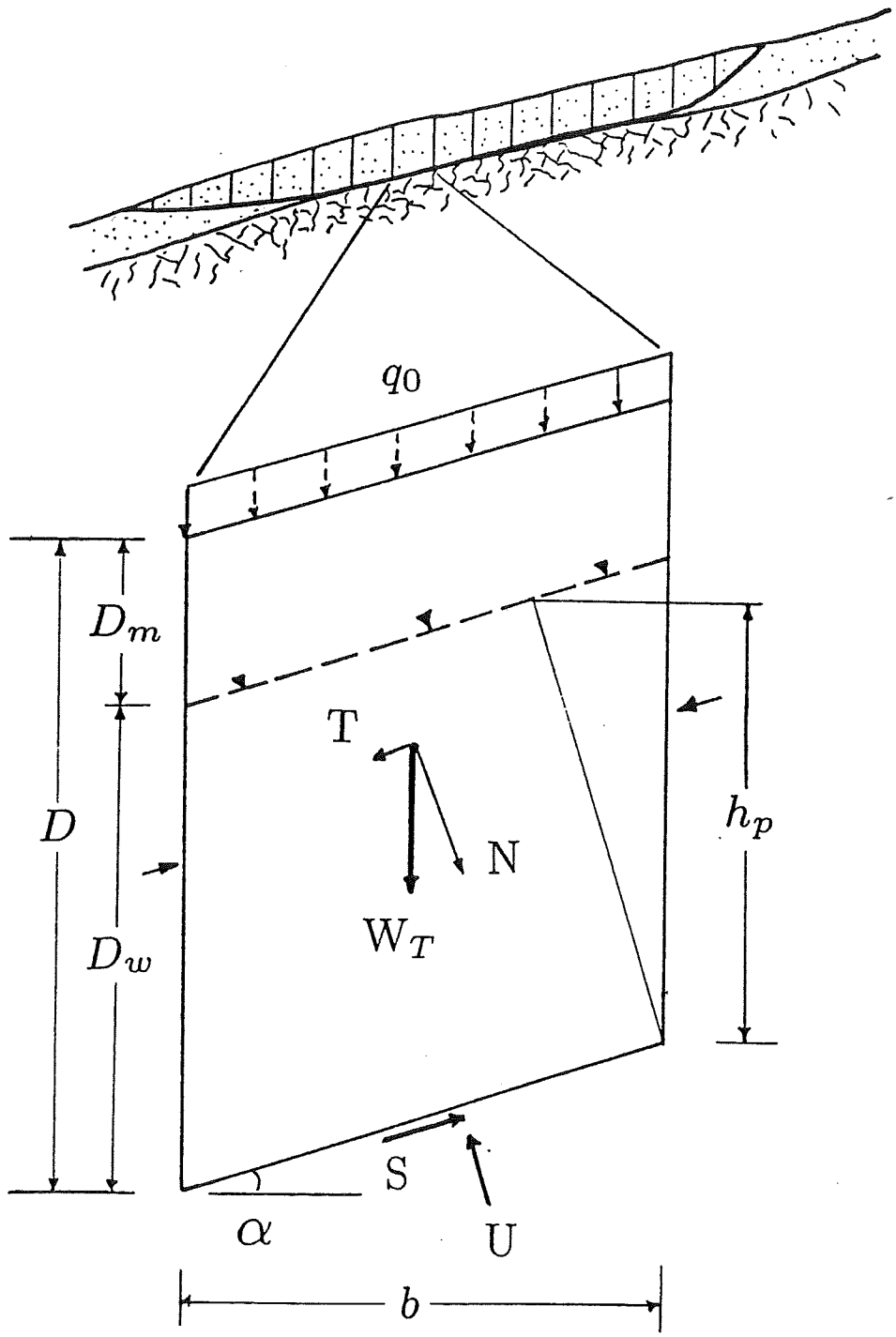

Figure A.1—Infinite slope model force diagram.

APPENDIX B—ROOT STRENGTH: A DETAILED LITERATURE REVIEW

Root strength has been measured or estimated in four ways: tensile strength measurements of individual roots, direct shear tests on soil-root masses, pull tests on large root systems or whole trees, and by back-analysis of existing failures. Each of these methods is described in more detail below.

Tensile Strength of Individual Roots and Their Use in Root Strength Models

Tensile strength of individual roots is measured by holding roots of various sizes in some type of clamp device and pulling until failure. Such measurements have found that the resisting tensile force increases with the diameter of the root, but the tensile strength per unit area of root decreases as the diameter of the root increases. These tensile strength values are used either directly or in a theoretical model.

When used directly, the root strength per unit area of soil, which is needed for stability analysis, is estimated from the tensile strength of individual roots and the numbers of roots. This typically is done by two mathematically similar methods. In the first method, the number of roots in various size classes within a soil sample are counted. The total root strength per unit soil area, t_R, is then computed by dividing the soil sample area into the sum of the products of the average resisting force of the roots and the number of roots for each size class. This can be expressed mathematically as:

$$t_R = \frac{\sum_{i=1}^{N} F_i n_i}{A} \tag{B.1}$$

where t_R is the average tensile strength of roots per unit area of soil (psf), F_i is the average resisting tensile force of roots in the ith size class (lb), n_i is the number of roots in the ith size class, and A is the area of soil in the sample count (ft^2).

Root strength measurements of this type have been made for Oregon coastal Douglas-fir by Burroughs and Thomas (1977), for hemlock and Sitka spruce by Wu and others (1979), for sugar maple by Reistenberg and Sovonick-Dunford (1983), and for 5-year-old yellow pine seedlings by Waldron and Dakessian (1981).

Greenway (1987) discusses a second (but mathematically equivalent) method for computing t_R based on work by Waldron (1977), Wu and others (1979), and Gray and Leiser (1982). In this method, t_R is estimated by multiplying the weighted average tensile strength per average area of root for roots of all size classes (T_R) by the root area ratio (A_R/A), which is the fraction of the soil area occupied by roots. Mathematically, this is expressed as:

$$t_R = T_R\left(\frac{A_R}{A}\right) \tag{B.2}$$

where T_R is the weighted average tensile strength per average root cross-sectional area, A_R is the total cross-sectional area of all of the roots counted, and A is the area of soil in the sample count.

T_R is computed by:

$$T_R = \frac{\sum T_i n_i a_i}{\sum n_i a_i} \tag{B.3}$$

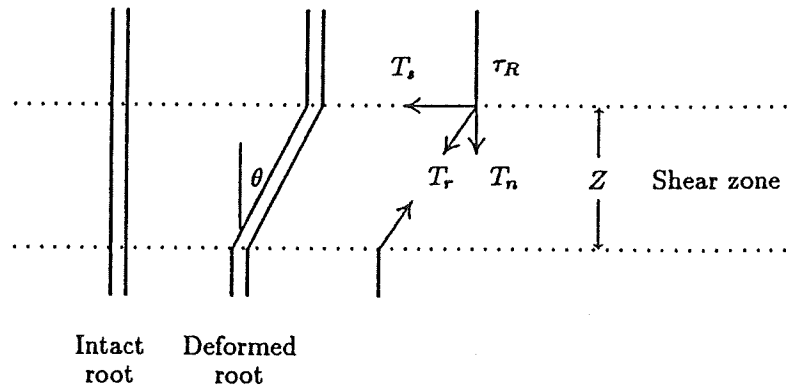

Figure B.1—Fiber reinforcement model (after Gray and Ohashi 1983).

where T_i is the average tensile strength per root cross-sectional area for the ith size class, a_i is the root cross-sectional area for the ith size class, and n_i is the number of roots in the ith size class.

Greenway (1987) has compiled T_R values for various species, which must then be multiplied by the A_R/A ratio at a given site to obtain t_R values for use in LISA. A_R/A values ranging from 0.0004 (Burroughs and Thomas 1977) to 0.0093 (Gray and Megahan 1981) to 0.017 (Gray and Ohashi 1983) have been reported. A_R/A values are so variable because they depend upon species, climate, and, most important, the depth at which the measurements are made. Therefore, it is difficult to estimate realistic A_R/A values from the literature; LISA users would need to make field measurements of A_R/A, which is impractical for a Level I or Level II analysis.

Waldron and Dakessian (1981) found with simulation studies using their model (described below) that even when roots were tightly held with no slippage, roots failed progressively during shear displacement. In other words, not all roots mobilize their maximum tensile resistance at the same time during slope failure. This limited the amount of root strength developed to about 56 percent of that calculated by assuming that all roots would mobilize maximum shear strength at the same time. Burroughs (1984) comments that t_R calculated by either equation B.1 or B.2 should be reduced by perhaps 25 percent for the same reason.

Waldron (1977), Wu and others (1979), Waldron and Dakessian (1981), and Gray and Leiser (1982) modify the tensile strengths of roots (t_R) using mathematical models, to estimate the root resistance for use in stability analysis (C_r). These models are all similar in that they resolve the tensile force that develops in the roots during shear (T_r) into a tangential component (T_s) that directly resists shear and a normal component (T_n) that increases the confining stress on the shear plane, thereby increasing the frictional component of soil shear strength. Figure B.1 illustrates the basic model. The simplest of these mathematical models is:

$$C_r = t_R[\sin\theta + \cos\theta \tan\phi] \tag{B.4}$$

where C_r is the shear strength increase from root reinforcement, t_R is the tensile strength of roots as computed by equation B.1 or B.2, ϕ is the angle of internal friction of the soil, and θ is the angle of shear distortion.

This model assumes that roots are initially oriented perpendicular to the failure plane. It is recognized that in nature, roots are likely oriented randomly

with respect to the failure plane, leading Gray and Leiser (1982) to propose a model in which the initial orientation angle is also a variable. However, Gray and Ohashi (1983) found with direct shear tests on fiber reinforced soils, that fibers oriented at 90° to the shear plane provided about the same increase in shear strength as randomly oriented fibers. They concluded that the assumption of perpendicular orientation satisfactorily approximates the shear strength increase along a surface crossed by randomly oriented roots.

Equation B.4 results in C_r being 0 to 30 percent greater than t_R, depending on the friction angle and angle of shear distortion. Because the angle of shear distortion usually is not known, Wu and others (1979) recommended that for soils with a friction angle between 30 and 40°, a value for C_r 20 percent greater than t_R would be reasonable. Gray and Megahan (1981) recommend that C_r be 12 percent greater than t_R; Gray and Leiser (1982) recommended that C_r be 15 percent greater. However, Reistenberg and Sovonick-Dunford (1983) and Waldron and Dakessian (1981) observed that the angle of shear distortion of roots was nearly 90° in slope failures, and therefore no increase in C_r above t_R would be predicted by the model.

Wu and others (1979) and Gray and Leiser (1982) used t_R computed as in equation B.1 or B.2, thereby assuming full mobilization of the tensile strength of roots. Other authors, particularly Waldron and Dakessian (1981) and Gray and Ohashi (1983) recognized that roots may slip or pull out before they break in tension. The pull-out resistance of roots is dependent on the soil type. It may be quite high for gravelly soils, where roots take tortuous paths around coarse fragments, but quite low for saturated clay soils. Waldron and Dakessian (1981) estimated root strength might be reduced by as much as 75 percent in saturated clay loam due to root pull out. This was estimated from a root strength of 5 kPa measured in direct shear compared to 18.5 kPa estimated using equation B.4 in which pull-out resistance is not considered. Gray and Ohashi (1983) therefore modified the model to account for pull-out resistance. Now:

$$t_R = \left(\frac{A_R}{A}\right)\sigma_R \tag{B.5}$$

where t_R is the *mobilized* tensile strength of roots per unit area of soil, and σ_R is the tensile stress developed in the root at the shear plane. σ_R can be estimated from the following expression (which assumes a linear tensile stress distribution along the root length):

$$\sigma_R = \left(\frac{4E_R\tau_R}{D_R}\right)^{\frac{1}{2}}[z(\sec\theta - 1)]^{\frac{1}{2}} \tag{B.6}$$

in which E_R is the longitudinal stiffness modulus of the root, τ_R is the skin friction stress (or pull-out resistance) along the root, D_R is the diameter of the root, and z is the thickness of the shear zone. Note that t_R in this model is no longer the tensile strength of the roots as measured in equations B.1 or B.2, but depends upon the stiffness modulus of the root and the root pull-out resistance, as well as upon D_R and z.

Gray and Ohashi (1983) found that pull-out resistance depends not only upon soil type, but upon overburden pressure and fiber length. In their direct shear tests on fiber-reinforced sands, there was a threshold confining stress below which fibers slipped or were pulled out, resulting in little shear strength increase by the fibers. However, it should be noted that the fibers used did not have the interlocking behavior roots might possess in granular soils, so it is not known whether a threshold stress might control root strength in nature.

Direct Shear Tests on Soil–Root Masses

Direct shear tests on soil–root masses have been performed in several ways. Waldron and Dakessian (1981) and Waldron and others (1983) performed laboratory direct shear tests on large columns of soil containing yellow pine roots. Endo and Tsuruta (1969a) carved out pedestals of soils beneath alder seedlings and sheared them along their base. Ziemer (1981a, 1981b) and Wu and others (1979, 1988a, 1988c) performed *in situ* direct shear tests on soil blocks isolated on the front, back, and bottom, and sheared along two opposing sides. Tsukamoto and Minematsu (1987) isolated the perimeter of small Sugi trees and sheared them along their bases. All of these tests show that the shear strength of the soil-root mass increases with the weight (or number) of the roots present in the soil mass. (This is consistent with equations B.1, B.2 and B.5.) When the shear strength of soil specimens with roots is compared to the shear strength of soil without roots, the roots appear to provide cohesion but not an increase in the friction angle of the soil (O'Loughlin and Ziemer 1982). (That is, the increase in strength is not dependent on normal or confining stress.)

Direct shear tests may better account for pull-out resistance and for the fact that maximum tensile strength is not mobilized by all of the roots simultaneously, but there are still problems with measuring root reinforcement in this way; specifically, at high strains, the soil block tends to be torn apart by the roots. Also, with Ziemer's device, roots can pass completely through the soil block, which may not correctly model the failure mode of the soil-root mass in nature. However, results of direct shear tests generally have been comparable to root strength per soil unit area computed from individual root tensile strength tests, except in the cases described above in which the pull-out resistance of the roots was very low (such as Waldron and Dakessian 1981 and Gray and Ohashi 1983).

Pull Tests on Large Root Systems and Whole Trees

This method may be the most reliable for measuring the effective tensile strength and pull-out resistance of root systems, because it simulates more closely what occurs during slope failure. Tests of this type have been attempted by Abe and Iwamoto (1985) and Tsukamoto and Kusakabe (1984). Endo and Tsuruta (1969b) performed tensile strength tests on blocks of soil and roots by attempting to pull the soil-root blocks apart. Tensile strength values measured were close to the shear strength values reported for the two methods described above.

Back-Analysis of Existing Failures

By estimating or measuring prefailure values for all other parameters needed in a stability analysis, root strength values can be back-calculated using information on existing failures. The assumption is that the factor of safety equals 1 at failure. This method does give approximate values, but unless the values for the other variables can be estimated confidently, this becomes a mathematical number exercise for which there are several possible combinations of values that give a factor of safety of 1. Back-calculated values reported in the literature were not used in estimating distributions for use in LISA. However, they do support that t_R values calculated with equation B.1 or B.2 are realistic even with all of the uncertainty about progressive root failure and pull-out resistance. For example, Reistenberg and Sovonick-Dunford (1983) counted the number of roots found on both the scarp and slip surface of an existing failure and computed

root strength using equation B.1. They computed a greater root strength per unit soil area in the scarp than on the slip surface because there were a greater number of roots in the scarp. When the appropriate root strength values were used in a method-of-slices stability analysis, they were able to calculate a factor of safety close to 1 for the prefailure conditions, indicating the values used for root strength were realistic, even though pull-out resistance and progressive root failure were not considered.

APPENDIX C—RATIONALE FOR SELECTING ROOT STRENGTH PDF'S

To estimate probability distributions for each root morphology type, we used the data tabulated in table 5.2, along with the following observations and assumptions to select PDFs for root strength.

- We assumed that the measured values of root strength reported in the literature and summarized in table 5.2 and figure 5.6 apply to soil-root morphology types B and C, where roots intersect the entire failure plane. As mentioned in appendix B, many of the root strengths reported were computed from tensile strength tests on individual roots and from root numbers, which probably overestimate root strength because not all roots would be loaded to failure simultaneously during a slope failure, and because of root slippage and pull out. However, none of the methods of measuring root strength described includes soil buttressing and arching. Gray and Megahan (1981) present a formula for calculating buttressing and arching resistance. However, they do not present any typical values nor indicate how the values should be used in a stability analysis. We have assumed that buttressing and arching would be significant enough in types B and C to offset any overestimating of root strength that would result from individual root tensile strength measurements. There also may be some increase in strength due to increased stress on the failure plane as calculated by equation B.4.

- Because the infinite slope equation assumes that root strength acts along the entire failure surface, the measured values of root strength must be reduced to some *apparent* values for types A and D where root strength acts only along the failure perimeter. To estimate reasonable values for apparent root strength, a comparison was made between the root strength values that give the same factor of safety for the infinite slope equation and for a three-dimensional block model (Burroughs 1984). The three-dimensional block model considers root strength to act only in the top 2 feet of soil, thereby increasing shear resistance along the block sides and tensile resistance along the block headwall. Roots are assumed not to penetrate the stable substrate, so there is no increase in shear resistance along the block base even when the soil is less than 2 feet thick. This is consistent with the type A and D conditions.

  The first step in the comparison was to find block lengths and widths that produced factors of safety equal to those calculated by the infinite slope equation for several combinations of slope and soil depth, and with root strength equal to zero. Length-to-width ratios of 1.1:1 or 1.2:1 at 45 percent slope, to 1.5:1 at 75 percent slope satisfied this step. Next, the factors of safety for each block were calculated using the three-dimensional model with root strength values of 50 to 400 psf. The apparent root strength values required to give

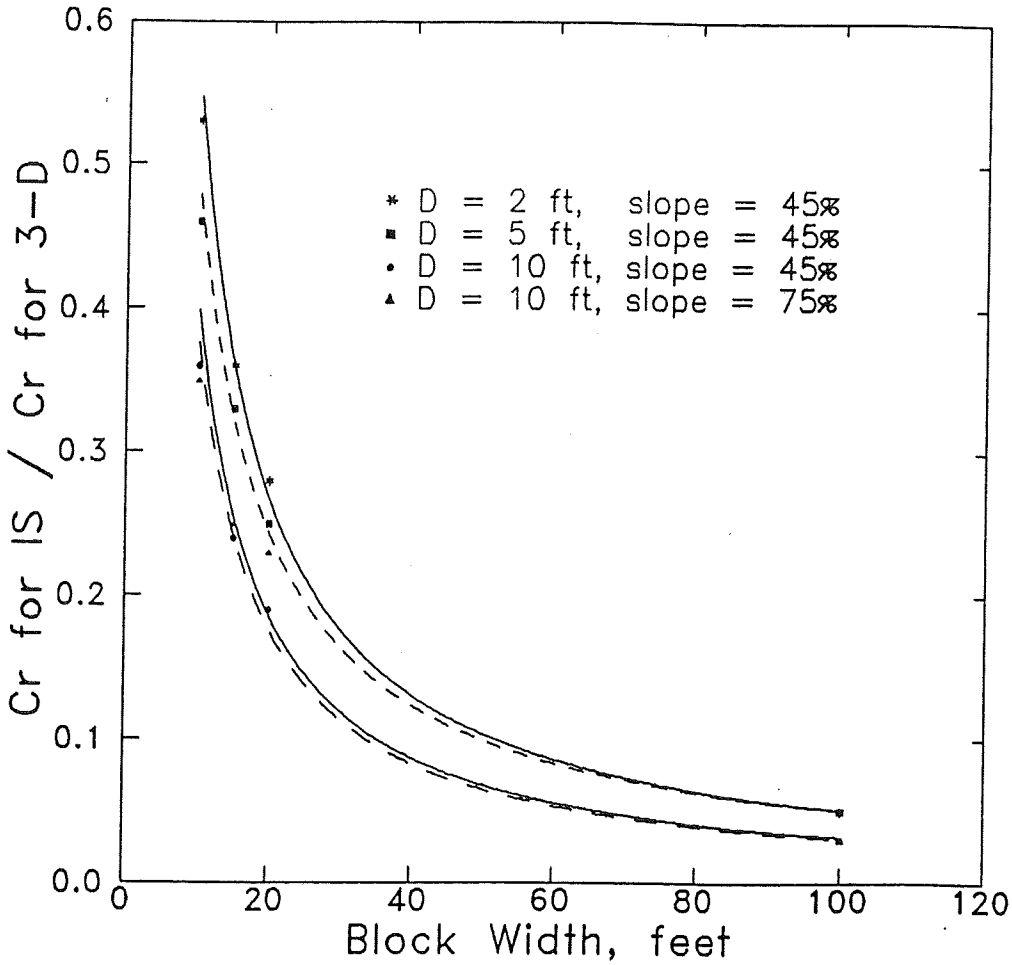

Figure C.1—Ratios of apparent root strength needed for the infinite slope model to root strength used in the three-dimensional block model to give the same FS.

the same factors of safety using the infinite slope equation then were back-calculated.

The results are shown in figure C.1. Two trends are observed. First, the apparent root strength decreases as the block width increases. For block widths of 100 feet, apparent root strength values are about 5 percent of the values used in the block model. This is consistent with what would be expected in relatively shallow soil conditions; as the size of the failure mass increases, the side and headwall resisting forces, and therefore root strength, have proportionately less influence on the stability of the soil mass.

The second trend is that for a given block width, the apparent root strength decreases as the soil depth increases. For instance, the apparent root strength values for a 20-foot-wide block are 28 percent (0.28) of the values used in the block model when the soil is 2 feet deep, and 18 percent (0.18) when the soil is 10 feet deep.

These trends were used to develop distributions for soil-root morphology types A and D from the distributions developed for types B and C.

- The criteria used to select distributions for each root morphology type are:

  1. We assumed the mode of the probability distribution describing type B to be about 100 psf, which is equal to the mode of the histogram in figure 5.6. For the type C distribution, we assumed a mode of about 150 psf to account for greater tree buttressing and root penetration along the base of the failure plane. We assumed modes of 40 psf for type A and 20 psf for type D based on the three-dimensional modeling of failures less than about 20 feet in width as described above.

  2. We assumed that all distributions should have large standard deviations to account for the great variability and uncertainty in reported values.

  3. We selected lognormal probability distributions to reflect the tendency for right skew in the data (as shown in fig. 5.6), thereby giving a low (but non-zero) probability of simulating relatively high values.

     Based on these criteria, the suggested distributions for root strength in dense timber stands are shown in figure 5.8. Height differences in the plots are due to the fact that the area under each plot must equal 1.0. Important things to note are the range in values, the mode, and the shape of the distributions.

The rationale for selecting PDF's for minimum root strength following clearcut timber harvest is discussed in section 5.3.4.3.

APPENDIX D—USING INFILTRATION EVENT RETURN PERIODS WITH PROBABILITIES OF FAILURE FROM LISA

As is stated in section 1.4, the probability of failure estimated using LISA is a *conditional* probability of failure that is valid only if the infiltration event, with the resulting groundwater (D_w/D) distribution used in the analysis, occurs. Time can be incorporated into the probability of failure estimate by weighting the conditional probability of failure with the probability of the groundwater distribution occurring during a specified time interval. This method considers the return periods of the rainfall or snowmelt infiltration events. Because return periods commonly are used in many professional fields and are understood by land managers, their use may improve understanding of LISA results. This method also improves an assessment of the likelihood of a major landslide event occurring during the 3 to 10 years of minimum root strength following timber harvest (see section 5.3.4.3). The method will show that as the length of time considered increases, the probability that a major infiltration event occurs increases and, therefore, the expected probability of failure increases. The expected probability of failure can be thought of as the *average* likelihood of failures (or the *average* land area in failure) over *many* N-year trial periods.

Unfortunately, neither precipitation (or snowmelt) data nor groundwater response data typically are available to do a detailed time-history analysis. Therefore, the method suggested here must still be based on subjective estimates of groundwater response in average or major infiltration events, and as such is only a tool to help illustrate how event return periods might be handled. This method makes two assumptions—that the infiltration events are independent, and that the probabilities remain constant from year to year. The steps of the method are outlined below.

1. Make subjective estimates for the distribution of peak groundwater (D_w/D) levels in response to a minor infiltration event, an average event, and a major event. (Although three events are illustrated here, the method does not require three events.)
2. Use LISA to estimate the conditional probability of failure ($P[FS\backslash\text{event } i]$) for each of the three infiltration events i — make three LISA runs changing only the groundwater distributions to obtain the corresponding probabilities of failure.
3. Assume a return period (RP_i) for each event, and for each event compute the probability that at least one event with that return period (or greater) will occur during the next N years ($P[\text{event } i]$). This probability can be computed using the equation
$$P[\text{event } i] = 1 - \left(1 - \frac{1}{RP_i}\right)^N . \qquad (D.1)$$
4. Compute the probabilities that the maximum event during an N-year period will be smaller than the average event, equal to or greater than the average event but less than the major event, and equal to or greater than the major event ($P[\max i]$) by taking the difference between pairs of probabilities computed in step 3. These probabilities should sum to 1.
5. Calculate the weighted probability of failure ($P[FS \cap \max i]$) by multiplying the conditional probability of failure estimated using LISA by the probability that the corresponding event will be the maximum event in N years; that is,
$$P[FS \cap \max i] = P[FS\backslash\text{event } i] \times P[\max i]$$

6. Compute the expected probability of failure for the specified time period by summing the weighted probabilities of failures.

An example will illustrate the method. Groundwater distributions for the minor, average, and major events have been evaluated, and conditional probabilities of failure of 0.002, 0.034, and 0.582 have been estimated with LISA. The return periods for the average and major events are assumed to be 2 years and 20 years, respectively; the minor event is assumed to be any event with less than a 2-year return. The exceedance probabilities for a 10-year period are desired because of concern about a 10-year postharvest period of minimum root strength.

Equation D.1 is used to compute the probabilities of at least one 2-year (or greater) event and of one 20-year (or greater) event occurring during a 10-year period:

$$P[\text{event } \geq 2 \text{ years}] = 1 - \left(1 - \frac{1}{2}\right)^{10} = 0.999$$

$$P[\text{event } \geq 20 \text{ years}] = 1 - \left(1 - \frac{1}{20}\right)^{10} = 0.401$$

The probability of at least one minor event occurring during the 10 years is 1.

The probability that the maximum event during that period will be minor, average and major is given below.

Maximum event	**Calculation**	
minor	$P[\text{max} < 2 \text{ years}] = 1 - 0.999$	$= 0.001$
average	$P[2 \text{ years} \leq \text{max} < 20 \text{ years}] = 0.999 - 0.401$	$= 0.598$
major	$P[\text{max} \geq 20 \text{ years}]$	$= 0.401$
		Total $= 1.000$

The weighted and expected probabilities of failure are shown in table D.1. Table D.2 summarizes the computations including 1-year and 25-year periods for comparison. Note that the probability of the maximum event being a major event increases as the length of time considered increases. Therefore, as the time increases, the groundwater distribution corresponding to a major infiltration event is more likely to occur, as is the probability of failure resulting from that groundwater distribution, causing the expected probability of failure to increase. This increase in expected probability of failure with longer analysis periods was also found by Miller (1988).

Table D.1—Computations of weighted and expected probability of failure for $N = 10$ years

	$P[FS \backslash \textbf{event } i] \times P[\textbf{max } i] = P[FS \cap \textbf{max } i]$		
Event	$P[FS \leq 1]$ **from** LISA	$P[\textbf{max } i]$	**Weighted** $P[FS \leq 1]$
Minor (event < 2 years)	0.002	0.001	0.000002
Average (2 years ≤ event < 20 years)	.034	.598	.0203
Major (event ≥ 20 years)	.582	.401	.2334
Expected probability of failure		=	.254

Table D.2—Expected probability of failure with analysis periods of 1, 10, and 25 years

Event	R_{pi}	LISA P_f	P[event i] $N = 1$	P[event i] $N = 10$	P[event i] $N = 25$	$N = 1$ P[event i]	$N = 1$ Weighted P_f	$N = 10$ P[event i]	$N = 10$ Weighted P_f	$N = 25$ P[event i]	$N = 25$ Weighted P_f
Minor	< 2	0.002	1.00	1.000	1.000	0.50	0.001	0.001	0.000	0.000	0.000
Average	2	.034	.50	.999	1.000	.45	.015	.598	.020	.277	.009
Major	20	.582	.05	.401	.723	.05	.045	.401	.233	.723	.421
				Expected P_f			0.061		0.254		0.430

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