SCALE PROBLEMS IN LANDSLIDE RISK MANAGEMENT – AN UPDATE ON US FOREST SERVICE THREE LEVEL SYSTEM

D.W. Parson[1], R.W. Prellwitz[2], T.E. Koler[3] & J.C. Cloyd[4]

[1] State of California North Coast Region, Regional Water Quality Control Board (e-mail: DParson@waterboards.ca.gov)
[2]Bitterroot Geotechnical Services (406-777-3325)
[3]El Dorado National Forest, U. S. Forest Service (e-mail: tkoler@fs.fed.us)
[4]Pacific Northwest Regional Office, U. S. Forest Service (e-mail: jcloyd@fs.fed.us)

Abstract: Landslide analyses in upland forests present challenges for geoscientists, engineers, and decision-makers. The common problem is how the change of scale influences the amount of data required to make reasonable assessments and decisions. The United States Forest Service provides a solution in their Slope Stability Reference Guide (Hall et al. 1994). In the last decade this solution has also been applied by Federal and State resource agencies and, to a lesser degree, on timber industrial lands. The reference guide also has been used for college coursework in engineering geology and as reference material for consultants. This paper is an update of how this solution has been applied in the last decade and outlines the improvements that have been added.

The Slope Stability Reference Guide applies a three-tiered gradational approach that is scale-dependent. The premise behind this system is that each tier, or level, forms a verifiable and reproducible information-driven database from which data can be extracted for other levels. Level I consists of reconnaissance mapping for the assessment of resource allocations, at a scale of 1:24,000. Level II is composed of reconnaissance mapping of corridors such as roadways and canals at a scale of 1:3,600 for resource planning. Level III consists of site-specific investigations, for resource development such as timber harvest and/or timber sale planning as well as logging road construction, reconstruction or obliteration, with data collected at a scale of 1:160. In many ways the United States Forest Service approach integrates the Jahnsian Steps to Geologic Safety (recognition, characterization, risk assessment, and mitigation), and hence is a loss reduction strategy.

INTRODUCTION

The United States Forest Service (USFS) practice of engineering geology provides a unique solution for tackling multi-scale slope stability problems in upland forests by implementing a three-level gradational approach that is scale-dependent. The premise behind this system is that each level (or Level) forms a verifiable and reproducible information-driven database upon which the next higher or lower level can be built as shown in Figure 1. Because each new level is built upon an existing level of information, the integration itself functions as a loss reduction strategy by focusing limited resources to areas of concern for project-specific applications.

Clearly, the technology and methodology exists to significantly reduce losses from landslides in forested terrain by using avoidance and prevention strategies. These strategies are achieved by applying landslide recognition, characterization, risk assessment, and mitigation techniques in the USFS three-level approach. This combination provides the essential framework to achieve tolerable levels of risk from landslide hazards and probable consequences at various scales.

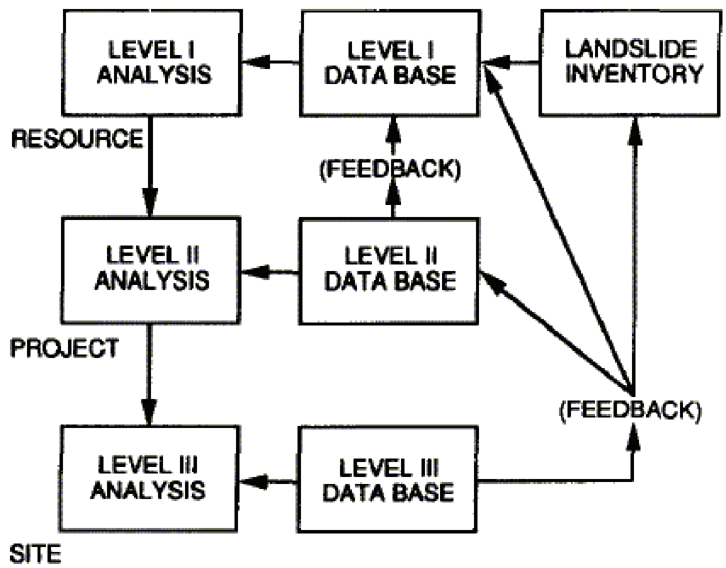

Figure 1. Flow chart for the USFS three-level system.

Application of this integrated approach saves time, money, and provides clients and decision makers with information needed to make informed decisions. In using this approach to achieve tolerable levels of risk from landslides at various scales, the engineering geologist will be able to provide input for: landslide recognition; determining landslide size and type; landslide characterization; determining the types of potential risk that the proposed project has for down slope receptors and other probable consequences; identifying risk levels; and, identifying mitigation alternatives.

Background

The multi-scale landslide issue presents unique challenges to geoscientists, engineers, and their clients, the decision-makers. These challenges have long been recognized in the engineering-geology community, and are summarized by Leighton (1976), "The technology is available to greatly reduce losses from landslides by avoiding or preventing them." Leighton estimated that, in California, a reduction in damaging failures of 95 to 99 percent is technically attainable through the use of three levels of investigation: regional, tract or community, and site, with progressively greater detail being obtained in the investigations of the smaller areas. With the passage of Federal environmental policy legislation in the early 1970s, the practice of engineering geology in the USFS became an accepted way to meet these legislated requirements. In addition, State environmental policy legislation necessitated the use of geoscientists to help develop timber harvest plans (THP) on State and private timberlands. The intent behind Federal and State laws was not only to evaluate the potential environmental impacts of proposed projects, but also to protect various potential receptors from these impacts using prevention, minimization, and mitigation techniques.

In 1994, the USFS published the three-volume *Slope Stability Reference Guide for National Forests in the United States* (Hall *et al*. 1994), henceforth referred to as the "Guide." This Guide was developed in the spirit of cooperation by a group of geotechnical specialists to address the landslide risk challenges of rugged terrain in America's National Forest System lands. The Guide received extensive detailed reviews by scientists from the US Geological Survey (USGS), universities, and other government agencies. The Guide is listed as a USFS reference standard for geotechnical services in the USFS Manual 2800 - Minerals and Geology, Chapter 2880 - Geologic Resources, Hazards and Services.

More recently, the USGS prepared the National Landslide Hazards Mitigation Strategy in response to a congressional directive to mitigate the detrimental effects of landslides on infrastructure, human and environmental receptors. In answer to a request from the USGS, the National Research Council produced Partnerships for Reducing Landslide Risk (Gilbert *et al.* 2004).

For all applications of engineering geology, we encourage practitioners to consider using "The Jahnsian Steps to Geologic Safety: The Engineering Geologic Approach," Cole *et al.* (1992). The four basic Jahnsian Investigative Steps (i.e., recognition, characterization, risk assessment, and mitigation) fully integrate with the Guide and the National Landslide Hazards Mitigation Strategy (Gilbert *et al.* 2004) for application to any tract of land where landslide hazards exist. These publications have a common theme of loss reduction through using prevention, avoidance, and mitigation strategies at various scales of application.

Three Levels of Analysis

The Guide presents the three-level slope stability analysis concept and discusses a variety of topics as they apply to slope stability including sample problems for recognition, characterization, risk analysis, remedial design, and construction specifications. The Guide's methodology allows for collection, and vertical and lateral integration, of information for multiple uses in slope stability analyses and assessment of risk to down slope receptors and other consequences and vulnerabilities. Determining which techniques to apply can be confusing for those who do not routinely perform slope stability analyses. In our collective experience, the lack of adequate recognition and characterization of the subsurface aspects of potential hillslope failure can result in negative impacts to down slope receptors and loss of resources. Assessing receptor presence and their ambient condition, hillslope susceptibility to failure under defined conditions, with spatial and temporal determination of risk can be implemented (although with varying reliability) for each level. These are the necessary elements for a functional loss reduction strategy in forested terrain.

Level I – Resource Allocation

Level I consists of reconnaissance mapping and office investigation elements for area planning purposes, at a scale of 1 inch = 2,000 feet (1:24,000). This level is applied to projects that cover large areas such as watershed analysis, ecosystem management support, and timber sale or salvage planning (i.e., Federal) or THP (i.e., State or industrial timberlands). Slope stability analyses typically include air photo review, review of existing geologic and geotechnical reports and maps, focused reconnaissance to verify slope processes, and to verify mapped soil and rock types. Landslide risk management decisions typically include recognition and development of geomorphic processes and zones based on slope form, soil and rock characteristics, geologic processes, and limited field work. The Level I Stability Analysis (LISA) and Deterministic Level I Stability Analysis (DLISA) computer programs are used in Level I work (Hammond et al., 1992; Koler, 1998). Recently, an updated version of LISA has been developed by Haneberg (2006) and applied on Federal, State and industrial timberlands. Haneberg's Probabilistic Slope Stability Software (PISA-m) provides a means for evaluating the same parameters in LISA plus a rigorous examination of ground water flux.

At this level, decisions are often made as to whether-or-not to manage or how intense the management activity can be in relationship to landslide risk. The data available are often inadequate to support critical decisions. The most important attribute of this analysis level is identifying landforms that have the greatest potential to put downslope receptors at risk, and therefore need the most attention at the next level of analysis.

Level II – Resource Planning

Level II involves reconnaissance mapping of corridor areas (i.e., roadways, penstocks, canals, etc.) typically at a scale of 1 inch = 300 feet (1:3,600), using the office elements from Level 1 along with focused fieldwork. At this level, the data are applied to better evaluate the potential for landslide movements from land-management activities. Level I data are field evaluated and additional data are gathered to improve the landslide database. The most critical landform locations can be identified for evaluation at the next level of analysis. An important Level II product is corridor stratification, where it is accomplished by geologic and geomorphic processes, and soil, rock and drainage characteristics are defined for each stratified segment of the corridor. This information, together with sketches of slope characteristics for various alternative corridor configurations, is useful for design purposes. The spatial analyses are often completed using slope stability charts, and computer programs such as Deterministic Stability Analysis for Road Access (DSARA) and the probabilistic Stability Analysis for Road Access (SARA). These models currently remain in a beta-version, and are not yet available for specialists. In lieu of these models, practitioners may consider using commercial software based on the infinite slope and/or method of slices equations.

Level III – Resource Development

Level III consists of detailed, site-specific investigations, usually for timber sale or timber salvage projects (i.e., Federal lands) or THP (i.e., State and if applicable industrial timberlands) as well as logging road construction and/or reconstruction or obliteration. Project-specific data are typically collected at a scale of 1 inch = 50 feet (1:160) or less, and this information is applied in the design of stabilization measures for mitigating slope stability problems. Level III products include the generation of field-developed cross sections, and where necessary, the installation of site-specific monitoring instrumentation.

Level III decisions contain an even more robust set of data intended for design of stabilization measures, using all of the data types from Level I and Level II, plus predictive computer programs to evaluate soil and rock slope stability under various design scenarios to fit terrain characteristics within each stratified segment. Commonly used computer programs include XSTABL, a method-of-slices analysis application (Sharma, 1992), and Federal Highway Administration’s reprint of Hoek and Bray’s rock slope stability analysis method for rock slopes (Golder and Associates, 1981).

Scale and Data Points Needed

According to Compton (1962) geologic studies that are performed at different scales rely on work performed first at the most coarse scale, with more refined assessments occurring at increasing scales of resolution. For example, detailed geologic studies require topographic and geologic mapping at scales larger than 1 inch = 200 feet, while regional mapping at intermediate scales of 1:24,000 to 1:62,500 are also needed. This is consistent with the USFS multi-level approach. According to Compton, the number of sampling points can be based on sampling plans used for similar projects, and alternative sampling plans can be evaluated statistically to determine which is likely to give the information needed with least effort and expense.

Koler and Neal (1989 and 1994) suggest that the number of data points, and the accuracy and reliability of the data, increases in direct proportion to the square of the percent increase in scale. For example, a field-developed landslide cross section at scale of 1 inch = 10 feet has 25 times as many data points as one developed at 1 inch = 50 feet. In terms of the three scales cited for each level of evaluation: at 1:600 scale for Level III would have approximately 36 times more data points than the number of data points collected for the 1:3,600 scale in Level II; Level II would have an approximate increase in data points of 44 times the number of data points collected in the 1:24,000 scale in Level I; and, Level III will have approximately 1,600 times more data points than those collected within a Level I analysis. In any case, landslide risk decisions are based on a specific set of data that are scale-dependent.

Engineering Geology Resources and Database Conditions

Data that are applied to any project should be compiled into functional database(s) for use not only in the current project but also for use by others on subsequent projects at different scales. This goal is technically achievable, and has been successfully implemented by some government organizations. Ideally, local, State, and Federal governments would have integrated databases to support cost-effective and time-efficient access for multiple users. Leighton (1976) observes that political problems usually arise with adopting new technical approaches. Alternatives to this dilemma include having one or more government bodies, or a professional association, supported by government funding, manage the integrated database. Data availability for use in a Geographic Information System (GIS) would likely be a significant component of a national loss reduction strategy. This need and methods to meet this need are described in Partnerships for Reducing Landslide Risk, (Gilbert *et al.* 2004).

A well-designed database can be used in mechanical stability analyses that consider all variables in their proper proportion to each other. The effects of changes that might result from land management activities can be evaluated, such as the loss of root strength, an increase in ground water from the loss of evapotranspiration or poor road drainage, and changes in slope geometry (i.e., road cut-and-fill slopes construction). The important application is the ability to answer the "what-if-we-manage-this way" questions that managers should ask. To evaluate management alternatives, separating and quantifying variables is necessary.

There are other less objective methods for evaluating landform stability that do not require a database. These subjective methods are often less expensive to apply and rely primarily on the identification of physical site features. These methods are used mostly at Level I, and usually result in a "manage-or-don't-manage" decision. Particularly at Level I, these methods generally do not lend themselves to application at the other levels. This seriously limits their application, and the ability to be constantly upgraded with site-specific data from Levels II and III.

Investigative Standards

The Guide encourages the application of the Unified Soil Classification System (Howard, 1986), Unified Rock Classification System (Williamson, 1984 and 1994), as well as methods described by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These investigative standards offer consistency, transparency, high quality, reliability, reproducibility, and objectivity, all of which support decision-making.

Historically, investigation standards applied on non-USFS lands in California have been less rigorous and have relied primarily on highly subjective surface observational approaches. While surface observational approaches are acknowledged as necessary components of recognition and characterization, some view this as simply a first start in the investigative process. For example, the staff of the North Coast Region Timber Harvest Division of the California Regional Water Quality Control Board (CRWQCB) suggest that a higher level of more objective characterization approaches need to be included in THPs. This would be included within a qualitative risk assessment of deleterious geologic conditions for down slope receptor (i.e., water quality) in water bodies listed as impaired under the Clean Water Act Section 303(d). Hence, applying the USFS three-level methodology, integrated with the four basic Jahnsian investigative steps and the National Landslide Hazards Mitigation Strategy elements is needed for landslide risk management to meet State-mandated legislation to protect water quality beneficial uses. CRWQCB's approach uses a combination of existing heuristic analysis for landslide hazard zonation with more objective methods based on various scales of more empirical and statistical analyses, and potential consequences to receptor(s) at risk to approve or modify proposed THPs.

Analytical Standards

The goal of a slope stability analysis for a proposed project is preventing or minimizing the consequences of potential deleterious impacts to down slope receptors, which requires an understanding of landslide hazard probabilities and the possible consequences associated with a proposed project. Proponents of the USFS multi-level approach historically have used objective Factor Of Safety (FOS) applications for Levels II and III evaluations, and a probabilistic FOS determination for Level I assessments. Prior to the advent of desktop computers, Level I evaluations were usually done subjectively through a process of overlays on a light table (Koler and Neal, 1989). Today's GIS technology supports using a combination of subjective and objective tools for broad scale applications, resulting in increased efficiency and overall effectiveness. In highly disturbed watersheds, the use of predictive slope stability models has yielded measurable effectiveness. These historic disturbances have affected soil and hydraulic conditions to the extent that many of the assumptions used in predictive models may not be valid. Clearly, no one tool can be used for all situations. Instead, a variety of tools and techniques is needed to properly identify 1) project scale needs, 2) recognition and characterization elements, 3) risk assessment components, and 4) mitigation techniques to prevent and minimize hillslope failures, all of which are components of a comprehensive loss prevention strategy.

CASE HISTORIES

A summary of the case histories presented in Koler and Neal (1989) are given below and compared with a more recent application of the three-level method on industrial timberlands in Northern California, as described by Koler (2000). The case histories given by Koler and Neal (1989) are located in the Quinault Ranger District of the Olympic National Forest in western Washington State as displayed in Figure 2. The work on industrial timberlands is located in Humboldt County near Eureka, California, also shown in Figure 2.

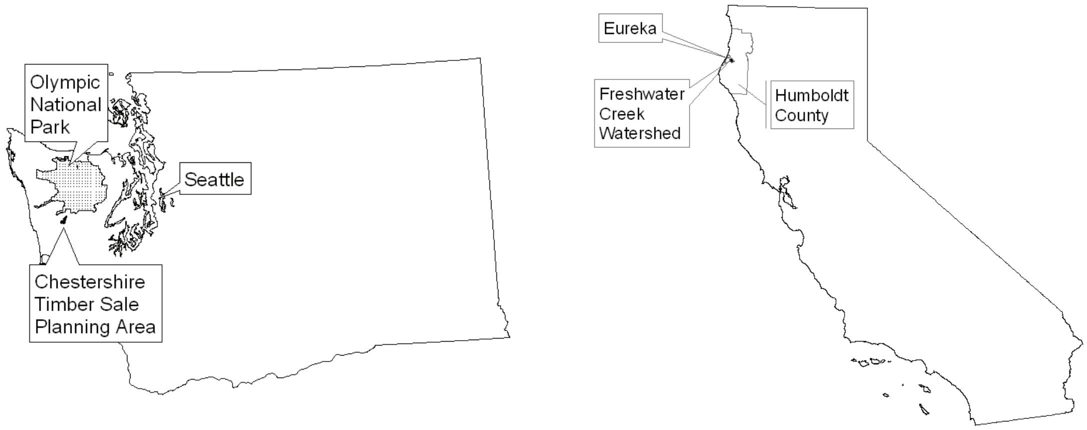

Figure 2. Locations of the case history studies in Western Washington and Northern California.

Level I

Chestershire Timber Sale Planning Area - Olympic National Forest, western Washington

Work described in the Olympic National Forest case histories was completed prior to the forest staff having access to a GIS. The work included the development of analysis polygons with similar characteristics that were hand-drawn on a Mylar sheet overlaid on a 1:24,000 topographic base map. The analysis polygons were constructed by methods that today would appear to be rustic in comparison with 21st century computer technology. In essence, the analysis polygons are the union and/or intersection of data polygons as expressed on Mylar map sheets overlain on a light table. Mylar data layers included soil units classified with the Unified Soil Classification System (USCS), rock units classified with the Unified Rock Classification System (URCS), and if possible, hydrogeologic map units (i.e., springs and seeps). In most cases, this information was not comprehensive across a Level I project area, and therefore information was gleaned from existing sources such as published reports and maps as well as the forest soil resource inventory. To fill the information gaps required forensic work that included field transects collecting missing data (i.e., soil, rock and hydrogeologic units); and, back calculation of physical index properties based on a combination of field samples and information from the forest materials lab (e.g., results from ASTM and/or AASHTO lab or field tests). Other Mylar layers available for polygon development were the landslide inventory, landform map, bedrock geology map, slope map, proposed timber sale units map and transportation planning map.

In the 1980s Prellwitz provided a Hewlett-Packard (HP) 41 program for slope stability assessments within the scale limits of a Level I analysis (Prellwitz, 1985 and 1988). The Slope Stability Infinite Slope (SSIS) program was the predecessor of Hammond et al. (1992) LISA and Haneberg's (2006) PISA-m. Although archaic by today's standards, the SSIS program provided a systematic process of analysing a watershed-scale project area.

The primary concerns in the Chestershire study area were the acceleration of the rate of sediment delivery into Chester Creek as a result of timber harvesting and road building. Chester Creek was a known anadromous fishery and additional management-related sediment discharge increased the potential for both short-term and long-term deleterious effects on the fishery. Due to the scale and spatial distribution of the proposed investigations, two levels (levels) of investigation were proposed. A Level I investigation of the Chestershire Timber Sale Planning Area and a Level III investigation of the Chester Creek Landslide were implemented to address the stated purposes. Initial investigations that included SSIS were completed in 1981 and 1982 for the Level I work. The investigation was later expanded in 1988 with new proposed management activities and timber sale units, and included the application of a beta version of LISA (Hammond et al., 1988). The final product from this work was a map showing groups of polygons assigned relative hazard rating zones.

The Level I zonation maps and data were used to derive a geotechnical assessment of transportation and harvesting alternatives as well as being used for an alterative rock source in the Chestershire Timber Sale Planning Area. These products were evaluated by the decision makers, who determined that the probability of reactivating the Chester Creek Landslide by reopening a road segment across the toe of the landslide was an unacceptable risk because further landslide movement would deliver significantly more sediment to the anadromous fish stream.

Today, generating this type of spatial analysis yielding landscape zonation with desktop computers and GIS software is relatively fast, and contributes to an overall loss reduction strategy. An explanation of this type of landslide hazard zonation technique applied at different scales is presented by Soeters and Van Westen (1996). Typical landslide zonation techniques include landslide inventories, heuristic analysis, statistical analysis, and deterministic analysis. Landscape zonation is commonly used to guide land management decisions in terms to risk to receptors and cost to implement, both of which are essential components in a meaningful loss reduction strategy. A more recent case history is therefore presented below.

Freshwater Creek Watershed Analysis – Humboldt County, northern California

A modified version of a Level I Analysis was proposed by Koler and Rollerson in 1999 in completing the mass-wasting module of a watershed analysis on industrial timberlands within the Freshwater Creek area near Eureka, California. This modification was published by Koler and Rollerson (1999), Koler (2000), Rollerson et al. (2000), and Conroy et al. (2000). The modification was an attempt to meet the requirements of completing watershed analysis. The proposed modification was an integration of the USFS Level I analysis with the Terrain Mapping Method developed and adopted in British Columbia by the Resources Inventory Committee within the British Columbia Earth Sciences Task Force (Bobrowsky et al., 1996). The integration provided a means for the geoscientists to evaluate slope stability polygons by geomorphic process and form as well as physical index properties.

In the decade since their initial report (Koler & Neal, 1989), Koler found that it was cost prohibitive to gather the number of data points required when an analyst moves from one scale to another. For example, if the analyst evaluates a watershed scale (2000 ft/1 in) and then decides to evaluate a Level II project (300 ft/1 in) within the watershed, the analyst will be "required" by Koler's and Neal's suggestion to collect 44 times more data in Level II than what was collected in Level I. Any geologist or engineer involved in watershed and corridor scale work will quickly grasp this dilemma – having enough resources to collect this large number of data points. Therefore, Rollerson et al. (2000) and Koler (2000) have shown that an alternative sampling procedure can be applied with representative results.

In this new approach, Koler laid a 1500 ft by 1500 ft grid laid over the watershed base map with the landform polygons. The number of node points needing field sampling was calculated through a stratified-random sampling calculation set to meet the statistical 95% confidence interval. For the Freshwater Creek watershed the required node points was 149 out of a total of 302 nodes. The landform polygon nodes were verified during field mapping and soil samples were collected at 25% of the sites based the spatial distribution of landform polygons. Penetration tests were completed at each of the soil sample sites with either the Standard

Penetration Test and/or the Williamson Drive Probe (Adams et al., 2003). These field tests in combination with laboratory tests (i.e., grain-size determination and Atterberg limits) provided the analysts with a suite of data including physical index properties within the landform polygons. This information was then applied within a Level I and Level II analysis of the watershed. A field review was completed to test the modelled outputs in the Level I and II analyses. This was accomplished by Prellwitz, who mapped and measured data at 128 landslides in 1999 and 2000, and then calibrated the shear strength values in the models using the field data in a process of back-calculation explained in Prellwitz (1994) (Adams et al., 2003).

Level II

Chestershire Timber Sale Planning Area - Olympic National Forest, western Washington

The Level I Chestershire Timber Sale Planning Area landscape zonation maps and data, and geotechnical assessment of transportation and harvesting alternatives data provided a functional foundation of information for the Level II analysis goal of locating and evaluating four alternative transportation corridors. The corridor work consisted of focused aerial photograph review and field reconnaissance mapping of each proposed corridor alignments at a scale of 1 inch = 300 feet (1:3,600). This effort substantiated Level I findings, and each possible corridor was stratified into terrain segments defined by geologic and geomorphic processes, and soil and rock properties, and drainage characteristics. Level II products include sketches of slope characteristics for each terrain segment within each of the four alternative corridor configurations. These data and maps were then used by decision makers.

The models applied in this level are Slope Stability Infinite Slope for Critical Height (SSISCH) and Slope Stability Method of Slices (SSMOS) for the HP 41 programmable calculator as described in Prellwitz (1985). Today, these two programs are now incorporated in a desktop computer program, Slope and Road Analysis (SARA), which is currently in a beta development stage.

Freshwater Creek Watershed Analysis – Humboldt County, northern California

Applying a Level II analysis of the Freshwater Creek watershed was important in calibrating the data used in the Level I analysis as described above. This is a good example of how well the data are transferable between levels. In the calibration process the analysts are able to compare field results with the modelled results to minimize errors in the LISA deterministic and probabilistic steps. The same process can also be applied to similar models such as PISA-m.

Level III

Chestershire Timber Sale Planning Area - Olympic National Forest, western Washington

Because the Chestershire Timber Sale Planning Area overlaps the area containing the Chester Creek Landslide, much of the Level I data could also be used to develop a conceptual model and scope of work to determine the probability of reactivating the Chester Creek Landslide by reopening a road segment that crosses the toe of the landslide. Implementation of the Level III analysis was nearly concomitant with the Level I analysis.

A site-specific geotechnical investigation was implemented for the road corridor. The corridor was divided into terrain segments based on soil, rock, surface and ground water, and topographic conditions. The purpose of using terrain segmentation was to provide representative conditions for each segment for design purposes. The project engineering geologist implemented slope stability analysis using several tools to evaluate stability conditions during and post construction.

For example, the Modified Bishop Method of Slices (Bishop, 1955) was used to analyse features with ongoing or predicted rotational movement. The infinite slope equation was used to analyse features with ongoing or predicted translational movement. Field-developed cross sections were constructed incorporating USCS and URCS data. Subsurface investigations using traditional drilling and sampling efforts were done to confirm conditions estimated from surface mapping. Samples collected from subsurface work were tested to obtain design foundation strength characteristics.

Design analyses were completed using the USFS Region 6 Retaining Wall Design Guide (Driscoll, 1979), from which a Hilfiker retaining wall was selected as the preferred alternative. Ultimately, the road corridor project was dropped and the retaining wall was not constructed because of unacceptable levels of environmental risk and economic concerns.

The Level III analysis of the Chester Creek Landslide resulted in a recommendation that no timber harvesting, road reconstruction, or new road construction be conducted adjacent to or within the landslide area. Factor of safety calculations for the Chester Creek Landslide by other practitioners also indicated a high probability of failure. Subsequent application of the USFS LISA slope stability model indicated that under natural conditions 68% of the area would continue to fail even without timber harvesting. With a 50% partial cut approximately 72% of the area would fail, and under clear cut harvesting approximately 77% of the area would fail. These subsequent slope stability analyses using LISA helped significantly to validate the earlier recommendations that no timber harvesting, road reconstruction, or new road construction be conducted adjacent to or within the landslide area.

Freshwater Creek Watershed Analysis – Humboldt County, northern California

Level III analyses in the Freshwater Creek watershed included THPs, hillslope stability analysis, and road construction/reconstruction projects. The primary techniques used were surface observational methods combined with California Forest Practice Rule components, Habitat Conservation Plan prescriptions, and an existing landslide hazard map. As with the typical deterministic Level III analyses recommended in the Guide, empirical data and some stochastic statistical analyses have been used as part of a prevent-and-minimize strategy intended to meet specific aquatic habitat loss reduction goals.

CONCLUSIONS

History has shown that the use of the four basic Jahnsian Investigative Steps (i.e., recognition, characterization, risk assessment, and mitigation) in conjunction with USFS three-level method to address variable scales for slope stability evaluations are essential and fully compatible with other identified standards of practice as well as the loss reduction goals stated in the National Landslide Hazards Mitigation Strategy. The USFS method is applicable whether in national forests or on private lands.

Engineering geologists and their team members (geotechnical engineers, biologists, civil engineers, biologists) can apply the appropriate level of investigation to meet project scale needs whether it is for a coarse scale project (Level I), corridor-specific project (Level II), or fine-scale project (Level III). Using new technology such as desktop computers, landform gridding, and GIS offers verifiable and cost-effective objective methods to buttress field methods, particularly in a predictive context. These tools are essential for making informed risk assessment and mitigation decisions to meet project design needs, and implement effective loss reduction strategies for protecting environmental, human health, and infrastructure receptors from landslide hazards.

Acknowledgments: We thank our colleagues who diligently reviewed the drafts of this manuscript in order improve its content. And we are especially thankful for the constructive criticisms provided by the anonymous peer reviewers who gave valuable suggestions for improving our text.

Corresponding author: Mr. David W. Parson, CEG, State of California North Coast Region, Regional Water Quality Control Board, 5550 Skylane Blvd, California, 80401, USA. Tel: +1 707 576 2556. Email: DParson@waterboards.ca.gov.

REFERENCES

ADAMS, W.C., PRELLWITZ, R.W. & KOLER, T.E., 2003, An economical approach to supplement investigations of soil relative density in forest engineering geology: SARA 2003, *12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering/39th U.S. Rock Mechanics Symposium*, Massachusetts Institute of Technology, June 26.

BISHOP, A.W., 1955. The use of the slip circle in the stability analysis of slopes. *Geotechnique*, **5**, 1, 7-17.

BOBROWSKY, P.T., BUCHANAN, R., CHATWIN, S., CLAGUE, J., FULTON, R., HOWES, D., REGER, R., RUTTER, N., RYDER, J. & VANDINE, D. 1996. Guidelines and Standards to Terrain Mapping in British Columbia: Earth Sciences Task Force, Surficial Geology Task Group, Resources Inventory Committee, 215.

COLE, W.F., SAYRE, T.M. & COTTON, W.R. 1992. The Jahnsian Steps to Geologic Safety: The Engineering Geologic Approach. *Reprint from the Proceedings of the 35th Annual Meeting of the Association of Engineering Geologists; October 2-9, 1992*: Long Beach, California, 423-428.

CONROY, W.J., DUBE, K.V. & KOLER, T.E. 2000 Evaluation of logging roads on industrial forestlands using watershed analyses: *American Society of Civil Engineers Watershed Management 2000*, Colorado State University, Fort Collins.

COMPTON, R.R. 1962. *Manual of Field Geology*: John Wiley & Sons, Inc., New York, New York, 378.

DRISCOLL, D. D. 1979. *Retaining wall Design Guide, U.S. Forest Service, Region 6*: Foundation Sciences, Inc. Portland, Oregon, 428.

GILBERT, J.F., DIETRICH, W.E., DUNCAN, J.M., LAMOREAUX, P.E., MADER, G.G., MARCUSON, W.F., MAY, P.J., MORGENSTERN, N.R., PREUSS, J., TURNER, A.K., YOUD, T.L. 2004. Partnerships for Reducing Landslide Risk. National Research Council, Committee on the Review of the National Landslide Hazards Mitigation Strategy, Board on Earth Sciences and Resources, Division on Earth and Life Studies. National Academy Press, 131.

GOLDER & ASSOCIATES 1981. *Rock Slopes – Design, Excavation, Stabilization*: US Federal Highways Administration, 513.

HALL, D.E., LONG, M.T. & REMBOLDT, M.D. (editors) 1994. *Slope Stability Guide for National Forests in the United States: U.S. Forest Service* Washington DC Office Engineering Publication EM 7170-13, 1019.

HAMMOND, C.J., HALL, D.E., MILLER, S. & SWETIK, P. 1988. Estimating probability of landslides by Monte Carlo simulation. In 24th Symposium on Engineering Geology and Soils Engineering: University of Idaho and Washington State University, Coeur d' Alene, Idaho, 319-331.

HAMMOND, C.J., HALL, D.E., MILLER, S. & SWETIK, P. 1992. Level I Stability Analysis (LISA) Documentation for Version 2.0: U.S. Forest Service Intermountain Research Station General Technical Report INT-285, Moscow, Idaho, 190.

HANEBERG, W. 2006. *Probabilistic Slope Stability Software*: Haneberg Geo Science, Seattle WA.

HOWARD, A.K. 1986. *Visual Classification of Soils, Unified Soils Classification System*: US Bureau of Reclamation Engineering and Research Center, Geotechnical Branch Training Manual No. 5, Denver, Colorado, 106.

KOLER, T.E., 1998, Evaluating slope stability in forest uplands with deterministic and probabilistic models: *Environmental and Engineering Geosciences,* **IV**, 2, 185-194.

KOLER, T.E. 2000. Landslide and roadway stability watershed analyses on industrial forestlands: *American Society of Civil Engineers Watershed Management 2000*, Colorado State University, Fort Collins.

KOLER, T.E. & NEAL, K.G. 1989. Chestershire and Backdrop Timber Sales: Case histories of the practices of engineering geology in the Olympic National Forest. In Galster, R.W., chairman, *Engineering Geology in Washington*: Washington Division of Geology and Earth Resources Bulletin 78, **2**, 933-944.

KOLER, T.E. & NEAL, K.G. 1994. Chestershire and Backdrop Timber Sales: Case histories of the practices of engineering geology in the Olympic National Forest. In Hall, D.E., Long, M.T. & Remboldt, M.D. (editors), *Slope Stability Guide for National Forests in the United States*: U.S. Forest Service Washington DC Office Engineering Publication EM 7170-13, 19-27.

KOLER T.E. & ROLLERSON, T.P. 1999. PALCO approach to watershed analysis: *Coastal Forest Site Rehabilitation Workshop*, Nanaimo, British Columbia, November 17.

LEIGHTON, F.B. 1976. Urban landslides: targets for land-use planning in California. In *Urban Geomorphology:* Geological Society of America, Special Paper 174, 37-60.

PRELLWITZ, R.W. 1985. *Slope Stability Analyses by Three Methods of Slices with the HP 41 Programmable Calculator*: U.S. Forest Service Publication EM 7170-7, 66.

PRELLWITZ, R.W. 1988. *Preliminary Slope Stability Analysis with Hewlett-Packard HP 41 Programmable Calculator*: U.S. Forest Service Publication EM 7170-9, 77.

PRELLWITZ, R.W. 1994. Soil slopes – Level II Analysis – constructed slopes. In Hall, D.E., Long, M.T. & Remboldt, M.D. (editors) 1994. Slope Stability Guide for National Forests in the United States: U.S. Forest Service Washington DC Office Engineering Publication EM 7170-13, 595-632.

ROLLERSON, T.P., KOLER, T.E. & Coyle, J.M. 2000, Combining empirical and deterministic approaches for landslide hazard assessment in Northern California watersheds: *Association of Engineering Geologists 43rd Annual Meeting Program with Abstracts,* San Jose, California, pp. 108.

SHARMA, S. 1992. *XSTABL*: Interactive Software Design, Moscow, Idaho, 98.

SOETERS, R. & VAN WESTEN, C.J. 1996. Slope instability recognition, analysis, and zonation. In Turner, A.K. & Schuster, R.L. (editors) 1996. *Landslides Investigation and Mitigation*: Transportation Research Board Special Report 247, National Academy of Sciences, Washington, DC, 129-177.
WILLIAMSON, D.A. 1984. Unified Rock Classification System: *Association of Engineering Geologists Bulletin* **XXI**, 3, 345-354.
WILLIAMSON, D.A. 1994. Unified Rock Classification System. In Hall, D.E., Long, M.T. & Remboldt, M.D. (editors), *Slope Stability Guide for National Forests in the United States*: U.S. Forest Service Washington DC Office Engineering Publication EM 7170-13, 281-290.