

LITERATURE REVIEW

EFFECT OF WOODY VEGETATION REMOVAL ON THE HYDROLOGY AND STABILITY OF SLOPES

One way to settle the argument about the effect of woody vegetation on the hydrology and stability of slopes is to cut down all the trees and see what happens. The effects of wide spread vegetation removal on the stability of natural slopes have been studied extensively as a result of a timber harvesting practice known as clear-cutting. It is useful and instructive to examine the consequences of such a practice vis a vis a policy promulgated and now being carried out by the US Army Corps of Engineers to remove all woody vegetation over 2 inches in diameter growing on or near the toe of earthen embankments or levees.

Widespread removal (clear-cutting) of trees on natural slopes and streambanks generally leads to an increase in slope failures. This is the overwhelming consensus of papers published in the scientific and technical literature as documented in the attached literature review. In some cases there may be a short-term benefit from tree removal resulting from a decrease in shear forces transmitted to a slope from wind. The adverse effect of wind depends, however, on such factors as the size and height of the canopy, stand density, and wind direction. The presence of tall, rigid trees growing near the water line of levees may also promote scour erosion around the base of the tree. These offending trees can be identified, selectively removed and/or pruned as part of an alternative vegetation management policy.

In the long run, cutting of trees on slopes leads to a gradual decrease in mass stability as a result of the decay of roots which previously acted as tensile reinforcements in the slope. Root decay can also lead to the formation of pipes in a slopes which promote internal or seepage erosion. The removal of tree canopy results in the loss of interception and evapo-transpiration which tends to promote wetter and less secure slopes. Canopy removal also results in less attenuation in the delivery rate of rainfall to the ground surface.

Considerably fewer studies have been carried out on the effects of woody vegetation removal on the mass stability of artificial embankments and levees. However, many of the results and findings from clear-cutting studies of natural slopes apply.... and are a cause for alarm in the case of a blanket, unexamined

removal policy on levees. Such a policy is tantamount in effect to an uncontrolled, national experiment. At the very least the position, size, age, etc of every tree that is removed on or near a levee should be entered into a GPS data base so that possible cause and effect relationships can be studied and the wisdom of such a policy properly evaluated at a later date.

One of the main arguments advanced by proponents of tree removal on levees is improved access, visibility, and flood fighting. It would be a great irony if all these goals were realized only to better witness, gain access to, and attempt to fight floods on a levee that is disintegrating and failing because of woody vegetation removal.

EFFECTS OF VEGETATION REMOVAL ON SLOPE HYDROLOGY AND STABILITY

Title: Effects of deforestation on slopes

Author: Brown, C.B. and Sheu, M.S.

Series/Source: *Journal Geotechnical Engineering Division (ASCE)*, 1975. **101**(2):142-165

Peer-reviewed: Yes

Code: RTSTAB, BDWFAL, SLSTAB(VR)

Abstract/Introduction: The creep and stability of slopes before and after logging were analyzed theoretically. The following effects of vegetation were included in the theory: (1) mechanical reinforcement of the soil by root systems; (2) vertical surcharge exerted by the weight of vegetation; (3) surfaces shears and moments caused by wind in the trees; and (4) modification of soil moisture and groundwater levels by evapo-transpiration. Results of analyses showed that immediately after tree removal the reduction in the overburden decreases creep rate. Also, this reduction and the drop in wind loading increases slope stability. The immediate effect of deforestation is, therefore, favorable, but adverse effects become evident when root systems decay and when a drop in evapo-transpiration causes a rise in the ground water table.

Objective(s): The objective of the study was to reconcile and explain differences in creep rate and stability that had been reported previously with regard to the impact of tree removal on slope stability, particularly with respect to the practice of clear-cutting. The paper resulted from a joint U. Michigan & U. Washington research project undertaken in the mid 1970s to investigate the impact of clear-cut logging practices in forested slopes. The UMich team monitored creep rates (using slope movement indicators) in forested vs. cut-over slopes in the western USA while the UWash team conducted theoretical analyses of both creep rates and safety factors in forested slopes vs. denuded, clear-cut slopes.

Study Location: Non specific

Methodology: Theoretical idealization of soil, slope, wind shear, surcharge, and soil moisture parameters.

Vegetation: Trees

Soil Properties: Idealized soil with range of density, cohesion, and friction angle.

Observations/Results: The following occur as a result of clear-cutting: 1) gradual loss of root reinforcement from root decay, 2) elimination of vertical surcharge from the weight of the trees, 3) elimination of external shears and moments from wind forces, and 4) increase in moisture content and perched water tables because of loss of evapo-transpiration. The surcharge effect is relatively unimportant because the distributed weight of even a well stocked forest is very minor compared to the weight of the soil. Furthermore, in some cases the vertical surcharge can be beneficial. A significant adverse wind shear effect requires a wind blowing down-slope past trees with large,

high canopies (sail effect). Other wind directions may result in windthrow/uprooting and local disturbance (divots) but have little effect on overall mass stability.

Recommendations: None

Title: Modelling effects of forest canopies on slope stability

Authors: Keim, R.F. and Skaugset, A.E.

Series/Source: *Hydrological Processes*, 2003. **317**:1457-1467

Peer-reviewed: Yes

Code: SLSTAB

Abstract: The potential effects of rainfall intensity “smoothing” by forest canopies on slope stability was investigated by modeling soil responses to measured rainfall and through-fall during high-intensity rain. Field measurements showed that maximum intensities of precipitation were generally reduced under forest canopies at two sites in the Pacific Northwest, USA. Modelling soil water pressure responses of a hypothetical hillslope to the field data resulted in estimates of slope stability that were generally greater under forest canopy than for the same hillslope without forest canopy.

Objective(s): To determine the role and importance of vegetation in affecting the hydrology and stability of natural slopes via the modulating influence on rainfall intensity “smoothing” of tree canopies.

Study Location: Data was collected from two forest stands in the Pacific Northwest. One stand was in the Gifford Pinchot National Forest, Cascade Mountains, southwestern Washington, USA. The other stand is located in the Dunn Research Forest of the Oregon State University, on the eastern margin of the Oregon Coast.

Methodology: Rainfall intensity data in and adjacent the two stands was collected. Each stand was equipped with a tipping-bucket rain gauge in a large nearby opening, and multiple through-fall gauges randomly located under the canopy. Pore pressure responses from non-steady infiltrating rainfall were modeled using a one-dimensional solution for pore water pressure using the Richards equation. Slope stability resulting from time-varying pore pressures was calculated using the “infinite slope” equation.

Vegetation: The overstory trees in the Washington state stand are old-age Douglas-fir, western redcedar, and western hemlock. The canopy at this stand is structurally complex because of its age. The spatial relationships between canopies of very large trees and younger individuals of tolerant species result in presence of canopy gaps. The overstory trees in the Oregon state stand are Douglas-fir, grand fir, and bigleaf maple. The canopy at this site is spatially quite homogeneous with little or no gaps.

Soil Properties: To compare modeled pore pressure and slope stability under rainfall and through-fall, responses of a hypothetical soil were used for which rates of drainage approximated the rates of measured precipitation.

Observations/Results: Results indicate that smoothing of precipitation intensities may translate into overall greater stability of hillslopes under forest canopies. In general, peak intensities of through-fall were damped in intensity and lagged in time relative to peak intensities of rainfall. Damping and lagging of rainfall intensity at both study sites generally increased modeled slope stability relative to openings (areas with no canopy).

Recommendations: Several areas for future investigation were cited: 1) elucidate how infiltrating precipitation causes hydrologic response in various soils, and determine the

limits for models of pore pressure propagation, 2) determine the importance of the forest floor (duff and litter layer) in mediating pore pressure response in the underlying soil, and 3) investigate the influence of shrub and herbaceous groundcover canopies.

Title: Slope instability caused by small variations in hydraulic conductivity

Author: Reid, M.E.

Series/Source: *Jour. of Geotechnical and Geoenvl. Engr.(ASCE)* 1997. **108**(8):717-725

Peer-reviewed: Yes

Code: SLSTAB

Abstract: Variations in hydraulic conductivity can greatly modify hillslope ground-water flow fields, effective-stress fields, and slope stability. In materials with uniform texture, hydraulic conductivities can vary over one to two orders-of-magnitude, yet small variations can be difficult to determine. The destabilizing effects caused by small (one-order-of magnitude or less) hydraulic conductivity variations using ground-water flow modeling, finite-element deformation analysis, and limit-equilibrium analysis are examined in this paper. The destabilizing effects of small hydraulic heterogeneities can be as great as those induced by typical variations in the frictional strength (approx 4→8 degrees) of texturally similar materials. Common “worst-case” assumptions about ground-water flow, such as a completely saturated “hydrostatic” pore-pressure distribution, do not account for locally elevated pre-water pressures and may not provide a conservative stability analysis.

Objective(s): To investigate the influence of small, local variations in hydraulic conductivity on slope stability and to determine the ability of standard geotechnical assumptions to provide conservative or “worst case” slope stability assessments.

Study Location: N/A... theoretical study.

Methodology: Gravity-driven ground-water flow regimes were modeled in saturated hillslopes with: a) homogeneous region, b) slope parallel boundary, c) horizontal boundary, and d) vertical boundary. The maximum pore pressure change and slope factor of safety for each of these boundary configurations were determined as a function of the hydraulic conductivity contrast.

Vegetation: Applicable to the extent that a former rootball represents a local zone in a slope with a different hydraulic conductivity. The rootball may have been excavated and backfilled with a compacted soil that has a lower hydraulic conductivity than the surrounding soil.

Soil Properties: In all four cases uniform elastic and density parameters typical of a granular soil (sand) were used ($c=0$, $\phi=42$ degrees, porosity=30%)

Observations/Results: Low hydraulic conductivity materials that impede downslope ground-water flow can create unstable areas with locally elevated pore-water pressures. This effect is particularly pronounced for regions with vertical boundaries. The effect increases steadily with increasing hydraulic conductivity contrasts. Heavy compaction of backfilled (former rootball zones) in a slope could be counter productive if this results in hydraulic conductivity substantially lower than the surrounding soil.

Recommendations: In site characterization work, special attention should be paid to any materials and conditions that might impede down slope ground-water flow and create unstable regions.

Title: The effects of timber removal on the stability of forest soils.

Author: O'Loughlin, C.L.

Series/Source: *Journal Hydrology (NZ)*, 1974. 13(2):121-134

Peer-reviewed: Yes

Code: SLSTAB(VR)

Abstract: The principal ways in which the removal of a forest cover influences the stability of sloping soils is briefly described. Potential destabilizing effects of surcharge are compensated by increased stability provided by root reinforcement. Moreover, in most forested slopes the total weight of the soil overlying a potential failure plane far exceed the weight of the forest layer. Methods by which relevant soil physical data can be obtained for use in stability analyses are outlined.

Objective(s): To determine how timber harvesting practices, e.g., clear-cutting, affect the stability of slopes

Study Location: New Zealand

Methodology: Infinite slope type stability analyses under dry and saturated conditions were applied to elucidate cause-and-effect relationships between deforestation and mass soil movements.

Vegetation: N/A... root strength (reinforcement) data from previous studies was used. Increased soil strength measured from field tests on root permeated soil pedestals beneath different types of trees (conifers, alders, birch) in different types of soil (till and silt loam) ranged 1 to 10 kPa. The large range in strengthening effects is due mainly to very different tree-root network densities in terms of root weight per unit volume of soil.

Soil Properties: In the absence of relevant data from New Zealand the analyses used soil strength, soil unit weight and pore pressure data collected from a steep, clear-cut slope in southwest British Columbia.

Observations/Results: Measurement of the decline in tensile strength of small roots in coastal British Columbia after death of the parent tree indicate that over half the strength is lost within 3 to 5 years after cutting. A forest cover can intercept precipitation, either in the crowns of trees or in the forest litter layers at the soil surface. The combination of transpiration and interception tends to delay or mitigate saturation of a soil mantle on steep slopes. Deterioration of tree roots and the changes which occur in the subsurface hydrological status of soils are the most significant tree-crop-related factors involved in accelerated mass wasting on recently deforested slopes.

Recommendations:

Title: Strength of tree roots and landslides on Prince of Wales Island, Alaska

Authors: Wu, T.H., W.P. McKinnell III, and D.N. Swanston

Series/Source: *Canadian Geotechnical Journal*, 1979. 16:19-33

Peer-reviewed: Yes

Code: SLSTAB(VR), RTMODL, RTSTAB

Abstract: The stability of slopes before and after removal of forest cover was investigated. Pore water pressures and shear strengths were measured and the soil properties were determined by laboratory and in situ tests. A model of the soil-root system was developed to evaluate the contribution of tree roots to shear strength. The computed safety factors are in general agreement with observed behaviors of the slopes. Decay of tree roots subsequent to logging was found to cause a reduction in the shear strength of the soil-root system.

Objective(s): Study of tree root contribution to slope stability

Study Location: Coastal forests in southeastern Alaska

Methodology: To study the effect of clear-cutting on stability, pore water pressures and creep rates were measured at several sites in 1964-1966, with additional measurements in 1972-1975. Permeability tests, piezometer stand pipes, and test pits were all employed to acquire data and samples of soil. These measurements were accompanied by laboratory investigations of soil strength and the contribution of tree roots to shear strength. Tree root tensile strengths were determined by attaching the upper end of a root to a calibrated spring. The device was pulled up by hand and the tensile force was determined from spring compression. A scale attached to the ground surface was used to measure the displacements of the end of the root. The ultimate load was plotted against root diameter. The number of roots per slip scar was estimated from the results of excavations of roots of representative trees. Tree weights were estimated in study plot areas by conducting tree counts and measuring tree diameters. A model was developed that indicates the contribution of tree roots to shear strength may be treated as a cohesion.

Vegetation: Spruce and fir conifer trees

Soil Properties: Soil, weathered soils, glacial till, and weathered bedrock

Observations/Results: Landslides that involve the shallow surface soils have been observed to be an important form of mass wastage on steep hillsides of southeastern Alaska. More frequently, landslides occur as a rotational slip located in the upper part of a deforested slope, usually at the head of a small gully or drainage depression. The slip is at the base of the weathered soil zone, 1- to 1.5-m depth. Most slides are in the autumn rain season. Tree roots extended into unweathered till (glacial deposits) and weathered bedrock. Results indicated that strength contributed by tree roots is important to the stability of steeper slopes. Loss of root strength following clear-cutting can seriously affect slope stability.

Recommendations: N/A

Title: Root strength changes after logging in southeast Alaska

Author: Ziemer, R.R., and D.N. Swanston

Series/Source: U.S. Dept. Agric., Forest Service, Research Note PNW-306, December 1977, Portland, Oregon. 10 pp

Peer-reviewed: Yes

Code: RTSTAB, SLSTAB(VR)

Abstract: A crucial factor in the stability of steep forested slopes is the role of plant roots in maintaining the shear strength of soil mantles. Roots add strength to the soil by vertically anchoring through the soil mass into failures in the bedrock and by laterally tying the slope together across zones of weakness or instability. Once the covering vegetation is removed, these roots deteriorate and much of the soil strength is lost. Measurements of change in strength of roots remaining in the soil after logging at Stoney Creek on Prince of Wales Island, southeast Alaska, indicate that loss of strength in smaller roots occurs rapidly for all species the first 2 yr. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) roots are more resistant to strength loss than are Sitka spruce (*Picea sitchensis* (Bong.) Carr.) roots. By 10 yr, even the largest roots have lost appreciable strength.

Objective(s): A study to measure the strength change of roots remaining in the soil after logging.

Study Location: Stoney Creek on Prince of Wales Island, southeast Alaska

Methodology: Root samples were collected from remaining stumps of various ages and from uncut tree stands. The root samples were shipped to the laboratory for testing in the direct shear apparatus (described in Ziemer 1978).

Vegetation: Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.)

Soil Properties: N/A

Observations/Results: Loss of strength in smaller roots occurs rapidly for all species the first 2 yr. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) roots are more resistant to strength loss than are Sitka spruce (*Picea sitchensis* (Bong.) Carr.) roots. By 10 yr, even the largest roots have lost appreciable strength.

Recommendations: None

Title: Roots and the stability of forested slopes

Author: Zeimer, R.R.

Series/Source: *Proceedings of the International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands*, 1981 January 25-31. Timothy R. H. Davies and Andrew J. Pearce (eds). Christchurch, N.Z. Int. Assn. Hydrol. Sci. Pub. No. 132: 343-361

Peer-reviewed: Yes

Code: RTSTAB, SLSTAB(VR)

Abstract: Root decay after timber cutting can lead to slope failure. In situ measurements of soil with tree roots showed that soil strength increased linearly as root biomass increased. Forests clear-felled 3 years earlier contained about one-third of the root biomass of old growth forests. Nearly all of the roots <2 mm in diameter were gone from 7-year-old logged areas while about 30% of the <17 mm fraction was found. Extensive brushfields occupied areas logged 12 to 24 years earlier. The biomass of brushfield roots <2 mm in diameter was 80% of that in the uncut forest, and fewer large roots were found there than in the forest. Roots <17 mm in diameter in the brushfield accounted for 30% of that found in the forest, and for total root biomass, only 10%. Individual, live brush roots were twice as strong as conifer roots of the same size. This difference may partially compensate for reduced root biomass in brushfields.

Objective(s): Results of (1) field-testing of a shear box to determine strength characteristics of root systems; (2) roots extracted from a soil pit study to determine biomass changes; (3) a root tensile strength obtained from a direct shear device; and (4) applications and inferences regarding slope stability and root systems.

Study Location: (1) coastal sands in northern California, and (2) Klamath mountains of northwestern California

Methodology: The shear box enclosed the soil block but remained open on two sides. Inside dimensions were 60 cm wide, 30 cm long, and 30 cm high. Shear stress was applied by a mechanical jack extended at a rate of 1.3 cm/min for 7 min. Stress was measured using a proving ring between the jack and the shear box. The Klamath site soil core roots were extracted, and roots were also extracted from soil excavations. The direct shear apparatus (refer to Ziemer, 1978) data was correlated to tensile strength.

Vegetation: Lodgepole pine (*Pinus contorta*) and white fir (*Abies concolor*) with several sub-dominant conifer species. Brushfields were mostly *Ceanothus velutinus*.

Soil Properties: (1) Coastal sands and (2) gravely fine sandy loam

Observations/Results: Soil strength increased linearly as root biomass increased. Forests clear-felled 3 years earlier contained about one-third of the root biomass of oldgrowth forests. Nearly all of the roots <2 mm in diameter were gone from 7-year-old logged areas while about 30 percent of the <17 mm fraction was found. Individual, live brush roots were twice as strong as conifer roots of the same size. This difference may partially compensate for reduced root biomass in brushfields. Net strength of the soil-

root matrix in brushfields was about 70% of that in uncut forests. If soils are barely stable with a forest cover, the loss of root strength following clear-felling can seriously affect slope stability.

Recommendations: None

Title: Effect of logging on subsurface pipeflow and erosion: coastal northern California, USA

Author: Ziemer, R.R.

Series/Source: Erosion, Debris Flows and Environment in Mountain Regions, *Proceedings of the Chendu Symposium, July 1992, Chendu, China*. International Association of Hydrological Sciences Publication No. 209. Wallingford, UK; 187-197

Peer-reviewed: No

Code: SOILER, SLSTAB(VR)

Abstract: Three zero-order swales, each with a contributing drainage area of about 1 hectare, were instrumented to measure pipeflows within the Caspar Creek Experimental Watershed in northwestern California, USA. After two winters of data collection, the second-growth forest on two of the swales was clearcut logged. The third swale remained as an uncut control. After logging, peak pipeflow was about 3.7 times greater than before logging. Before logging, little sediment was transported through the pipes. Suspended sediment concentrations before logging were less than 20 mg/liter and coarse-grained sediment was rare. After logging, there was great spatial and temporal variability in sediment transport. Sediment loads increased dramatically from some pipes during some storms, but from other pipes, sediment discharge remained unchanged after logging.

Objective(s): A study of subsurface pipeflows (seepage-induced erosion and water discharge through subsurface tunnel networks) in steeply-sloped forests.

Study Location: near the Pacific Ocean in the headwaters of the North Caspar Creek Experimental Watershed in northwestern California.

Methodology: Subsurface soil pipes (tunnels) exposed by trenching or enlarging existing collapse features were connected via PVC pipe plumbing networks discharging subsurface water flow into containers instrumented with pressure transducers. Sediment was also collected in the containers and analyzed for particle-size distribution. Rainfall, piezometric level, soil water tension, and downstream channel discharge were also measured. After two winters of data collection, the second-growth forest on two of the swales was clearcut logged. The third swale remained as an uncut control.

Vegetation: Douglas fir (*Pseudotsuga menziesii* Mirb. Franco), coast redwood (*Sequoia sempervirens* D. Don Endl.) and understory shrubs.

Soil Properties: well-drained with moderately slow permeability, 40% clay and about 10% gravel, clayey, vermiculitic, isomesic typic tropudult derived from sedimentary sandstones.

Observations/Results: After logging, peak pipe (subsurface tunnel) flow was about 3.7 times greater than before logging. Before logging, little sediment was transported through the pipes. Suspended sediment concentrations before logging were less than 20 mg/liter and coarse-grained sediment was rare. After logging, there was great spatial

and temporal variability in sediment transport. Sediment loads increased dramatically from some pipes during some storms, but from other pipes (tunnel networks), sediment discharge remained unchanged after logging.

Recommendations: None

Title: Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona

Author: Pollen-Bankhead, N., Simon, A., Jaeger, K., and Wohl, E.

Series/Source: *Geomorphology* 103 (2009) 363–374

Peer-reviewed: Yes

Code: BKSTAB, SOILER, SLSTAB(VR)

Abstract: In this study, root tensile strengths and distributions in streambanks were measured and used in combination with a root-reinforcement model, RipRoot, to estimate the additional cohesion provided to layers of each streambank. The additional cohesion provided by the roots in each 0.1-m layer ranged from 0 to 6.9 kPa for Tamarisk and from 0 to 14.2 kPa for Russian-olive. Average root-reinforcement values over the entire bank profile were 2.5 and 3.2 kPa for Tamarisk and Russian-olive, respectively. The implications of vegetation removal on bank stability and failure frequency were evaluated in two incised reaches by modeling bank-toe erosion and bank stability with and without vegetation. Results showed that the effects of root-reinforcement provided by Tamarisk and Russian-olive have a significant impact on bank stability and bank-failure frequency. Because the bank materials are dominated by sands, cohesion provided by roots is significant to bank stability, providing an average 2.8 kPa of cohesion to otherwise cohesionless bank materials. Bank retreat rates at one site following vegetation removal have approximately doubled when compared to the control reach (from an approximate rate of 0.7–0.8 m/y between 2003 and 2006 to 1.85 m/y during the year modeled).

Objective(s): To investigate the causes of channel narrowing and incision in Canyon de Chelly National Monument and to determine the role/influence of Tamarisk and Russian-olive on streambank stability.

Study Location: Canyon de Chelly National Monument in northeastern Arizona

Methodology: Root tensile strengths for Tamarisk and Russian-olive were measured using a device called the Root-Puller, comprised of a metal frame with a winch attached to a load cell and displacement transducer and both connected to a Campbell CR510 data logger. The Root-Puller is attached to the bank face and different-sized roots. Cranking the winch applies a tensile stress to the root (measured as a load, in Newtons) that increases until tensile failure of the root occurs. The diameter of each root is recorded along with the logged history of tensile stress and shear displacement. The maximum load applied to each root before breaking and root diameter were used to calculate the tensile strength of each root. Root diameter–tensile strength relations were established for the two species to use as input to the fiber–bundle root–reinforcement model, RipRoot. Geotechnical properties of the banks were measured in situ with an Iowa Borehole Shear Tester. Samples of bank materials were taken for each stratigraphic layer at each site, and sieved to half-Phi intervals in the laboratory to

obtain particle size distributions for bank stability and toeerosion algorithms. In addition, cross-sectional surveys were carried out at the sites at the beginning and end of the modeled period to provide bank geometry information to input in the **streambank stability model (BSTEM 4.1)** and to **validate the modeling results.**

Vegetation: Tamarisk (*Tamarix ramosissima*) and Russian-olive (*Elaeagnus angustifolia*)

Soil Properties: Effective cohesion and friction angle values were assigned for each bank stability model layer, in addition to critical shear stress and erodibility coefficient values.

Observations/Results: The model runs carried out in this study considered only the short term impact of invasive vegetation removal. The model predictions and field observations after vegetation removal both show accelerated rates of widening once root reinforcement has been removed from these banks, especially in bank materials with little inherent cohesion and/or consolidation. Approximately 2.2 times more erosion was predicted by BSTEM for one streambank site and approximately 4.4 times more erosion was predicted for the other site in the unvegetated versus vegetated scenarios. Removal of the invasive species Tamarisk and Russian-olive and their root-reinforcement affects have been shown to result in increases in bank-erosion rates from 120–383%. Bank-retreat rates are predicted to increase between 300 and 723%.

Recommendations: **BSTEM combined with RipRoot can be used in conjunction to quantify the effects of riparian species on streambank stability.**

Title: Effects of land management on soil mass-movement.

Author: Sidle, R.C., Pearce, A.J., and O'Loughlin, C.L.

Series/Source: In Hillslope Stability and Land Use. Water Resources Monograph Series 11, American Geophysical Union, Washington, D.C. 1985. pp. 71-

Peer-reviewed: Yes

Code: SLSTAB(VR)

Abstract: Timber harvesting is a major land management practice that can affect hillslope stability by: 1) reducing root reinforcement because of root-wood deterioration, site disturbance, and introduction of different plant species; and 2) temporarily increasing water inputs and soil moisture because of reduced evapo-transpiration, changes in volume and rate of snowmelt, and overstory canopy modifications.

Objective(s): To review findings in the scientific literature with regard to the impact of tree removal on the slope stability and the frequency of landslides.

Study Location: N/A

Methodology: Literature review

Vegetation: Trees... non specific

Soil Properties: N/A

Observations/Results: Wide spread removal (clear-cutting) increases the frequency and extent of slope failures. Paper examines the effect of partial or selective cuts which leave part of the tree canopy intact. Landslide frequency was found to increase only slight as overstory crown cover was reduced from 100% to 11%, but for crown cover reduced below 11% a major increase in slope failures occurs. In contrast to these findings, for crown covers less than 80%, landslide occurrence appears to be more sensitive to reductions in shrub cover, which indicates the importance of woody, understory vegetation in stabilizing slopes.

Recommendations: Greater use should be made of partial or selective cutting (as opposed to clear-cutting) to minimize stability problems and slope failures. Timber harvesting options that preserve the integrity of understory species should be considered on potentially unstable sites.

Title: A theoretical model of the effects of timber harvesting on slope stability.

Author: Sidle, R.C.

Series/Source: *Water Resources Research*. 1992. 28(7): 1897-1910

Peer-reviewed: Yes

Code: SLSTAB(VR)

Abstract: An infinite slope stability model is proposed which incorporates changes in root cohesion and vegetation surcharge through several timber management cycles along with the stochastic influence of rainfall on pore water pressure. Simulations of probability of failure indicate that alternate thinnings and clear-cuts alone produce less stable conditions than shelterwood harvesting systems and partial cuts. Repeated harvesting cycles with progressively shorter rotations, reduced regeneration potential of new vegetation, and destruction of understory vegetation during logging or site preparation can all increase the probability of failure. These analyses can provide land managers with options for acceptable vegetation management strategies on potentially unstable hillslopes.

Objective(s): To investigate the effect of alternative timber harvesting practices, viz, clear-cuts, partial cuts, and shelterwood) on slope hydrology and stability

Study Location: Selected hillslopes in coastal Alaska and western USA

Methodology: Recovery of rooting strength and tree surcharge following timber harvest are simulated by a sigmoid relationship. Root deterioration of harvested vegetation, on the other hand, is described by an exponential decay function. The effects of long-term timber management on probability of failure are simulated by overlaying the impacts of a prior vegetation removal on a more recent removal. For each year the critical pore water pressure (u_{crit}) needed to trigger slope failure is computed. An empirical function relating piezometric level to antecedent rainfall, storm intensity, and total precipitation is presented to assess the probability of occurrence of u_{crit} , based on historical rainfall records for a site in coastal Alaska.

Vegetation: Coniferous forests

Soil Properties: Simulation studies are based on soil, site, and root strength data from selected sites.

Observations/Results: Slope stability simulations for various silvicultural systems indicated that clear-cuts and alternate thinnings produced the least stable conditions, largely based on net root strength decline following harvesting. A 75% partial cut reduced the probability of failure more than five times compared to clear cuts.

Recommendations: The model used in the study applies only to shallow, translational failures overlying a bedrock contact. While actual values of probability of failure calculated by the model should be viewed with caution because of assumptions inherent in the infinite slope model and the spatial variability of site parameters, the model provides a viable relative comparison of silvicultural systems.

Title: Soil pipes and slope stability.

Author: Pierson, T.C.

Series/Source: *Quarterly Journ. Engr. Geology (London)*. 1983. **16:** 1-11

Peer-reviewed: Yes

Code: SLSTAB(VR)

Abstract: Experiments with a Hele-Shaw viscous-flow analogue apparatus supported earlier suggestions, based on field evidence, that a causal link may exist between some soil pipes and slope failure. The analogue has shown that when a pipe is blocked or is a dead-end passageway (a closed pipe), the cavity can readily fill with water during rainstorms (or during temporary inundation). Pipes partially filled with standing water will generate pore pressures in the surrounding soil matrix in proportion to the hydrostatic head achieved. Long pipes parallel to the fall line of the slope have the potential, when partially filled with water, of generating soil pore-water pressures much greater than those generated by total saturation of the soil. Such pore-pressure increases could trigger landslides at sites that would otherwise be stable.

Objective(s): To investigate the influence of soil pipes with different orientations and degrees of drainage (e.g., closed, partially blocked, or open at their downstream end) on the flow regime and phreatic surface, and ultimately on the stability of a slope.

Study Location: N/A... theoretical study

Methodology: A Hele-Shaw model was constructed to simulate two-dimensional, subsurface flow in a shallow soil interrupted by a closed soil pipe, which was parallel to the fall line of the slope and to the perched water table in the slope. The model uses two vertical and parallel, clear perspex plates that enclose a viscous fluid (oil or glycerine) between them. The apparatus represents an idealized vertical slice of an isotropic soil interrupted by a longitudinally bisected soil pipe. All the flow vectors in this plane will be parallel to it in the apparatus and in the soil being modeled. Flow nets could be approximated during the model runs by tracking small bubbles and particles of grit as they moved in the oil between the plates.

Vegetation: N/A

Soil Properties: N/A

Observations/Results: Results of the model runs indicate that closed soil pipes occurring in hillslope soils, when filled with water, will cause large localized increases in soil water pressure. This decreases soil shear strength locally and may increase the chance of slope failure. In shallow soils, pipes do not have to be particularly long for relatively large pore pressures to develop. Often the pressures generated at the end of a pipe can exceed those achieved by total saturation of the soil matrix.

Recommendations: Results of the study are applicable to soil pipes formed by penetrating roots that die and decay, leaving open (or partially open) tubular passageways. The orientation of the pipes and extent of drainage (open or closed) also play a role

Title: Woody plants on flood protection levees: A contradiction?

Authors: Lammeranner, W. and Meixner, H.

Series/Source: Publ. by Univ. of Natl. Resources and Applied Life Sciences, Dept. of Civil Engr. and Natl. Hazards, Institute of Soil Bioengineering and Landscape Construction, Vienna, Austria (2009). See also: *Proceedings 2nd Intl. Conf. on Ground Bio- and Eco-Engineering, The Use of Vegetation to Improve Slope Stability*, Beijing, China, 14-18 July 2008.

Peer-reviewed: No

Code: SLSTAB(VR)

Abstract: This technical article describes the influence of woody structures and plant associations on the stability and maintenance of levees. Paper explores whether a contradiction exists in allowing woody plants to grow on earthen levees because of possible damage to their security and preservation. Investigates interaction between levees and woody plants (e.g. large trees) and examines assumptions that have been cited for excluding woody plants from levees. Argues that many of these assumptions are based on anecdotal evidence, often with problematic and questionable logic.

Objective(s): To determine the influence of woody vegetation on the stability and maintenance of levees and to decide whether there is a rational basis for excluding trees from earthen flood protection levees. To describe how a flexible and dense cover of woody shrub type vegetation can contribute to increased stability and to reduced maintenance.

Study Location: March River basin, Austria

Methodology: Review of research work and published articles in the European technical literature

Vegetation: Comparison of benefits/limitations of a grass vs. woody plant cover

Soil Properties: N/A

Observations/Results: Contrary to popular belief and practice about the adverse impacts of woody vegetation on levees, numerous technical articles were cited that demonstrated the positive effects of woody structures on stability and maintenance. The reinforcement of the main body of a dike by a grove of trees is much higher and effective in comparison to the reinforcement of the top soil layer by a grass sward. The increase in stability against landslides was found to be at least ten times higher. Levee shorelines with supple trees are less affected by floods; woody plants with supple stems can bend over in a flood against the ground surface and protect the ground surface against erosion. In addition, a frictional surface consisting of tree trunks and branches retards flow velocity and dissipates the energy of floods much better compared to a grass sward. In densely vegetated slopes, areas of root death in a levee are quickly colonized and occupied by a new generation of roots from surrounding trees. Thus, the stability of the dike is not affected by the root death of a single tree, because in a dense stand or grove the live roots will intermingle and intersperse with dead roots. Woody structures on dams and dikes can also offer protection against burrowing animals.

Recommendations: To avoid damage by muskrats a fully shaded shore is recommended, as produced by the emergence of continuous shrub vegetation.

Title: Woody plants on flood protection dams – design, construction and operation of a test facility

Authors: Lammeranner, W., Meixner, H. and Florineth, F.

Series/Source: *Osterreichische Ingenieur- und Architekten-Zeitschrift (OIAZ)*, 152. Jg. Heft 10-12/2007. See also: *Geophysical Research Abstracts*, Vol. 11, EGU2009-13759 (2009).

Peer-reviewed: Yes

Code: SLSTAB

Abstract: A field test facility was constructed to compare the performance of different types of ground cover on the stability and integrity of river levees. Tests were conducted to investigate percolation and seepage with respect to different vegetation covers. The article describes the design, construction, and planning of the research facility. Some initial monitoring results are presented.

Objective(s): Project focuses on the effects of small to medium sized flexible woody plants with flexible on the structural integrity and maintenance of river levees. The aim of the project is compare the performance of a grass sward vs. a woody plant cover.

Study Location: River March basin, Austria

Methodology: Data are drawn from a site with two, naturally scaled dikes. Hydraulic loading is accomplished by using the dykes to form an enclosed basin that is charged with water. Percolation and seepage tests are conducted with different types of plant cover, viz., grass vs. woody plants using seepage monitoring pipes and collection troughs, piezometers, tensiometers, moisture sensors, and temperature probes that were built into the test levees during construction. Overtopping tests are also conducted with these two types of ground cover. Results from the test site are complemented by data collected from field surveys of the River March and other nearby rivers.

Vegetation: Turf vegetation (grass and herbaceous plants) and different types of flexible, woody vegetation. The woody plants involved are willows (*Salix purpurea L.*) established with the following soil bioengineering techniques: (1) dormant cuttings; (2) live brush mattresses; and (3) live brushlayers.

Soil Properties: The test levees are homogeneous embankments with a fill height of 2.7 m and a slope inclination of 2(V):3(H). The levees consist of a mineral silt-sand-gravel mixture.

Observations/Results: Moisture/density measurements on the test levees showed that compaction standards were met. Grain size distribution tests on the levee soils also showed that specified gradation requirements were achieved. Vegetation growth one year after planting was satisfactory despite relatively high soil densities.

Recommendations: Performance of different types of plant cover will be quantified. The gained data can be integrated into dike stability models.

Title: The Spring 2008 Midwest Flood: Observations of Missouri and Iowa Levee Breaches

Authors: Kelley, J.R., Vroman, N., Groves, C., Harder, L, and Sills, G.

Series/Source: USACE Engineer Research and Development Center, ERDC/GSL SR-091, 59 pp (2009)

Peer-reviewed: YES

Code: SLSTAB(VR)

Abstract: During spring 2008, the Midwestern portion of the continental United States experienced flooding that led to overtopping and levee breaches along several Midwest levee systems. Post-levee failure conditions were observed at the Pin Oak, Cap au Gris Levee, and Birdland Levee systems. Levee distress in the form of heavy seepage and sand boils were noted at the East St. Louis Levee system. At the Cap au Gris and Birdland Levee systems, large trees were present in the vicinity of the levee failures. Roots from these large trees were exposed in the scour hole left from the levee failures and extended a considerable distance from the tree trunk to the levee, and even through the levee.

Objective(s): The study documented in this report was conducted to support the levee vegetation impact study being conducted by ERDC. These levee systems were selected due to their potential to provide valuable information on vegetation impacts on levee performance and failure mechanisms for levees.

Study Location: Four levee systems included the East St. Louis Levee, Pin Oak and Cap au Gris levee system located along the Mississippi River and the Birdland Levee system along the Des Moines River.

Methodology: Field reconnaissance, site visits, and interviews with USCOE staff.

Vegetation: Sycamores, cottonwoods

Soil Properties: Pin Oak levee systems soil described as moderately erosive, brown silty clay (CL classification). Cap au Gris described as a gray silty clay (CL classification) with moderately rapid erosion rate. The Birdland Levee was constructed with miscellaneous fill materials and contained rubble and debris. Sand seams were also present within the levee cross section

Observations/Results: Based on observations of the inspection, there was no direct evidence that the roots were detrimental to the performance of the levees. The four levee failures inspected during the field visit were a result of the following failure modes: 1) defects the levee embankment, possibly caused by animal burrows and dens, 2) overtopping erosion, and 3) co-location with an area of previous failure and known weakness. Removing trees and their root balls by bulldozing them over without remediating the disturbed ground and extracting the root system appears to exacerbated a marginal under-seepage condition. Large roots from trees at the two Cap au Gris sites penetrated through the levee from the waterside toe to the landside toe. Much of the existing levee system in the Midwest, if situated near large trees, is possibly embedded with extensive root systems. This represents a considerable challenge in maintaining the integrity of the levee system and requires a flexible approach to managing this issue.

Recommendations:

Title: Seepage and piping in dams.

Author: Martin, R.E.

Series/Source: Presentation (PPT slide show) to Virginia ASCE Geotechnical Meeting, May 2005

Peer-reviewed: No

Code: SLSTAB, SOILER

Abstract: Internal erosion is one of the principal causes of dam failure. The enabling conditions for internal erosion are: 1) sufficiently high gradient to cause soil particles to migrate, 2) unfiltered exit, and 3) susceptible soils, viz., silts and sands. Presentation reviewed different types of internal erosion failures, viz., 1) segregation piping, 2) continuing erosion, and 3) piping. Piping is the erosion of cohesionless soils to form a “pipe” from downstream to source of seepage. Piping can occur at very low critical gradients, on the-order-of 0.3 to 0.8. Discharge of turbid water at outlet or discharge point a good indicator of internal erosion or piping.

Objective(s): To review types of internal erosion leading to failure in earth dams. To describe manifestations and examples of dam failure caused by internal erosion

Study Location: Washington power canal embankment

Methodology: Case study review

Vegetation: N/A

Soil Properties: Silts and fine sands contained within stratum consisting of gravel and cobbles.

Observations/Results: Under favorable conditions (e.g., gap-graded soils or soils with internally unstable gradations) relatively small gradients can produce internal erosion and piping. Unfiltered seepage discharge locations permit continued movement of fines in a seepage stream. In the case of the Washington Power canal embankment heavy pumping caused internal erosion of silts and sands from stratum containing gravel and cobbles (open graded non-self filtering). This pumping imposed a hydraulic gradient of 0.6. Internal erosion can occur for a long time before it results in a hydraulic blowout or slope failure.

Recommendations:

Title: Hydraulic fracturing in embankment dams.

Author: Sherard, J.L.

Series/Source: *Journ. of Geotechnical Engr. (ASCE)*, Vol. 112, No. 10, pp. 905-927

Peer-reviewed: Yes

Code: SLSTAB, SOILER

Abstract: Examines evidence for concentrated leaks through impervious sections in earth dams and embankments caused by hydraulic fracturing. Hydraulic fracturing is a tensile separation along an internal surface in an earthen embankment or dam. The effective stress on this surface approaches zero; that is, the neutral or pore water pressure equals the total confining stress. These surfaces become the locus for fractures that are jacked open by pore water pressures during hydraulic loading. No pre-existing fractures, holes, or other void volume defects are required, and the problem only becomes manifest when water levels rise on one side of an embankment. This hydraulic fracturing is facilitated by differential settlement and internal stress transfer within an earthen structure. Usually these concentrated leaks do not cause erosion either because the velocity is too low or because the leak discharges into an effective filter. Subsequently, the leakage channel is squeezed shut by softening or swelling of the embankment materials forming the walls of the crack.

Objective(s): To determine to what extent hydraulic fracturing in earth dams occurs and can cause internal erosion or seepage problems.

Study Location: Multiple sites in the USA

Methodology: Visual examination and study of earth dams with reported seepage or internal erosion problems.

Vegetation: N/A

Soil Properties: Earthen dams and embankments with homogeneous, impervious sections

Observations/Results: The study showed there is sufficient evidence to conclude that concentrated leaks occur commonly through impervious sections in earth dams and embankments by hydraulic fracturing without it being observed, even in dams which are not subjected to unusually large differential settlements. This action probably occurs to some degree in most embankment dams. Low, homogeneous embankments or dams (without internal filters or drains) are particularly vulnerable to hydraulic fracturing following the first hydraulic loading. Low embankments tend to have lower vertical (confining) stresses to counter internal pore water pressures. Levees along stream channels fall into this category. One, low earthen (UNVEGETATED) dam that Sherard inspected developed a concentrated leak, and erosion tunnels (pipes) 225-meters long under a 50:1 hydraulic gradient when the reservoir head acting on the upstream (outboard) face of the dam was not more than 4 meters. This relatively low head and gradient initiated the hydraulic fracturing.

Recommendations: Hydraulic fracturing is yet another potential cause of internal erosion and through seepage in earthen embankments. Hydraulic fracturing does not require the presence of roots or root holes. This damage mechanism should be investigated as an alternative explanation to alleged piping caused by roots.

Title: Levee armoring: woody biotechnical considerations for strengthening Midwest levee systems.

Authors: Wallace, D., Baumer, C., Dwyer, J. and Hershey, F.

Series/Source: Paper presented Symposium on Restoration of Aquatic Ecosystems, St. Paul, MN, June 20-23, 1994

Peer-reviewed: No

Code: SOILER, SLSTAB

Abstract: Secondary levees associated with major rivers and upstream tributary levee systems in Missouri experienced an estimated 2019 levee breaks during the historic 1993 floods. Reviews and interviews indicated that fewer breaks occurred along levee sections with woody corridors or with woody cover on the levees. Levee armoring with properly designed woody material will slow floodwater velocities, dissipate energy, reduce scouring potential, and increase soil shear strengths. These hydraulic changes and biomechanical attributes would increase levee protection, reduce maintenance costs, and reduce flood damage to floodplain fields by trapping sediment

Objective(s): To examine potential woody interactions with levee systems and present some armoring designs that purposely incorporate woody plants. To determine effect of woody corridor width (levees with forested buffer zones or with woody cover on the levee) on occurrence of levee failures

Study Location: Main stem and upstream tributary levees in Missouri

Methodology: Field studies and reviews

Vegetation: Not specified

Soil Properties: Not specified

Observations/Results: Field reviews of levee performance along a portion of Shoal Creek in Caldwell County revealed only a single levee break (internal tile line failure) with woody cover and woody corridors of 20 to 100 meters in width. Conversely, levees with woody corridors completely absent and in grass sod, upstream from the wooded corridor site experienced multiple breaks in a similar length of levee.

Recommendations: Based on hydraulic and biomechanical considerations the authors believe maximum levee protection should incorporate both woody corridors and levee woody plantings. Instead of excluding woody vegetation, the authors recommend that levee designs should actively incorporate woody materials as corridor plantings between the levee and river and as protective cover on the structure itself as long as inspection and flood fighting capabilities are maintained. They suggest four different designs using combinations of woody materials for trial use and study on Midwest levee systems. All of these designs would be incorporated with a river side woody corridor of appropriate width.

Title: Risk of landsliding in shallow soils and its relation to clear-cutting in Southeastern Alaska.

Authors: Wu, T.H. and Swanston, D.N.

Series/Source: *Forest Science*, Vol. 26, No. 3, pp. 495-410 (1980)

Peer-reviewed: Yes

Code: SLSTAB(VR)

Abstract: A probabilistic approach was adopted to evaluate the risk of landsliding associated with clear-cutting in shallow soils in Southeastern Alaska. The paper summarizes the mechanism of debris avalanche and the environmental factors that control slope stability... including woody vegetation removal or clear-cutting. Procedures are outlined that may be used to evaluate risk of debris avalanches and assess potential damage or loss. Analysis of slopes near Hollis, Alaska, was used as an example. A one-dimensional infiltration-seepage model was used to calculate the response of the piezometric level in a slope to rainfall. The probability of the piezometric height in a slope exceeding the height required for failure was calculated for both an intact (forested) slope and the same slope after clear-cutting.

Objective(s): To examine the use of a probabilistic risk analysis to evaluate the risk of shallow landsliding (debris slides) associated with clear-cutting

Study Location: Maybeso Valley, near Hollis, Alaska

Methodology: Probabilistic slope stability analyses

Vegetation: Sitka spruce, western hemlock, and Alaska yellow-cedar

Soil Properties: Average soil properties for slopes in Maybeso Valley: $c' = 5.3$ kPa, $\phi' = 34.7$ deg, $s_r = 0$, $\alpha = 39$ deg, $h + h' = 1.22$ m, $W_f = 0$, $W_t = 0$ (which represents the slope after clearing)

Observations/Results: The probability of the piezometric height exceeding the height for failure was considerably higher for a clear-cut slope compared to the same slope in a forested condition. The procedure outlined in the paper may be used to assess the risk and cost of landslides due to clear-cutting. It is based on the principles of soil mechanics and seepage. Soil properties needed for the analysis may be determined from standard tests. Uncertainties caused by natural variations in soil properties, slope angles, and precipitation, and inaccuracies in the analytical models may be accounted for.

Recommendations:

Title: Unsteady state phreatic surface in earth dams.

Author: Huang, Y.H.

Series/Source: *J. of Geotechnical Engr.* (ASCE), Vol. 112, No. GT1, pp. 93-98 (1986)

Peer-reviewed: Yes

Code: SLSTAB

Abstract: In the stability analysis of earth dams (or levees), it is necessary to know the location of the phreatic surface. A simple method was developed for estimating the unsteady state phreatic surface in earth dams as a function of time. The method is useful in the steady state analysis of temporary earth dams (or earthen levees) where the steady state phreatic surface may not develop during the life span of the dams. In most cases, it is assumed that, after a period of time, a steady state seepage condition will finally develop, so the steady state phreatic surface should be used for the analysis. However, the assumption of steady state seepage in temporary dams (or river levees) may not be reached during their design life. In the case of river levees, which are usually high and dry most of the time, it would be useful to know how long it takes for the phreatic surface to progress across a levee when the flood stage rises above the levee base. Although the method is based on transient flownets and yields only approximate results, the uncertainty in determining the permeability (hydraulic conductivity) of the earthen structure and effective porosity of soils usually precludes the use of other more refined methods and thus, make this simple method particularly attractive

Objective(s): The purpose of the paper is to present a simple method for estimating the location of an unsteady state phreatic surface in earth dams as a function of time after hydraulic loading

Study Location: N/A

Methodology: Theoretical analysis

Vegetation: N/A

Soil Properties: N/A

Observations/Results: Upon initial hydraulic loading of an earth dam or levee the phreatic surface will progress across the dam from the upstream face until it reaches a steady state position near the downstream face. In the case of river levees this method can be used to estimate the time required for the phreatic surface in a levee to intersect the landward toe. The only information required is the geometry of the dam cross section, the average hydraulic conductivity of the dam, the effective porosity, and the height of water level (flood stage height) above the base of the dam. With proper discretion, the method should provide valuable information for the design (and stability assessment) of levees and temporary dams.

Recommendations: