INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

U·M·I

University Microfilms International
A Bell & Howell Information Company
300 North Zeeb Road. Ann Arbor. MI 48106-1346 USA
313/761-4700 800/521-0600

Order Number 9312663

An area approach to forest slope stability

Chandler, Douglas Scott, Ph.D.

University of Washington, 1992

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

An Area Approach to Forest Slope Stability

by

Douglas Scott Chandler

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

University of Washington

1992

Approved by________________________________
(Chairperson of Supervisory Committee)

Program Authorized
to Offer Degree CIVIL ENGINEERING

Date 11 DEC 1992

In presenting this dissertation in partial fulfillment of the requirements for the Doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to University Microfilms, 300 North Zeeb Road, Ann Arbor, Michigan 48106, to whom the author has granted "the right to reproduce and sell (a) copies of the manuscript and/or (b) printed copies of the manuscript made from microform."

Signature

Date 12-11-92

University of Washington

Abstract

An Area Approach to Forest Slope Stability

By Douglas Scott Chandler

Chairperson of the Supervisory Committee:
Professor Josiah E. Colcord
Department of Civil Engineering

An area approach to analyzing the slope stability of thinly-soiled forest areas under consideration for timber harvest is presented. The objective of the research was to develop a probabilistic approach that considers the effects of subsurface drainage concentration, the decay and regrowth of tree roots, the variable nature of soil, and the stochastic nature of precipitation events which typically trigger landslides. The analysis is useful in comparing the stability of an area under alternative land use scenarios.

To perform the analysis, the area to be analyzed is divided into a rectangular grid, composed of square grid cells, each with an associated soil depth and elevation. A topographic analysis determines the slope, aspect, and upslope contributing area for each cell. A hydrologic analysis routes the largest 24 hour precipitation event of each year to solve for the peak annual water table conditions at each cell. The root reinforcement and the vegetation loading are modeled through time using empirical relationships describing the decay and regrowth of trees and tree roots. The factor of safety is solved at each grid cell for every year of every trial using a Monte Carlo analysis of the infinite slope equation to account for the uncertainty of the most important variables.

By having both spatial and temporal dimensions in the model, the probabilistic analysis is able to account for uncertainty and spatial variation of the input parameters, and the stochastic nature of weather. In addition, the spatial dimension provides a more meaningful method of combining the specific conditions that exist at the individual grid cells (as opposed to totally random combination). For example, the specific soil depth that occurs at a point, will be combined with the specific slope and water table conditions that also exist at that point.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to acknowledge the steady support and consistently good advice from my committee chair, Professor J.E. Colcord. I would also like to acknowledge the guidance of my committee member Dr. T.W. Cundy for the original inception of the idea for this research, and his continued support and technical direction even when my ideas waived from the original plan. Special thanks are also due to committee member Dr. S.A. Veress for his technical review and to graduate faculty representative Dr. J.B. Adams his efforts and support.

1.0 INTRODUCTION

1.1 Problem Statement

There are a variety of negative impacts resulting from forest landslides. Besides the obvious threat to life and property, forest landslides are a major detriment to fish habitat in that they produce and deliver large amounts of sediment to streams. Since slope stability is affected by the presence and type of vegetation, the possibility of inducing slope instability has become a major factor in determining the harvestability of timberlands.

In order to evaluate the potential impacts of logging on the stability of a forested slope, a forest land manager must consider a number of factors that affect stability. Many of these factors, such as the effects of root reinforcement and near-surface drainage concentration, are particularly important to forest applications. A need exists for a stability analysis that will integrate existing knowledge of the specific factors important to forest slope stability. The method should be able to analyze a given forest area that is under consideration for timber harvest to compare the probability of failure for both the "harvest" and the "no harvest" alternatives for a specific time period after logging. Land management decisions could then be made based on the calculated risks.

Prior probabilistic analyses consider either the uncertainty of the input parameters (Vanmarcke, 1977; Ward et al., 1979, 1981; Cheng and Christopher, 1991) or the stochastic nature of weather (Sidle, 1987, 1992), but none that consider both. It is apparent that both the stochastic nature of rainfall and the uncertainty of the spatial variables are important in determining slope stability. However, accounting for both these sources of uncertainty introduces many interdependencies that could not be accounted for in prior methodologies.

The objective of the research described in this dissertation is to develop a first generation computer model to analyze the stability of forest areas considering the effects of subsurface drainage concentration, the decay and regrowth of tree roots, the variable nature of soil, and the stochastic nature of precipitation events. The desired scale of the analysis would ideally be such that it could analyze typical land management units such as entire drainage basins. However, the scale of the analysis must also be detailed enough so that it can account for the localized factors that typically cause forest landslides.

1.2 The Role of Land Form

Landforms that develop from slope failures have long been recognized as primary indicators of slope instability. Examples of recognized unstable landforms include rotational slumps, sag ponds, failure scarps, mudflows, and most recently, colluvium-filled bedrock hollows. Practicing engineers and geologists can often identify points of slope instability based primarily on surface observations of the landform. Although the presence of such landforms indicates past instability, judgements of the present stability by these observations are primarily intuitive, and provide no basis to quantitatively assess the risk of slope failure.

For many of the recognized unstable landforms, subsurface or surface drainage is a primary factor that leads to the instability and thus also to the resulting landform. Subsurface drainage is generally a critical factor in the stability of forest areas (Buchanan and Savigny, 1990).

A drainage landform of particular interest when evaluating the stability of forested mountainous areas is the colluvium-filled bedrock hollow. Bedrock hollows are shallow, concave landforms that concentrate subsurface drainage due to their topographic form

(Dietrich and Dunne, 1978). Hollows are often referred to as zero-order drainage basins; this is a logical extension of the labelling convention that refers to surface streams with no tributaries as first-order streams, second-order streams as being composed of two or more first-order tributaries, third-order streams as being composed of two or more second-order tributaries, etc. etc.

Hollows, or zero-order basins, usually have no surface flow, and are typically located on steep slopes near drainage divides. These landforms are common initiation sites of landslides and debris flows (Benda and Cundy, 1990). The failure of hollows is thought to be self-perpetuating and cyclical in nature in that colluvium accumulates in the shallow depressions due to their topographic form, and then the hollows periodically unload by landsliding. The unloading occurs when the soil depth gets too large to be supported by the shear strength at the base of the soil profile. The unloading is generally triggered by large precipitation events. The loading/unloading cycle has been reported to range from as short as 10 years to as long as several thousand years (Selby, 1982). The hollows are relatively stable after unloading, but are relatively unstable toward the end of the accumulation period when they are considered "loaded". Hollows can be prematurely triggered when a reduction in soil shear strength occurs due to timber harvest and the associated loss of root reinforcement.

Since topography and drainage play a key role in the stability of forest areas, any analytical method to evaluate forest slope stability must consider the topographic form and the mechanics of drainage concentration. Although the analytical methodology should ideally be applicable to planer and divergent topography as well, it should first and foremost be able to treat hollows. In addition, based on the premise that the soil depth distributions that develop on forest slopes are integrally tied to the topographic form of the slope, the level of detail of the input soil depth data should be fine enough to recognize soil depth variations that may result from subtle topographic features.

A basic premise of and motivation for the analytical methods used by this research is that the soil depths are not random over the slope, but rather develop and accumulate due to the topographic form (Sidle, 1987). It is therefore important, when analyzing the stability of a forest area, that the specific soil depths that occur at various points are combined with the specific slope angles and water table conditions that also occur at those points. For example, in a partially loaded hollow, the soil depths and the water level during storms are typically greater in the center of the hollow than on the midslopes and sides. This would tend to make the center of the hollow the least stable area. However, counteracting these effects is the fact that the slope angle is flatter in the bottom of the hollow. Therefore, in the colluvial loading/unloading cycle of the hollow, shortly after unloading (landsliding) the bottom of the hollow, the steep side slopes of the hollow are the most susceptible to failure. As soil accumulates in the bottom of the hollow, the bottom becomes less and less stable. A primary distinction of the analytical methods used in this research is the ability to take into account the various spatial interdependencies that evolve in forest hollows.

1.3 The Role of Temporal and Spatial Variation

Existing research clearly indicates that reinforcement of soil by tree roots and the buildup of water table due to precipitation are critical factors in determining the stability of forested slopes (Buchanan and Savigny (1990), Burroughs and Thomas (1977), Gray and Megahan (1981), Sidle (1992), Tubbs (1974), Wu et.al. (1979), Ziemer (1981). Since the decay and regrowth of tree roots after logging and the probability of extreme storm events are time dependent, temporal relationships are important when considering the effects of timber harvest on slope stability. For example, Ziemer (1981), found that due to the lag between the decay of the harvested tree's roots and the regrowth of new roots, a "window of vulnerability" to landsliding exists several years after harvesting. Because of the demonstrated importance of these temporal factors, the stability analysis of harvested areas should consider time as a dimension, and should provide a method wherein temporal variables such as storm events and the decay and regrowth of vegetation can be considered.

As was previously discussed, the spatial variability of soil depth, slope and water table conditions are also important and therefore should be realistically represented in the model. Since soil depth, slope, and water conditions are influenced by the topographic form of hollows, the scale of the overall analysis must be detailed enough to represent their form. This relatively detailed scale requires fairly intensive site data.

To account for the uncertainty of factors such as soil and vegetation characteristics, the analysis should also be probabilistic. By considering the uncertain factors to be random distributions, probabilistic approaches generally yield the "probability of failure" rather than the deterministic "factor of safety". The probability of failure is a more meaningful indication of the stability of the slope (Vanmarcke, 1977). This is especially true when dealing with natural slopes where the soil characteristics are quite variable and therefore uncertain at any particular point. Although the term "spatial variation" which refers to the variation of the parameters in space, is not exactly the same as the "error" or "uncertainty" of the parameter estimates, they are treated the same in this dissertation since the result of spatial variation throughout an area is uncertainty at any given point. More discussion on this topic is included in Section 11.

In addition to the uncertainty of the input parameters, the probabilistic nature of the forest slope stability also is influenced by the stochastic nature of weather. The analysis should also be able to account for this factor when determining the probability of failure. In this sense, the probability of failure should be associated with a specific time period, for example, a slope may have a 25% chance of failing in the next 10 years. This is especially important when considering root decay and regrowth.

1.4 Review of Previous Work

A great deal of research has been directed toward the general topic of slope stability analysis. In practice, there are two general problems in addressing slope instability: 1) recognizing potentially unstable areas, and 2) given an potentially unstable area, making detailed evaluation of its stability.

The problem of recognizing areas of potential instability is encountered frequently by land use planners, zoning authorities, etc. who have large areas to manage and would like to delineate unstable areas. Given a specific site, the second problem of making a more detailed evaluation of its stability under existing or proposed conditions is a problem that is frequently encountered in the design of roads and other facilities.

Although the current methods employed to perform landslide hazard delineation are quite different than those presently employed to perform detailed site stability analyses, the distinction is really just a matter of feasibility. At present, it simply is not feasible to perform detailed stability analyses over large areas, so alternative methods are employed for landslide hazard delineation. This research, which is specifically directed toward evaluating forest slope stability, has potential for both landslide hazard delineation of large areas and for detailed site stability evaluation. As such, previous work of landslide hazard delineation and detailed site evaluation are discussed.

There are a number of existing areal approaches to slope stability. These approaches include remote sensing techniques, factor overlay methods, statistical models, and a few physically based process models. Remote sensing methods coupled with pattern recognition techniques have been used to delineate landslide hazards within large areas. In using this approach, remotely sensed data, particularly aerial photography, is analyzed for features distinctive of landslide hazards (Liang and Belcher, 1958; Poole, 1969, 1972). These features include visible slide scarps and paths, sag ponds from rotational failures, broken terrain indicating recent movement, interrupted drainage features, tension cracks, and any other features that would indicate past or impending movements. This approach can be quite effective, but is subjective in nature and cannot account for any factors other than those that can be directly observed and interpreted by the photo interpreter.

The most common landslide hazard delineation method currently in use is the factor overlay method. In this approach, certain factors related to landslide occurrence are individually delineated, and the areas where factors coincide are then classified by some scheme that relates the relative hazard at that location. A number of stability analyses have been performed by this general method including those by: Krynine and Judd (1957); Baker and Chieruzzi (1959); Evans and Gray (1971); Cleveland (1971); Nilsen and Brabb (1973); the Building Research Advisory Board (1974); Tubbs (1976); and Klock (1985).

The factor overlay method is conceptually correct in that it recognizes that slope instability results from a combination of different factors. The method has gained some use among zoning authorities and other regulatory agencies with access to Geographic Information Systems (GIS) to perform the overlay. Since landslide mechanisms vary from area to area, factor overlay methods are necessarily area specific. An essential step in the development of a factor overlay analysis for a specific area is to identify the existing landslide mechanisms and the corresponding conditions necessary for the mechanism to occur. This is generally accomplished using records of previous landsliding in the area and/or by interpreting the existing geologic landforms that indicate recent landsliding.

The use of a computerized GIS is not prerequisite to using the factor overlay method. The general approach of studying the mechanisms and conditions under which previous landslides occurred, and then delineating other locals in the area with similar conditions was done for the Seattle area without the aid of computers to manage the data by Tubbs (1974). In this study, fifty landslides that occurred in a single year were studied in some detail. The study was able to identify the most common landslide mechanisms and the prevailing geologic conditions for the Seattle area. The study then went on to delineate where the prevailing geologic conditions exist in the Seattle area. The study also concluded that widespread landsliding is very dependent upon weather conditions, and will typically occur in the Seattle area when 1.5 inches or more of rain falls in a single day.

A factor overlay analysis of forest areas is presented by Klock (1985), wherein the cumulative effects of various forest management practices are considered. In this approach, a "Watershed Cumulative Effects" model allows a forest land manager to follow an index of watershed condition through time under various management scenarios. The model isn't specifically geared to evaluating slope stability, rather it emphasizes the effects of land management on the downstream aquatic ecosystems.

Two general problems with factor overlay methods is that they are usually subjective in nature due to the lack of defined guidelines for developing and weighting various factors, and that they are often non-sensitive to very localized factors. One method to develop factor weighting schemes is to use empirically developed models. These models, developed through statistical analyses of measurable data, attempt to provide an empirical combination of factors related to slope stability. Multiple regression and discriminant function analyses are common techniques for developing such relationships (Jones, Embody and Peterson, 1961; Waltz, 1971; Neely and Rice, 1990). Empirically derived relationships have several major drawbacks in that they require large amounts of data to develop the equations, and the equations are applicable only to the limited area where the data was collected.

A major practical problem with factor overlay methods for delineating areas of slope instability is non-sensitivity. Non-sensitivity occurs because the wide variety of possible mechanisms of slope instability often preclude a blanket approach over a large area. Even for areas where uniform geologic conditions result in a single common mechanism of instability, the grid sizes of typical GIS's are too large to detect many localized conditions.

In order to evaluate very localized conditions that occur at specific sites, physically based process models can be applied. This approach relies on models that are derived from observed natural phenomena and basic laws of physics and are more representative of the actual processes that occur. Geotechnical slope stability analyses fall into this category.

Typical geotechnical models of slope stability relate the forces acting on the slope. One set of forces, primarily gravity, act to move earth materials down slope. The other set of forces, primarily the shear strength of the soil, resists the driving forces. When driving forces exceed resisting forces, a landslide occurs. Geotechnical models have been developed to account for primary factors in landslide occurrence such as soil strength, ground water influences, vegetative effects, slope inclination, etc. More discussion on previous work in this area is presented in Section 3 of this dissertation.

There have been several attempts at applying geotechnical models over large areas in order to delineate landslide hazard. A primary problem with this approach is in collecting and managing all the site data necessary to perform the analyses over large areas. However, this task is considerably simplified by considering only one mechanism (such as surficial sloughing), and a common subsurface profile (such as a thin layer of soil over bedrock) as is often present in forested mountain areas.

Ward et al. (1979, 1981) developed a model of forest landslide potential using a simplified factor of safety analysis to be applied to a large forest area on a cell by cell basis. Ward's model is applied over a large area, using relatively coarse grid cell dimensions. The user estimates appropriate soil, vegetation, and groundwater conditions for each cell based on the best available information. The soil cohesion, root cohesion, and soil friction angle are considered to be static, uniformly distributed random variables. The remaining variables are considered to be static and deterministic. A derived distribution of the factor of safety against landsliding is determined based on the infinite slope equation.

Ward's model does not incorporate a means to predict the ground water conditions based on topography and precipitation, nor does it consider time as a dimension. Since the water table is a critical component of slope stability, the lack of a hydrologic model is a major limitation of the analysis. Without time as a dimension, the stochastic nature of precipitation and the dynamic nature of the vegetation effects can not be considered. With these limitations, the calculated probability of failure is associated only with an assumed uniform water table condition and static vegetation effects and not with a specific time period of analysis.

Sidle (1987), developed a conceptual dynamic model to evaluate the probability of failure of a hollow over time. The model considers the conditions at one point in a hollow, starting at a time immediately after an initial failure. The model considers the root cohesion, the soil depth, and the weight of the vegetation to be deterministic parameters that are empirical functions of time. Any land management practices that may change the various input parameters or empirical functions over time can be considered for any year or years. The soil characteristics and the slope angle are considered to be static (constant) and deterministic. The water table conditions are quantitatively related to rainfall, which is considered a stochastic variable.

After calculating the above-described deterministic parameters for each year, the critical level of saturation of the soil mantle (M_{crit}) is calculated from the infinite slope equation by setting the factor of safety equal to 1.0. The probability of failure is then equal to the probability of a storm big enough to cause M_{crit} to occur.

No general relationship between M and rainfall is provided with Sidle's model, but several specific methodologies applicable to various situations are discussed. The results of an example analysis of a hypothetical hollow is presented. For the example problem, the relationship between rainfall and M was based on an empirical model developed from 40 storms in coastal Alaska (Sidle, 1986). The final result of the example problem indicated an increasing probability of failure with time as the soil depths in the hollow accumulated.

This theoretical model was refined (Sidle, 1992) to account for the effects of specific long term timber management practices. The method was applied to simulate conditions at a specific site in coastal Alaska under several alternative timber management scenarios. The model employs empirical decay and growth functions to model root reinforcement.

While Sidle's conceptual model is a good example of combining existing models of the various factors affecting forest slope stability, it does not specifically consider the topographic form, the distribution of soil depths, and the mechanics of drainage concentration within the hollow. In this sense, the hollow is basically considered to be one point, with conditions that represent average, or possibly worst case conditions over the entire area of the hollow. In addition, Sidle's model also does not consider the spatial variability and uncertainty of the most important input factors. The probabilistic results of Sidle's model (the results are presented as a probability of failure per year) stem entirely from the stochastic nature of precipitation. In other words, the critical pore pressure needed to cause failure is calculated in a deterministic fashion, and then is related to the probability of a storm occurring that would cause that pore-pressure to develop.

1.5 Objectives of This Research

Many of the individual processes and phenomena affecting forest slope stability have been studied in some detail by previous researchers. Several efforts at combining existing facets of present knowledge into models of forest slope stability have been previously attempted, but have shortcomings as are discussed in the preceding section.

The intent of this research is to develop a more comprehensive analysis to evaluate the risk of slope failures in thinly-soiled mountainous areas under consideration for timber harvest. Similar to Sidle (1987, 1992) and Ward et al. (1979, 1980), this research uses the infinite slope equation as the appropriate geotechnical model for analyzing stability. It is recognized that the analysis would thus not be applicable to areas susceptible to deep-seated rotational failures, rock falls, or a variety of other failure mechanisms that can occur.

Similar to Ward et al. (1979, 1980), the methodology utilizes a GIS data format and an area approach. The topographic analysis utilized allows the model to be sensitive to spatial terrain features such as hollows. In order to recognize hollows, the suggested grid size is smaller than was utilized by Ward. In addition, the analytical methods, which include a Monte Carlo probabilistic approach and a built in hydrologic model, take advantage of the computer format and the number crunching ability of modern computers. Similar to Sidle (1987, 1992), the approach views time as an important variable, and in addition to considering precipitation as a stochastic temporal variable, it also recognizes the temporal nature of root decay and regrowth. This feature makes the model sensitive to timber harvesting, regrowth, and weather patterns.

In summary, the purpose of this research is to develop a more comprehensive analysis that has the following features:

- Analyzes an area rather than a point by using a GIS data format.
- Has a built in hydrologic model.
- Is probabilistic by considering both the spatial variation/uncertainty of input parameters and the stochastic nature of weather.
- Considers the decay and regrowth of vegetation.

While many aspects of forest slope stability such as vegetation effects and forest hydrology have been studied in considerable detail, existing knowledge has never been combined in such a comprehensive analysis. In addition, the concept of a probabilistic analysis that considers both the spatial variation/uncertainty of the input parameters and the stochastic nature of weather is new.

The Methods section that follows provides and overview of the analysis, and then describes the details of the infinite slope equation, the Monte Carlo probabilistic approach, the topographic analysis, the hydrologic modeling, and the vegetation modeling.

2.0 OVERVIEW OF METHODS FOR THIS RESEARCH

2.1 Overview of Computer Program

The primary product of this research is a computer model that evaluates the slope stability of a forest area over a user specified time period. The model, which is written in FORTRAN, is named FASSA, an acronym for "Forest Area Slope Stability Analysis". An overview of the model is presented in this section, with detailed descriptions of the various components presented in later chapters. The later chapters also describe alternative methods that were considered during the course of this research.

There are five major internal components to FASSA: a topographic analysis performed by the subroutine TOPOGS which calculates the slope, aspect, and upslope contributing area at each grid cell location; a vegetative analysis performed by the subroutine VEG which calculates the root cohesion and the vegetative loading at each grid cell for each year of the analysis; a hydrologic analysis performed by the subroutine HYDRO which calculates the saturated soil depth at each grid cell for the worst storm of each year; the subroutine SOIL which assigns the randomly varying soil properties during the analysis; and the framework of the Monte Carlo solution of the infinite slope equation which is performed in the main program. All parts of the computer program were written entirely by the author except for TOPOGS, which utilized portions of an earlier program by Zevenbergen and Thorn (1985).

To perform the analysis, the area to be analyzed has to be discretized into a rectangular matrix of square grid cells. Input data is read into the program from 5 data files that must be created prior to execution of the program. Briefly, the data files consist of:

- Z.DAT - A digital terrain model of the approximate elevations at each grid cell location. Parameters describing the grid layout and the uncertainty of the elevation estimates are also included in this data file.

- SDM.DAT - A file containing mean soil depths at each grid cell location (note:

the soil depth at each grid cell location is varied about the mean soil depth at that location during program execution).

- SOIL.PAR - A file containing the mean values and the coefficients of variation of the soil properties.
- VEG.PAR - A file containing parameters describing the decay and regrowth of trees and tree roots with regard to the effects on soil strength and slope loading.
- HYDRO.PAR - A file describing the statistical variation in the annual maximum 24 hour precipitation events for the subject area.

An abbreviated flow chart of the FASSA program is shown in Figure 1. Descriptions of the individual components of the analysis, and discussion of some of the alternative methods that were considered in the course of the research are provided in the following sections.

2.2 Data Management and Structure

Because the FASSA analysis requires fairly intensive data and computations, data management is a critical component of the system. The data consists mostly of specific land attributes linked with a particular geographic location, therefore modern principles of Geographic Information Systems (GIS) are used to manage and manipulate the spatial data.

Central to the entire analysis is a 2-dimensional coordinate system wherein grid cell addresses correspond with their actual locations in an N by M rectangular matrix. The topography can thus be represented and stored by a digital terrain model consisting of

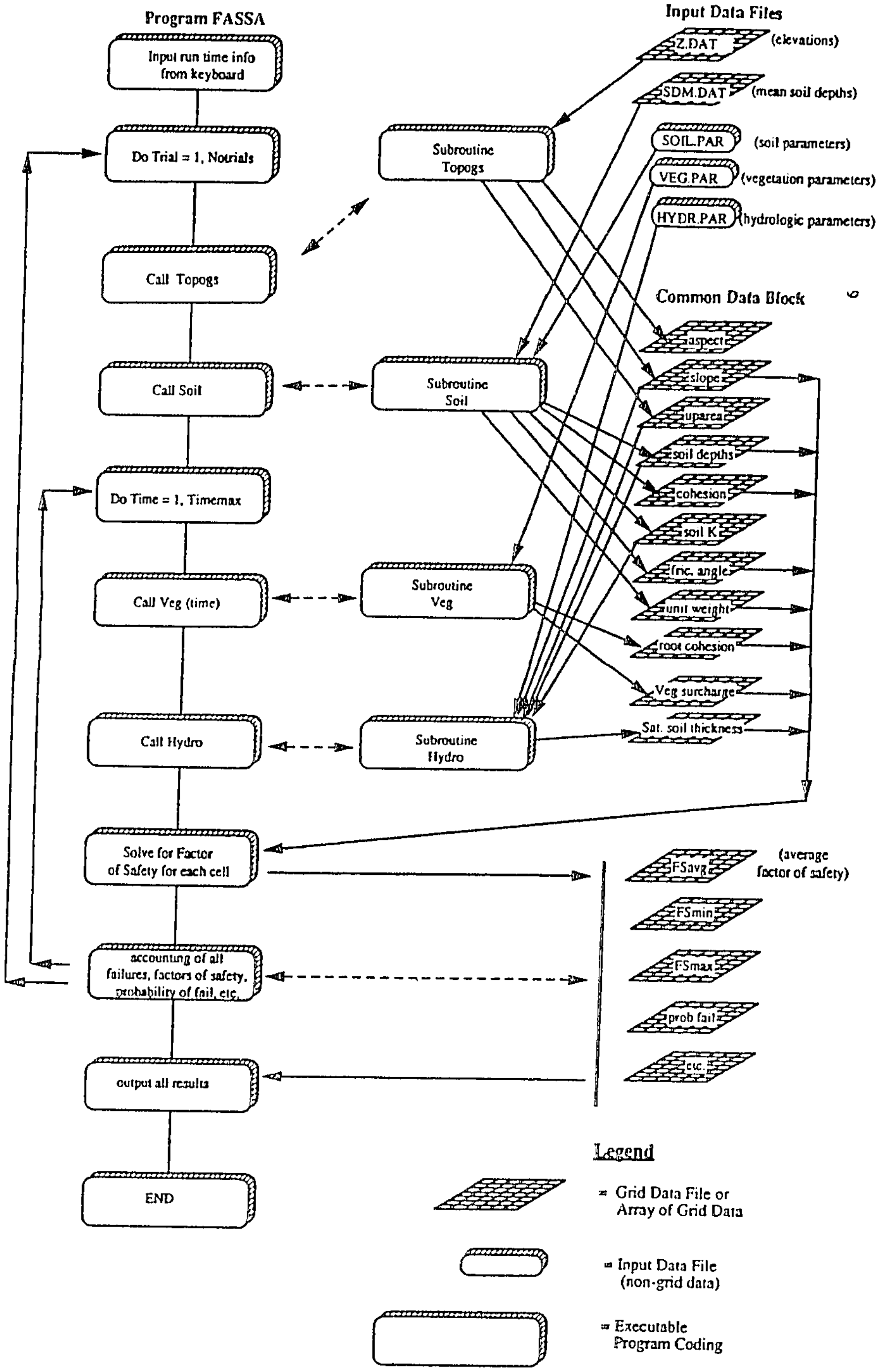


Figure 1

FASSA Program Flow Chart

an N by M rectangular matrix of elevations, and header information describing the orientation of the grid in space and the grid cell dimension. This same data format is also used to store other grid cell attributes such as soil depth, topographic indices, soil properties, and all intermediate and final results of the analysis such as the factors of safety, the saturated soil depth ratio, and number of failures. The grid array layout and labeling conventions for spatial data are presented in Figure 2.

A system of custom computer programs was written by the author to process and analyze the spatial data. Although not an integral part of the analysis, these programs greatly assist in preparing, editing, and displaying the FASSA program input and output. A list of the data management programs and a summary of their purposes is provided in Appendix A.

As was previously described, the area to be analyzed is discretized into a rectangular grid, composed of square grid cells. The size of the grid and the total area of analysis is user specified, but the present computer code is designed to run on personal computers and is dimensioned for a maximum grid size of 60 by 60 cells. The optimum grid cell dimension depends upon several factors including both the complexity of the terrain and the accuracy of the grid topographic data. More discussion on this topic is provided later, but based on the experience with the program to date, the optimum grid size is about 5 to 10 meters for typical forest applications.

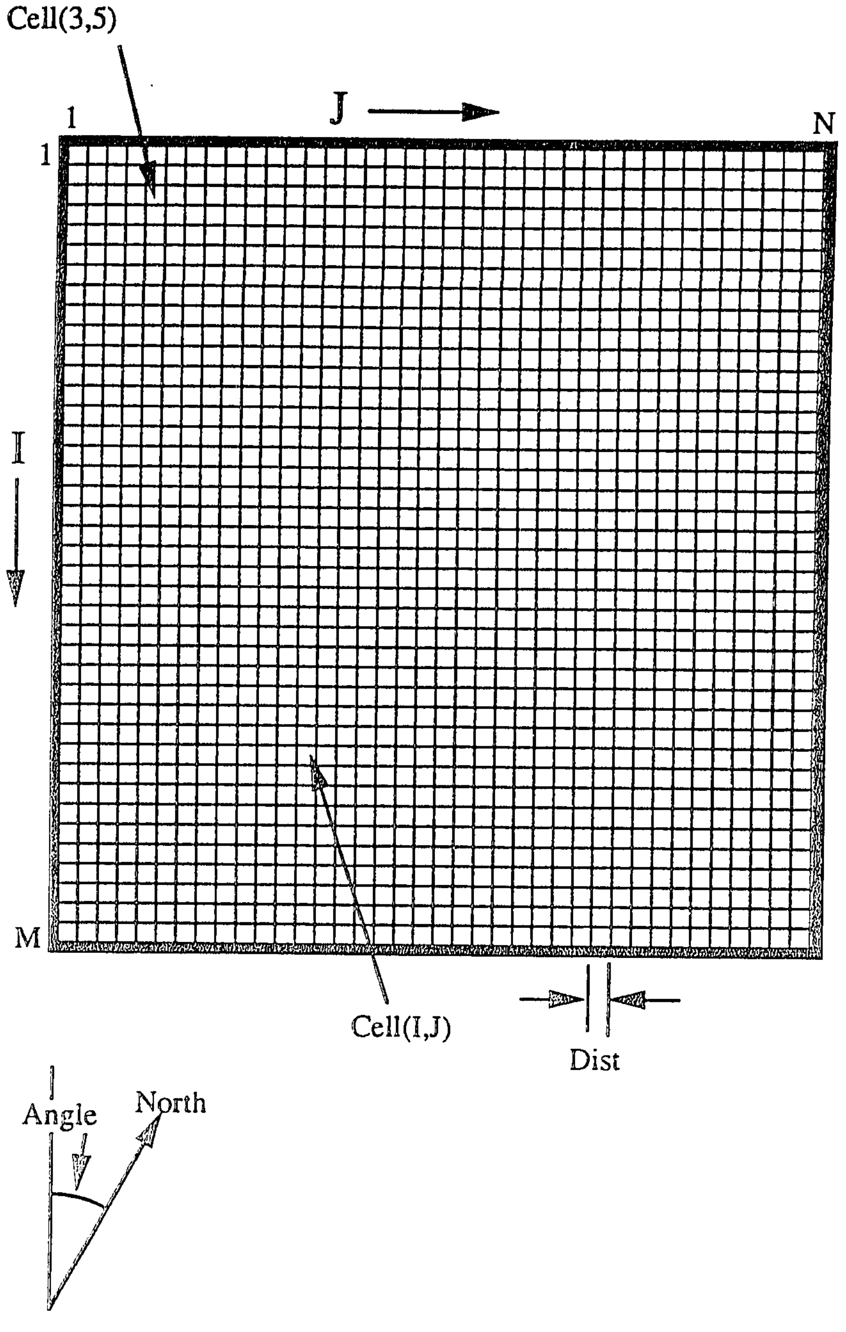


Figure 2

Grid Layout and Label Convention for Spatial Data

3.0 SLOPE STABILITY ANALYSIS

3.1 General

There are two current approaches to detailed analysis of slope stability; limit equilibrium analyses, and deformation analyses. Limit-equilibrium methods of slope stability analysis attempt to relate the forces acting on a potential failure mass within the slope. One set of forces, predominated by gravity, acts to drive the potential failure mass downslope. The other set of forces, predominated by the shear strength of the earth materials, resist the driving forces. In calculating the resisting forces, limit-equilibrium methods assume that the soil is on the verge of failure over the entire failure surface simultaneously. This assumption is valid for typical soils that exhibit ductile plastic behavior. The end product of traditional limit-equilibrium stability calculations is a factor of safety which is the ratio of the resisting forces to the driving forces.

In deformation analyses, slopes are discretized into individual elements, for which the stress and deformation conditions are solved considering the stress-strain properties of the earth materials. In concept, this is an attractive approach, but in practice is seldomly applied to natural slopes. Although the analytical methods to perform deformation analyses are now readily available using finite element methods, the difficulties in assigning appropriate soil stress-strain parameters and initial boundary conditions to natural slopes has limited the use of this method primarily to man-made embankments.

Although the data requirements for deformation analyses are more extensive, the difficulties in assigning appropriate soil parameters also exists for limit equilibrium methods. As is demonstrated later in this section, the greatest obstacle to evaluating slope stability by any method is generally not in the accuracy of the mechanics of the analysis, but rather in the accurate determination of field conditions. Therefore, an analytical method that considers the variation in soil properties and the inevitable inaccuracies in determining them is desirable.

3.2 Limit Equilibrium Methods

A variety of limit equilibrium analyses have been developed to evaluate slope stability. One of the most versatile general methods is referred to as the "Method of Slices". In this approach, the assumed failure mass is broken into a series of vertical slices and the equilibrium of each slice is considered. A number of variations of the method of slices exist. The difference between the various methods is in the assumptions that are made about the side forces (the inter-slice forces) to make the solution statically determinant.

The Ordinary Method of Slices (Fellenious, 1936) assumes that the side forces of each slice act parallel to the base of that slice. This is one of the simplest of the many "methods of slices", and generally yields a conservative (low) factor of safety. Bishop's method (Bishop, 1955; Janbu et al., 1956) assumes that the side forces act horizontally. Bishop's method is more cumbersome to perform since it involves a trial and error solution, but is generally accepted as more rigorous.

There are additional methods of slices which are even more rigorous, such as those developed by Morgenstern and Price (1965), and Spencer (1967, 1973, and 1981). These methods not only consider the normal and tangential equilibrium, but also the moment equilibrium for each slice. These methods can be used on non-circular failure surfaces.

For thinly-soiled mountain hollows, the failure mechanism is generally shallow surficial sloughing of the soil layer. This failure mechanism can be approximately analyzed using the relatively simple infinite slope analysis (Lambe and Whitman, 1969; Ward et al., 1981; Gray and Megahan, 1981). The infinite slope analysis is generally considered applicable when ever the depth of the failure mass is small compared to the length of the failure mass.

In the FASSA program, the factor of safety (FS) against an infinite slope type failure is calculated for each grid cell by the following equation (Ward, et. al., 1979, 1981):

$$FS = \frac{[2(C+\Delta C_r)/(\gamma_w * SD * \sin(2\alpha))] + [(L-M)(\tan \phi / \tan \alpha)]}{L}$$

Where L is a loading term composed of soil and tree weights:

$$L = \frac{q_o}{\gamma_w * SD} + \frac{\gamma_s M}{\gamma_w} + \frac{\gamma_m (1-M)}{\gamma_w}$$

Where:

C = Soil cohesion.

ΔC_r = Apparent cohesion caused by roots.

ϕ = Effective angle of internal friction of the soil.

γ_s = Soil unit weight when saturated.

γ_m = Soil unit weight at field moisture content.

γ_w = Unit weight of water.

α = Slope angle.

SD = Soil depth measured vertically.

M = Saturated soil depth/soil depth.

q_o = Weight of Vegetation per unit area.

The sensitivity of each of the factors to the infinite slope equation was investigated by Gray and Megahan (1981), and their results are presented in Figure 3. The graph in Figure 3 is a collection of curves representing the percent change in the factor of safety that results from a change in each of the individual factors while holding the others constant.

Although the infinite slope analysis is one of the least rigorous of the widely accepted limit-equilibrium analyses of slope stability, it is demonstrated in the following section

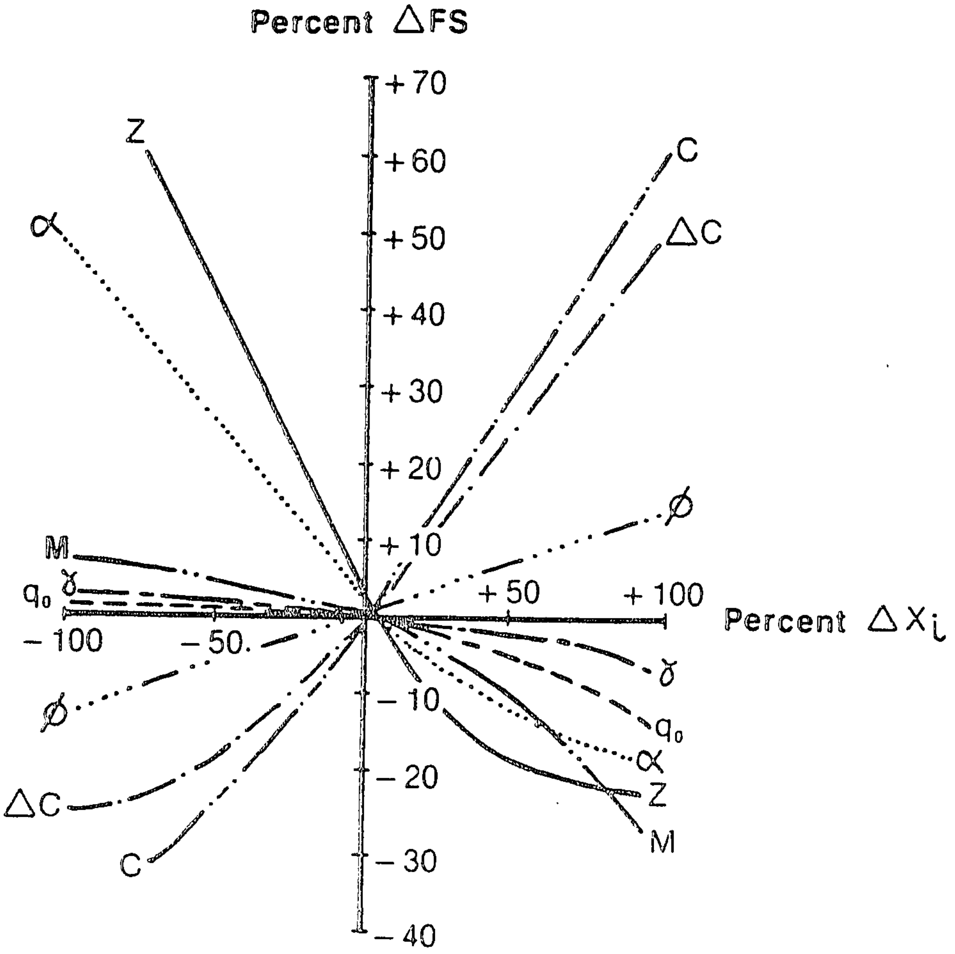


Figure 3

Sensitivity of Infinite Slope Factors

(after Gray & Megahan, 1981, reprinted with permission from Sidle et. al., 1985) of this dissertation that the reliability of the calculated factor of safety for shallow sloughs is most limited by the reliability of the assumed site conditions rather than by the method of analysis or the determination of the exact failure surface configuration. It therefore follows that the analysis should emphasize proper consideration of the variability and uncertainty of the site conditions rather than attempt more rigorous analysis of the supposed failure mass.

3.3 Modelling the Failure Mechanism

To establish the applicability of the relatively simple infinite slope analysis to this model, it is demonstrated that the calculated factor of safety of thin surficial slides is more sensitive to the proper identification of the soil parameters than to the proper identification of the exact failure surface or to the method of analysis. To demonstrate this, consider the three potential failure surfaces for the planer slope shown in Figure 4.

As can be seen in the figure, failure surface #1 is most like an infinite slope failure (a shallow surficial slough), failure surface #2 is relatively deep-seated and circular in shape, and failure surface #3 is in between the preceding two failure surfaces. To demonstrate the sensitivity of the solution to the method of analysis, the factor of safety of each of the three failure surfaces was analyzed by; 1) the Infinite Slope Equation (Lambe and Whitman, 1969). 2) the Ordinary Method of Slices (Fellenius, 1936) and 3) the Simplified Bishop Method of Slices (Bishop, 1955; Janbu et al., 1956).

To analyze failure surface #1 as a circular failure surface, a very long radius was assumed. For analyzing failure surface #2 and #3 as an infinite slope, the soil depths were assumed to be 5.5 meters and 2.2 meters respectively. The details of the analyses are provided in Appendix D.

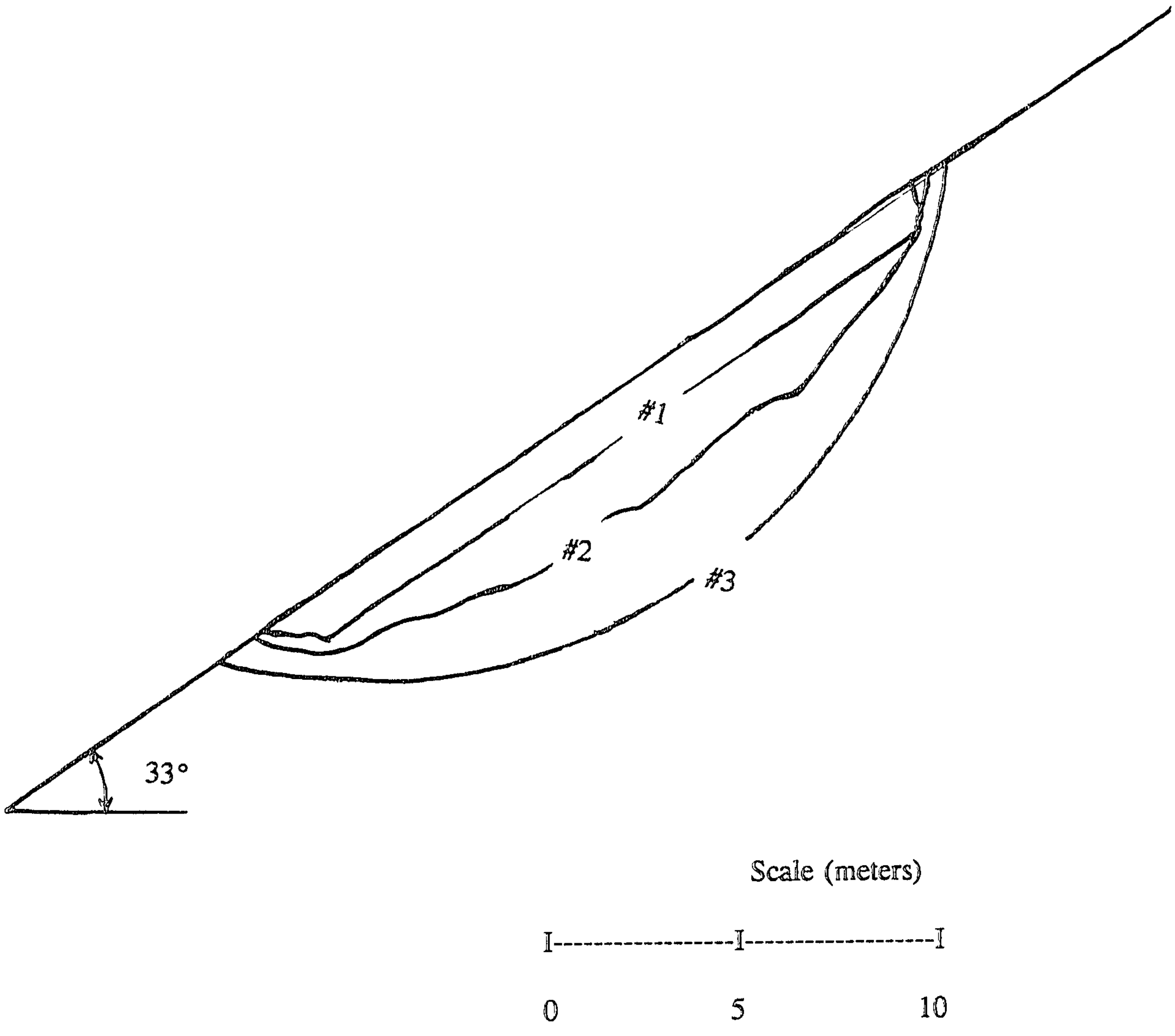


Figure 4

Three Failure Surfaces Analyzed

To demonstrate the sensitivity of the solution to the correct determination of soil parameters, in each of the analyses, the cohesion, friction angle and unit weight of the soil were varied individually approximately 2 standard deviations above and below the given average value while the remaining parameters where held constant. The values of the soil parameters shown in Table 1 were assumed. The values are assumed to be normally distributed and independent.

Table 1

Assumed Soil Parameters

Parameter	Mean Value	Coefficient of Variation
Soil Cohesion	5 kn/sq. meter	0.20
Friction Angle	35 degrees	0.15
Unit Weight	15 kn/cu. meter	0.05

The results of the factor of safety calculations for all cases are summarized in Table 2. As can be seen from Table 2, for failure surface 1, the factor of safety calculated by all three methods were practically the same. For failure surface #3 (wherein the failure surface is still relatively thin compared to its length), the factor of safety calculated by the infinite slope equation was always within ±10% of the factors of safety calculated by Bishops Method and the Ordinary Method of Slices. For failure surface #2 (which is relatively deep), the factor of safety calculated by the infinite slope analysis was significantly different (about 32% less) than that calculated by Bishops method and about 14% less than that calculated by the Ordinary Method of Slices. These results generally confirm that the infinite slope equation gives results comparable to more complex and rigorous methods when applied to thin, surficial sloughs wherein the thickness of the failure mass is small compared to its length. The results also indicate that for cases where the soil parameters are not well known, the errors caused by the incorrect estimates of the soil parameters are more significant than the small variations between the various analytical methods.

Table 2

Summary Table of Calculated Factors of Safety

		Calculated Factor of Safety		
Failure Surface	Changed Parameter	Infinite	Bishops	Ordinary
1	average	1.57	1.56	1.53
1	C = 8	1.87	1.73	1.70
1	C = 3	1.37	1.39	1.36
1	$\phi = 45.5°$	2.06	2.08	2.03
1	$\phi = 24.5°$	1.20	1.16	1.14
1	$\gamma = 18.7$	1.53	1.52	1.49
1	$\gamma = 15.3$	1.63	1.61	1.58
2	average	1.19	1.74	1.50
2	C = 8	1.24	1.85	1.62
2	C = 3	1.15	1.66	1.42
2	$\phi = 45.5°$	1.68	2.44	2.09
2	$\phi = 24.5°$	0.82	1.20	1.04
2	$\gamma = 18.7$	1.18	1.72	1.48
2	$\gamma = 15.3$	1.21	1.76	1.52
3	average	1.37	1.50	1.42
3	C = 8	1.55	1.67	1.59
3	C = 3	1.25	1.39	1.31
3	$\phi = 45.5°$	1.86	2.06	1.93
3	$\phi = 24.5°$	0.99	1.07	1.02
3	$\gamma = 18.7$	1.34	1.48	1.39
3	$\gamma = 15.3$	1.40	1.53	1.45

Notes:

C given in kn/sq. meter
γ given in kn/cu. meter

In conclusion, the infinite slope equation is considered to be appropriate for the relatively thin surficial sloughs that are common in thinly-soiled, forested mountain areas. More rigorous analyses would generally not provide a significantly better answer for most applications of the FASSA model since the major source of errors in calculating factors of safety of natural slopes will generally be in determining the proper input factors. For this reason, the FASSA analysis focusses on taking proper account of the uncertainties and interdependencies of the most important factors. This is done using a Monte Carlo computer analysis organized around a framework that accounts for both temporal and spatial variables. The following chapters describe the methods employed to determine the various input factors to the infinite slope equation for each grid cell.

4.0 PROBABILISTIC APPROACH

Considering the relatively high variability and uncertainty of several of the input parameters to the slope stability calculations, a probabilistic stability analysis is desirable. A number of probabilistic approaches have been developed around the limit-equilibrium analyses to account for the uncertainty of the input factors of the analysis. The result of a probabilistic analysis is an estimate of the probability of failure of the slope rather than the factor of safety.

In probabilistic approaches, the most important input factors are considered to be random variables with probability distributions. Generally, the random variables are assumed to be normally distributed about a known mean with a known standard deviation. To perform the stability analysis using random distributions instead of deterministic numbers, approaches such as the point estimation method (Rosenblueth, 1975) have been developed which replace the continuous distributions with a series of weighted points with the same mean, skewness, variance, etc. This type of approach has been demonstrated by a number of workers for a variety of situations including Vanmarcke (1977), Wu and Kraft (1970), Sidle (1987, 1992), Ward et al. (1979, 1981) and Cheng and Christopher (1991). Generally, the random variables are considered to be independent of each other.

Another approach to probabilistic stability analyses is to employ a Monte Carlo simulation, wherein the stability analysis is performed many times (presumably by computer), and the most important input variables are randomly varied between each realization of the analyses according to the given probability distribution of the variable. This is the approach employed by the FASSA program. The mean values and the coefficients of variation of each variable are specified by the user or are calculated by the program based on parameters specified by the user. The methods of Box and Mueller (1958), are used to generate the random deviates of each variable for each realization of the analysis.

The Monte Carlo simulation is employed by the program to predict the probability of failure of each grid cell. In this Monte Carlo simulation, the soil cohesion, soil friction angle, soil unit weight, and soil saturated hydraulic conductivity are all treated as normally distributed, independent random variables with the mean values and standard deviations of each variable applicable to the entire grid area. The apparent cohesion from roots and the vegetation surcharge are also treated as normally distributed independent variables with a single distribution applicable to the entire grid, except that the mean values for each year are deterministic functions of time.

The soil depths and elevation estimates are also treated as independent, normally distributed random variables, except that mean values are specified for each grid cell location. The water table conditions at each grid cell are functions of the randomized topography and the stochastic representation of weather. By assigning individual mean values of soil depth to each grid cell location, the relationship between the topography, soil depth, and water table conditions can be accounted for.

Consideration was also given to the possibility of assigning individual mean values of the soil and vegetation parameters to each grid cell. This would be a better representation of the spatial variability _if_ sufficient data was available. However, for the relatively small size of the area that can be analyzed by the present computer code, this feature would not often be an advantage, and is actually a disadvantage in cases where sufficient data is not available as is explained below.

In the current computer code, the random distributions that represent the soil and vegetation parameters, are assumed to represent both the "spatial variability" of the parameter and the "uncertainty" of the estimate. "Spatial variation" is the amount the parameter varies from point to point, where as the "uncertainty" would arise from errors in sampling and measuring the value of the parameter at a point. Considering that both spatial variability and sampling/measurement errors result in uncertainty at a given grid cell location, there is no analytical distinction made between the two sources of uncertainty.

The present version of FASSA varies each of the soil and vegetation parameters over the whole grid as a unit. For example, all the cells in the grid will have the same friction angle during each realization of the Monte Carlo analysis. Based on the desire to represent spatial variation within the grid, early versions of the FASSA program varied the soil and vegetation parameters at each cell individually (ie. each grid cell varied independently even though all cells had the same means and standard deviations). This would result in a different value of friction angle (for example) for each grid cell during a single realization of the Monte Carlo analysis. Although both methods produce the same end result with regard to total number of failures in the grid and for each grid cell, the earlier method resulted in a higher incidence of at least one failure occurring during each realization of the Monte Carlo analysis. In fact, for large grids, under typical marginally stable forest conditions, there was almost never a realization wherein at least one cell didn't fail. The reason was that by varying the parameters of each of the grid cell independently, each realization of the entire grid, was actually many realizations of the individual grid cells.

In conclusion of this point, varying the soil and vegetation parameters independently in each grid cell or over the whole grid at once appears to produce the same end result with regard to total number of failures in the grid and for each grid cell. This makes sense considering that the parameter values of each grid cell have the same distribution by either method. However, to prevent an unrealistically high incidence of at least one failure occurring during each realization of the Monte Carlo analysis, all parameters that have a single mean value and standard deviation that apply to the whole grid should be varied as a unit over the grid.

If it were decided to assign individual distributions of the individual soil and vegetation parameters to the grid cells, the spatial variability represented by the differing distributions should be realistically determined, or there will be a higher incidence of at least one cell failing during each realization. In other words, if individual distributions are assigned to each grid cell, the distributions should be representative of the conditions within each cell.

As was previously mentioned, the probabilistic nature of the FASSA program also accounts for the stochastic nature of precipitation events. Based on the authors research of previous work, the consideration of both the stochastic nature of precipitation and the uncertainties of the input parameters in a single analysis is unique among existing methods of slope stability evaluation. While the rules of probabilistic combination are complex, the author believes that the conceptual framework of the FASSA analysis allows a realistic and sound method for combining these two distinct sources of uncertainty.

5.0 TOPOGRAPHIC ANALYSIS

5.1 General

Based on the importance of drainage concentration and slope angles it is apparent that the measurement and representation of the topography is a critical component of the overall analysis. In addition to the physical importance of topography on slope stability, the representation of topography in the model determines the basis of the data structure for the rest of the analysis.

Several possibilities exist for topographic modelling. Three basic systems were considered for incorporation into the FASSA model:

1) A Triangulated Irregular Network (TIN) and the associated data structures are finding increased use in topographic modelling for engineering applications. The TIN methodology models the topography as a collection of irregular triangular facets. The data structure of the TIN regards the nodes of the TIN network as the primary data. The topological relations between nodes are built into the database using pointers from each node to each of its neighboring nodes. Several variations of the TIN methodology have been devised including those of Peuker et al. (1978) and Dutton (1984). The advantages of the TIN structure include very simple calculations of slope and aspect since each facet is planer. A variety of hydrologic models are therefore possible using a TIN. Silfer et. al. (1987) presents an example of a deterministic, finite difference hydrologic model that utilizes a TIN as a basis. The main disadvantage of a TIN for any simulation model is the relatively complex data structure. In addition, the TIN boundaries, which represent the topography, may not coincide with the natural boundaries of the soils and vegetation.

2) A contour-based topographic model wherein the terrain is discretized into small irregularly shaped polygons based on contour lines and their orthagonals (streamlines). An example of this type of model is presented by Moore et. al.

(1988). The advantage of this system include a very accurate delineation of upstream contributing areas, but the primary disadvantage is that a much greater amount of topographic data is needed (in a contour line format) than is needed to describe a similar surface using a TIN or a grid format.

3) A grid network wherein the terrain is represented by a rectangular matrix of elevations. This is the most common data structure for digital terrain models and is the data structure selected for the FASSA program. Examples of other similar models that have used this data structure are described by Armstrong (1976), Ahnert (1976), and Hirano (1976) who all used grid networks for their three-dimensional simulation models of landform development. A number of workers including Heerdegen and Beran (1982), Evans (1980), and Zevenbergen and Thorn (1987) have fitted 5 to 9 parameter polynomials to grid elevation data to solve for slope and aspect at any given point based on the surface described by the point and its 8 neighboring points. The primary advantage of the grid network is in the simple data structure. The primary disadvantage for this case is the rather crude approximation of upslope contributing area for each cell. The problem occurs because the assumed passing of flow from a cell to one of its eight neighboring cells results in a relatively rough approximation of the actual flow direction.

5.2 Topographic Methods Used by FASSA

Data input to the FASSA model includes a digital terrain model of the area to be analyzed. The input digital terrain model consists of a rectangular grid of elevation mean values, and an associated estimate of the standard deviation of the elevation values. The necessary measurements of the existing topography could be made by any method. The use of stereo pairs of aerial photographs with an analytical plotter is particularly efficient because the digital output of the analytical plotter is directly usable by the computer, and stereo photographs of sufficient scale are generally more available for forested areas than sufficiently detailed topographic maps. However, an obvious problem with using photogrammetry in densely forested areas is that the trees obstruct the view of the ground surface.

The method that has been employed by the author to digitize a rectangular digital terrain model with uniform grid spacing is as follows:

1) Digitize all breaks in topography such as ridge tops, gullies, and all other significant grade breaks into X, Y, and Z coordinates using either a topographic map on a digitizing table, or stereo aerial photographs on an analytical plotter, or results of conventional surveys.

2) The commercial program "SURFER" by Golden Software Inc. is used to calculate the surface described by the collection of randomly spaced X, Y, and Z coordinates and then to calculate the elevations of points on a user specified, regularly spaced rectangular grid. The SURFER program allows the surface to be interpolated by several methods including Kriging (Davis, 1986), inverse distance (Surfer Users Manual, 1989) or the minimum curvature method of grid interpolation (Briggs, 1974). Based on numerous trials using all three methods, the Kriging method consistently returned interpolated terrain models most similar to the actual terrain, in the authors opinion. For this reason, the Kriging method is used by the author for the examples in this dissertation.

3) The output file from the SURFER program must then be converted to the correct data format for input into the FASSA program. This is accomplished using the GRDTODAT program written by the author.

The topographic analysis internal to FASSA is performed by the Fortran subroutine "TOPOGS" at the start of each trial of the run. The methodologies used in TOPOGS were adapted from an earlier program by Zevenbergen and Thorne (1988). TOPOGS evaluates the topographic indices: slope; aspect; and upslope contributing drainage area. To do this, a nine-parameter polynomial that describes the surface of the 3 x 3 submatrix surrounding each point is determined. The surface passing through all 9 points of the 3 x 3 submatrix is described by the partial quartic equation:

$$Z = AX^2Y^2 + BX^2Y + CXY^2 + DX^2 + EY^2 + FXY + GX + HY + I$$

The nine parameters A through I can be determined from the nine elevations of the 3 x 3 submatrix by Lagrange polynomials. With the determination of parameters A through I, the surface is defined and the slope and aspect at the center point can be evaluated. The slope (α) is the first derivative of Z with respect to S, where S is the horizontal distance in any direction Θ.

$$\alpha = dZ/dS = G \cos\Theta + H \cos\Theta$$

Since, the solution is only wanted at the central point (where $X = Y = 0$), and at the central point $\cos\Theta = -G/(G^2 + H^2)^{1/2}$ and $\sin\Theta = -H/(G^2 + H^2)^{1/2}$, the slope at the central point can be reduced to:

$$\alpha = -(G^2 + H^2)^{1/2}$$

The negative sign indicates that the direction, Θ, is downslope and is by convention ignored. The maximum slope direction (the aspect) is found by differentiating the above equation with respect to Θ to find its minimum.

$$d\alpha/d0 = -G \sin\Theta + H \cos\Theta = 0$$

or

$$\Theta_{max} = ASPECT = \arctan(-H/-G)$$

The signs of the numerator and denominator (H and G) in this equation determine in which quadrant the aspect lies.

The upslope contributing area (uparea) is calculated for each cell using the previously determined aspects to determine the direction of flow from each cell. The uparea of each cell is the sum of all the upareas of adjacent contributing cells, plus the area of the cell itself. The uparea of each cell is passed on to one of the 8 adjacent neighboring cells, depending upon the aspect of the cell. Several passes through the grid matrix are necessary (from different directions) to arrive at the correct uparea for every cell in the grid. An option in the program allows the user to manually add uparea to specific grid cells to simulate manmade discharge points such as drywells or road drainage culverts. The topographic indices calculated by TOPOG are written to the common arrays to be used in the remainder of the analyses in the FASSA program.

5.3 Grid Cell Dimension

The selected grid cell dimension is clearly an important consideration. The optimum grid cell dimension is related to the density and reliability of the input data. Although definitive methods of determining the optimum grid cell dimension have only been developed with regard to the topographic data, the precision and spatial variability of the soil and vegetative parameters and the soil depth data are equally important in determining the optimum grid cell dimension. This aspect is discussed in more detail in the Section 11 of this dissertation.

In addition to being related to the precision and spatial variability of the input data, the minimum recommended grid cell dimension is also related to the absolute value of the soil depth due to the assumed infinite slope failure mechanism. Since the infinite slope equation assumes that the length of the failure mass is substantially greater than its depth, the author suggests that the grid cell dimension be at least 6 or 8 times the average soil depth so that the stability of the individual grid cells are relatively independent of neighboring cells.

With regard to the topography, the optimum grid cell dimension depends both on the precision of the topographic data, and the complexity of the terrain. The notion that a smaller grid cell dimension would always be better is not true. For example, it is intuitive that significant errors could result in the calculated slopes and aspects of grid cells 1 meter in dimension if the precision of the elevation data was plus or minus 1 meter; however, if the grid cell dimension was lengthened to 10 meters, that precision in elevation data may be adequate, and the results would probably be better. It is also intuitive that it would require a finer grid cell dimension to describe very complex or broken topography than would be required for gently rolling or nearly flat topography.

A number of optimizing methods have been developed to determine the best grid cell dimension for a given data set. Several of these analysis methods can be performed using the computer subroutine STATS by Zevenbergen and Thorn (1985). Given a digital terrain model (DTM) and a value for the precision of the given grid cell elevations, the STATS program will determine the optimum grid cell dimension. The determination can be performed by three different methods incorporated into the STATS program. The method favored by the authors of STATS is the method of least squares to minimize the errors of calculating slopes. For the DTM of the hydrologic study area (shown in Figure 5), for which the estimated precision of the grid cell elevations are on the order of plus or minus 1 meter, the optimum grid cell dimension was analyzed to be about 4.5 meters.

With regard to the topographic analysis, perhaps the most significant effect of the grid cell dimension in the FASSA program is on the determination of upslope contributing area (uparea). Since the uparea is an important factor in the hydrologic analysis, additional discussion of this point is given in the section on hydrologic modelling. However, to demonstrate the effect of grid cell dimension, the upareas of the study hollow shown in Figure 5 were calculated using a grid cell dimension of 6 meters, and using a grid cell dimension of 2 meters (both sides of the above determined optimum of 4.5 meters). The results are presented in Figures 6 and 7. As can be seen by comparing the figures, the smaller grid cells resulted in the channelizing of the uparea flow routes. The results of the analysis using the larger grid cells, which are considered to be closer to optimum size for the given topographic precision, did not channelize the subsurface flow as much. In reality, small surface irregularities that would not be discerned by larger grid cells would affect the localized surface drainage. However, small surface variations would have only minor affect on the subsurface drainage since the process of infiltration would not be greatly affected by minor surface irregularities and the build up of a saturated flow depth over the buried bedrock surface would tend to "flood out" minor irregularities in the bedrock surface. In addition, since the bedrock surface is more important in determining subsurface flow, and is less precisely known than the soil surface, the larger grid cell dimensions are thought to result in a better representation of the actual site conditions for this case.

In summary, the optimum grid cell dimension is intimately tied to the nature of the input data. A general discussion of the concept of an optimum grid cell dimension with regard to the topographic data is given above. The same relationships between terrain complexity (spatial variation of data) and precision (uncertainty) of the data are as applicable to the soil and vegetation parameters as they are to the elevation data. In addition, there are physical constraints on the grid cell size due to the mechanics of the infinite slope analysis (the grid cell dimension should be at least 6 or 8 times the soil depth) and the need to distinguish the topographic form of hollows. It should also be noted that the optimum grid cell dimension will likely be different for each parameter or criteria considered. Due to the complexity, no rigorous method has been devised to determine the optimum grid cell dimension for the analysis. Based on engineering judgement considering typical conditions, the author recommends a grid cell dimension in the range of about 5 to 15 meters.

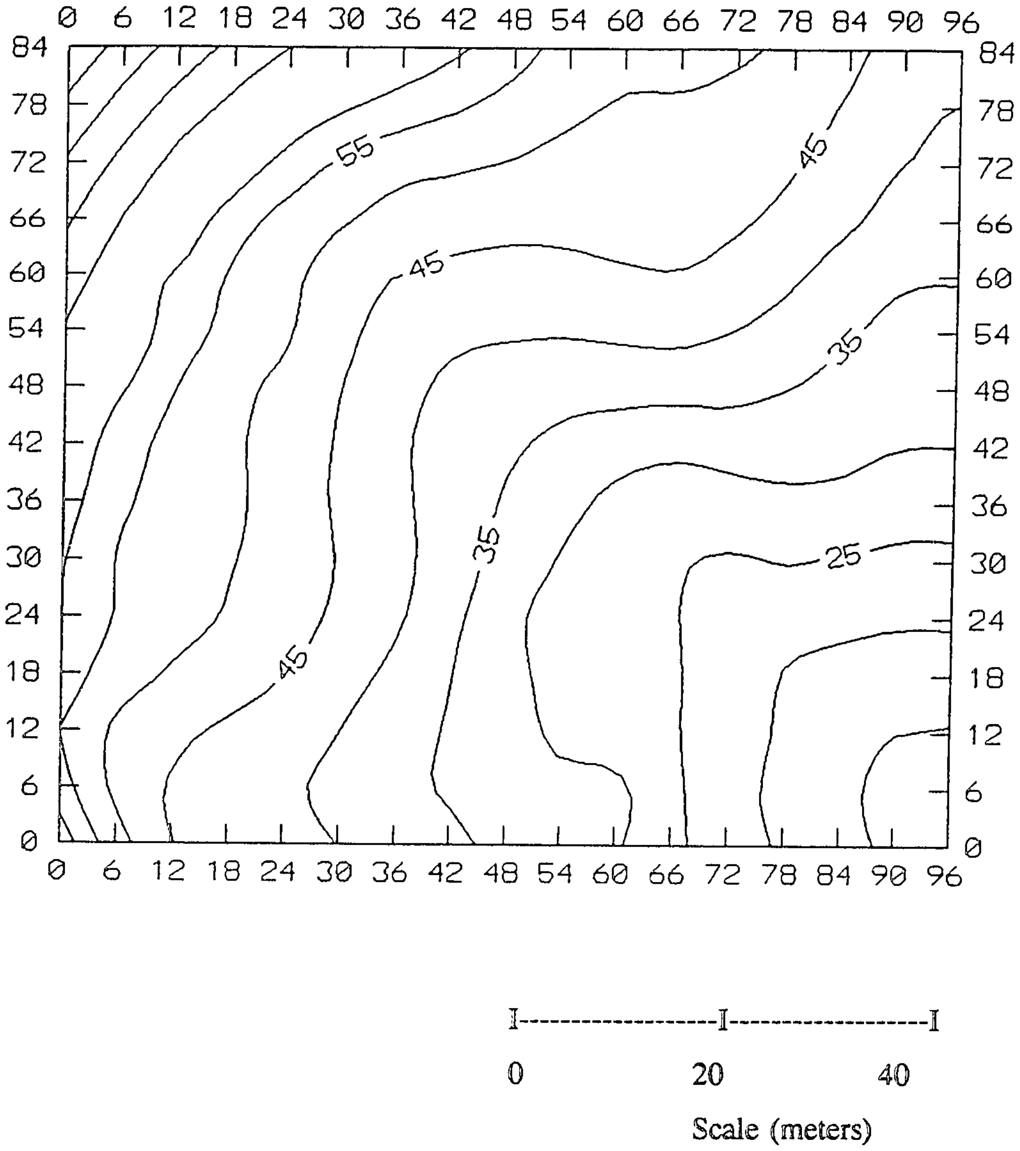
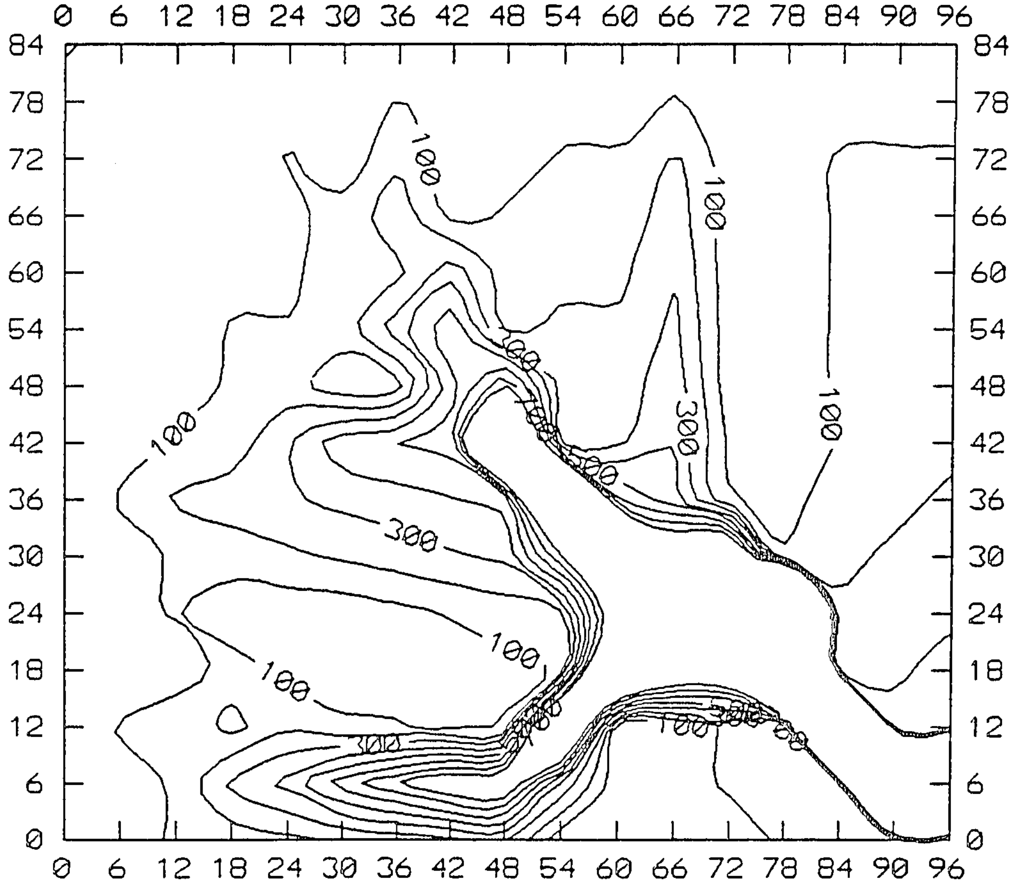


Figure 5

Topography of Study Hollow

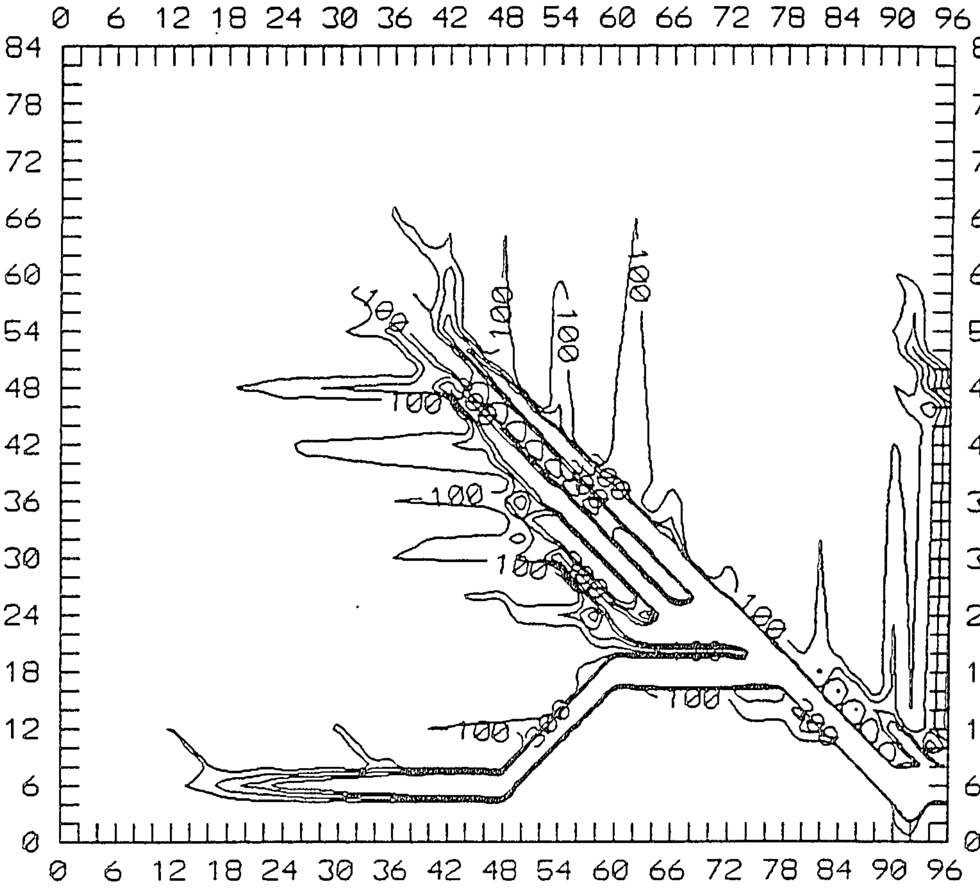


Note: Contours represent square meters of uparea

I------------------I------------------I
0 20 40
Scale (meters)

Figure 6

Upslope Areas Estimated With 6 Meter Grid Cell



Note: Contours represent
square meters of uparea

I-------------------I-------------------I
0 20 40
Scale (meters)

Figure 7
Upslope Areas Estimated With 2 Meter Grid Cell

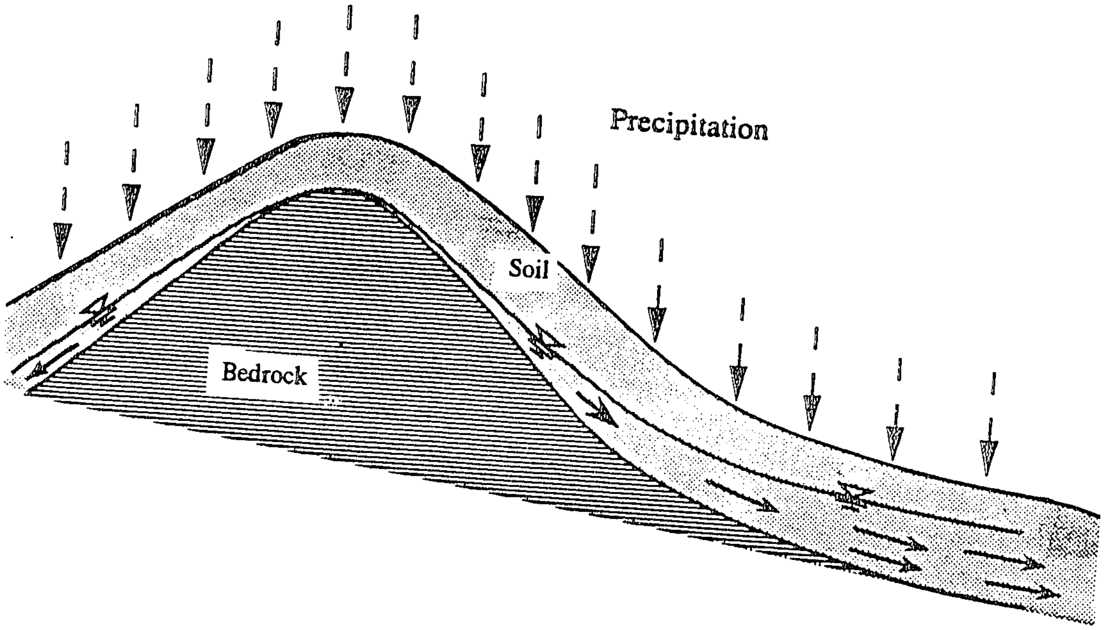
6.0 HYDROLOGIC MODELLING

6.1 General

The water table elevation is a critical factor in the evaluation of slope stability, but is also difficult to predict without relatively detailed and complex modelling of the specific hydrogeologic regime. Since the water table conditions in forested mountain areas are typically transitory, changing with the weather, a method is needed that will model the relationship between weather and the resulting water table. Although it varies with site conditions, previous research indicates that the flow in typical forested areas can commonly be characterized by 100 percent infiltration of precipitation (Dyrness, 1969), the development of a saturated zone above the underlying bedrock or consolidated material, and then saturated flow in the soil roughly parallel to the bedrock surface, Buchanon et al. (1990), Reddi an Wu (1991), Jackson (1991). This situation, which is assumed for the FASSA hydrologic model, is illustrated schematically in Figure 8. As would be expected for this flow regime, high water tables develop in areas with significant upslope contributing areas. These areas occur near the bottoms of long planer slopes or in areas of convergent topography such as hollows.

The time required for the full development of the transitory water table depends on the nature of the precipitation and the site conditions. Several general rules of thumb regarding the correlation between precipitation and landsliding in the Puget Sound Region have evolved by general observations of experienced workers in the field.

One such rule of thumb is for the widespread occurrence of slope failures on natural slopes when at least 3 inches (about 8 millimeters) of rain occurs in 2 days (W.L. Shannon, 1989, personal communication). Tubbs (1974) stated a similar conclusion that widespread landsliding occurs in Seattle when approximately 1.5 inches (about 4 millimeters) of rain occurs in a single day. Peck (1967) states that "The larger the sliding mass and the lower its average permeability, the longer is the period of rainfall that is most likely to correlate well with the movements." Peck presents several case histories wherein movements of large failure masses were correlated to the rainfall in the



∇ Water Table

Figure 8

Transitory Water Table in Mountain Soils preceding 10 day period. This is consistent with the occurrence of relatively small surficial sloughs correlating to the rainfall occurring in a single day.

Results of piezometer monitoring in forested, mountainous areas by Swanston (1967) and Cundy (1990), indicate that the water table responds rather quickly to precipitation everywhere on a slope, but the downslope and convergent zones exhibit the highest responses and longest buildups and recessions. In general, these observations also indicate that peak water tables in hollows usually lag several hours from the peak storm intensities for typical storms in the Pacific Northwest lasting 6 to 10 hours.

Piezometry studies by Swanston (1967) in southeast Alaska indicated that soil pore water pressures in thinly-soiled mountainous terrain were well-correlated to the daily precipitation amounts. In this study, regression analysis of the data from ten piezometers indicated that the piezometric head could be estimated from the daily rainfall by an equation of the form:

$$Y = a + b/X + cX$$

Where: Y = piezometric head
X = daily rainfall amount
a, b & c = constants determined by the regression analysis.

A distinction was noted between piezometers located on upper slopes outside of drainage depressions as compared to piezometers located on lower slopes and within drainage depressions. The correlation coefficients for the regression analysis were 0.81 for piezometers outside drainage depressions and 0.86 for piezometers within drainage depressions.

In summary, the results of the study by Swanston (1967) indicated that:

1) the piezometric head fluctuates quickly with precipitation such that it is highly correlated to the 24-hour rainfall amounts.

2) the piezometric head also depends on topography in that the piezometric level rises higher at points with significant upslope contributing area as compared to points with little contributing area.

6.2 Hydrologic Modelling Employed by FASSA Program

A number of methods were considered to model the above described nature of the transitory water table. The desired operation mode of FASSA is to model slope stability over time taking into account the local climate. Based on the previously described correlation between the daily rainfall and piezometric levels, and the fact that 24-hour precipitation levels values are one of the more commonly available forms of precipitation data, it was desirable to utilize 24-hour precipitation values for climatologic input into the program. The selected approach was to estimate the peak groundwater conditions resulting from a particular rainfall event by assuming steady state, saturated flow conditions and conservation of mass.

The hydrologic model is derived by assuming that the flow through each grid cell (Q) is equal to the upslope contributing area multiplied by the steady state rainfall intensity. The appropriate steady state rainfall intensity is based on the annual maximum series of 24 hour precipitation values for the area. In other words, the rainfall intensity that is input into the model for each year of the analysis, is proportional to the largest 24 hour rainfall event for that year.

Since the 24 hour precipitation values represent the average rainfall intensity over 24 hours, the program factors this intensity as specified by the user to get a steady state intensity to be used in the analysis. The program also has a feature that allows upslope contributing area to be manually added to specified grid cells to simulate man made discharge points such as drywells and road culvert discharge points.

Once the flow through a grid cell is calculated using the upslope area and the rainfall intensity, the depth of the flow can be calculated using Darcy's law assuming saturated flow:

$$Q = kia$$

Where:

Q = Flow through grid cell

k = Saturated hydraulic conductivity (m/day or ft/day).

i = Hydraulic gradient which is approximately equal to the sine of the slope angle for this case

a = Area of flow which is equal to the flow depth (perpendicular to the slope) multiplied by the width of the grid cell.

Substituting the quantity $(A * I)$ for Q, where:

A = Contributing area above the cross-section in question. This area is measured from plan view.

I = Rain fall intensity (m/day or ft/day).

and substituting sin α for i, where:

α = Slope angle.

and substituting the quantity (SD * M * cos α * DIST) for the area of flow where:

SD = Soil depth measured vertically (meters or feet).

M = The saturated soil depth/total soil depth.

DIST = Grid cell dimension (meters or feet).

Yields:

$$A * I = k * \sin \alpha * SD * M * \cos \alpha * DIST$$

Solving the above equation for the ratio of the saturated soil depth to the total soil depth:

$$M = A * I/(k * \sin \alpha * \cos \alpha * DIST * SD)$$

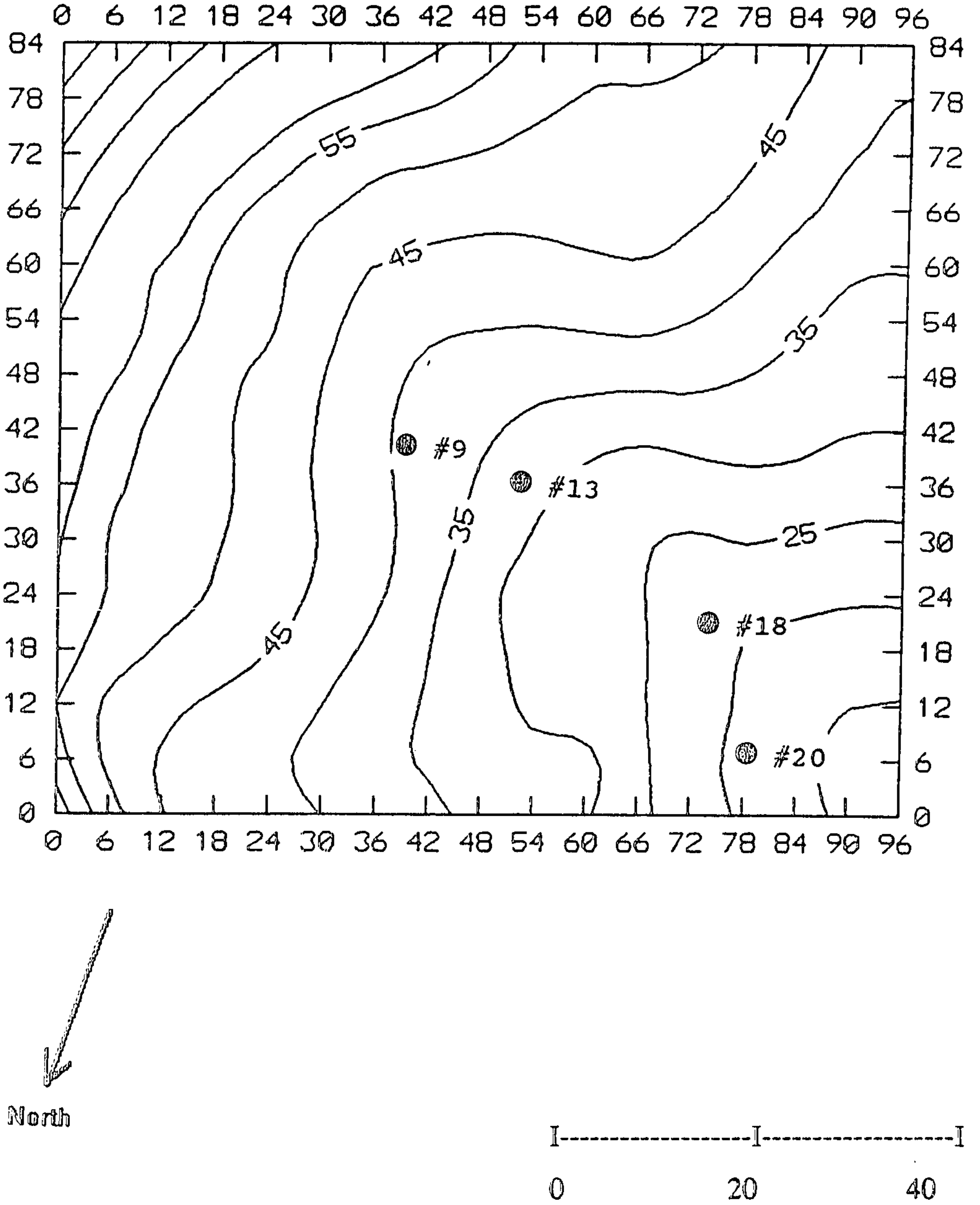
6.3 Comparison of Predicted to Measured Piezometric Levels

To check the results of the above described method, the water surface elevations predicted by the FASSA model were compared to actual peak water levels measured during selected rainfall events in an instrumented study hollow at the University of Washington Experimental Forest. The instrumented study hollow, located on the west side of the Mount Rainier National Park near Eatonville, Washington was used as an example test site for the development of this hydrologic model. The site has been developed by Dr. Terrance Cundy of the University of Washington College of Forest Resources for studies relating to forest hydrology and slope stability. Site instrumentation includes pressure transducer monitored piezometers and a tipping bucket rain gauge which are read automatically at half hour intervals by a data logger.

The soil depths at the site were measured by graduate student research assistants using seismic refraction and hand borings. These depths were later checked at several locations by the author using a case hardened steel probe driven with an electric jack hammer. The saturated hydraulic conductivity of the soils were measured by research assistants using insitu borehole permeability methods and laboratory permeability tests on recompacted samples.

The study area topography was measured using stadia surveying. The topography and the location of the piezometers selected for comparison are shown in Figure 9. Measured field data taken from this study site was used in testing the hydrologic analysis methods in FASSA to the extent possible. However, the site is not an ideal example of a thinly-soiled mountain hollow that the FASSA program is designed to analyze. Specifically, the soil profile at the study hollow consists of a relatively deep residual soil that has an indistinct boundary with the underlying bedrock.

The results of the comparisons for each of four piezometers considered are presented in Figures 10 through 13. Note that these figures only compare the "peak" piezometric levels (expressed as a percentage of the total soil depth) for a range of 24 hour precipitation values as predicted by the FASSA model and as measured at the piezometers for several storms. Note that the FASSA model was more accurate for piezometers 9 and 13, which are located higher in the hollow, as compared to piezometers 18 and 20. The author suspects that the reason may be that the steady state assumption based on 24-hour precipitation values is more applicable to the piezometers that are higher in the basin because they have a shorter time of concentration. In other words, the flow rates at the lower piezometers are more affected by long term variations



Note: Contour Interval = 5 meters

Scale (meters)

Figure 9

Topography of Study Hollow and Location of Selected Piezometers

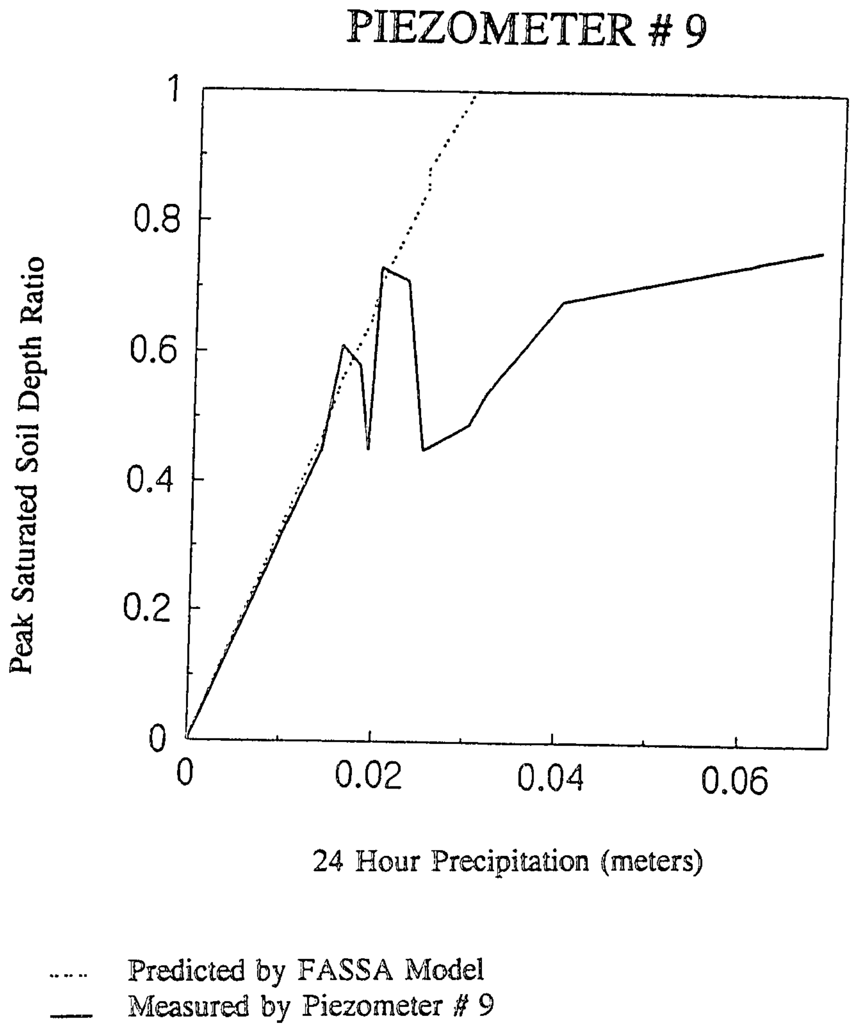


Figure 10

Saturated Soil Ratios at Piezometer # 9

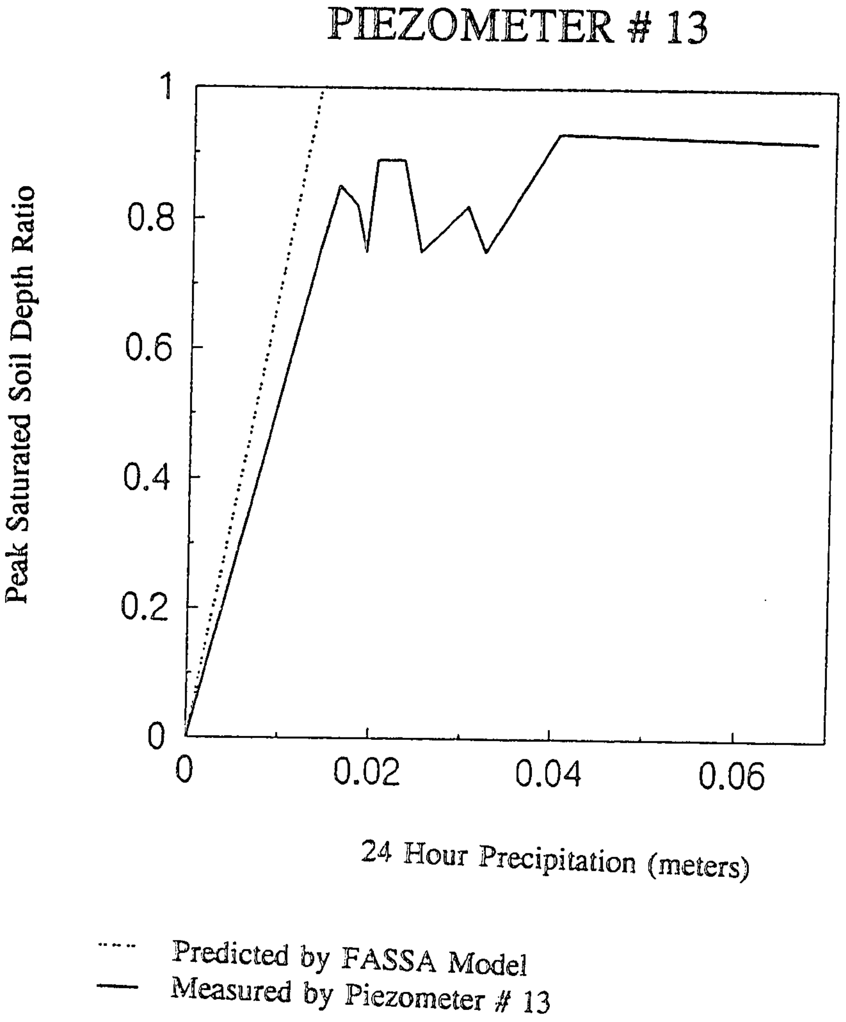


Figure 11

Saturated Soil Ratios at Piezometer # 13

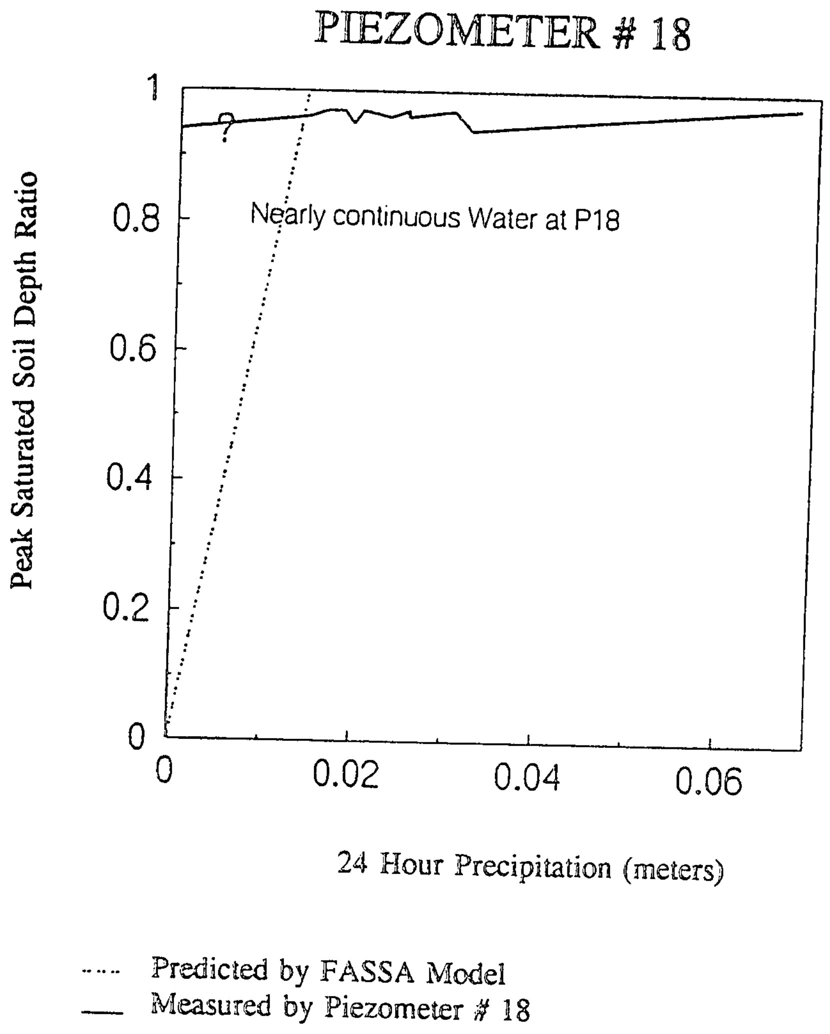


Figure 12

Saturated Soil Ratios at Piezometer # 18

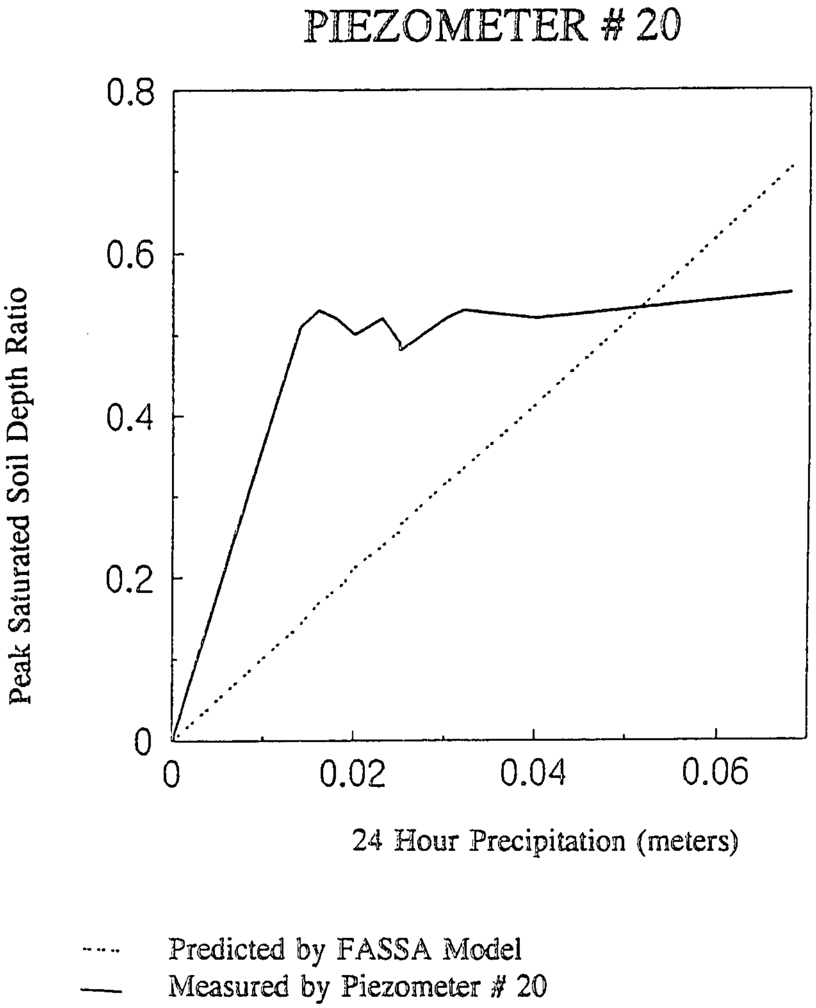


Figure 13

Saturated Soil Ratios at Piezometer # 20

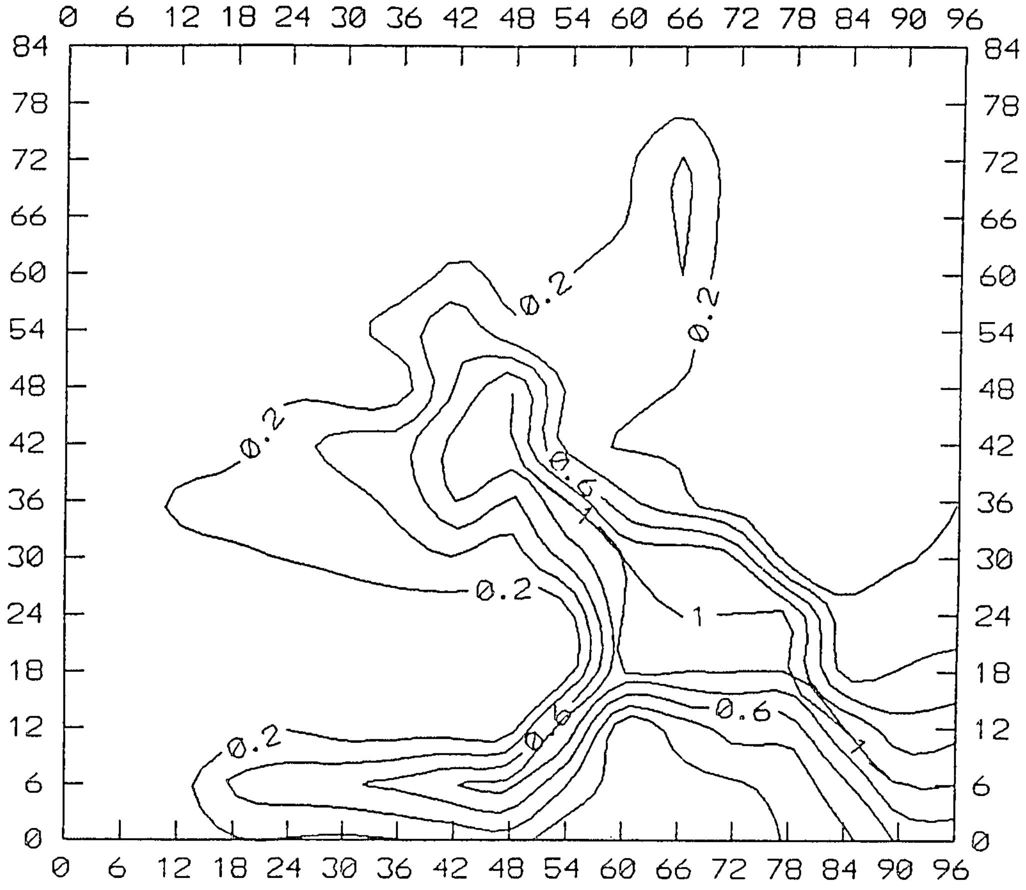
in precipitation rather than short term fluctuations as are indicated by the 24-hour precipitation. More discussion of this point is included later in this dissertation. Note also that the results are slightly conservative (estimated too high) for the range of 24-hour precipitation values that generally cause landslides (over 4 millimeters/day).

Results of the FASSA hydrologic analysis for the entire hollow are presented in Figures 14 and 15. The results are presented as a contour map of the ratio between the saturated soil depth and the total soil depth. Figure 11 presents the saturated soil depth ratios for a 1-inch, 24 hour precipitation event, and Figure 14 presents the contours for a 2-inch, 24 hour precipitation event. These piezometric levels are in reasonable agreement with the measured levels along the central axis of the hollow for similar size storms.

6.4 Applicability of Hydrologic Model

In spite of the reasonable results it generally produces, the hydrologic analysis is generally the source of the most uncertainty in the results of the FASSA analysis, in the authors opinion. In general, the FASSA hydrologic model is too simplified to accurately account for all the possible factors that influence the piezometric level. For general analysis of large areas, such as typical land management units, the present analysis is probably appropriately accurate. However, for smaller areas of analysis, such as a single hollow, where a higher level of accuracy may be desired, the author believes that a more detailed hydrologic analysis would benefit the overall analysis.

The inaccuracies associated with the present analysis stem from the assumption of steady state conditions. The steady state assumption implies that the entire upslope contributing area of each grid cell contributes flow to the cell simultaneously at the assumed steady state rainfall intensity. This would generally only occur for relatively small hollows. Although the steady state assumption is definitely not applicable to high order streams



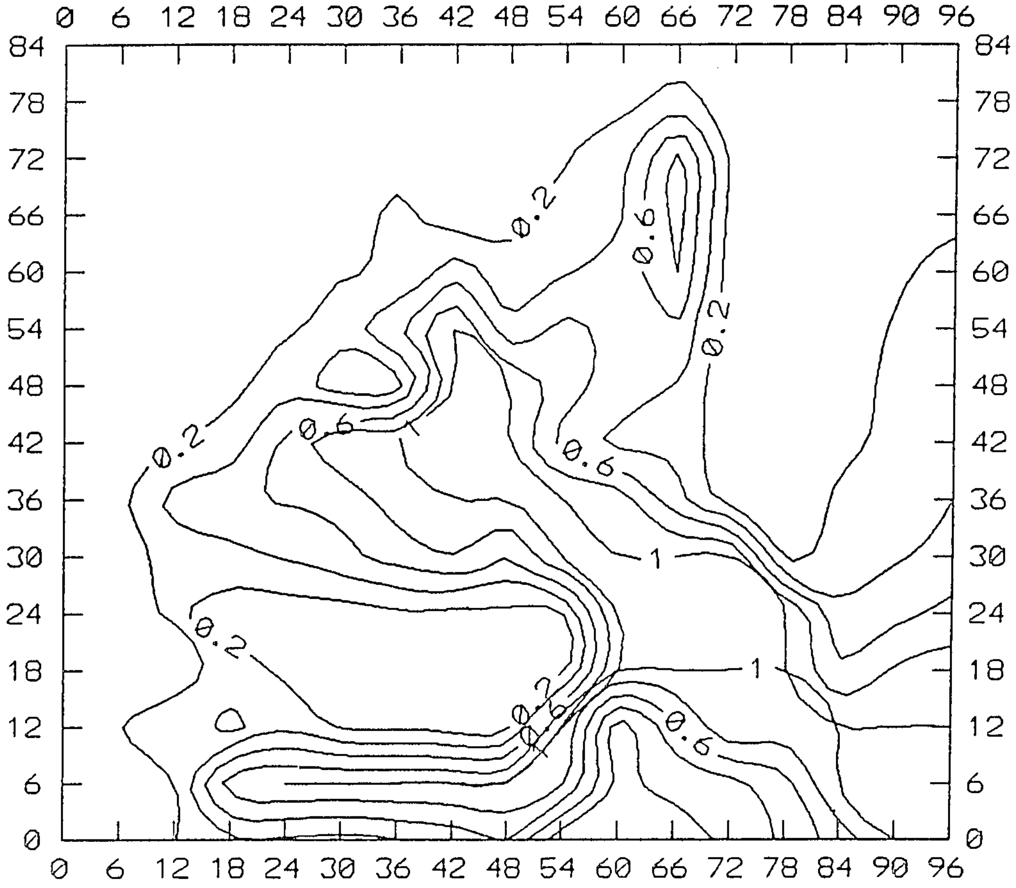
I-------------------I-------------------I

0 20 40

Scale (meters)

Figure 14

Saturated Soil Depth Ratios for 1-inch Rain



I------------------I------------------I

0 20 40

Scale (meters)

Figure 15

Saturated Soil Depth Ratios for 2-inch Rain lower in a basin, the grid cells located within the stream channels can be excluded from the analysis simply by ignoring them in the final results. This is appropriate since they are obviously not candidates for shallow surficial sloughing.

If stream channels are excluded, the hydrologic model is generally expected to be applicable to the remainder of the terrain, and especially hollows. To explore the applicability of the FASSA model to a typical hollow, consider the following simplified view of the hydrologic regime of the hollow that is analyzed for the example problem presented later in this dissertation:

The hollow is roughly 300 feet across at its widest point and about 320 feet from top to bottom (map distance). There is about 150 feet difference in elevation from the top of the hollow to the bottom, resulting in an average slope angle along the axis of about 25 degrees. The slope distance from top to bottom along the axis is about 350 feet. Considering the assumed hydraulic conductivity of the surface soils to be about 100 feet per day (which is typical for a silty sand), and the hydraulic gradient to be equal to the sine of the average slope angle, by Darcy's law, the velocity of the flow in the soil mantle is on the order of 40 feet per day. However, Darcy's law calculates the flow velocity assuming flow through the entire cross section of the saturated soil. Assuming a porosity of the soil of about 0.6, the flow would actually travel at a rate of about 67 feet per day through the pores of the soil. Based on this flow velocity, the time of concentration of the basin (the time for flow from the top of the basin to the bottom of the basin) is about 5 days.

It is apparent that for this case, steady state conditions would thus not be established in within the 24 hour storm duration. Therefore, in spite of the positive comparisons with the piezometric data of the University of Washington study hollow and the previously mentioned strong correlation between 24-hour precipitation values and pore-water pressures, the model's basis is too simple to be applicable to all situations that it is intended to model.

In spite of this problem, 24-hour precipitation values still tend to correlate well to piezometric levels (Swanston, 1967). The reason is probably because large 24-hour precipitation events often occur during longer storm events that have established somewhat high piezometric levels prior to the onset of the particular 24-hour storm analyzed. The piezometric level does indeed respond to the individual 24-hour storm event, but it is also dependent upon the rainfall that occurred several days prior.

In conclusion, the present FASSA hydrologic model generally gives the correct pattern of response to precipitation, slope, hydraulic conductivity, etc.. Based on this, and its relative simplicity, it is considered to be appropriate for a first generation model wherein continuous simulation of hydrology is desired. If future generation analyses are directed toward analyzing larger areas, this model, or a similarly simple model would probably remain appropriate. However, if future generation models tend toward more detailed analysis of smaller areas (such as single hollows) a more comprehensive transient flow model that considers several days worth of precipitation data (at least as long as the time of concentration of the hollow) would be appropriate. The development of a more detailed hydrologic analysis is discussed further in the suggestions for further research of this dissertation.

7.0 MODELLING VEGETATION EFFECTS

Since the analysis is directed at analyzing forest areas under consideration for timber harvest, vegetation effects are an important element of the model. Two effects of vegetation upon slope stability were considered: One, the reinforcement of the soil attributed to tree roots, and two, the surcharge loading of the slope by the weight of the vegetation.

There are additional effects of vegetation on slope stability, the most notable affecting the soil moisture conditions. Evapotranspiration by plants can have a significant effect on the incipient soil moisture conditions and thus the peak water table conditions for some storm events. Vegetation can also affect the infiltration capacity of the soil and has some effect due to precipitation interception by the forest canopy. These influences are ignored in this model since their effect on the piezometric levels are relatively minor compared to the accuracy of the hydrologic model. Small negative effects of vegetation due to loading of the slope from the shear exerted by a downhill wind have also been demonstrated (Wu, 1976 and Gray and Megahan, 1981). However, this effect is also minor compared to the reinforcement of the soil attributed to tree roots and the surcharge loading of the slope by the weight of the vegetation.

The reinforcement of soil by tree roots has been studied by a number of researchers including Burroughs and Thomas (1977), Chandler (1982), Gray and Megahan (1981), O'Loughlin and Ziemer (1982), Waldron (1977), Waldron and Dakessian (1981), Waldron et. al. (1983), and Ziemer (1981). The results of these investigations have illuminated a number of details regarding the reinforcement mechanisms and the resulting strength increases for a variety of situations. In general, the increase in soil strength from roots can be represented by an apparent soil cohesion.

The apparent cohesion from roots declines as the roots deteriorate after timber harvest. The total root cohesion at any time after harvest can be considered to be composed of the declining component from the decaying roots, plus the increasing component from the new roots if the area is revegetated. Figure 14 presents a typical relationship between the relative root reinforcement due to live and dead roots with respect to time after logging (Ziemer, 1981).

The root cohesion can vary considerably depending upon soil and vegetation conditions with typical values reported by researchers ranging between 1 and 12 kPa ($\approx$ 20 to 250 psf) for forested sites (Selby, 1982). The FASSA program incorporates a number of empirical relationships that define the form of the root reinforcement verses time relationship, which is then scaled according to user specified parameters.

For example, as can be seen from Figure 16, the dead root component of the total root cohesion decays asymptotical to some minimum value. This minimum value is actually zero for the long term case, but is non-zero within the time frame of the data due to the larger roots, which decay more slowly. This is represented in the FASSA program by a decay function of the form:

$$\Delta C_d = \Delta C_{dmin} + a e^{-bt}$$

Where:

ΔC_d = Dead Root Cohesion at Time t

ΔC_{dmin} = Minimum Dead Root Cohesion

a = Initial $\Delta C_d - \Delta C_{dmin}$

e = Base of natural logarithms

t = time in years

b = a constant $\approx 5/(\text{decay time in years})$

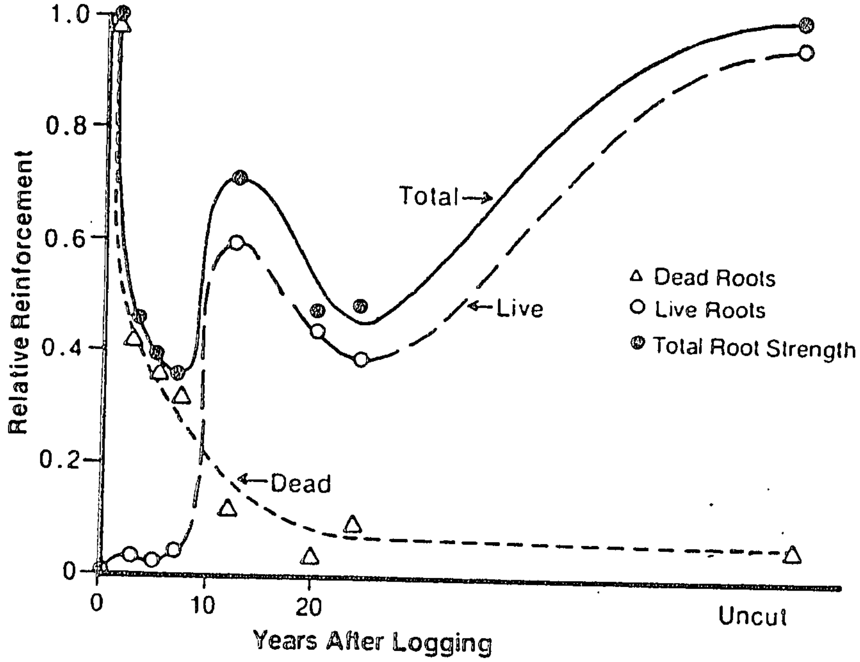


Figure 16

Apparent Root Cohesion verses Time After Logging

(after Ziemer, 1981, Reprinted with permission from Sidle, et. al., 1985)

In the FASSA program, to define the declining root cohesion attributed to the deteriorating roots, the user must specify the initial dead root cohesion, the minimum dead root cohesion, and the decay time in years. These relationships are described and the user is prompted for the appropriate values in the preprocessor program MAKEVEG, which then builds the appropriate VEG.PAR file to be used by VEG subroutine of the FASSA program.

There are a number of possibilities to model the live root component of the total root cohesion. Ziemer (1981) proposed a linear relationship between root cohesion and the biomass of roots per unit of soil for Pinus Contorta roots in coastal sands in Northern California. Since the growth of biomass with time can generally be represented by some exponential growth function, the equations could presumably be combined to result in a mathematical expression relating the root cohesion directly to time. However, since both the growth function and the reinforcement function would vary with the climate, plant species, and soil conditions of the site, no universal equation of this form would be applicable to all sites.

After consideration of several methods, the method that was selected is to scale the relative live root cohesion presented in Figure 14 (by Ziemer, 1981) according to a maximum live root cohesion. The maximum live root cohesion at the particular site in question would be estimated by considering the tree species and density compared with published values measured from similar species and densities.

If more specific data for the particular site is available, the VEG program will accept any curve defining the live root cohesion verses time that may be specified by the user. The curve is specified by providing up to 200 points of live root cohesion verses time. The program interpolates between points for intermediate time values. These two options provide both an easy method that is applicable to most situations, and a more difficult, but totally flexible method to specify the live root cohesion over the time period of analysis.

Although the effect upon slope stability due to the weight of the vegetation is relatively small (Gray and Megahan, 1981), it is relatively easily incorporated into the model. The model assumes that the total weight of the vegetation varies with time according to the following logistics function (Arya and Lardner, 1979):

$$q_o = q_{omax}/(1+c\ e^{-kt})$$

Where:

q_o = surcharge loading at time t (psf or Pa)
q_{omax} = user specified maximum surcharge load (psf or Pa)
c = a user specified constant (dimensionless)
e = the base of natural logarithms
k = a user specified constant (years^{-1})
t = time (years)

Figure 17 presents an example growth curve using $c = 60$, $k = 0.07$, and $q_{omax} = 300$ Newtons per square meter (= 7 pounds per square foot). The constants c and k can be varied to change the shape of the curve depending upon the particular species, climate, etc. As with the root cohesion, comparisons with measured values in similar forests should be made in order to estimate the maximum (terminal) vegetation surcharge, and the time it takes to achieve.

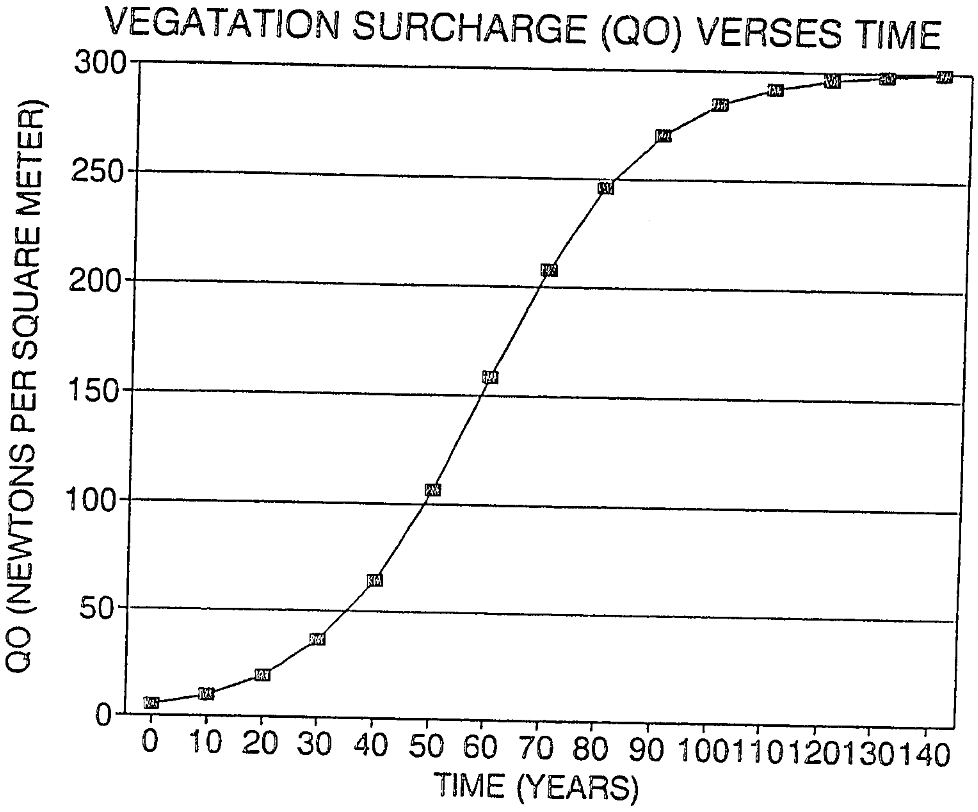


Figure 17

Example Growth Curve For Vegetation Surcharge

8.0 SUMMARY OF FASSA ANALYSIS

As indicated by the flow chart in Figure 1, the FASSA program begins by reading in all the pertinent data from the input files and keyboard. After the input data is read in, the individual trials of the Monte Carlo Analysis are started. The Monte Carlo analysis, by definition, is performed by repeatedly solving problem while varying the random variables between each trial. At the beginning of each trial, a new realization of the topography and the soil parameters are calculated by the TOPOGS and the SOIL subroutines. The topographic indices and soil parameters are written to common arrays which are used in subsequent portions of the trial.

For each trial, the time is varied from zero to the user specified maximum time. For each year of the trial, the vegetative conditions are calculated by the subroutine VEG and the hydrologic conditions at each grid cell are calculated by subroutine HYDRO. Stability calculations are then performed for each grid cell for each year, and the appropriate accounting of the number of failures, the minimum, maximum, and average factors of safety, and the average saturated soil depth ratios.

The number of trials needed for a statistically significant answer depends upon the coefficients of variation that are applied to the random variables. Based on results of trials performed during the development of the program, a minimum of about 500 trials is recommended for comparing various land use options, but less trials will generally give a reasonable indication of overall stability.

Based on the intensive computational requirements for this type of approach, it is apparent that efficient programming organization and data structure is necessary for the program to run on personal computers. Based on an a typical analysis that performs 500 Monte Carlo trials, with a grid size of 50 by 50, and a 50 year time period, 500 topographic analyses and over 60,000,000 solutions of both the hydrology and the infinite slope equation are required.

9.0 PROGRAM EVOLVE

9.1 Purpose

Soil depths are an important factor in the determination of slope stability and are difficult to measure in steep inaccessible terrain. The FASSA program requires as input a mean value of the soil depth for each grid cell. Even in the best of conditions, it is generally impractical to measure the soil depth at every grid cell location in the hollow to be analyzed. Therefore, a method is needed to interpolate limited soil depth data over the entire hollow so that a mean soil depth value can be assigned to each grid cell location.

If soil depth data is known at numerous specific locations within the hollow, the commercial SURFER program can be used to interpolate the data over the entire area by the same methods as were used for the gridding of the topographic information. However, this method requires a significant number of known soil depths, and does not take into account the relationship between soil depth and topography in assigning the soil distribution. Specifically, the knowledge that soil tends to accumulate in convergent zones of the hollows is not taken advantage of by a straight interpolation of soil depth data.

The EVOLVE program was written by the author to estimate the soil depths in hollows using limited soil depth data, and considering the processes of soil formation and downslope transport of soil materials. The program predicts soil depths that will occur in a given topography by simulating the processes that form and distribute soils. Since the EVOLVE program uses the same data format as the FASSA program, it is easily applied to a particular digital terrain model prior to analyzing the hollow with FASSA. The EVOLVE program is not an integral part of the FASSA program, but rather an accessory analysis that can be used in extrapolating limited soil depth data.

9.2 Previous Work

Simulation models of weathering, downslope transport of the weathered material, and fluvial transport have been developed by a number of workers including Kirkby (1976), Anhert (1976), Hirano (1976), Gossmann (1976), and Armstrong (1976). These models predict the evolution of landforms over time due to the simulated slope processes. The models generally consist of a matrix of elevations (a digital terrain model) and a corresponding matrix of soil depths, which are changed through time by the various processes that are considered by the models. The concepts and individual process models used in the EVOLVE program were taken from this previous work to the extent possible.

9.3 Description of Methods Used in EVOLVE

In general, the input to the EVOLVE program is contained in three input data files summarized as follows:

- Z.DAT - A digital terrain model of elevations at each grid cell location in the same format as is input into the FASSA program.
- SD.DAT - A file containing the initial soil depths at each grid cell location.
- EVOLVE.DAT - A file containing the needed constants to define the evolve mechanisms as described below.

The simulation thus begins with a digital elevation model of the land surface divided into grid cells, each of which has several calculated or assigned attributes including an elevation and a soil depth. The soil depth at any point represents the total amount of material which is potentially mobile by any of the considered processes. The program starts by calculating the slope and aspect of each grid cell using the previously described subroutine TOPOGS.

Using the topographic indices calculated by subroutine TOPOGS, three distinct soil forming and soil moving processes are modeled: 1) weathering of bedrock; 2) downslope transport by soil creep and slope wash; and 3) accumulation and attrition of forest organics into the soil profile.

The processes operating in the model are specified as equations that calculate the rate of the mechanism and the resulting inflow and outflow of soil for each grid cell. Iterations of the model are performed for a given time step, and the movement of the sediments through the system are accounted for by the continuity equation wherein the change in elevation and soil depth for each cell is dependent upon the difference between the inflow and the outflow to that cell. The topography is recalculated at a user specified time interval to take account of the evolving elevations. The continuity equations for the elevation and the soil depth at each grid cell are:

$$\Delta Z = IN - OUT$$

and:

$$\Delta SD = IN - OUT + W_a$$

where:

ΔZ = Change in elevation of the cell.

OUT = The amount (height) of material moving out of the cell

IN = The amount (height) of material moving into the cell

ΔSD = The change in soil depth.

W_a = The depth of weathering of bedrock.

Where all the above variables are expressed in consistent units of length. OUT for each cell is derived from soil creep and slope wash and is a function of the slope angle:

$$OUT = T_{st} * K_s * \sin(\alpha)/DIST$$

where:

T_{st} = The time step (in years)

K_s = Slope transport constant (length^2/year)

α = The slope at the cell

DIST = The grid cell dimension (length)

A typical value for the slope transport constant (K_s) is given by Armstrong (1976) to be on the order of 10 cm^3/cm/year. OUT can be no more than the existing soil depth at the cell. IN is the total amount of incoming sediment for each cell. As for OUT, IN is expressed as a depth over the entire cell area. IN equals the sum of all the OUTs of contributing neighbor cells plus the accumulation of forest organics. For this model, the accumulation rate of forest organics is assumed to be a constant, and of a magnitude specified by the user.

The weathering rate of the underlying bedrock is assumed to be a function of both the type of bedrock material and the depth of soil cover. The equation for weathering from Armstrong (1976) is:

$$W_a = W_p * e^{-(Kw * SD)}$$

where:

W_a = the actual weathering rate (length/year)

W_p = the potential weathering rate at a bare rock surface

K_w = a dimensionless constant for the bedrock material

SD = the soil depth at the cell

e = the base of natural logarithm

The direction and rate of soil transport through the system is thus based on the user specified constants and the aspect and slope of each grid cell. During the simulation, the topography is recalculated for the new soil distribution at a user specified time step. The source code listing of the EVOLVE program is given in Appendix C. An example of the use of the EVOLVE program is presented later in this dissertation. In general, the results of the simulation appear to be reasonable in that the resulting soil depths are greater in convergent zones than in planer and divergent zones.

10.0 APPLICATIONS AND EXAMPLE ANALYSIS

10.1 General

The FASSA program is designed to analyze the probability of slope failure for forested, mountain areas. The primary application is as a tool for forest land managers in making decisions on whether to harvest or not to harvest a specific area. In the decision making process, the FASSA program could be used to compare probability of slope failure occurring within a given time period for both the "harvest" and the "no harvest" alternatives.

Although the FASSA program is specifically designed for evaluating the effects of timber harvest, it is also applicable to other cases. One such example of an excellent application for the FASSA analysis was encountered by the author while working for Shannon & Wilson, Inc., geotechnical consultants, in Seattle, Washington. Due to the experimental nature of the FASSA program, and the fact that it was in an early stage of development at the time of the clients request, the specific results of the program were not cited in the report presented to the client. The purpose of presenting the example analysis herein is to demonstrate a typical application of the model and in the process clarify some of the useful aspects and features of the model. For this purpose, some general discussion of the model capabilities are included in the example problem.

10.2 Background Information for Example Problem

The setting for the example problem is the Sunny Shores Community located on the east shore of Puget Sound north of Everett, Washington as shown in Figure 18. The community is located on the beach, at the toe of a steep forested slope. The slope, which is prone to frequent landslides, descends from about 300 feet in elevation down to the shores of Puget Sound (at sea level). Access to the community is via a narrow road that traverses the steep hillside.

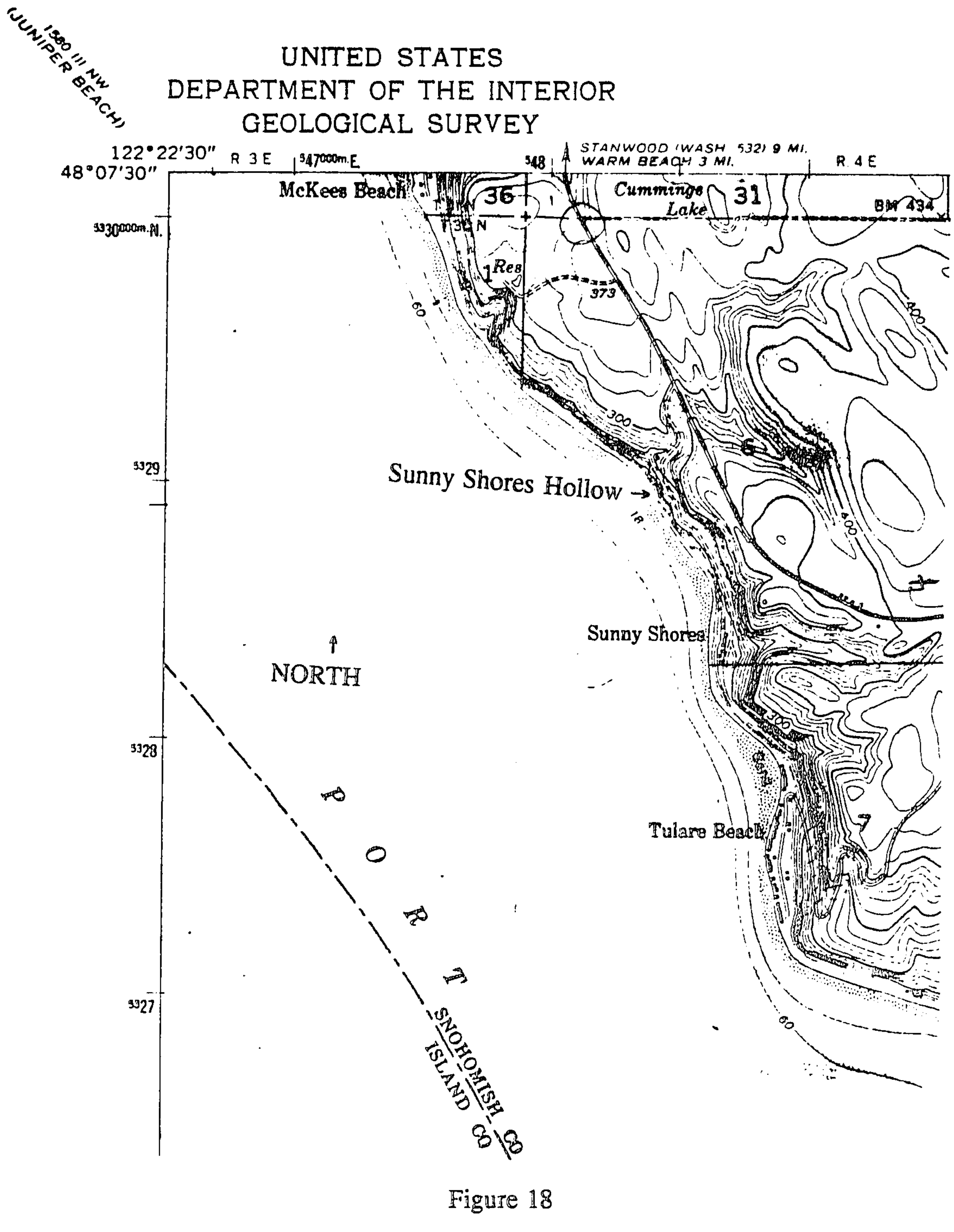


Figure 18

Sunny Shores Location and Topography

(Source: USGS 7.5 minute, Tulalip Quadrangle)

The near-surface geologic materials outcropping on the hillside generally consist of siltstone and sandstone exposed near the toe of the slope and very dense glacial deposits on the mid and upper slopes. The glacial deposits consist primarily of advance glacial outwash. The advance glacial outwash material is a very dense, lightly cemented sandy gravel. The slopes are covered with a thin layer of colluvial sand and gravel derived from the underlying very dense materials. Based on numerous probings, test pits, and observations of landslide scarps by the author, the mantle of colluvium is typically 1.5 to 3.0 feet thick and has abundant roots and organic matter. The slope appears to be mostly planer on the 1:24,000 scale topographic map shown in Figure 17, but actually has numerous subtle drainage hollows.

The slope is prone to frequent sloughing of the surficial colluvium. The author has inspected seven separate landslides that have occurred on this slope in less than three years time and has interviewed numerous longtime residents as to the history of landsliding at this site. In general, the geologic processes that appear to be at work in this vicinity are consistent with the processes that are intended to be modelled by the EVOLVE and the FASSA programs. Four of the seven landslides that were investigated by the author originated in hollows. Of the three landslides that did not originate in hollows, one was attributed to the disturbance caused by the access road, and two were caused by undermining of the toe of the slope by beach erosion.

As was described at the start of this dissertation, the failure of hollows is thought to be self-perpetuating and cyclical in nature in that colluvium concentrates in the hollows due to their topographic form, and then periodically unloads by landsliding. The unloading occurs when the soil depth gets too large to be supported by the shear strength at the base of the colluvium. The unloading is nearly always triggered by large precipitation events.

Based on observations at the site and conversations with the longtime residents, some of the hollows on this slope may have a relatively short cycle time. When exposed by a landslide, the underlying granular glacial outwash develops a colluvial cover quickly due to its susceptibility to ravelling from raindrop impact and wetting and drying cycles. As an indication of how quickly this process can occur, several inches of colluvial sand and gravel could be observed in the bottom of a landslide scarp that had occurred only 2 years prior. In addition, pebbles could be observed rolling down the landslide path at any time for nearly a year after the slide occurred, and significant accumulations of colluvium would have to be removed from the road where it crossed the landslide path after every significant rain during this period.

Although most of the landslides investigated by the author occurred in hollows located on the mid and upper slopes, there is ample evidence of previous landslides occurring near the toe of the slope due to undercutting of the toe by beach erosion. The hollows on the upper slope may be more active than typical hollows because the continuous toe cutting by beach erosion does not allow the hillside to erode to a more stable configuration. In general, the most active portions of the slope support a heavy growth of fast-growing madrona trees with deciduous undergrowth. Other portions of the slope, are vegetated with douglas fir.

10.3 Description of Example Problem

In April, 1991, Sunny Shores residents noticed some seepage emanating from the bank above the Sunny Shores access road. Since they had previously only observed seepage from this location during or shortly after extreme rainfall events, they thought it unusual to observe nearly continuous seepage during most of the rainy season. Shannon & Wilson was requested to visit Sunny Shores to observe the seepage and provide our opinion as to the probable cause and possible consequences of the seepage.

Based on the authors observations at the site, the natural upslope contributing area to the observed seepage is a small natural basin (a hollow) extending several hundred feet behind the bank. Since the seepage area was located directly below two recently constructed upslope houses, the owners of the houses were questioned as to possible sources of water from the houses.

Based on conversations with the homeowners, it was learned that the septic drainfields of both houses were not within the upslope contributing area of the observed seepage. However, a dry well (which is basically a drainfield to dispose of runoff surface water) serving approximately 5000 square feet of impervious house and driveway area did discharge into the top of the hollow.

The natural topography was such that the homesites did not naturally drain toward the hollow. As such, this diversion of flow to the dry well at the top of the hollow essentially added approximately 5000 square feet of drainage area to the hollow. The Sunny Shores residents then wanted know the consequences of this additional drainage, and if it had a significant destabilizing effect upon the hollow.

10.4 Technical Approach to the Problem

During the initial site visit, preliminary site data was gathered using the 1:24,000 scale USGS topographic map, an Abney level to measure slopes, a 5/8" diameter steel probe to measure the depth of the colluvial soil cover at several locations, and a posthole digger to excavate shallow test pits to obtain soil samples.

Based on information available after the initial site visit, it was estimated that the hollow above the seepage area has a natural upslope contributing area of about 50,000 square feet. The addition of 5000 square feet of drainage area to the hollow was thus considered to be fairly significant.

The slopes over most of the hollow were measured with the Abney level to be between about 35 and 40 degrees from horizontal, although some localized areas were even steeper. In general, the steepest areas are the mid-slopes of the hollow.

Based on soil probing and two test excavations, the soil depths varied between about 1.5 and 3.0 feet in depth (measured vertically). The near surface soils are a relatively loose sand and gravel, with abundant roots and organics. Although the soil was relatively loose, it was also angular and coarse, and was estimated to have a friction angle of about 36 degrees. Based on the coarse texture of the soil, the soil cohesion is assumed to be negligible (except from roots). Based on rough measurements of in place density of a driven thin-walled tube sample, the insitu dry unit weight of the soil was about 80 pounds per cubic foot. Assuming an average specific gravity of the soil of about 2.0 (which assumes the soil solids are about 70% mineral and 30% organic by volume) the porosity (the volume of the solids divided by the total volume) of the soil would be about 0.6. From these assumed soil phase ratios, the saturated unit weight of this material can be calculated to be about 105 pounds per cubic foot.

Using the above described information collected during the initial site visit, the following trial calculations of the infinite slope equation were performed to get an idea of the existing stability of the hollow and to demonstrate the problems associated with traditional, deterministic factor of safety approach to evaluating slope stability. The results of the calculations are presented in Table 3.

Table 3

Results of Trial Infinite Slope Stability Calculations

	Trial Number					
Parameter	1	2	3	4	5	6
Friction Angle (degrees) =	36	36	36	36	36	36
Soil Cohesion (psf) =	0	0	0	0	0	0
Saturated Unit Weight (pcf) =	105	105	105	105	105	105
Soil Depth (feet) =	3	3	3	3	2	2
Saturated Soil Depth Ratio =	1.0	1.0	1.0	1.0	1.0	0.5
Slope (degrees) =	42	42	42	42	42	42
Surcharge From Vegetation (psf) =	0	0	7	7	7	7
Root Cohesion (psf) =	0	160	160	80	80	160
Calculated Factor of Safety =	0.33	1.35	1.34	0.84	1.08	2.17

The first calculation demonstrates the results of the conservative approach wherein the worst case conditions are assumed to occur at one location on the slope (i.e. the steepest slopes, the greatest soil depth, and fully saturated soil layer). In addition, the vegetation effects of root reinforcement and vegetation surcharging of the slope are also ignored. It is apparent from the resulting low factor of safety (0.33) that this most conservative approach is not realistic.

In the second and third trials, the effects of root reinforcement and vegetation surcharge are considered by assuming a root cohesion of 160 psf (which is a typical value for forested slopes) individually in trial 2, and the considering the additional effect of vegetation surcharging in trial 3. As can be seen from by the comparison of the results of calculation numbers 1 and 2, root reinforcement is a critical component of slope stability at this location. Conversely, as is seen by the comparison of calculation numbers 2 and 3, no significant effect of the vegetation surcharge is noted for this case.

This is typical for granular soils wherein the primary strength is from friction. Vegetation surcharge can have a significant effect in cases where the soil is primarily cohesive.

Considering the sensitivity of the factor of safety to the root reinforcement, and the relative uncertainty and variability of this strength component, a conservative analysis may assume a low value of root reinforcement. By reducing the root reinforcement from 160 psf to 80 psf, a more conservative estimate of the factor of safety is obtained in trial 4. The results of calculation number 4, which takes into account the vegetation effects, still indicates a factor of safety of less than one. In the authors experience, this will typically be the case for a calculation that combines the worst case conditions for the entire hollow at one location.

In order to get a more reasonable estimate of the actual stability of the hollow, numerous calculations that consider the conditions at specific locations on the hollow should be performed. For example, trial 5 calculates the factor of safety at one of the steepest midslope locations where probing indicted that the soil depth was about 2 feet. The results indicated a factor of safety of 1.08. This calculation would indicate that the slope is just barely stable.

A less conservative but still realistic estimate may assume that this midslope location is not subject to a fully saturated soil profile. Trial 6 assumes a saturated soil ratio of 0.5, and in addition assumes a less conservatism estimate of the root cohesion. The resulting factor of safety is 2.17.

This last calculation would indicate that the hollow is quite stable. However, as can be seen by comparing the results of all of the above calculations, a wide range of factors of safety can be calculated for the above slope. All of the above calculations are realistic, yet with the above results, it is difficult to draw any conclusions as to the stability of the hollow, let alone the effect of adding the dry well. In the authors experience, this is typical for a deterministic analysis of a natural slope, and demonstrates why an alternative analytical approach is needed.

It is apparent from the above calculations that the uncertainty and variability of the important input variables should be considered in evaluating slope stability. Given the relatively high uncertainties and variabilities of natural slopes and soils, the probability of failure, which takes into account the variable nature of the input parameters, is generally more meaningful than the calculated factor of safety. For example, a factor of safety of 1.34, as was determined for calculation number 3, would be considered fairly safe for a man-made embankment with well-known geometry and soil conditions. However, when the relatively high variability of natural soils is considered, the probability of failure for this same factor of safety may be too high for many applications.

The ability to calculate a probability of failure at specific locations on the slope is thus an advantage of the FASSA analysis over traditional deterministic factor of safety analyses, especially for evaluating natural slopes with high variability. Another significant advantage of the FASSA analysis for this case is its ability to evaluate an area as opposed to a point. As was illustrated above, the input parameters change over relatively short distances within the hollow. In addition, the FASSA analysis has a built-in hydrologic analysis that can take into account the weather and the mechanics of subsurface drainage.

As is illustrated by the above discussion, even though timber harvest is not an issue for this case, the problem still lends itself well to the FASSA program. The desired result is a comparison of the probability of slope failure of the hollow with the dry well and without the dry well. This comparison would be difficult to quantify by any other existing methods. The difference in the slope stability of the two cases depends upon how the addition of the dry well changes the peak piezometric levels for the existing hydrologic regime, and how sensitive the slope stability of the individual locations affected is to the changed piezometric levels. This comparison can be made by first running a FASSA analysis of the natural conditions existing at the hollow, and then performing a second analysis of the hollow wherein the addition of the dry well is simulated by adding the equivalent up-slope drainage area to the grid cells where the dry well is located (this is an option built-in to the program). The comparison of the number of simulated failures for both cases is an indication of the destabilizing effect of the dry well. These analyses were performed by the author and are described in the following sections.

10.5 Preparing the Data Input for the FASSA Program

As was previously described, data is read into the program from 5 data files that must be created prior to execution of the program. Briefly, the data files consist of:

- Z.DAT - A digital terrain model of elevations at each grid cell location.

- SDM.DAT - A file containing mean soil depths at each grid cell location (note: the soil depths are varied about the mean soil depths during program execution).

- SOIL.PAR - A file containing the mean values and the coefficients of variation of the soil properties.

- VEG.PAR - A file containing parameters describing the decay and regrowth of trees and tree roots with regard to the effects on soil strength and slope loading.

- HYDRO.PAR - A file describing the statistical variation in the annual maximum 24 hour precipitation events for the subject area.

These input data files, and how they were obtained for this example problem are described in the following sections.

10.6 Obtaining the Digital Terrain Model

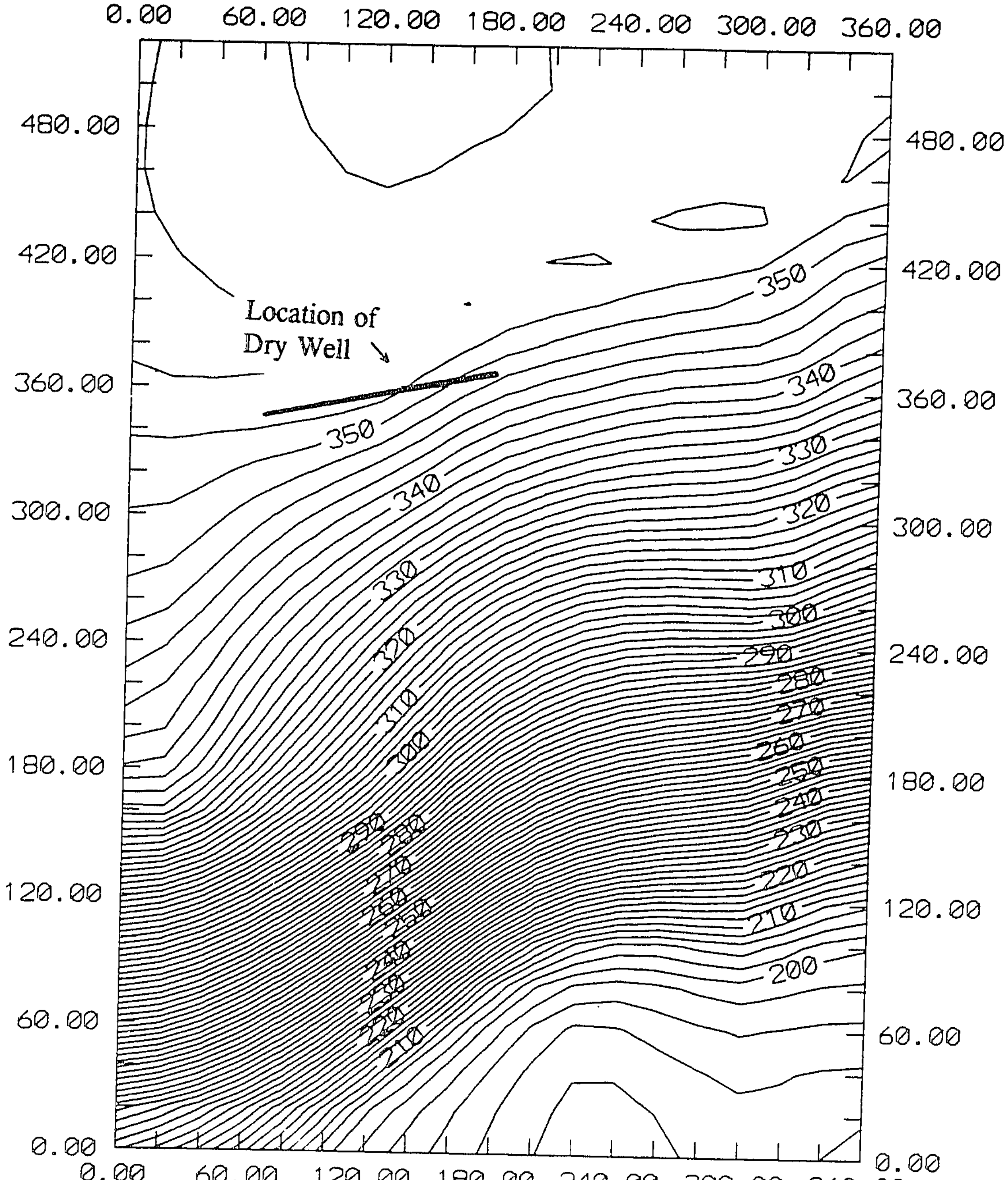
A more detailed topographic model than the existing 1:24,000 scale USGS maps was needed of the hollow. Photogrammetric analysis of existing air photos was used to measure the site topography. The photogrammetric measurements were made by the author on a CARTO Instruments AP-190 analytical plotter using 1:40,000 scale and 1:12,000 scale stereo pairs of black and white air photos. Since there were no known surveyed ground control points within the photos, the methods of Reutebuch and Shea (1988) were used to provide control for the photos. This technique basically consists of controlling the 1:40,000 scale photos using visible points from a 7.5 minute USGS quadrangle map, and then bridging the control down to the 1:12,000 scale photos using points visible in both sets of photos.

The topographic measurements of the hollow was then made from the 1:12,000 scale photos. Even though the terrain is fairly heavily vegetated, the general form of the hollow could be reasonably well-defined from the air photos. However, much of the vegetation at this site is low, deciduous bushes and trees which makes this task possible for this particular site. Based on the authors observations of surrounding terrain that was vegetated with large coniferous trees, the use of photogrammetric measurement of the topography of most forested hollows would not be possible. In these cases, the topography of the hollows would have to be measured by other means such as traditional surveys.

After the photogrammetric measurements were completed, the raw X, Y, and Z coordinates were then processed by the commercial SURFER program as described earlier in this dissertation to produce a digital terrain model of regularly spaced elevations. For this case, the selected grid cell dimension was 20 feet. The digital terrain model was then converted to a format that could be used by the FASSA program using the GRDTODAT program written by the Author.

The topography of the hollow, obtained by these methods, is shown in Figure 19. The location of the dry well is approximately shown in the figure. In general, this topography appears to be a good representation of the actual topography except down in the lower right hand corner of the map (which is on or below the road) where only scattered elevation points were measured. For the interpretation of the results of the FASSA program, this area is not within the area of interest, and is ignored.

The dry well serves about 5000 square feet of impervious drainage area, and is discharged into a pipe approximately 120 feet long. The dry well can be simulated in the FASSA program by manually adding an uparea of 833 square feet to each of 6 grid cells (6 x 833 $\approx$ 5000) located along the alignment of the dry well. This is accomplished during the running of the program by manually entering the grid cell locations and the corresponding added drainage area for each cell at the appropriate computer prompt. Another possible method to simulate the additional drainage from the dry well is to modify the input topography to simulate the additional drainage area at the location of the dry well. This methodology was attempted by the Author, but the results were sensitive to the exact shape of the topographic modification such that the results were not considered reliable. In addition, this type of approach would only work if the dry well location was near the drainage divide where the topography could be modified to simulate additional upslope drainage area.



I---------I---------I

0 40 80

Scale (feet)

Contour Interval = 2 feet

Figure 19

Topography of Sunny Shores Hollow

10.7 Obtaining the Digital Soil Depth Model

The soil depths at this hollow were actually relatively easy to measure during the winter months, when the soils were wet, by using a pointed 5/8th-inch-diameter steel probe with a welded-on "T" handle to push the probe into the ground. The depth of the soil layer over the hard underlying materials was readily apparent using this tool. The author has used this tool at numerous other sites to measure depth of the soil layer and has found it to be quite effective when the soil profile is wet. This method is generally not effective when the ground is dry or when relatively dense or coarse soils are encountered, due to the increased resistance to penetration by the probe.

Even when a relatively easy measurement method such as probing is possible, it is still generally impractical to measure the soil depth at every grid cell location in the hollow to be analyzed. In order to interpolate the soil depth data over the entire hollow, the EVOLVE program was used as described below.

During the initial site visit, the author excavated two test pits with a post hole digger and made numerous probings around the hollow. The approximate soil depths were recorded on a field sketch of the hollow, but the exact locations of the tests were not measured. Based on the probings and test excavations, it was noted that the soil was generally about 2 feet deep on the mid slopes, up to about 3 feet deep in the bottom of the hollow, and as shallow as 1 to 1.5 feet near the drainage divides and upper slopes. The exception to these soil depths occurs immediately above the present road cut. In this area, sloughing has occurred since the construction of the road (which was about 50 years ago), which has reduced the soil cover in this area to a more stable depth.

To generate a soil depth model, consistent with the observed soil depths, the previously described Evolve program was used. As was previously described, the necessary input to the evolve program consists of the following three data files:

- Z.DAT - A digital terrain model of elevations at each grid cell location. This is the same digital terrain model of the hollow that is input into the FASSA program.
- SD.DAT - A file containing the initial soil depths at each grid cell location. For this run, the initial soil depths were assumed to be zero.
- EVOLVE.DAT - A file containing the needed constants to define the evolve mechanisms as previously described. For this run, the following values were used:

  Accumulation rate of forest organics = .0001 feet/year
  Potential weathering rate of bare rock = .001 feet/year
  Dimensionless weathering constant = 2.0
  Slope transport constant = .01 square feet/year
  Time interval for recalculating topography = 1000 years

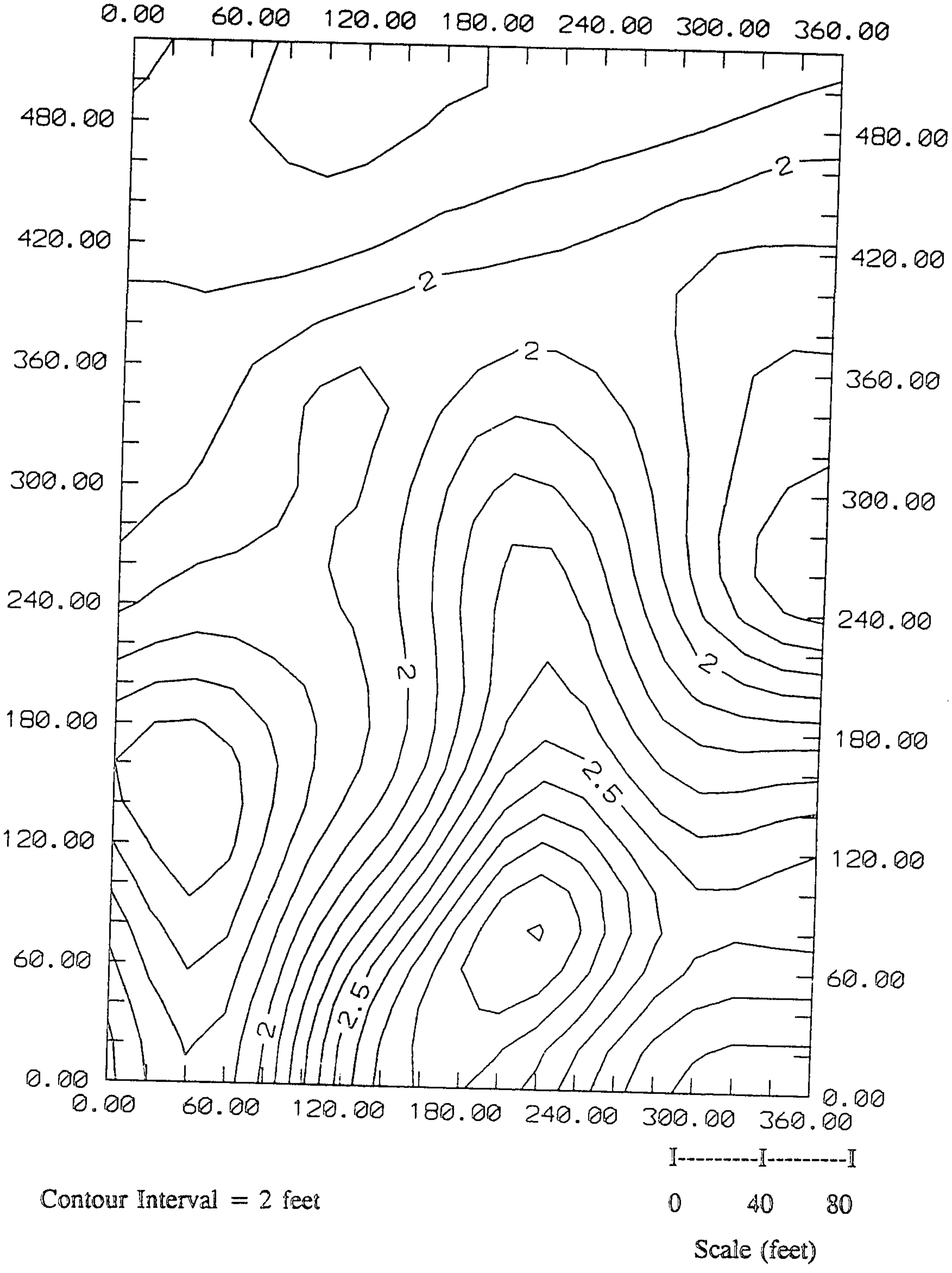
The selection of these values was based on typical ranges of values suggested by other researchers and on trial and error. The above listed final values were selected because they produced soil depths that were approximately the same as were observed in the hollow. In other words, the known soil depths were used to calibrate the EVOLVE program, thereby estimating the soil depths between the locations of known soil depths using a method with a rational basis. Trial and error is necessary to balance the rate of the soil forming processes (bedrock weathering and accumulation of organics) with the soil transport mechanisms (which are assumed to be proportional to the sine of the slope) until the resulting soil depths are consistent with the available data.

Since it is not known how long the existing soil depths actually took to evolve, no attempt is made to calibrate the absolute values of the factors so that the net rate of the processes are consistent with reality. All that matters for purpose of this example is that the soil forming mechanisms and the soil transport mechanisms are proportioned so that the observed soil depths are eventually achieved. The EVOLVE analysis can be continued from successive runs by using the output soil depth and topography from one run as the input to the next run. The "evolved" soil depths for the example hollow are presented in Figure 20.

10.8 Selection of Soil Properties

Based on the numerous observations of the near-surface soils by the Author, the soil characteristics are fairly uniform over the area of the hollow, and for that matter over the entire Sunny Shores hillside. This would be expected since the underlying source materials, and the soil forming processes are quite uniform over most of the area.

In the present FASSA version, the soil characteristics are assumed to vary at all locations in the hollow around one mean value for each characteristic. For example, the mean value of the friction angle for the soil in all the grid cells in the example hollow is 36 degrees. The friction angle of each grid cell varies independently around that mean such that for an individual FASSA trial, all the grid cells will have different values. The individual values are varied randomly about the mean value according to the user assigned coefficient of variation. Table 4 lists the mean values and coefficients of variation for the soil parameters used in the example analysis.



Contour Interval = 2 feet

Figure 20

Evolved Soil Depths for Sunny Shores Hollow

Table 4

Soil Parameters Used in Example Analysis

Parameter	Mean Value	Coefficient of Variation
Friction Angle	36 degrees	0.10
Soil Cohesion	0 psf	0.20
Saturated Unit Weight	105 pcf	0.05
Sat. Hydraulic Conductivity	100 ft/day	0.30

These values are estimates by the Author based on the observed soil type. The solution of the probability of slope failure is quite sensitive to these values. However, since the goal of this example is to compare the probability of failure with and without the dry well, the exact value of these parameters is not as critical as it would be for an absolute determination. In other words, it was found by making several runs of the analysis that while the calculated probability of failure is sensitive to the soil parameters, the percent increase in the probability of failure due to the drywell is not very sensitive to the soil parameters selected.

The above soil parameters are input to the FASSA analysis through the input file "SOIL.PAR". The SOIL.PAR input file can be built using the preprocessor "MAKESOIL.EXE" which will prompt the user for the appropriate values and write the values to the SOIL.PAR file.

10.9 Selection of Vegetation Parameters

As was previously discussed, two effects of vegetation upon slope stability are considered in the FASSA model: One being the reinforcement of the soil attributed to tree roots, and the second being the surcharge loading of the slope by the weight of the vegetation. The FASSA program is designed specifically for applications wherein the effects of timber harvest are the primary effect being considered. As was described previously, for these cases, the program has several options for defining the root cohesion for any time during the period of analysis. However, for this case where the purpose is not to evaluate timber harvest, the vegetation effects are static (not changing) and therefore the dynamic modelling of the vegetation effects is not wanted. To accommodate this, the period of analysis is set to one year for this analysis.

Since the rate of root growth and decay do not have to be considered for this case, the only parameters that have to be specified to define the vegetation effects are the net soil cohesion and the vegetation surcharge load. Table 5 presents the assumed values.

Table 5

Vegetation Parameters Used in Example Analysis

Parameter	Mean Value	Coefficient of Variation
Root Cohesion	160 psf	0.50
Vegetation Surcharge	7 psf	0.50

Typical values of root cohesion reported by researchers range between about 1 and 12 kPa (about 20 to 250 psf), with 8 kPa (160 psf) being a typical value for forested sites (Sidle, et. al., 1985).

10.10 Selection of Hydrologic Parameters

The necessary weather data is defined by a curve of 24 hour precipitation amounts verses the return period. The values presented in Table 6 define the curve used for the example problem.

Table 6

Hydrologic Parameters Used in Example Analysis

24 Hour Precipitation (feet)	Return Period (years)
0.081	1.01
0.110	1.10
0.169	2.00
0.224	5.00
0.247	10.00
0.286	20.00
0.322	50.00
0.354	100.00

The hydrologic parameters that need to be defined in the FASSA program are input via the data file "HYDRO.PAR".

10.11 Summary of Analysis

The difference in the slope stability of the two cases (with dry well and without dry well) depends upon how the addition of the dry well changes the peak piezometric levels for the existing hydrologic regime, and how sensitive the slope stability of the individual locations affected is to the changed piezometric levels. As was previously described, this comparison was made by first running a FASSA analysis of the natural conditions existing at the hollow, and then performing a second analysis of the hollow wherein the dry well was simulated by manually adding an equivalent upslope drainage area to the location of the dry well. Both analyses were run for 1000 trials, with a period of analysis of 1 year. The entire FASSA program input and output are presented in Appendix C, with selected output presented in Tables 7 and 8.

10.12 Interpretation of Results

A number of statistics are accumulated and reported during each run of the program. Page 1 of the output presents the size and geometry of the grid, the number of trials, the time period of analysis, a summary of the units used in the analysis, the total number of factor of safety calculations (realizations of the Monte Carlo Analysis), the total number of failures (calculated factors of safety less than 1.0), and a table showing the average number of failed cells for each year of the analysis and the probability of at least one cell failing in the grid for each year of the analysis. For this run, the time period of the analysis was only one year, so the table is short. For timber harvest simulations, wherein root decay and regrowth are important factors, this table provides a comparison of the relative risk of failure for each year of the analysis.

As can be seen in the program output in Appendix C, 1000 trials were performed to simulate the natural conditions (without the dry well) and 1000 trials were performed to simulate conditions with the drywell. Since there are 513 cells in the grid (19 x 27), there was a total of 513,000 factor of safety calculations (realizations of the Monte Carlo analysis) performed for each case. Of the 513,000 realizations performed for the case without the drywell, there was a total of 13,149 realizations wherein the calculated factor of safety was less than 1.0 (13,149 failures). For the case with the drywell, there was a total of 13,166 failures. In addition, the probability of at least one cell failing during the year was 0.290 for both the natural conditions and with the drywell. At first glance, this may erroneously be interpreted to mean that the probability of failure is practically not affected by the addition of the drywell. However, closer evaluation indicates that the interpretation is not nearly so simple and that the addition of the drywell may be significant.

By studying the "Average Number of Failures at Each Grid Cell During the Analyzed Period" which is given on page 6 of the run output and is reproduced in Table 7, it can be seen that most of the grid cells did not experience any failures. The most likely location to fail is at I = 21 (row 21) and J= 10 (column 10). The average number of failures during the analyzed period at this location was 0.26. Since the analyzed period in this case was one year, this can be interpreted to mean a 26% chance of failure at this location per year. Notice that the probability of failure of the least stable cell is not much different that the "Probability of at least one failure during year" statistic in the program output (which is .290 for both the drywell and the natural conditions). This means that the least stable grid cell usually failed whenever conditions were such to cause a failure elsewhere in the grid. The Author suggests that in reality, the probability of the hollow failing is better represented by the probability of the least stable cell failing rather than the probability of at least one cell in the grid failing. The reasons are discussed in the following paragraphs.

Assuming that in reality, a failure at any one of the grid cell locations would represent failure of the hollow, the first instinct is to combine the probabilities of failure of the individual grid cells assuming they were independent events to find the probability of at least one cell failing in a given year. The problem with this interpretation is that dividing the grid into finer grid cells, without changing any other characteristic, increases the calculated probability of at least one cell failing. The error in this method of interpreting results lies in the incorrect assumption that the probabilities of failure of the individual grid cells are independent.

The author suggests interpreting the probability of the hollow failing as being approximately equal to the probability of the least stable cell failing. The logic of this interpretation is based on the supposition that based on the input mean soil depths and topography, there is a single least stable point in each hollow that would fail before any

Table 7
Average Number of Failures at Each Grid Cell During the Analyzed Period

Before Drywell (location of drywell underlined for reference)

.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00	.00	.00	.00	.00	.01
.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01	.01	.01	.01	.01	.01	.03	.02	.03
.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01	.02	.03	.03	.04	.07	.07	.06	.06
.00	.00	.00	.00	.00	.00	.00	.02	.01	.03	.04	.04	.04	.06	.06	.08	.09	.09	.09
.00	.00	.00	.00	.00	.00	.02	.03	.05	.07	.07	.08	.07	.07	.08	.10	.12	.10	.09
.00	.00	.00	.01	.01	.02	.04	.08	.10	.12	.11	.11	.08	.08	.10	.11	.09	.09	.10
.00	.00	.02	.03	.05	.05	.08	.13	.14	.16	.16	.16	.13	.13	.10	.10	.10	.09	.07
.03	.05	.04	.06	.06	.10	.13	.17	.20	.23	.21	.19	.17	.12	.07	.08	.07	.06	.05
.05	.06	.03	.03	.07	.12	.14	.18	.22	.26	.23	.23	.17	.11	.06	.04	.03	.01	.01
.06	.07	.03	.02	.07	.10	.15	.17	.19	.21	.19	.06	.02	.01	.00	.00	.00	.00	.00
.05	.07	.06	.03	.05	.08	.16	.17	.18	.08	.01	.00	.00	.00	.00	.00	.00	.00	.00
.09	.08	.08	.03	.04	.06	.10	.13	.04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.10	.09	.08	.03	.05	.06	.04	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.05	.05	.05	.02	.03	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.07	.06	.05	.01	.03	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

With Drywell (drywell and cells affected by drywell underlined)

.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00	.00	.00	.00	.00	.01
.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01	.01	.01	.01	.01	.01	.03	.02	.03
.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.01	.02	.03	.03	.04	.07	.07	.06	.06
.00	.00	.00	.00	.00	.00	.00	.02	.01	.03	.04	.04	.04	.06	.06	.08	.09	.09	.09
.00	.00	.00	.00	.00	.00	.02	.03	.05	.07	.07	.08	.07	.07	.08	.10	.12	.10	.09
.00	.00	.00	.01	.01	.02	.04	.08	.10	.12	.12	.11	.08	.08	.10	.11	.09	.09	.10
.00	.00	.02	.03	.05	.05	.08	.13	.14	.16	.17	.16	.13	.13	.10	.10	.10	.09	.07
.03	.05	.04	.06	.06	.10	.13	.17	.20	.23	.21	.19	.17	.12	.07	.08	.07	.06	.05
.05	.06	.03	.03	.07	.12	.14	.18	.22	.26	.23	.23	.17	.11	.06	.04	.03	.01	.01
.06	.07	.03	.02	.07	.10	.15	.17	.19	.21	.19	.06	.02	.01	.00	.00	.00	.00	.00
.05	.07	.06	.03	.05	.08	.16	.17	.18	.08	.01	.00	.00	.00	.00	.00	.00	.00	.00
.09	.08	.08	.03	.04	.06	.10	.13	.04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.10	.09	.08	.03	.05	.06	.04	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.05	.05	.05	.02	.03	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
.07	.06	.05	.01	.03	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table 8
Average Ratio of Water Depth/Soil Depth at Each Grid Cell

Before Drywell (location of drywell underlined for reference)

.99	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.99	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	1.0	1.0	1.0	.98	.99	.99	1.0	1.0	.91	.91
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	.99	.99	1.0	1.0	1.0	1.0	.70	.85	.85
1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	1.0	1.0	1.0	.99	.99	.76	.94	.59	.95	.78	.93
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	.81	.93	.85	.95	.80	.94	.49	.78	.98	.92
1.0	1.0	1.0	1.0	1.0	1.0	1.0	.83	.84	.76	.90	.87	.94	.86	.96	.72	.40	.87	.98
1.0	1.0	.92	1.0	.89	.82	.59	.72	.66	.96	.91	.91	.95	.90	.96	.80	.32	.58	.90
1.0	1.0	.98	.99	.88	.80	.38	.63	.77	.99	.92	.91	.96	.93	.97	.87	.54	.28	.73
1.0	1.0	1.0	.99	.94	.88	.35	.57	.72	1.0	.92	.92	.97	.95	.98	.93	.73	.55	.86
1.0	1.0	1.0	1.0	.96	.37	.90	.51	.65	.73	1.0	.94	.96	.96	.98	.96	.86	.74	.94
.75	1.0	1.0	.99	.99	.96	.52	.88	.58	.69	1.0	.95	.97	.96	.99	.97	.92	.82	.96
.61	.92	1.0	1.0	.99	.98	.95	.62	.89	.69	1.0	.96	.98	.97	.99	.97	.92	.86	.96
.54	.88	.93	1.0	1.0	.98	.98	.95	.70	.91	.75	1.0	.98	.97	.98	.97	.92	.89	.96
.58	.90	.91	.92	1.0	.99	.97	.98	.94	.76	.90	1.0	.98	.97	.99	.97	.93	.90	.97
.54	.88	.86	.88	.90	.99	.99	.97	.98	.94	.77	1.0	.98	.98	.99	.98	.94	.92	.97
.40	.73	.76	.83	.87	.90	.99	.98	.96	.96	.93	1.0	.98	.98	.99	.98	.95	.93	.97
.26	.52	.66	.77	.84	.88	.91	.99	.98	.95	.96	1.0	.98	.98	.99	.98	.97	.95	.98
.42	.64	.23	.75	.81	.85	.88	.90	.98	.97	.95	1.0	.99	.99	.99	.99	.97	.97	.99
.56	.73	.22	.41	.79	.83	.86	.89	.90	.97	.97	1.0	.99	.99	.99	.99	.98	.99	.99
.68	.82	.42	.21	.53	.81	.84	.86	.88	.88	.97	1.0	.99	1.0	1.0	1.0	1.0	1.0	1.0
.78	.88	.57	.19	.35	.61	.82	.85	.87	.89	.96	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.85	.92	.70	.20	.34	.45	.64	.84	.89	.97	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.88	.94	.79	.19	.34	.46	.54	.76	.98	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.94	.97	.89	.19	.36	.48	.66	.92	1.0	1.0	1.0	1.0	1.0	1.0	.91	1.0	1.0	1.0	1.0
.96	.98	.93	.20	.36	.47	.66	.92	.99	1.0	1.0	1.0	1.0	1.0	1.0	.96	.98	1.0	1.0

With Drywell (drywell and cells affected by drywell underlined)

.99	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.99	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	1.0	1.0	1.0	.98	.99	.99	1.0	1.0	.91	.91
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	.99	.99	1.0	1.0	1.0	1.0	.70	.85	.85
1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	1.0	1.0	1.0	.99	.99	.76	.94	.59	.95	.78	.93
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.99	.81	.93	.85	.95	.80	.94	.49	.78	.98	.92
1.0	1.0	1.0	1.0	1.0	1.0	1.0	.83	.84	.76	.90	.87	.94	.86	.96	.72	.40	.87	.98
1.0	1.0	.92	1.0	1.0	1.0	.98	.97	.94	.96	.91	.91	.95	.90	.96	.80	.32	.58	.90
1.0	1.0	.98	1.0	1.0	.98	.38	.92	.95	1.0	.92	.91	.96	.93	.97	.87	.54	.28	.73
1.0	1.0	1.0	1.0	1.0	.99	.35	.57	.93	1.0	.92	.92	.97	.95	.98	.93	.73	.55	.86
1.0	1.0	1.0	1.0	.99	.37	.98	.51	.65	.91	1.0	.94	.96	.96	.98	.96	.86	.74	.94
.75	1.0	1.0	.99	1.0	.99	.52	.97	.58	.69	1.0	.95	.97	.96	.99	.97	.92	.82	.96
.61	.92	1.0	1.0	.99	1.0	.99	.62	.96	.69	1.0	.96	.98	.97	.99	.97	.92	.86	.96
.54	.88	.93	1.0	1.0	.98	1.0	.98	.70	.96	.75	1.0	.98	.97	.98	.97	.92	.89	.96
.58	.90	.91	.92	1.0	.99	.97	.99	.98	.76	.96	1.0	.98	.97	.99	.97	.93	.90	.97
.54	.88	.86	.88	.90	.99	.99	.97	.99	.98	.77	1.0	.98	.98	.99	.98	.94	.92	.97
.40	.73	.76	.83	.87	.90	.99	.98	.96	.98	.97	1.0	.98	.98	.99	.98	.95	.93	.97
.26	.52	.66	.77	.84	.88	.91	.99	.98	.95	.98	1.0	.98	.98	.99	.98	.97	.95	.98
.42	.64	.23	.75	.81	.85	.88	.90	.98	.97	.95	1.0	.99	.99	.99	.99	.97	.97	.99
.56	.73	.22	.41	.79	.83	.86	.89	.90	.97	.97	1.0	.99	.99	.99	.99	.98	.99	.99
.68	.82	.42	.21	.53	.81	.84	.86	.88	.88	.97	1.0	.99	1.0	1.0	1.0	1.0	1.0	1.0
.78	.88	.57	.19	.35	.61	.82	.85	.87	.89	.96	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.85	.92	.70	.20	.34	.45	.64	.84	.89	.97	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.88	.94	.79	.19	.34	.46	.54	.76	.98	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.94	.97	.89	.19	.36	.48	.66	.92	1.0	1.0	1.0	1.0	1.0	1.0	.91	1.0	1.0	1.0	1.0
.96	.98	.93	.20	.36	.47	.66	.92	.99	1.0	1.0	1.0	1.0	1.0	1.0	.96	.98	1.0	1.0

other point. That point is identified by the FASSA analysis as having the least favorable combination of drainage, slope angle, and soil depth.

In reality, there are several possible conditions that would make this interpretation incorrect. For example, the least stable location may change for different storm characteristics, (ie the point would tend to be higher in the hollow for short intense storms and lower in the hollow for longer, less intense storms). Or, the soil strengths may be higher at the indicated location, which allowed the combination of soil depths and slope angle to evolve in the first place. However, these conditions are not represented in the FASSA analysis, and therefore could not possibly be evaluated based on the FASSA results. As such, there is no reason to try to complicate the interpretation of the results to try to account for them.

Conceptually, it is attractive to simply count the number of times when at least one failure occurs in the grid to calculate the probability of failure. As was previously mentioned, this statistic is kept by the FASSA program and the results are printed in the output. However, as was also previously mentioned, the problem with this approach, is that by making a finer grid, the calculated probability of a failure occurring somewhere in the grid increases, and vice versa by making a coarser grid. The Author believes there may be some virtue in this approach, but that there would have to be an "inherently correct" grid cell dimension associated with the analysis in order use this interpretation. Since no methodology of identifying the "inherently correct" grid cell dimension is available, this method of interpretation is discouraged when using the present version.

In summary, interpretation of the probability of failure is relatively easy for cases where there is a single least stable cell that fails every time any other cell fails. For these cases, probability of failure occurring somewhere in the hollow is equal to the probability of failure of the least stable cell. For cases where this is not true, the interpretation is more difficult, but the author suggests using the probability of failure of the least stable cell as an approximation of the probability of failure for the entire grid. Engineering judgement should be applied to the interpretation when a clear "least stable" cell is not present in the grid. This general subject is one of the suggested topics of future research.

10.13 Conclusions from Sunny Shore Analysis

As can be seen by comparing the results from before and after the drywell (see Table 7) the stability of the least stable cell was not affected by the addition of the drywell, and the probability of at least one failure occurring during the year was not affected significantly (the statistic is reported to 3 significant figures). As can be seen in Table 8, according to the FASSA analysis, the addition of the dry well does not change the water table conditions at the least stable grid cell since the drywell is not located within its upslope contributing area.

The analysis indicates that the dry well only substantially affects the piezometric levels of a relatively small number of cells at and for a short distance below the dry well. Lower in the hollow, where the entire soil layer is typically saturated by the natural conditions, there is no effect of the additional drainage to the peak piezometric level. Because of this, the probability of failure of individual grid cells was affected by the drywell in only two locations. In these cells, (which are underlined in the lower matrix of Table 7) the probability went from 0.11 up to 0.12 at one grid cell and from 0.16 up to 0.17 at the other grid cell. This means that the probability of failure went up significantly (an increase of between 6 and 9 percent) at these locations.

Since the least stable cell (with or without the drywell) is not affected by the drywell, a strict interpretation of the results would indicate that the overall stability of the hollow was not significantly affected by the addition of the drywell. However, upon closer inspection of the results, it was noted by the author that the individual grid cells that the FASSA analysis identified as the least stable cells are located directly in the center of the hollow, slightly above the road cut in a location that appears to have recently failed. However, since the soil depths used in the analysis were generated using limited site measurements in conjunction with the EVOLVE program, the input soil depth data appears to be incorrect. The author believes that this unfavorable combination of deep soil and steep slopes no longer exists at this location, because sloughing along the top of the road cut has already occurred, thereby reducing the soil cover to a more stable depth.

If, as the author believes, the soil depths at the indicated least stable location and the immediately surrounding grid cells are actually much less than those indicated, the two cells that were unfavorably affected by the drywell would be very nearly the least stable locations in the hollow. If this is the case, the results indicate that the stability of the hollow would be substantially decreased by the drywell. Based on these results, the soil depths at these locations should be field checked and the analysis rerun using the corrected data.

This example demonstrates what the author believes is a good use of the FASSA program. The author believes that the results of the analysis are useful in evaluating the effects of the drywell. Even though the strictly interpreted results may not be correct due to incorrect soil depths, the results are still useful in assessing the impact of the drywell. After working through the problem, a much better understanding of the impacts of the drywell are gained. Based on the analysis performed, coupled with some engineering judgement, the author would conclude that the drywell has significant potential to increase the probability of failure in the hollow. In addition, if the field checks of the soil depths indicated that the original input was incorrect, the input data could be easily adjusted and the analysis rerun.

11.0 COMPARISON OF THE MODEL TO REALITY AND OTHER ANALYSES

11.1 Comparisons of FASSA With Other Analyses

Probabilistic approaches to slope stability take on many forms, some of which are described in previous sections of this dissertation. The probabilistic nature of previous stability analyses stem from one of two general sources; 1) the uncertainty associated with the parameter assignments, and 2) the stochastic nature of weather. Examples of the first type are given by Vanmarcke (1977), Wu and Kraft (1970), Ward et al. (1979, 1981) and Cheng and Christopher (1991). These analyses are static and the resulting probability of failure is not associated with any specific time period, but rather is the probability that the calculated factor of safety is less than unity based on the uncertainty of the input parameters. The uncertainty of the input parameters arises from both spatial variation of the parameters and sampling/measurement error.

Sidle (1987, 1992) presents an example of the second type. A deterministic, dynamic analysis is used to calculate the critical level of saturation of the soil mantle (M_{crit}) needed to fail the slope on any given year. The probability of failure occurring during that year was then equal to the probability of a storm that would cause M_{crit} to occur.

The probabilistic nature of the FASSA program stems from both the uncertainty of the parameter determinations and from the stochastic nature of weather. All of the important input parameters are considered to be random variables, some of which are inter-dependent (for example the slope angle and the water table). This is accomplished using a Monte Carlo simulation through time of the area to be analyzed.

The spatial and temporal organization of the FASSA program is what makes it unique among existing stability analyses. While the author believes that the analytical framework of the FASSA methodology does allow this extremely complex combination to occur in a logical manner, more research on this topic is recommended. The inter-dependencies between variables are too numerous to mention, but include the temporal relationship between vegetation effects and weather, and the spatial relationships between slope, soil depth, and water levels. The realistic method of combining factors in FASSA does yield different, and the author believes more realistic, results than simple random combination of the same numbers.

To demonstrate this last point, the author wrote another computer program called PROBFAIL to randomly combine the various parameters in the factor of safety equation and compared the results with the results from the FASSA analysis. The source code listing of the program (called PROBFAIL.FOR) is provided in Appendix B. To assure that the same numbers were being combined in both analyses, a variation of the FASSA program was developed that would store every realization of the soil depth, the root cohesion, the vegetative surcharge, and the saturated soil depth ratio that was calculated by the FASSA program during a run. These groups of numbers (which for the case analyzed included 513,000 values of each factor) were then analyzed to find their mean values and standard deviations. Once the mean values and standard deviations of these four parameters were found, they were randomly combined in a Monte Carlo Simulation of the infinite slope equation with the same mean values and standard deviations of the friction angle, the cohesion, and unit weights that had been used in the FASSA run. The resulting number of failures, and the maximum and minimum calculated factors of safety are compared with the results of the FASSA program in Table 10. The output from the PROBFAIL program is presented in Appendix C.

As can be seen in the results, the total number of failures was about 6% less for FASSA than for PROBFAIL. The minimum and maximum factors of safety, and the probability of failure were also significantly different for the two analyses. Interpretation of the results of the PROBFAIL analysis is vague since it essentially represents the random combination of the conditions that exist over the whole hollow. None-the-less, it does demonstrate that a different result is obtained by the random combination of the parameters as opposed to the dependent combination that occurs in the FASSA program.

It should be noted here that strict interpretation of many aspects of most other slope stability methodologies are even more vague than those of FASSA or PROBFAIL. As was previously discussed, many, if not most probabilistic analyses that yield a "probability of failure" do not have a time interval associated with that probability. Since the probability of failure obviously increases when larger time intervals are considered, (ie. the probability of a slope failing in the million years is much higher than its probability of failing in the next 10 seconds) this lack of a strict interpretation of other analyses can be of practical significance.

Interpretation of acceptable "factors of safety" of slopes is also vague for any value other than 1.0. Since there are no rigorous interpretations of acceptable factors of safety, widely accepted "standards" for various applications have simply evolved based on experience. From this perspective, the lack of a more rigorous interpretation of the FASSA results is typical for the state of knowledge in slope stability analysis.

Table 9

Summary of Input to FASSA and PROBFAIL

Parameter	Mean Value	Standard Deviation
Soil Depth	2.11	0.522
Root Cohesion	160.88	78.67
Vegetation Surcharge	7.06	3.45
Saturated Soil Depth Ratio	0.89	0.21
Slope Angle	17.12	13.71
Friction Angle	36.00	3.60
Soil Cohesion	0.00	8.00
Saturated Unit Weight	105.00	5.25

Table 10

Comparison of Output From FASSA and PROBFAIL

Description	FASSA	PROBFAIL
Total Number of Calculations	513,00	513,00
Total Number of Failures	13,149	12,448
Minimum Factor of Safety	0.38	0.16
Maximum Factor of Safety	468.12	9,818,675
Probability of Failure	0.26 for worst grid cell	0.024

11.2 Comparisons With Nature

The FASSA analysis attempts to model some of the processes of nature to evaluate slope stability of a forested hollow. The model utilizes the available applicable knowledge of the processes that affect forest slope stability (such as root reinforcement and subsurface drainage concentration) and modern analytical methods (such as Monte Carlo probabilistic analyses and topology based on geographic information systems).

It would be very difficult to provide conclusive proof as to the effectiveness of the overall FASSA program. In general, it would be necessary to gather all the necessary site data for the analysis of many sites. In addition to the initial site characterization, the necessary data would also have to include years worth of the temporal data such as weather and observed landslides at the site. This approach to verification of the model is not considered feasible.

However, it is possible to verify many of the individual components of the model by comparing them to observations of nature. This dissertation presents considerable field evidence supporting the effectiveness of the various component analyses that make up the FASSA program.

In summary of the various components, the infinite slope model employed by the analysis is demonstrated to be applicable to thinly-soiled mountainous areas. It is also demonstrated that the topographic model effectively returns the necessary topographic indices including slope, aspect and upslope contributing area for each grid cell. The vegetative model provides a reasonable approximation of root reinforcement and vegetative loading. The hydrologic model, which is designed to estimate the water table conditions at each grid cell for each simulated storm, is quite simplified, but it does provide the correct pattern of response and the proper sensitivity to the various factors. The analysis also employs a Monte Carlo probabilistic methodology that effectively takes into account the uncertainty of the most important input factors and the stochastic nature of weather. Each portion of the computer code has been quite extensively tested individually and in concert with the rest of the analysis by the author to verify that it returns reasonable results and that no major programming bugs are present in the code.

Although the analysis takes into account many of the major natural factors that influence the stability of forested hollows, there are many areas wherein the model deviates significantly from nature. One is with regard to the idea that the hollows evolve to their topographic form in a much more ordered manner than is represented in the model. For example, the author believes that the soil strength properties are not truly independent of the other parameters such as slope and soil depth. The author believes that these factors are likely to be correlated due to the landform evolutionary mechanisms at work. The model ignores these relationships by assuming that the spatial variation of the soil properties are random. This deficiency may significantly affect the overall accuracy of the model.

Another deviation from nature that has been brought up is the representation of the variability of the parameters by the normal distribution. While the normal distribution is convenient from an analytical standpoint, there is no conclusive evidence that this distribution is correct for all of the input parameters. In particular, the "tails" of the distribution, wherein occasional extreme values can occur, is probably not representative of natural conditions. One possible approach is to cut off the tails of the distribution at some point. While this probably has merit in making the representation more realistic, the author does not believe that the occasional extreme values are of any significant consequence in the results of the analysis.

12.0 SUMMARY

This dissertation presents a first generation, computerized, mechanical, probabilistic, areal stability analysis of forested mountain areas. The analysis is presently useful in making a relatively detailed probabilistic analysis of a single forest hollow, but could be expanded to be used as a tool for forest land managers to assist in making the decision whether to harvest or not to harvest a larger area. The program is used to evaluate the stability of the area over a user specified time period after timber harvest. The decision to harvest or not harvest would be based in part on the comparison of the probability of slope failure with or without the timber harvest.

The analysis is performed within a FORTRAN computer program named FASSA, an acronym for "Forest Area Slope Stability Analysis". The present code is designed for personal computers, and is dimensioned to analyze a single mountain hollow. The logistics of expanding the area of analysis to encompass a larger area such as an entire basin or other land management unit is discussed in the suggestions for future research.

To run the analysis, data is read into the program from 5 data files that must be created prior to execution of the program. The required input data consists of:

- A digital terrain model of the area to be analyzed.
- A digital mean soil depth model of the area to be analyzed.
- The mean values and the coefficients of variation of the soil properties.
- Parameters describing the decay and regrowth of trees and tree roots with regard to the effects on soil strength and slope loading.

- Parameters describing the statistical variation in the annual maximum 24 hour precipitation events for the subject area.

There are five major internal components to FASSA: a topographic analysis performed by the subroutine TOPOGS which calculates the slope, aspect, and upslope contributing area at each grid cell location; a vegetative analysis performed by the subroutine VEG which calculates the root cohesion and the vegetative loading for each year of the analysis; a hydrologic analysis performed by the subroutine HYDRO which calculates the saturated soil depth at each grid cell for the worst storm of each year; the framework of the Monte Carlo simulation which assigns the randomly varying soil properties during the analysis; and the solution of the infinite slope equation performed in the main program.

The research demonstrates that these features can be effectively combined into a working computer model, and that the overall model has several analytical advantages over existing analytical methods.

The most obvious advantage of the model is that it provides a practical methodology to assemble and analyze the tremendous amount of data that needs to be considered in analyzing the stability of an area over time (rather than analyzing a single location at a given time as do most analyses). The other advantages are a result of the analysis considering an area rather than a single location.

The spatial dimension provides three specific attributes to the analysis. First, the area approach allows the topographic and hydrologic analysis of the area that predicts the water table conditions for each input precipitation event. Second, the area approach allows evaluation at all points within the analyzed area rather than the more typical geotechnical analysis which must search for the least favorable conditions, and then combine them for the worst case or the typical case. This attribute allows the various site conditions to be combined in a more realistic manner than would occur by randomly combining the random distributions of the various factors. And third, the area approach provides a conceptual framework for the Monte Carlo simulation wherein factors that vary spatially, can be randomly varied in space while still allowing temporal factors to vary in time. This ability to probabilistically account for both the uncertainty of the spatial parameters and the stochastic nature of weather is unique among existing slope stability analyses.

Some of the most important limitations and approximations of the analysis are listed below:

1) All of the component analyses are quite simplified versions of nature and therefore subject to error. The hydraulic analysis in particular is very simplified and quite approximate.

2) The probabilistic representation of the input data could be improved. It is clearly related to the grid cell dimension, but the relationship is not presently clear. In addition, the use of the normal distribution may or may not be an adequate representation of the data.

3) The analysis requires large quantities of data which can be difficult to obtain.

Additional work on some of these points are recommended in the suggestions for future research.

13.0 SUGGESTIONS FOR FUTURE RESEARCH

13.1 Improving the Hydrologic Model

The weakest link in the present FASSA analysis, and therefore the suggested emphasis of future research, is the hydrologic model. The current model attempts to limit the necessary weather data input to a statistical recurrence relationship of 24-hour precipitation values. The 24-hour precipitation value is then converted to a steady state rainfall intensity that is used to predict the flow through each grid cell. This is done by assuming that the entire upslope contributing area of the cell contributes flow simultaneously at the assumed steady state intensity.

Although peak piezometric levels in mountain hollows have been demonstrated to be strongly correlated with the 24-hour precipitation, they are also dependent upon the precipitation occurring in preceding days. Based on the comparisons of measured piezometric values with measured rainfall data, the simplified FASSA model can be calibrated to a particular site to give reasonable results. However, its reliability at different sites is unknown.

It is desirable to have a model that can be applied to any site, and the incorporation of such a model into the overall FASSA framework is the suggested emphasis of future research. In the authors opinion, any such hydrologic model will necessarily be a more complicated, transient analysis, that takes into account a longer, more detailed precipitation record.

The development and testing of such a model is presently underway at the University of Washington. The model is a finite difference analysis of subsurface saturated flow on steep, thinly-soiled hillslopes (Jackson, 1991). It predicts piezometric response over time at any location within the modelled hillslope to specific rainfall events.

The input data and the computing requirements for the finite difference model are necessarily greater than those needed for the FASSA model. The required input data includes half hour rainfall totals for the duration of the period being analyzed. With this in mind, the overall design of the present FASSA program should be redesigned if this model, or a similar detailed model, were to be incorporated into the analysis.

The author suggests consideration be given to the "design storm" approach wherein only one storm would have to be analyzed. Alternatively, a number of incremental design storms, corresponding to various recurrence intervals (i.e. 2 year storm, 5 year storm, etc.) could be analyzed for the particular hollow at the start of the analysis. A recurrence relationship for the peak piezometric levels (i.e. 2 year peak, 5 year peak, etc.) for each grid cell could then be developed that would be used throughout the rest of the analysis. This approach would allow the computing requirements to remain at a feasible level.

13.2 Similar Analysis for Soil Covers on Synthetic Liners

Another direction for future research is the development of a similar analysis for sloped soil covers on synthetic liners. This is an extremely common stability problem that has been encountered several times by the Author in his work as a consulting geotechnical engineer. The most common example encountered by the Author is surficial sloughing of earth cover over synthetic liners on landfill side slopes. The problem is often considered temporary because the earth cover is eventually supported by the waste materials that are placed against it. However, the occurrence of significant storms during the time the unsupported slopes are exposed is unavoidable, and often causes widespread sloughing of the cover materials. There are also many examples of permanent slopes that have soil covers over synthetic liners.

This problem is made to order for an analysis similar to FASSA. The cover materials often have well-known, and relatively consistent engineering properties. In addition, the design topography and soil depth have much less uncertainty than the topography and soil depth of natural slopes. The hydrologic model presently employed by FASSA may be quite realistic for most landfill applications since the slopes are generally shorter, and the cover materials are generally highly pervious (therefore the time of concentration would generally be within the 24 hour duration).

An additional feature which should be incorporated into any model of sloped soil covers over synthetic liners is a model to account for synthetic reinforcement of the soil cover. This complication would be where the model would have to deviate substantially from the present FASSA analysis, in which the stability of each grid cell is assumed to be independent of its neighboring cells by the using the infinite slope equation.

The design storm approach may be the most appropriate for this case. In other words, the topography, reinforcement, and cover depth would have to be designed to survive a specific design storm with an acceptable factor of safety.

13.3 Expand the Area of Analysis

Another possible direction for future research is to expand the present FASSA program to accept a larger area of analysis, such as an entire first order basin or a typical land management unit. The main analytical challenge of expanding the area of analysis beyond the limits of a single hollow would be in handling surface streams. The processes presently modelled in the FASSA program are not applicable to surface streams. A practical method for the computer to recognize and separate out the surface streams would have to be developed.

A potential disadvantage of expanding the area of analysis is the possibility of the analysis being "coarsened" to the status of most other areal approaches that are designed to delineate possible unstable areas within larger areas rather than to make absolute analyses of stability. In order to return reliable results, the input data has to be relatively detailed and accurate. If the area of analysis was expanded, there would probably be a tendency to coarsen the level of detail of the input data, when in actuality, the level of detail necessary to analyze a large area would be no less than the detail required for a small area.

13.4 Improve Representation of Input Data

Another idea that is presently undeveloped in the model is the relationship between spatial variability and the grid cell dimension. This idea is discussed with regard to the topographic analysis, but it is also applicable to the assignment of mean values and standard deviations of the soil parameters. As was previously discussed, the grid cell dimension is inherently related to the nature of the input data, and additional work in identifying these relationships is recommended.

REFERENCES

Ahnert, F., 1976, "Brief Description of a Comprehensive Three-Dimensional Process-Response Model of Landform Development", Zeitschrift fur Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 29-49.

Arya, J.C., and Lardner, R.W., 1979, "Mathematics for the Biological Sciences", Prentice-Hall, Inc., Englewood Cliffs, New Jersey, p. 157.

Armstrong, A.C., 1976, "A Three-Dimensional Simulation of Slope Forms", Zeitschrift fur Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 20-28.

Baker, R.F., and Chieruzzi, R., 1959, "Regional Concept of Landslide Occurrence", Bulletin No. 216, Highway Research Board, pp. 1-16.

Benda, L.E., and Cundy, T.W., 1990, "Predicting Deposition of Debris Flows in Mountain Channels", Canadian Geotechnical Journal, V. 27, pp. 409-417.

Beven, K., 1982, "On Subsurface Stormflow: Predictions with Simple Kinematic Theory for Saturated and Unsaturated Flows", Water Resour. Res., V. 18(6), pp. 682-690.

Bishop, A.W., 1955, "The Use of the Slip Circle in the Stability Analysis of Earth Slopes", Geotechnique, V.5, pp. 7-17.

Box, G.E.P., and Mueller, M.E., 1958, "A Note on the Generation of Random Deviates", Annals of Mathematical Statistics, V. 29, pp. 610-611.

Briggs, Ian C., 1974, "Machine Contouring Using Minimum Curvature", Geophysics, V. 39, pp. 39-47.

Buchanan, P., and Savigny, K.W., 1990, "Factors Controlling Debris Avalanche Initiation", Canadian Geotechnical Journal, V. 27, pp. 659-675.

Buchanan, P., Savigny, K.W., and DeVries, J., 1990, "A Method of Modeling Water Tables at Debris Avalanche Headscarps", Journal of Hydrology, V. 113, pp. 61-88.

Building Research Advisory Board, 1974, "Methodology for Delineating Mudslide Hazard Areas", National Research Council, National Academy of Sciences.

Burrough, P., 1986, "Principles of Geographic Information Systems for Land Resources Assessment", Oxford Press.

Briggs, Ian C., 1974, "Machine Contouring Using Minimum Curvature", Geophysics, V. 39, pp. 39-47.

Burroughs, E.R., and Thomas, B.R., 1977, "Declining Root Strength in Douglas-Fir After Felling As a Factor in Slope Stability", USDA Forest Service Research Paper INT-190, May.

Chandler, D.S., 1982, "The Effect of Plant Roots on Soil Strength", Submitted in partial fulfillment of requirements for MSCE degree, Montana State University.

Chandler, D.S., 1988, "Qualifying Exam Question from T.W. Cundy", University of Washington.

Cheng, S.C., and Christopher, B., 1991, "A Probabilistic Review of Geotextile Reinforced Slope Design", Geosynthetics' 91 Conference Proceedings, February 26-28, Atlanta, Georgia, pp. 455-468.

Cleveland, G.B., 1971, "Regional Landslide Prediction", Open File Release 72-73, California Division of Mines and Geology, Sacramento, California.

Cundy, T.W., 1988, "Class notes and handouts from FORP 417, Hillslope Stability and Land Use", University of Washington, Spring Quarter.

Cundy, T.W., and Schiess, P., 1987, "Development of a Model for Sediment Delivery to Channels by Landslides and Debris Flows", Proposal to the U.S. Forest Service Pacific Northwest Forest and Range Experiment Station, May 15.

Cundy, T.W., 1990, University of Washington, Piezometer Records From Instrumented Forest Hollow, Pack Forest, Washington.

Day, R.W., & Axten, G.W., 1989, "Surficial Stability of Compacted Clay Slopes", ASCE Journal of Geotechnical Engineering, V. 115(4), pp. 557-581.

Davis, John C., 1986, "Statistics and Data Analysis in Geology", John Wiley and Sons, New York.

Desai, C.S., and Christian, J.T., 1977, "Numerical Methods in Geotechnical Engineering", McGraw Hill.

Dietrich, W., and Dunne, T., 1978, "Sediment Budget for Small Catchment in Mountainous Terrain", Zeitschrift für Geomorphologie, N.F., Supplementband, V. 29, pp. 191-206.

Duncan, J.M., Seed, R.B., Wong, K.S., and Ozawa, Y., 1984, "FEADAM84: A Computer Program for Finite Element Analysis of Dams", Geotechnical Engineering Report No. SU/GT/84-03, Department of Civil Engineering, Stanford University, November.

Dunne, T., and Leopold, L.B., 1978, "Water in Environmental Planning", W.H. Freeman and Company, New York.

Dutton, G., 1984, "Geodesic Modelling of Planetary Relief", Cartographica, V. 21, pp. 188-207.

Dyrness, C.T., 1969, "Hydrologic Properties of soils on Three Small Watersheds in the Western Cascades of Oregon", Research Note, PNW - 111, USDA, Portland, Oregon.

Evans, I.S., 1980, "An Integrated System of Terrain Analysis and Slope Mapping", Zeitschrift für Geomorphologie, N.F., Supplementband, V. 36, pp. 274-295.

Evans, J.R., and Gray, C.H., 1971, "Analysis of Mudslide Risk in Southern Ventura County, California", Open File Release 72-73, California Division of Mines and Geology.

Fellenius, W., 1936, "Calculation of the Stability of Earth Dams", Transcripts of Second Congress on Large Dams (Washington), V.4, p. 445.

Freeze, R.A., and Cherry, J.A., 1979, "Groundwater", Prentice Hall, Inc., Englewood Cliffs, NJ.

Gossmann, H., 1976, "Slope Modelling with Changing Boundary Conditions - Effects of Climate and Lithology", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 72-88.

Gray, D.H., and Megahan, W.F., 1981, "Forest Vegetation Removal and Slope Stability in the Idaho Batholith", Res. Pap. INT-97, 34pp., Forest Service USDA, Ogden, Utah.

Harr, M. E., 1977. "Mechanics of Particulate Media, A Probabilistic Approach", Mcgraw-Hill, New York.

Heerdegen, R.G. and Beran, M.A., 1982, "Quantifying Source Areas Through Land Surface Curvature and Shape", Journal of Hydrology, V. 57, pp. 359-373.

Hirano, M., 1976, "Mathematical Model and the Concept of Equilibrium in Connection with Slope Shear Ratio", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 50-71.

Holtz, R.D., and Krizek, R.J., 1971, "Statistical Evaluation of Soils Test Data", Proceedings, the First International Conference on Application of Statistics and Probability to Soil and Structural Engineering, pp. 230-266.

Huang, Y.H., 1983, "Stability Analysis of Earth Slopes", Van Nostrand Reinhold Company, Inc., New York.

Jackson, R., 1991, "FRE9CMH (Freatic Model, Version 9, Units of cm and hrs), Operation Manual", University of Washington, March.

Janbu, N., Bjerrum, L, and Kjaernsli, B., 1956, "Veiledning Vedløsing av Fundamenteringsoppgaver", (Soil Mechanics Applied to Some Engineering Problems), in Norwegian with English Summary, Norwegian Geotechnical Institute, Publication 16, Oslo.

Jones, F.O., Embody, D.R., and Pertson, W.L., 1961, "Landslides Along the Columbia River Valley, Northeastern Washington", U.S. Geological Survey Professional Paper 367.

Kirkby, M.J., 1976, "Deterministic Continuous Slope Models", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 1-19.

Klock, G.O., 1985, "An Approach to Modeling the Cumulative Effects of Forest Practices on Downstream Aquatic Ecosystems", Journal of Soil and Water Conservation, V. 40(2), pp. 237-241.

Krynine, D.P., and Judd, W.R., 1957, "Principles of Engineering Geology and Geotechnics", McGraw-Hill, New York, NY, p 639.

Lambe, T.W., and Whitman, R.V., 1969, "Soil Mechanics", John Wiley & Sons, Inc., New York.

Liang, F., and Belcher, J.D., 1958, "Air Photo Interpretation in Landslides and Engineering Practice", Highway Research Board, Special Report No. 29, Publication 544.

Lohnes, R.A., Alvaro, M., and Handy, R.L., 1972, "In-situ Measurement of Soil Creep", Journal of the Soil Mechanics and Foundation Division ASCE, January, pp.143-147.

Lumb, P. , 1966, "The Variability in Natural Soils", Canadian Geotechnical Journal, V. III, No 2.

Moore, I.D., and Burch, G.J., 1986, "Modelling Erosion and Deposition: Topographic Effects", Transactions of the ASAE, V. 29,(6), pp 1624-1630.

Moore, I.D., O'loughlin, E.M., and Burch, G.J., 1988, "A Contour-Based Topographic Model for Hydrologic and Ecologic Applications", Earth Surface Processes and Landforms, V. 13, pp. 305-320.

Moyersons, J, & De Ploey, J., 1976, "Quantitative Data on Splash Erosion, Simulated on Unvegetated Slopes", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 120-131.

Neely, M.K., and Rice, R.M., 1990, "Estimating Risk of Debris Slides After Timber Harvest in Northwestern California", Bulletin of the Association of Engineering Geologists, V. XXVII, No. 3, pp. 281-289.

Nilsen, T.H., and Brabb, E.E., 1973, "Current Slope-Stability Studies in the Sand Francisco Bay Region", Journal of Research, USGS, V. 1(4), pp. 431-437.

O'Loughlin, E.M., 1981, "Saturation Regions in Catchments and Their Relationships to Soil and Topographic Properties", Journal of Hydrology, V. 53, pp. 229-246.

Peuker, T.K., Fowler, R.J., Little, J.J., and Mark, D.M., 1978, "The Triangulated Irregular Network", Proceedings of the DTM Symposium, American Society of Photogrammetry & The American Congress on Survey and Mapping, St. Louis, Missouri, pp. 24-31.

Peck, R.B., 1967, "Stability of Natural Slopes", Journal of the Soil Mechanics and Foundation Division ASCE, July, pp.403-417.

Poole, D.H., 1969, "Slope Failure Forms: Their Identification, Characteristics and Distribution as Depicted by Selected Remote Sensor Returns", Proceedings, Sixth International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan.

Poole, D.H., 1972, "An Evaluation of the Utility of Remote Sensor Returns for a Study of Slope Failure Phenomena", Remote Sensing Institute Technical Report 14, East Tennessee State University, Johnson City, Tennessee.

Pusch, R., and Feltham, P., 1981, "Computer Simulation of Creep of Clay", Journal of the Geotechnical Engineering Division ASCE, January, pp. 95-104.

Reddi, L.N, Wu, T.H., 1991, "Probabilistic Analysis of Ground-Water Levels in Hillside Slopes", Journal of the Geotechnical Division ASCE, V.117, N.6, pp. 872-890.

Reutebuch, S.E., & Shea, R.D., 1988, "A Method to Control Large-Scale Aerial Photos When Surveyed Ground Control is Unavailable", Paper presented at the Second Forest Service Remote Sensing Applications Conference: "Remote Sensing For Resource Inventory, Planning, and Monitoring", April 11-15, Slidell, Louisiana.

Rosenblueth, E., 1975, "Point Estimates for Probability Moments", Proceedings, National Academy of Science, V.72(10), pp. 3812-3814.

Selby, M.J., 1982, "Hillslope Materials and Processes", Oxford University Press.

Sidle, R.C., 1986, "Groundwater Accretion in Unstable Hillslopes of Coastal Alaska", Conjuctive Water Use; Proceedings of Budapest Symposium, IAHS Publication 156, pp. 335-343.

Sidle, R.C., 1987, "A Dynamic Model of Slope Stability in Zero-Order Basins", Erosion and Sedimentation in the Pacific Rim, Proceedings of the Corvallis Symposium, August.

Sidle, R.C., 1992, "A Theoretcial Model of the Effects of Timber Harvesting on Slope Stability", Water Resources Research, V. 28, N. 7, pp. 1897-1910.

Sidle, Pearce and O'Loughlin, 1985, "Hillslope Stability and Land Use", American Geophysical Union.

Silfer, A.S., Kinn, G.S., Hassett, J.M., 1987, "A Geographic Information System Utilizing the Triangular Irregular Network as a Basis for Hydrologic Modelling", Auto Carto 8 Proceedings, Eighth International Symposium on Computer Assisted Cartography, ASPRS, pp. 129-136.

Singh, A. and Lee, K., 1970, "Variability in Soil Parameters", Idaho Eighth Annual Conference on Geological and Soil Engineering.

Speight, J.G., 1976, "Numerical classification of Landform Elements From Air Photo Data", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 154-168.

Swanston, D.N., 1967, "Soil-Water Piezometry in a Southeast Alaska Landslide Area", U.S.F.S. Research Note, November.

Todten, H., 1976, "A mathematical Model to Describe Surface erosion caused by Overland Flow", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 89-105.

Transportation Research Board, 1978, "Landslides: Analysis and Control", Special Report 176, National Academy of Sciences, Washington, D.C.

Trofimov, A.M. & Moskovkin, V.M., 1976a, "Some Problems of the Theory of Moving Water along a Slope", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 106-109.

Trofimov, A.M. & Moskovkin, V.M., 1976b, "On the Problem of Stable Profiles of Deluvial Slopes", Zeitschrift für Geomorphologie, Supplementband 25, Quantitative Slope Models, pp. 110-113.

Tubbs, D.W., 1974, "Landslides in Seattle", State of Washington Department of Natural Resources, Information Circular 52.

Vanmarcke, E.H., 1977, "Reliability of Earth Slopes", ASCE Journal of the Geotechnical Engineering Division, November.

Varnes, D.J., 1958, "Landslide Types and Processes", Highway Research Board, Special Report No. 29, Landslides and Engineering Practice, Nat. Res. Coun. Publ. 544, Washington, D.C., Chapter 3, pp. 20 -45.

Veress, S.A., 1987, "Photogrammetry Programs, DLT, Intersection and Resection", University of Washington, CETS 599, Winter Quarter.

Waldron, L.J., 1977 "Shear Resistance of Root Permeated Homogenous and Stratified Soil", Soil Science Soc. of Amer. Jour., V. 41, pp. 843-849.

Waldron, L.J., and Dakessian, S., 1981, "Soil Reinforcement by Roots; Calculations of Increased Soil Shear Resistance from Root Properties", Soil Science, V. 132(6), pp 427-435.

Waldron, L.J., Dakessian, S., and Nemson, J.A., 1983, "Shear Resistance Enhancement of 1.22-meter Diameter Soil Cross Sections by Pine and Alfalfa Roots", Soil Science Coc. Am. J., V. 47(1), pp 9-14.

Waltz, J.P., 1971, "An Analysis of Selected Landslides In Alameda and Contra Costa Counties, California", Association of Engineering Geologists Bulletin, V. 3(2).

Ward, T.J., Li, R.M., and Simons, D.B., 1979, "Mathematical Modeling Approach For Delineating Landslide Hazards in Watersheds", Engineering Geology and Soils Engineering Symposium Proceedings.

Ward, T.J., Li, R.M., & Simons, D.B., 1981, "Use of a Mathematical Model for Estimating Potential Landslide Sites in Steep Forested Drainage Basins", Erosion and Sediment Transport in Pacific Rim Steepland, I.A.H.S. Publ. No. 132, Christchurch.

Wu, T.H., 1976, "Investigation of Landslides on Prince of Wales Island, Alaska", Geotechnical Engineering Report No. 5, Dept. of Civil Engineering, Ohio State University, Columbus, Ohio, February.

Wu, T.H., and Kraft, L.M., 1966, "Safety Analysis of Slopes", Journal of the Soil Mechanics and Foundation Division, ASCE, Vol 96, No. SM2, Proc. Paper 7174, March, pp. 609-630.

Wu, T.H., McKinnel, W.P., Swanston, D.N., 1979, "Strength of Tree Rootsw and Landslides on Prince of Wales Island, Alaska", Canadian Geotechnical Journal, V.16, pp.19-33.

Yates, S.R., and Warrick, A.W, 1985, "Hillside Seepage: An Analytical Solution to a Nonlinear Dupuit-Forchheimer Problem", Water Resources Research, V.21, N.3, pp.331-336

Zevenbergen, L.W., and Thorn, C.R., 1987, "Quantitative Analysis of Land Surface Topography", Earth Surface Processes and Landforms, V. 12, pp. 47-56.

Zevenbergen, L.W., and Thorn, C.R., 1985, Fortran computer program "TOPO", Dept. of Geography and Earth Science, Queen Mary College (University of London), London, U.K., April 15.

Ziemer, R.R., 1981, "Roots and the Stability of Forested Slopes", IAHS AISH Publication 132, pp. 343-357.

APPENDIX A

DESCRIPTIONS OF DATA MANAGEMENT PROGRAMS

DESCRIPTIONS OF DATA MANAGEMENT PROGRAMS

Data management for the FASSA analysis consists of manipulating a variety of data arrays and files describing the attributes at each grid cell. A system of custom computer programs was written by the author to process and analyze the spatial data. A list of the data management programs (which are not part of the FASSA program) and a summary of their purposes is provided as follows:

DATTOGRD.EXE - Converts spatial data from the .DAT file format needed for the FASSA program to the .GRD file format needed for input into the SURFER program so that the data can be displayed or printed in the Surfer formats (topographic maps or gridded surface representations).

GRDTODAT.EXE - Converts spatial data from the .GRD file format to the .DAT format so the gridded data from the SURFER program can be analyzed by the FASSA program.

GRDTOXYZ.EXE - Converts spatial data from the .GRD file format to a collection of X, Y, Z coordinates. This program is useful when using the SURFER program to densify or to thin the grid cell spacing.

FACTDAT.FOR - Multiplies the data values in a .DAT file by a user specified factor. This is useful for converting units of measurement.

SUBDAT.FOR - Subtracts one .DAT file from another. This is useful for operations such as subtracting the soil depth from the topography to result in the bedrock topography of the area.

SMOOTHDAT.FOR - Smooths the **.DAT** values with their neighboring data values using a user specified weighting scheme. This is useful for smoothing user generated soil depths or other spatial attributes.

MAKEFILE.EXE - Makes a blank .DAT file with uniform value. This is useful when testing the FASSA program or as an initial soil depth file for the EVOLVE program (which is described later).

MAKEHYDR.EXE - Is the preprocessor program that prompts the user for the relevant hydrologic data, then builds the HYDRO.PAR file to be used with the FASSA program.

MAKESOIL.EXE - Is the preprocessor program that prompts the user for the relevant soil data, then builds the SOIL.PAR file to be used with the FASSA program.

MAKEVEG.EXE - Is the preprocessor program that prompts the user for the relevant vegetation data, then builds the VEG.PAR file to be used with the FASSA program.

In addition to the above listed custom written programs, the commercially available computer program "Surfer", by Golden Software, Inc. is useful to perform the initial gridding and to display and output the processed data.

APPENDIX B

COMPUTER SOURCE CODE LISTINGS OF FASSA PROGRAMS

COMMON Block for Include Statement
Page 1 of 1

```
 COMMON N, M, ANGLE, DIST, EPS, INDICATOR,
*TIME, TRIAL, TIMEMAX, RCCOVAR, QOCOVAR, SEED, RANDNL,
*DRCMAX, DRCMIN, DECAYTIME, NUMPTSVEG,
*QOMAX, QC, QK,  UWW,
*NUMPTS, FACTOR, INTENSITY, INTENMAX,
*FAM, FACOVAR, CM, CCOVAR, SUWM, SUWCOVAR, KM, KCOVAR, SDCOVAR,
*T(200), LRC(200), INTEN(200), PROB(200),
*RCM(200), QOM(200), Z(60,60), SLOPE(60,60), ASPECT(60,60),
*UPAREA(60,60), FLAG1(60,60), FLAG2(60,60), UPDIST(60,60),
*SD(60,60), SDM(60,60), RC(60,60), QO(60,60), K(60,60),
*FA(60,60), C(60,60), SUW(60,60), SAT(60,60), ZM(60,60),
*SATAVG(60,60), FS(60,60), FAIL(60,60), PROBFAIL(60,60),
*FSMIN(60,60), FSMAX(60,60), FSAVG(60,60),
*NUMB, ANSDA, IDA(20), JDA(20), DADA(20),
*FADF1, FADF2, CDF1, CDF2, SUWDF1, SUWDF2, SDDF1, SDDF2,
*KDF1, KDF2, QODF1, QODF2, RCDF1, RCDF2, SWITCH, SWITCH2
 REAL PROBFAIL, K, LRC, INTEN, PROB, INTENMAX, KM, KCOVAR,
*INTENSITY, KDF1, KDF2
 INTEGER SWITCH, TIME, TIMEMAX, TRIAL
```

```
c***********************************************************************
c  Program FASSA3 (Forest Area Slope Stability Analsyis - 3)
c  Douglas S. Chandler, Dept. of Civil Engineering
c  University of Washington
c  Seattle, Washington
c
c  This version considers the input elevations of the DTM
c  to be random variables.  The ZM values are mean values.
c  It also can write all the SD's, RC's, QO's, and SAT's generated
c  by the run to data files  SD.DAT, RC.DAT, QO.DAT, & SAT.DAT.
c  It also uses subroutines VEG2 and SOIL2, which assign a uniform
c  value of all the veg and soil parameters to the whole grid for
c  each trial.
c***********************************************************************
c This program calculates the probability of failure by landsliding
c for individual grid cells within a larger land area over a specified
c period of time.  The land area is divided into a matrix of square
c grid cells and the factor of safety against failure for each cell is
c calculated based on the infinite slope equation.  To determine the
c probability of failure, a Monte Carlo simulation is used wherein the
c infinite slope equation is solved many times, varying the input as
c normally distributed random variables of given means and variances.
c***********************************************************************
C
C DESCRIPTION OF NECESSARY INPUT DATA
C
C PRIMARY INPUT TO THIS PROGRAM IS BY READING FROM EXTERNAL FILES BUILT
C PRIOR TO THE EXECUTION OF THE PROGRAM.  PARAMETER FILES (WITH THE FILE
C EXTENSION .PAR) ARE BUILT BY PREPROCESSORS TO DEFINE THE MEAN VALUES,
C COEFICIENT OF VARIATION, ETC. OF THE VARIABLES.  THE .PAR FILES ARE
C THEN USED DURING THE EXECUTION OF THE PROGRAM TO BUILD AND ALTER THE
C THE GRID ARRAYS THAT ARE USED IN THE ANALYSIS.
C
C
C ALTHOUGH SEVERAL COMBINATIONS OF UNITS CAN BE USED, THE FOLLOWING
C UNITS ARE SUGGESTED:
C
C  - USE DEGREES FOR ANGLE INPUT AND OUTPUT, PROGRAM WORKS IN RADIANS.
C
C  - SHEAR STRENGTHS & PRESSURES (COHESION & TREE LOADING)
C      USE NEWTONS/SQUARE METER  'OR'  POUNDS/SQUARE FOOT
C
C  - UNIT WEIGHTS
C      USE NEWTONS/CUBIC METER 'OR'  POUNDS/CUBIC FOOT
C      UNIT WEIGHT OF WATER = 9810 NCM  OR  62.4 PCF
```

```
C
C - VELOCITIES (RAINFALL INTENSITIY, HYDRAULIC CONDUCTIVITY)
C     USE METERS/DAY  'OR'  FEET/DAY
C
C***********************************************************************
C
C   THE FOLLOWING INPUT FILES ARE NEEDED TO BEGIN EXECUTION OF THE
C   PROGRAM:
C
C      Z.DAT - MEAN GRID CELL ELEVATIONS
C      SDM.DAT - MEAN GRID CELL SOIL DEPTHS
C      VEG.PAR - PARAMETERS DEFINING THE VEGETATION
C      SOIL.PAR - PARAMETERS DEFINING THE SOIL PROPERTIES
C      HYDRO.PAR - PARAMETERS DEFINING THE HYDROLOGIC CONDITIONS
C
C
C   DATA FORMAT FOR INPUT FILES Z.DAT AND SDM.DAT
C
C   FREE FORMAT (DATA SEPERATED BY SPACES OR COMMAS
C   LINE 1:         N, M, ANGLE, DIST, EPS
C   LINES 2...M+1   GRID VARIABLES (Z OR SDM)
C                   LEFT TO RIGHT, TOP TO BOTTOM
C
C
C   WHERE:
C
C   N = NUMBER OF COLUMNS OF THE MATRIX
C   M = NUMBER OF ROWS OF THE MATRIX
C   DIST = DISTANCE BETWEEN GRID POINTS
C   ANGLE = ANGLE IN DEGREES THE GRID IS ROTATED
C         (0 TO 360 DEGREES, COUNTER CLOCKWISE)
C   EPS = ESTIMATED BOUND ON ERRORS OF ELEVATIONS OR THE
C        COEFICIENT OF VARIATION OF RANDOM GRID VARIABLES
C   Z(I,J) = ELEVATION OF GRID POINT I,J
C          (I = ROW NUMBER)
C          (J = COLUMN NUMBER)
C
C   SDM(I,J) = MEAN SOIL DEPTH (MEASURED VERTICALLY) AT THE GRID CELL
C
C  THIS SAME FORMAT IS USED FOR ALL GRID ARRAYS IN THE PROGRAM
C  EXECUTION, AND CAN BE USED FOR OUTPUT OF ALL GRID CELL VARIABLES
C  SO THAT THEY CAN BE VEIWED AS IS OR CONVERTED TO THE GRID FORMAT
C  (USING THE DATTOGRD.EXE PROGRAM) TO BE DISPLAYED IN THE SURFER
C  PROGRAM.
C
```

```
C---------------------------------------------------
C
C  TO BUILD 'VEG.PAR', USE THE PREPROCESSOR 'MAKEVEG.EXE'.
C
C  RC = APPARENT ROOT COHESION (IS THE SUM OF THE FOLLOWING COMPONENTS)
C    DRC = DEAD ROOT COHESION (IS A FUNCTION OF TIME SINCE CUTTING)
C    LRC = LIVE ROOT COHESION (IS A FUNCTION OF TREE AGE & SPECIE)
C
C  QO = WEIGHT OF THE VEGETATION (IS A FUNCTION OF TREE AGE & SPECIE)
C___________________________________________________________________
C
C  TO BUILD 'SOIL.PAR', USE THE PREPROCESSOR IS 'MAKESOIL.EXE'.
C
C   FA = FRICTION ANGLE (GIVEN IN DEGREES, PROGRAM CONVERTS TO RADS)
C   C = SOIL COHESION
C   SUW = SATURATED UNIT WEIGHT OF THE SOIL
C NOTE: MOIST UNIT WEIGHT IS ASSUMED TO BE 90% OF SATURATED UNIT WEIGHT
C
C   K = SATURATED HYDRAULIC CONDUCTIVITY OF SOIL
C___________________________________________________________________
C
C  HYDROLOGIC INPUT - PREPROCESSOR IS 'MAKEHYDR.EXE'
C
C   SAT = SATURATED SOIL DEPTH/ SOIL DEPTH
C
C---------------------------------------------------
C
C  THE GRID ARRAYS THAT ARE CREATED DURING THE EXECUTION OF THE
C  PROGRAM ARE:
C
C            ZM - MEAN GRID CELL ELEVATIONS
C            Z - GRID CELL ELEVATIONS (CHANGED EACH TRIAL)
C            ASPECT - GRID CELL SLOPE ASPECTS
C            SLOPE - GRID CELL SLOPES
C            UPDIST - LONGEST UPSLOPE DISTANCE TO DIVIDE
C            UPAREA - UPSLOPE CONTRIBUTING AREA
C            FA - GRID CELL FRICTION ANGLES
C            C - GRID CELL COHESION
C            SUW - GRID CELL SATURATED UNIT WT OF SOIL
C            K - GRID CELL SATURATED HYDR. CONDUCTIVITY
C            SDM - MEAN GRID CELL SOIL DEPTHS
C            SD - GRID SOIL DEPTH (CHANGED EACH TRIAL)
C            FS - GRID CELL FACTOR OF SAFETY
C            PROBFAIL - GRID CELL PROBABILITY OF FAILURE
C
```

```
C
      PROGRAM FASSA3
$debug
      INCLUDE 'COMMON.BLK'
      DIMENSION NUMFAIL(200), GRIDFAIL(200)
      INTEGER OUTOFSET(60,60)
      REAL INT1, INT2, L
      CHARACTER*50 RUNID
C
      WRITE(*,*)'Program FASSA3'
      WRITE(*,*)'Forest Area Slope Stability Analsyis'
      WRITE(*,*)'Douglas S. Chandler, Dept. of Civil Engineering'
      WRITE(*,*)'University of Washington'
      WRITE(*,*)'Seattle, Washington'
      WRITE(*,*)'April, 1991'
      WRITE(*,*)
      WRITE(*,*)
C
      WRITE(*,*)'THE FOLLOWING INPUT FILES ARE NEEDED TO BEGIN'
      WRITE(*,*)'EXECUTION OF THE PROGRAM:'
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)'Z.DAT - MEAN GRID CELL ELEVATIONS'
      WRITE(*,*)'SDM.DAT - MEAN GRID CELL SOIL DEPTHS'
      WRITE(*,*)'VEG.PAR - PARAMETERS DEFINING THE VEGETATION'
      WRITE(*,*)'SOIL.PAR - PARAMETERS DEFINING THE SOIL PROPERTIES'
      WRITE(*,*)'HYDR.PAR - PARAMETERS DEFINING HYDROLOGIC CONDITIONS'
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)'THESE FILES SHOULD BE IN THE DEFAULT DIRECTORY'
      WRITE(*,*)'EXECUTION OF THE PROGRAM'
      WRITE(*,*)
      WRITE(*,*)'FILE NAME OF OUTPUT SUMMARY FILE?'
C
C OPEN ALL DATA FILES NEEDED IN THE ANALYSIS
C
      OPEN (10, FILE = 'Z.DAT')
c     OPEN (11, FILE = 'ASPECT.DAT')
      OPEN (12, FILE = 'SLOPE.DAT')
      OPEN (13, FILE = 'SD.DAT')
c     OPEN (14, FILE = 'UPDIST.DAT')
c     OPEN (15, FILE = 'UPAREA.DAT')
      OPEN (16, FILE = 'RC.DAT')
      OPEN (17, FILE = 'QO.DAT')
c     OPEN (18, FILE = 'K.DAT')
```

```
c     OPEN (19, FILE = 'FA.DAT')
c     OPEN (20, FILE = 'C.DAT')
c     OPEN (21, FILE = 'SUW.DAT')
      OPEN (22, FILE = 'SAT.DAT')
c     OPEN (23, FILE = 'SDM.DAT')
c     OPEN (30, FILE = 'VEG.PAR')
      OPEN (31, FILE = 'HYDRO.PAR')
c     OPEN (32, FILE = 'SOIL.PAR')
      OPEN (40, FILE = 'FS.DAT')
      OPEN (42, FILE = 'PROBFAIL.DAT')
      OPEN (50, FILE = ' ')
      WRITE(*,*)
      WRITE(*,*)'RUN IDENTIFICATION? (50 CHARACTERS OR LESS)'
      READ(*,1100) RUNID
      WRITE(*,*)
      WRITE(*,*) 'NUMBER OF TRIALS TO RUN ANALYSIS?'
      READ (*,*) NOTRIAL
      WRITE(*,*)
      WRITE(*,*) 'TIME PERIOD OF ANALYSIS?'
      READ (*,*) TIMEMAX
      WRITE(*,*)
      WRITE(*,*) 'UNIT WEIGHT OF WATER?'
      WRITE(*,*) '(62.4 for U.S. Units, 9810 for Metric Units)'
      READ (*,*) UWW
      WRITE(*,*)
      WRITE(*,*) 'WOULD YOU LIKE TO MANUALLY ADD DRAINAGE AREA'
      WRITE(*,*) 'TO ANY OF THE INDIVIDUAL GRID CELLS TO SIMULATE'
      WRITE(*,*) 'A MANMADE DISCHARGE POINT'
      WRITE(*,*)
      WRITE(*,*) 'PUSH Y FOR YES, N FOR NO'
      READ(*,1200) ANSDA
      IF(ANSDA.EQ.'N'.OR.ANSDA.EQ.'n')  GO TO 5
      WRITE(*,*)
      WRITE(*,*) 'HOW MANY GRID CELLS WOULD YOU LIKE TO ADD DRAINAGE'
      WRITE(*,*) 'AREA TO? (MAXIMUM = 20)'
      READ(*,*)NUMB
      DO 3 NUM = 1,NUMB
      WRITE(*,*) 'INPUT I, J, AND DRAINAGE AREA, ON ONE LINE SEPARATED'
      WRITE(*,*) 'BY SPACES, THEN HIT RETURN'
      WRITE(*,*)
      WRITE(*,*) 'NOTE THAT I = THE ROW NUMBER FROM THE TOP OF THE GRID'
      WRITE(*,*) 'AND J = THE COLUMN NUMBER FROM LEFT OF THE GRID.'
      WRITE(*,*)
      WRITE(*,*)
      READ(*,*) IDA(NUM), JDA(NUM), DADA(NUM)
```

```
  3 CONTINUE
  5 WRITE(*,*)
    WRITE(*,*)
    WRITE(*,*) 'INPUT RANDOM NUMBER SEED VALUE!'
    READ (*,*)  SEED
    READ(10,*) N, M, ANGLE, DIST, EPS
    WRITE(*,*)
    WRITE(50,*)'Program  FASSA3'
    WRITE(50,*)'Forest  Area Slope Stability Analsyis - 3'
    WRITE(50,*)'Douglas  S. Chandler, Dept. of Civil Engineering'
    WRITE(50,*)'University  of Washington'
    WRITE(50,*)'Seattle,  Washington'
    WRITE(50,*)'November,  1992'
    WRITE(50,*)
    WRITE(50,*)
    WRITE(50,1100)  RUNID
    WRITE(50,*)
    WRITE(50,*)'GRID  INDICES'
    WRITE(50,*)
    WRITE(50,300)'N  = number of grid columns = ', N
    WRITE(50,300)'M  = number of grid rows =    ', M
    WRITE(50,400)'DIST  = grid cell dimension = ', DIST
    WRITE(50,400)'ANGLE  = angle grid rotated ccw from North = ', ANGLE
    WRITE(50,*)
    WRITE(50,*)'HEADER  FOR DAT FILES'
    WRITE(50,*)
    WRITE(50,*) N, M, ANGLE, DIST, EPS
    WRITE(50,*)
    WRITE(50,*)'RUN  DATA'
    WRITE(50,*)
    WRITE(50,300)'Number  of Trials = ', NOTRIAL
    WRITE(50,300)'Time  Period of Analysis (years) = ', TIMEMAX
    IF(UWW.EQ.62.4)  WRITE(50,*)'U.S.  units (lbs, feet, days)'
    IF(UWW.EQ.9810)  WRITE(50,*)'Metric  units (Newtons, meters, days)'
     DO 10 I=1,M
      READ (10,*) (ZM(I,J), J=1,N)
 10  CONTINUE
    SWITCH = 1
    SWITCH2 = 1
    FAIL = 0
    OUTOFSET = 0
    SATAVG = 0
    NTOTFAIL = 0
    INDICATOR = 1
    RANDNL = 0
```

```
      FSAVG = 0
      FSMIN = 1000
      FSMAX = 0
      NUMFAIL = 0
      IF(ANSDA.EQ.'N'.OR.ANSDA.EQ.'n')  GO TO 20
      WRITE(50,*) 'THE FOLLOWING DRAINAGE AREAS WERE MANUALLY ADDED'
      WRITE(50,*) 'TO THE FOLLOWING GRID CELL LOCATIONS TO SIMULATE'
      WRITE(50,*) 'A MAN MADE DISCHARGE POINT'
      WRITE(50,*)
       DO 15 NUM = 1,NUMB
        I = IDA(NUM)
        J = JDA(NUM)
        WRITE(50,*)
        WRITE(50,*)'I=  ',I, 'J= ',J,'ADDED DRAINAGE AREA =',DADA(NUM)
   15  CONTINUE
   20 WRITE(50,*)'            SUMMARY OF RUN RESULTS'
      WRITE(50,*)
      WRITE(13,*) N, M, NOTRIAL, TIMEMAX
      WRITE(12,*) N, M, ANGLE, DIST, EPS
       DO 58 I=1,M
   58  WRITE(12,*) (SLOPE(I,J), J=1,N)
      DO 60 TRIAL = 1,NOTRIAL
        WRITE(*,900)'TRIAL  = ', TRIAL
       CALL RANDOMZ
       CALL TOPOGS
       CALL SOIL2
         WRITE(*,*)
         WRITE(*,950) 'cohesion = ', C(1,1)
         WRITE(*,950) 'fric angl (radians) = ', FA(1,1)
         WRITE(*,950) 'sat unit wt = ', SUW(1,1)
         WRITE(*,*)
         DO 50 TIME = 1, TIMEMAX
          CALL VEG2
          CALL HYDRO
          INDICATOR = 100
          NUMFAILS = 0
           DO 40 I=1,M
C The following 4 lines can be disabled to make program run faster
C when you are not doing a subsequent 'PROBFAIL' analysis.
C            WRITE (13,100)(SD(I,J),J=1,N)
C            WRITE (16,100)(RC(I,J),J=1,N)
C            WRITE (17,100)(QO(I,J),J=1,N)
C            WRITE (22,100)(SAT(I,J),J=1,N)
            DO 40 J=1,N
            IF (SLOPE(I,J).LE.0.0)  SLOPE(I,J)  =  .00001
```

```
      WRITE(50,700)'(YEAR)', 'CELLS FOR EACH YEAR', 'CELL FAILING DURING
     * YEAR'
        DO 75, TIME = 1, TIMEMAX
        XFAIL = NUMFAIL(TIME)
        XTRIAL = NOTRIAL
        GRIDFAIL(TIME) = GRIDFAIL(TIME)/NOTRIAL
        WRITE(50,1000) TIME, XFAIL/XTRIAL, GRIDFAIL(TIME)
   75   CONTINUE
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'SOIL  PARAMETERS'
      WRITE(50,*)
      FAM = FAM * 57.2958
      WRITE(50,400)'Mean  Friction Angle (degrees) = ', FAM
      WRITE(50,400)'Coef.  of variation of Friction Angle =', FACOVAR
      WRITE(50,*)
      WRITE(50,400)'Mean  Soil Cohesion (NSM or PSF) = ', CM
      WRITE(50,400)'Coef.  of variation of Soil Cohesion = ', CCOVAR
      WRITE(50,*)
      WRITE(50,400)'Mean  Saturated Unit Weight (NCM or PCF) = ', SUWM
      WRITE(50,400)'Coef.  of variation of Sat. Unit Weight = ', SUWCOVAR
      WRITE(50,*)
      WRITE(50,400)'Mean  Hydrualic Conductivity (MPD or FPD) = ', KM
      WRITE(50,400)'Coef.  of variation of Hydr. Conductivity = ', KCOVAR
      WRITE(50,*)
      WRITE(50,400)'Coef.  of variation of Soil Depths = ', SDCOVAR
      WRITE(50,*)'Array  of Mean Soil Depths listed later'
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'HYDRAULIC  PARAMETERS'
      WRITE(50,*)
      WRITE(50,*)'The  rainfall data is presented in a curve of the '
      WRITE(50,*)'24  hour rainfall (in Meters or Feet) verses the '
      WRITE(50,*)'recurrence  interval (in years).'
      WRITE(50,*)
      WRITE(50,300)'Number  of points defining the curve = ', NUMPTS
      WRITE(50,*)
      WRITE(50,500)'24  HOUR RAINFALL', 'RECURRENCE INTERVAL (YEARS)'
       DO 80, I=1,NUMPTS
   80 WRITE(50,600) INTEN(I)/FACTOR, 1/PROB(I)
      WRITE(50,*)
      WRITE(50,400)'Factor  Applied to Intensities = ', FACTOR
      WRITE(50,*)
      WRITE(50,400)'Maximum  Factored Intensity = ', INTENMAX
      WRITE(50,*)'VEGATATION  PARAMETERS'
```

```
      WRITE(50,*)
      WRITE(50,*)'Vegetation parameters are calculated for each year of'
      WRITE(50,*)'analysis based on data given in the file "veg.par".'
      WRITE(50,*)'The resulting mean root cohesion and vegetation '
      WRITE(50,*)'surcharge for each year are presented below.'
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,700)'YEAR', 'TOTAL ROOT COHESION', 'VEGETATION SURCHARGE'
       DO 81, I = 1,TIMEMAX
 81   WRITE(50,800) I, RCM(I), QOM(I)
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'MEAN Z (ELEVATION)'
       DO 82 I=1,M
 82   WRITE(50,100) (Z(I,J), J=1,N)
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'MEAN SLOPE IN DEGREES'
       DO 84 I=1,M
 84   WRITE(50,150) (SLOPE(I,J), J=1,N)
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'MEAN UPAREA'
       DO 86 I=1,M
 86   WRITE(50,150) (UPAREA(I,J), J=1,N)
      WRITE(50,*)
       DO 87 I=1,M
        DO 87 J=1,N
        IF(ASPECT(I,J).LT.0.0) ASPECT(I,J)=ASPECT(I,J)+360
        IF(ASPECT(I,J).GT.360.0) ASPECT(I,J)=ASPECT(I,J)-360
 87   CONTINUE
      WRITE(50,*)
      WRITE(50,*)'MEAN ASPECT'
       DO 88 I=1,M
 88   WRITE(50,150) (ASPECT(I,J), J=1,N)
      WRITE(50,*)
      WRITE(50,*)
       WRITE(50,*)'MEAN SOIL DEPTH AT EACH GRID CELL'
       DO 90 I=1,M
 90   WRITE(50,100) (SDM(I,J), J=1,N)
      WRITE(50,*)
      WRITE(50,*)
       WRITE(50,*)'AVERAGE NUMBER OF FAILURES AT EACH GRID'
       WRITE(50,*)'CELL DURING THE ANALYZED PERIOD'
       DO 92 I=1,M
```

```
 92  WRITE(50,100) (PROBFAIL(I,J), J=1,N)
     WRITE(50,*)
     WRITE(50,*)
      WRITE(50,*)'NUMBER OF FAILURES AT EACH GRID CELL DIVIDED'
     WRITE(50,*)'BY THE TOTAL NUMBER OF FAILURES FOR THE WHOLE GRID'
     IF(NTOTFAIL.LT.1.0) NTOTFAIL = 1
     DO 93 I=1,M
 93  WRITE(50,200) ((FAIL(I,J)/NTOTFAIL), J=1,N)
     WRITE(50,*)
     WRITE(50,*)
     WRITE(50,*)'AVERAGE RATIO OF WATER DEPTH/SOIL DEPTH FOR EACH CELL'
      DO 94 I=1,M
 94  WRITE(50,100) (SATAVG(I,J), J=1,N)
     WRITE(50,*)
     WRITE(50,*)
     WRITE(50,*)'AVERAGE FACTOR OF SAFETY AT EACH GRID CELL'
      DO 97 I=1,M
 97  WRITE(50,100) (FSAVG(I,J), J=1,N)
     WRITE(50,*)
     WRITE(50,*)
     WRITE(50,*)'MINIMUM FACTOR OF SAFETY AT EACH GRID CELL'
      DO 98 I=1,M
 98  WRITE(50,100) (FSMIN(I,J), J=1,N)
     WRITE(50,*)
     WRITE(50,*)
     WRITE(50,*)'MAXIMUM FACTOR OF SAFETY AT EACH GRID CELL'
      DO 99 I=1,M
 99  WRITE(50,100) (FSMAX(I,J), J=1,N)
100 FORMAT(100(F6.2,2X))
150 FORMAT(100(F7.0,1X))
200 FORMAT(100(F6.5,2X))
250 FORMAT(100(I6,2X))
300 FORMAT(2X,A50,I4)
400 FORMAT(2X,A50,F9.3)
500 FORMAT(2X,A20,2X,A30)
600 FORMAT(10X,F7.3,15X,F6.2)
700 FORMAT(2X,A6,5X,A25,2X,A25)
800 FORMAT(2X,I4,14X,F8.2,17X,F8.2)
900 FORMAT(2X,A22,I5,A20,I5)
950 FORMAT(2X,A26,F8.2)
1000 FORMAT(1X,I7,17X,F13.2,13X,F5.4)
1100 FORMAT(A50)
1200 FORMAT(A1)
     RETURN
     END
```

```
      SUBROUTINE RANDOMZ
      INCLUDE 'COMMON.BLK'
C       THIS SUBROUTINE BUILDS A RANDOM ELEVATION DATA ARRAY USING
C       THE MEAN ELEVATION ARRAY ZM(60,60)
        DO 20 I = 1,M,2
         DO 20 J = 1,N
          CALL RANGEN(SEED, RAN, R2)
          RAN1 = RAN
          CALL RANGEN(SEED, RAN, R2)
          RAN2 = RAN
          DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
          DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
          Z(I,J) = ZM(I,J) + EPS * DF1
          IF(I.NE.M) Z(I+1,J) = ZM(I+1,J) + EPS * DF2
 20   CONTINUE
      RETURN
      END
```

```
C*****************************************************************
C   THIS SUBPROGRAM USES METHODS OF TOPOGRAPHIC ANALYISIS FROM  *
C   AN EARLIER PROGRAM CALLED  "TOPO" , WHICH WAS WRITTEN BY:  *
C                                                 *
C   LYLE W. ZEVENBERGEN                                    *
C   COLIN R. THORNE                                    *
C   DEPT OF GEOGRAPHY & EARTH SCIENCE                        *
C   QUEEN MARY COLLEGE (UNIV. OF LONDON)                      *
C                                                 *
C   THIS PROGRAM "TOPOG" WAS WRITTEN BY:                     *
C                                                 *
C   DOUGLAS S. CHANDLER, DEPT. OF CIVIL ENGINEERING              *
C   UNIVERSITY OF WASHINGTON                              *
C   SEATTLE, WASHINGTON                                 *
C   JULY, 1989                                        *
C                                                 *
C----------------------------------------------*
C                                                 *
C   THIS PROGRAM DETERMINES THE TOPOGRAPHIC INDICES (SLOPE,      *
C   ASPECT, UPSTREAM AREA AND UPSLOPE DISTANCE) FOR POINTS      *
C   WITHIN AN ALTITUDE MATRIX. THE EQUATION:                 *
C                                                 *
C        2 2    2      2    2    2                     *
C   Z = AX Y  + BX Y + CXY  + DX  + EY  + FXY + GX + HY + I     *
C                                                 *
C   IS SOLVED FOR EACH 3X3 SUB-MATRIX.  ALL THE TI'S CORRESPOND *
C   TO THE CENTRAL POINT OF THE SUB-MATRIX.                  *
C                                                 *
C----------------------------------------------*
C                                                 *
C   N = NUMBER OF COLUMNS OF THE ALTITUDE MATRIX               *
C   M = NUMBER OF ROWS OF THE ALTITUDE MATRIX                 *
C   EPS = BOUND ON ERRORS IN ELEVATION ESTIMATES              *
C   DIST = DISTANCE BETWEEN GRID POINTS                    *
C   ANGLE = ANGLE IN DEGREES THE GRID IS ROTATED              *
C          (0 TO 360 DEGREES, COUNTER CLOCKWISE)             *
C   Z(I,J) = ELEVATION OF GRID POINT I,J                  *
C         = ZERO (0) IF ELEVATION IS NOT KNOWN              *
C           (I = ROW NUMBER)                          *
C           (J = COLUMN NUMBER)                         *
C   ASPECT(I,J) = ANGLE (DEGREES) THE DOWNSLOPE GRADIENT IS     *
C                FROM NORTH (0 TO 360)                  *
C   SLOPE(I,J) = SLOPE IN RADIANS                         *
C   UPAREA(I,J) = UPSTREAM AREA IN SQUARE L UNITS              *
C   UPDIST(I,J) = DISTANCE POINT IS FROM DIVIDE IN L UNITS      *
```

```
C                                              *
C-------------------------------------------*
C                                              *
C   DATA: IF FREE FORM, (DATUM SEPARATED BY SPACES)          *
C         LINE 1: N M ANGLE DIST EPS                     *
C         LINES 2...: ELEVATIONS (LEFT TO RIGHT, TOP TO BOTTOM) *
C                   ZEROS FOR UNKNOWN ELEVATIONS            *
C                                              *
C*********************************************************************
      SUBROUTINE TOPOGS
$debug
      DIMENSION ZT(9)
      INCLUDE 'COMMON.BLK'
      SMAX=0.0
      DO 170 J=1,N
        DO 170 I=1,M
          ASPECT(I,J)=0.0
          SLOPE(I,J)=0.0
          UPAREA(I,J)=0.0
          UPDIST(I,J)=0.0
  170 CONTINUE
C
C NOW THE PROGRAM DETERMINES SLOPE AND ASPECT.
C ASPECT IS DEFINED BY THE MAXIMUM SLOPE DIRECTION. IF
C THE 3X3 SUBMATRIX IS INCOMPLETE, THIS POINT IS NOT ANALYZED
C AND IS FLAGGED BY SETTING ASPECT=-1.
      DATA PI/3.14159/
      MM1=M-1
      NM1=N-1
      DSQ=DIST**2
      DSQ4=DSQ*4.0
      D2=DIST*2.0
      DO 300 I=2,MM1
      DO 300 J=2,NM1
        IF(Z(I,J).EQ.0.0) GOTO 300
        IZ=0.0
        DO 200 I1=1,3
        DO 200 J1=1,3
          IZ=IZ+1
          II=I+I1-2
          JJ=J+J1-2
          ZT(IZ)=Z(II,JJ)
          IF (Z(II,JJ).GT.0.0) GOTO 200
            ASPECT(I,J)=-1.0
            GOTO 300
```

```
 200   CONTINUE
       FLAG2(I,J)=1.0
       D=((ZT(4)+ZT(6))/2.0-ZT(5))/DSQ
       E=((ZT(2)+ZT(8))/2.0-ZT(5))/DSQ
       F=-(ZT(1)-ZT(3)-ZT(7)+ZT(9))/DSQ4
       G=-(ZT(4)-ZT(6))/(D2)
       H=(ZT(2)-ZT(8))/(D2)
        ASPECT(I,J)=-1.0
       IF (G.EQ.0.0.AND.H.EQ.0.0) GOTO 300
        ASPECT(I,J)=ATAN2(H,G)*180/PI+180
        SLOPE(I,J)=SQRT(G**2+H**2)
 300 CONTINUE
C
C NOW THE PROGRAM DETERMINES DRAINAGE AREA (UPAREA) AND
C UP-SLOPE DISTANCE (UPDIST) FOR ALL NODES IN THE ALTITUDE
C SUBMATRIX.  SINCE ASPECT VALUES ARE USED TO DETERMINE
C FLOW DIRECTIONS, ANY NODE WITH AN UNKNOWN ASPECT VALUE,
C IT IS APPROXIMATED BY A NEIGHBORING NODE'S ASPECT.
C
     DSQ=DIST**2
     DSQ4=DSQ*4
     D2=DIST*2
     DO 320 I=1,M
     DO 320 J=1,N
 320 FLAG1(I,J)=0.0
     MM1=M-1
     NM1=N-1
     DO 500 I=2,MM1
     DO 500 J=2,NM1
       IF (ASPECT(I,J).NE.-1.0) GOTO 500
        DO 400 I1=1,3
        DO 400 J1=1,3
          II=I-I1+2
          JJ=J-J1+2
          IF(Z(II,JJ).EQ.0.0.OR.ASPECT(II,JJ).EQ.-1.0) GOTO 400
            ASPECT(I,J)=ASPECT(II,JJ)
            SLOPE(I,J)=SLOPE(II,JJ)
            GOTO 500
 400    CONTINUE
        ASPECT(I,J)=0.0
 500 CONTINUE
    DO 600 J=1,N
      IF(Z(1,J).EQ.0.0) GOTO 550
       ASPECT(1,J)=ASPECT(2,J)
       SLOPE(1,J)=SLOPE(2,J)
```

```
  550  IF(Z(M,J).EQ.0.0) GOTO 600
       ASPECT(M,J)=ASPECT(MM1,J)
       SLOPE(M,J)=SLOPE(MM1,J)
  600 CONTINUE
     DO 650 I=1,M
       IF(Z(I,1).EQ.0.0) GOTO 625
       ASPECT(I,1)=ASPECT(I,2)
       SLOPE(I,1)=SLOPE(I,2)
  625  IF(Z(I,1).EQ.0.0) GOTO 650
       ASPECT(I,N)=ASPECT(I,NM1)
       SLOPE(I,N)=SLOPE(I,NM1)
  650 CONTINUE
C
C      THE FINAL ADJUSTMENTS NEEDED BEFORE UPSTREAM AREAS CAN BE
C      CALCULATED: WHEN ANY TWO NEIGHBORING POINTS HAVE ASPECTS
C      WHICH ARE POINTED TOWARDS EACH OTHER THEY WILL TRY TO PASS
C      THEIR AREA AND UPSTREAM AREA TO EACH OTHER. THE POINT WITH
C      THE LOWER ELEVATION MUST "GIVE IN" AND ACCEPT THE OTHER'S
C      AREA AND UPSTREAM AREA. TO DO THIS THE LOWER POINT'S ASPECT
C      IS CHANGED SUCH THAT IT IS POINTING TO ANOTHER NEIGHBORING
C      POINT. THE ONE CHOSEN IS THE ONE WITH THE LOWEST ELEVATION.
C
     ICOUNT=0
  670 FLGQ=0.0
     ICOUNT=ICOUNT+1
     DO 800 I=1,M
     DO 800 J=1,N
       IF(Z(I,J).EQ.0.0) GOTO 800
       I1=I
       J1=J
       IF(ASPECT(I,J).GT.22.5.AND.ASPECT(I,J).LE.157.5) I1=I-1
       IF(ASPECT(I,J).GT.202.5.AND.ASPECT(I,J).LE.337.5) I1=I+1
       IF(ASPECT(I,J).GT.112.5.AND.ASPECT(I,J).LE.247.5) J1=J-1
       IF(ASPECT(I,J).GT.292.5.OR.ASPECT(I,J).LE.67.5) J1=J+1
       IF(I1.LT.1.OR.I1.GT.M) GOTO 800
       IF(J1.LT.1.OR.J1.GT.N) GOTO 800
       IF(Z(I1,J1).EQ.0.0) GOTO 800
       IF(Z(I,J).GT.Z(I1,J1)) GOTO 800
       I2=I1
       J2=J1
       IF(ASPECT(I1,J1).GT.22.5.AND.ASPECT(I1,J1).LE.157.5) I2=I1-1
       IF(ASPECT(I1,J1).GT.202.5.AND.ASPECT(I1,J1).LE.337.5) I2=I1+1
       IF(ASPECT(I1,J1).GT.112.5.AND.ASPECT(I1,J1).LE.247.5) J2=J1-1
       IF(ASPECT(I1,J1).GT.292.5.OR.ASPECT(I1,J1).LE.67.5) J2=J1+1
       IF((I2.NE.I).OR.(J2.NE.J)) GOTO 800
```

```
          ZTEMP=10000.0
          IZ=0
          DO 700 I3=1,3
          DO 700 J3=1,3
           IZ=IZ+1
           II=I+I3-2
           JJ=J+J3-2
           IF(IZ.EQ.5) GOTO 700
           IF(II.EQ.I1.AND.JJ.EQ.J1) GOTO 700
           IF(II.LT.1.OR.II.GT.M) GOTO 700
           IF(JJ.LT.1.OR.JJ.GT.N) GOTO 700
           IF(Z(II,JJ).GT.ZTEMP) GOTO 700
            IZ1=IZ
            ZTEMP=Z(II,JJ)
  700      CONTINUE
          IF(IZ1.EQ.1) ASPECT(I,J)=135.0
          IF(IZ1.EQ.2) ASPECT(I,J)=90.0
          IF(IZ1.EQ.3) ASPECT(I,J)=45.0
          IF(IZ1.EQ.4) ASPECT(I,J)=180.0
          IF(IZ1.EQ.6) ASPECT(I,J)=0.0
          IF(IZ1.EQ.7) ASPECT(I,J)=225.0
          IF(IZ1.EQ.8) ASPECT(I,J)=270.0
          IF(IZ1.EQ.9) ASPECT(I,J)=315.0
          IF(I.EQ.1) ASPECT(I,J)=90.0
          IF(I.EQ.M) ASPECT(I,J)=270.0
          IF(J.EQ.1) ASPECT(I,J)=180.0
          IF(J.EQ.N) ASPECT(I,J)=0.0
          FLGQ=1.0
  800 CONTINUE
      IF(ICOUNT.GT.10) GOTO 810
      IF(FLGQ.EQ.1.0) GOTO 670
C
C    CALCULATE UPSTREAM AREAS.  MOVE THROUGH THE MATRIX GOING
C    TO THE RIGHT AND DOWN, LEFT AND DOWN, RIGHT AND UP, AND
C    LEFT AND UP.  UPAREA(I,J) CAN ONLY BE CALCULATED IF ALL
C    NEIGHBORING POINT'S (WHICH ARE POINTING AT I,J) HAVE KNOWN
C    UPSTREAM AREAS. THIS IS WHY MOVING THROUGH THE MATRIX IN
C    DIFFERENT DIRECTIONS IS NECESSARY.
C
C
C    NOW ADD IN ADDITIONAL DRAINAGE AREA THAT SIMULATES A MAN
C    MADE DISCHARGE POINT.
C
      IF(ANSDA.EQ.'N'.OR.ANSDA.EQ.'n') GO TO 310
       DO 305 NUM = 1,NUMB
```

```
      I = IDA(NUM)
      J = JDA(NUM)
      UPAREA(I,J) = UPAREA(I,J) + DADA(NUM)
  805 CONTINUE
C
  810 DO 1200 K0=1,50
      K1=(K0+1)/2
      K2=K0/2*2-K0
      K3=K1/2*2-K1
      DO 1000 IT=1,M
      DO 1000 JT=1,N
      I=IT
      J=JT
      IF (K2.EQ.0) I=M-IT+1
      IF (K3.EQ.0) J=N-JT+1
       IF(FLAG1(I,J).EQ.1.0) GOTO 1000
       IF(Z(I,J).EQ.0.0) GOTO 1000
       IISTRT=1
       IIEND=3
       JJSTRT=1
       JJEND=3
       IF(I.EQ.1) IISTRT=2
       IF(I.EQ.M) IIEND=2
       IF(J.EQ.1) JJSTRT=2
       IF(J.EQ.N) JJEND=2
       DO 900 I1=IISTRT,IIEND
       DO 900 J1=JJSTRT,JJEND
       II=I+I1-2
       JJ=J+J1-2
        IF (Z(II,JJ).EQ.0.0) GOTO 900
        IJ=3*I1+J1-3
        IJ2=(IJ+1)/2*2-IJ-1
        DTEMP=DIST
        IF (IJ2.EQ.0) DTEMP=DIST*1.414
        GOTO (1,2,3,4,5,6,7,8,9),IJ
    1 IF(ASPECT(II,JJ).LE.292.5.OR.ASPECT(II,JJ).GT.337.5)
     * GOTO 900
        GOTO 850
    2 IF(ASPECT(II,JJ).LE.247.5.OR.ASPECT(II,JJ).GT.292.5)
     * GOTO 900
        GOTO 850
    3 IF(ASPECT(II,JJ).LE.202.5.OR.ASPECT(II,JJ).GT.247.5)
     * GOTO 900
        GOTO 850
    4 IF(ASPECT(II,JJ).LE.337.5.AND.ASPECT(II,JJ).GT.22.5)
```

```
     * GOTO 900
         GOTO 850
    5    GOTO 900
    6 IF(ASPECT(II,JJ).LE.157.5.OR.ASPECT(II,JJ).GT.202.5)
     * GOTO 900
         GOTO 850
    7 IF(ASPECT(II,JJ).LE.22.5.OR.ASPECT(II,JJ).GT.67.5)
     * GOTO 900
         GOTO 850
    8 IF(ASPECT(II,JJ).LE.67.5.OR.ASPECT(II,JJ).GT.112.5)
     * GOTO 900
         GOTO 850
    9 IF(ASPECT(II,JJ).LE.112.5.OR.ASPECT(II,JJ).GT.157.5)
     * GOTO 900
  850     IF(FLAG1(II,JJ).NE.1.0) GOTO 860
           UPAREA(I,J)=UPAREA(I,J)+UPAREA(II,JJ)+DSQ
           IF(UPDIST(II,JJ).GE.UPDIST(I,J))
     *       UPDIST(I,J)=UPDIST(II,JJ)+DTEMP
          GOTO 900
  860       UPAREA(I,J)=0.0
           UPDIST(I,J)=0.0
           FLGEND=1.0
           GOTO 1000
  900    CONTINUE
        FLAG1(I,J)=1.0
 1000   CONTINUE
       IF (FLGEND.EQ.0.0) GO TO 1200
       FLGEND=0.0
 1200 CONTINUE
C
C
      DO 1300 I=1,M
      DO 1300 J=1,N
      IF (Z(I,J).EQ.0.0) GO TO 1300
      UPDIST(I,J)=UPDIST(I,J)+DIST
      UPAREA(I,J)=UPAREA(I,J)+DIST**2
       ASPECT(I,J)=90-ASPECT(I,J)-ANGLE
       IF (ASPECT(I,J).LT.0.0) ASPECT(I,J)=ASPECT(I,J)+360.0
       IF (ASPECT(I,J).GT.360.0) ASPECT(I,J)=ASPECT(I,J)-360.0
C  THE NEXT LINE CONVERTS SLOPE TO RADIANS
       SLOPE(I,J) = ATAN(SLOPE(I,J))
 1300 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SOIL
C      This Version varies each cell individually
      INCLUDE 'COMMON.BLK'
      REAL KSD
      IF(INDICATOR.EQ.100) GO TO 15
      OPEN(23,FILE = 'SDM.DAT')
      OPEN(32,FILE = 'SOIL.PAR')
C       THIS SUBROUTINE BUILDS THE NEEDED SOIL DATA ARRAYS USING
C       INFORMATION FROM THE FILE "SOIL.PAR".
      READ(32,*) N, M, ANGLE, DIST
      READ(32,*) FAM, FACOVAR
      READ(32,*) CM, CCOVAR
      READ(32,*) SUWM, SUWCOVAR
      READ(32,*) KM, KCOVAR
      READ(32,*) SDCOVAR
      READ(23,*) N, M, ANGLE, DIST
       DO 10 I = 1,M
        READ(23,*) (SDM(I,J), J=1,N)
   10  CONTINUE
      REWIND 23
      REWIND 32
      FAM = FAM/57.2958
   15 FASD = FAM * FACOVAR
      CSD =CM * CCOVAR
      IF(CM.LT.40) CSD = 40 * CCOVAR
      SUWSD = SUWM * SUWCOVAR
      KSD = KM * KCOVAR
       DO 20 I = 1,M,2
        DO 20 J = 1,N
         CALL RANGEN(SEED, RAN, R2)
         RAN1 = RAN
         CALL RANGEN(SEED, RAN, R2)
         RAN2 = RAN
         DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
         DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
         FA(I,J) = FAM + FASD * DF1
         IF(FA(I,J).LT.0.227) FA(I,J)=0.227
         IF(I.NE.M) FA(I+1,J) = FAM + FASD * DF2
         IF(FA(I+1,J).LT.0.227) FA(I+1,J)=0.227
         CALL RANGEN(SEED, RAN, R2)
         RAN1 = RAN
         CALL RANGEN(SEED, RAN, R2)
         RAN2 = RAN
         DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
         DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
```

```
      C(I,J) = CM + CSD * DF1
      IF(C(I,J).LT.0.0) C(I,J)=0.0
      IF(I.NE.M) C(I+1,J) = CM + CSD * DF2
      IF(C(I+1,J).LT.0.0) C(I+1,J)=0.0
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
      K(I,J) = KM + KSD * DF1
      IF(K(I,J).LE.0.0) K(I,J)=.001*KM
      IF(I.NE.M) K(I+1,J) = KM + KSD * DF2
      IF(K(I+1,J).LE.0.0) K(I+1,J)=.001*KM
20 CONTINUE
    DO 30 I = 1,M,2
     DO 30 J = 1,N
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
      SUW(I,J) = SUWM + SUWSD * DF1
      IF(SUW(I,J).LE.0.0) SUW(I,J)=.1*SUWM
      IF(I.NE.M) SUW(I+1,J) = SUWM + SUWSD * DF2
      IF(SUW(I+1,J).LE.0.0) SUW(I+1,J)=.1*SUWM
30 CONTINUE
    DO 40 I = 1,M,2
     DO 40 J = 1,N
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
      SD(I,J) = SDM(I,J) + SDCOVAR*SDM(I,J)*DF1
      IF(SD(I,J).LE.0.0) SD(I,J)=.001
      IF(I.NE.M) SD(I+1,J) = SDM(I+1,J) + SDCOVAR*SDM(I,J)*DF2
      IF(SD(I+1,J).LE.0.0) SD(I+1,J)=.001
40 CONTINUE
  RETURN
  END
```

```
      SUBROUTINE SOIL2
C      This version varies the whole grid as a unit
      INCLUDE 'COMMON.BLK'
      REAL KSD
      IF(INDICATOR.EQ.100) GO TO 15
      OPEN(23,FILE = 'SDM.DAT')
      OPEN(32,FILE = 'SOIL.PAR')
C       THIS SUBROUTINE BUILDS THE NEEDED SOIL DATA ARRAYS USING
C       INFORMATION FROM THE FILE "SOIL.PAR".
      READ(32,*) N, M, ANGLE, DIST
      READ(32,*) FAM, FACOVAR
      READ(32,*) CM, CCOVAR
      READ(32,*) SUWM, SUWCOVAR
      READ(32,*) KM, KCOVAR
      READ(32,*) SDCOVAR
      READ(23,*) N, M, ANGLE, DIST
       DO 10 I = 1,M
        READ(23,*) (SDM(I,J), J=1,N)
  10  CONTINUE
      REWIND 23
      REWIND 32
      FAM = FAM/57.2958
  15 FASD = FAM * FACOVAR
      CSD =CM * CCOVAR
      IF(CM.LT.40) CSD = 40 * CCOVAR
      SUWSD = SUWM * SUWCOVAR
      KSD = KM * KCOVAR
      IF(SWITCH.EQ.1) GO TO 18
      SWITCH = 1
      GO TO 21
  18 SWITCH = 2
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      FADF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      FADF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
         CALL RANGEN(SEED, RAN, R2)
         RAN1 = RAN
         CALL RANGEN(SEED, RAN, R2)
         RAN2 = RAN
         CDF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
         CDF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
```

```
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      KDF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      KDF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
        CALL RANGEN(SEED, RAN, R2)
        RAN1 = RAN
        CALL RANGEN(SEED, RAN, R2)
        RAN2 = RAN
        SUWDF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
        SUWDF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
      RAN2 = RAN
      SDDF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
      SDDF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
       DO 20 I = 1,M
        DO 20 J = 1,N
         FA(I,J) = FAM + FASD * FADF1
         IF(FA(I,J).LT.0.227) FA(I,J)=0.227
         C(I,J) = CM + CSD * CDF1
         IF(C(I,J).LT.0.0) C(I,J)=0.0
         K(I,J) = KM + KSD * KDF1
         IF(K(I,J).LE.0.0) K(I,J)=.001*KM
         SUW(I,J) = SUWM + SUWSD * SUWDF1
         IF(SUW(I,J).LE.0.0) SUW(I,J)=.1*SUWM
         SD(I,J) = SDM(I,J) + SDCOVAR*SDM(I,J)*SDDF1
         IF(SD(I,J).LE.0.0) SD(I,J)=.001
20 CONTINUE
     GO TO 31
21   DO 30 I = 1,M
        DO 30 J = 1,N
         FA(I,J) = FAM + FASD * FADF2
         IF(FA(I,J).LT.0.227) FA(I.J)=0.227
         C(I,J) = CM + CSD * CDF2
         IF(C(I,J).LT.0.0) C(I,J)=0.0
         K(I,J) = KM + KSD * KDF2
         IF(K(I,J).LE.0.0) K(I,J)=.001*KM
         SUW(I,J) = SUWM + SUWSD * SUWDF2
         IF(SUW(I,J).LE.0.0) SUW(I,J)=.1*SUWM
         SD(I,J) = SDM(I,J) + SDCOVAR*SDM(I,J)*SDDF2
         IF(SD(I,J).LE.0.0) SD(I,J)=.001
30 CONTINUE
31 RETURN
     END
```

```
      SUBROUTINE VEG2
C     This version randomly assigns veg properties to the whole grid
C     only once per trial (at time = 1) and then factors the veg
C     properties at each cell for each year thereafter.
C     THIS SUBROUTINE RETURNS THE ROOT COHESION (RC) AND THE
C     SLOPE LOADING DUE TO TREES (QO) FOR ANY TIME DURING THE
C     ANALYSIS.  THE SUBPROGRAM READS THE APPROPRIATE PARAMETERS
C     FROM A FILE NAMED 'VEG.PAR', AND THE TIME IS PASSED IN THE
C     COMMON.BLK FROM THE MAIN PROGRAM.  THE FILE VEG.PAR CAN BE
C     BUILT USING THE PREPROCESSOR 'MAKEVEG'.
      INCLUDE 'COMMON.BLK'
      REAL LRCM, LRCDIF, LRCSPAN
      IF(INDICATOR.EQ.100)  GO TO 15
      OPEN(30,FILE = 'VEG.PAR')
      READ(30,*) N, M, ANGLE, DIST, RCCOVAR, QOCOVAR
      READ(30,*) DRCMAX, DRCMIN, DECAYTIME
      READ(30,*) NUMPTSVEG
       DO 10, L = 1, NUMPTSVEG
   10   READ(30,*) T(L), LRC(L)
      READ(30,*) QOMAX, QC, QK
      REWIND 30
   15 EXPON = (-5.0*TIME)/DECAYTIME
      DRCM = DRCMIN + (DRCMAX-DRCMIN)*(2.718**(EXPON))
      IF(TIME.LE.T(1))  LRCM = LRC(1)*TIME/T(1)
       DO 20, L = 1, NUMPTSVEG-1
   20   IF(TIME.GT.T(L).AND.TIME.LE.T(L+1))  GO TO 30
      GO TO 40
   30 TSPAN = T(L+1) - T(L)
      TDIF = TIME - T(L)
      LRCSPAN = LRC(L+1) - LRC(L)
      LRCDIF = TDIF*LRCSPAN/TSPAN
      LRCM = LRC(L) + LRCDIF
   40 IF(TIME.GT.T(NUMPTSVEG))  LRCM = LRC(NUMPTSVEG)
      RCM(TIME) = LRCM + DRCM
      RCSD = RCM(TIME) * RCCOVAR
      QOM(TIME)=QOMAX/(1+QC*EXP(-QK*TIME))
      QOSD = QOM(TIME) * QOCOVAR
      IF (TIME.NE.1)  GO TO 71
      IF(SWITCH2.EQ.1)  GO TO 58
      SWITCH2 = 1
      GO TO 61
   58 SWITCH2 = 2
      CALL RANGEN(SEED, RAN, R2)
      RAN1 = RAN
      CALL RANGEN(SEED, RAN, R2)
```

```
  RAN2 = RAN
  RCDF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
  RCDF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
     CALL RANGEN(SEED, RAN, R2)
     RAN1 = RAN
     CALL RANGEN(SEED, RAN, R2)
     RAN2 = RAN
     QODF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
     QODF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
   DO 60 I = 1,M
    DO 60 J = 1,N
     RC(I,J) = RCM(TIME) + RCSD * RCDF1
     IF(RC(I,J).LT.0.0) RC(I,J)=0.0
     QO(I,J) = QOM(TIME) + QOSD * QODF1
     IF(QO(I,J).LT.0.0) QO(I,J)=0.0
60 CONTINUE
  GO TO 71
61  DO 70 I = 1,M
    DO 70 J = 1,N
     RC(I,J) = RCM(TIME) + RCSD * RCDF2
     IF(RC(I,J).LT.0.0) RC(I,J)=0.0
     QO(I,J) = QOM(TIME) + QOSD * QODF2
     IF(QO(I,J).LT.0.0) QO(I,J)=0.0
70 CONTINUE
71  DO 80 I = 1,M
    DO 80 J = 1,N
     QO(I,J) = QO(I,J) * QOM(TIME)/QOM(1)
     RC(I,J) = RC(I,J) * RCM(TIME)/RCM(1)
80 CONTINUE
91 RETURN
  END
```

```
      SUBROUTINE HYDRO
C     THIS SUBROUTINE RETURNS THE RATIO OF THE SATURATED SOIL
C     DEPTH DIVIDED BY THE SOIL DEPTH (SAT).
      INCLUDE 'COMMON.BLK'
      REAL PROBSPAN, PROBDIF, INTENDIF, INTENSPAN
      IF(INDICATOR.EQ.100) GO TO 15
      OPEN(31,FILE = 'HYDRO.PAR')
      READ(31,*) NUMPTS, FACTOR
       DO 10, L = 1, NUMPTS
        READ(31,*) INTEN(L), PROB(L)
        INTEN(L) = INTEN(L)*FACTOR
        PROB(L) = 1/PROB(L)
        IF(PROB(L).GT.1.0) PROB(L) = 1.0
   10  CONTINUE
      REWIND 31
   15 CALL RANGEN(SEED, RANDOM, R2)
      DO 20, L = 1, NUMPTS
        IF(L.EQ.NUMPTS) GO TO 25
        IF(RANDOM.LE.PROB(L).AND.RANDOM.GT.PROB(L+1)) GO TO 35
   20 CONTINUE
   25 INTENSITY = INTEN(NUMPTS)
      GO TO 45
   35 PROBSPAN = PROB(L+1) - PROB(L)
      PROBDIF = RANDOM - PROB(L)
      INTENSPAN = INTEN(L+1) - INTEN(L)
      INTENDIF = PROBDIF*INTENSPAN/PROBSPAN
      INTENSITY = INTEN(L+1) + INTENDIF
   45 IF(INTENSITY.GT.INTENMAX) INTENMAX = INTENSITY
      DO 50 I=1,M
       DO 50 J=1,N
       SAT(I,J)=(INTENSITY*UPAREA(I,J))/(K(I,J)*SIN(SLOPE(I,J))*
     # COS(SLOPE(I,J))*DIST*SD(I,J))
       IF(SAT(I,J).GE.1.0) SAT(I,J) = 1.0
   50 CONTINUE
      RETURN
      END
```

```
  SUBROUTINE RANGEN(SEED,RANDNL,RANDN0)
  REAL LAMBDA,MU
  RHO=10.**35
  LAMBDA=101.
  MU=111.
  IF(RANDNL.NE.0) GOTO 20
  X=AMOD(LAMBDA*SEED+MU,RHO)
  DO 10 I=1,500
  X=AMOD(LAMBDA*X+MU,RHO)
10 CONTINUE
  RANDNL=X/RHO
  RETURN
20 CONTINUE
  RANDN0=RANDNL*RHO
  RANDNL=AMOD(LAMBDA*RANDN0+MU,RHO)/RHO
  RETURN
  END
```

```
c**********************************************************************
c Program EVOLVE
c Douglas S. Chandler, Dept. of Civil Engineering
c Dr. Terrence W. Cundy, College of Forest Resources
c University of Washington
c Seattle, Washington
c
c**********************************************************************
c This program simulates the evolution of a steep forested hollow
c through time due to bedrock weathering and soil creep.
c**********************************************************************
C
C   DESCRIPTION OF GRID VARIABLES
C
C   N = NUMBER OF COLUMNS OF THE ALTITUDE MATRIX              *
C   M = NUMBER OF ROWS OF THE ALTITUDE MATRIX               *
C   DIST = DISTANCE BETWEEN GRID POINTS                  *
C   ANGLE = ANGLE IN DEGREES THE GRID IS ROTATED            *
C         (0 TO 360 DEGREES, COUNTER CLOCKWISE)         *
C   Z(I,J) = ELEVATION OF GRID POINT I,J               *
C          (I = ROW NUMBER)                       *
C          (J = COLUMN NUMBER)                      *
C   ASPECT(I,J) = ANGLE (DEGREES) THE DOWNSLOPE GRADIENT IS    *
C              FROM NORTH (0 TO 360)              *
C   SLOPE(I,J) = GRADIENT IN RADIANS                   *
C   UPAREA(I,J) = UPSTREAM AREA IN SQUARE L UNITS            *
C   UPDIST(I,J) = DISTANCE FROM GRID CELL TO DIVIDE         *
C   SD(I,J) = SOIL DEPTH MEASURED VERTICALLY              *
C-----------------------------------------------
C
C   DATA FORMAT FOR ALL I/O FILES WITH GRID VARIABLES
C
C   FREE FORMAT (DATA SEPERATED BY SPACES OR COMMAS
C   LINE 1:       N, M, ANGLE, DIST, EPS
C   LINES 2...M+1  GRID VARIABLES SUCH AS ASPECT, ELEVATION,
C                SOIL DEPTH, ETC.  (LEFT TO RIGHT,
C                TOP TO BOTTOM)
C
c**********************************************************************
C
C   DESCRIPTION OF EVOLVE VARIABLES
C
C   INPUT DATA FOR THIS PROGRAM IS BY READING FROM EXISTING FILES.
C   NECESSARY INPUT FILES WITH GRID VARIABLES IN THE
C   FORMAT DESCRIBED ABOVE ARE:
```

```
C              Z.DAT - INITIAL GRID CELL ELEVATIONS
C              SD.DAT - INITIAL GRID CELL SOIL DEPTHS
C
C   AN ADDITIONAL INPUT FILE WITH THE EVOLVE DATA IS NEEDED TO INPUT
C   THE FOLLOWING VARIABLES:
C
C       DUFFACUM = ACCUMULATION RATE OF FOREST DUFF (LENGTH/TIME)
C       WP = POTENTIAL WEATHERING RATE ON BARE ROCK (LENGTH/TIME)
C       KW = WEATHERING CONSTANT (DIMENSIONLESS)
C       KS = SLOPE TRANSPORT CONSTANT (LENGTH SQUARED/TIME)
C       TSTMAX = TIME INTERVAL FOR RECALCULATING TOPOGRAPHY (TIME)
C       TIMEMAX = TIME PERIOD TO RUN THE ANALYSIS
C
C-------------------------------------------------
C
C   DATA FORMAT FOR EVOLVE.DAT
C   FREE FORMAT (DATA SEPERATED BY SPACES OR COMMAS
C   LINE 1: DUFFACUM, WP, KW, KS, TSTMAX, TIMEMAX
C
    PROGRAM EVOLVE
$DEBUG
    INCLUDE 'COMMON.BLK'
    DIMENSION OUT(100,100)
    INTEGER TIME, TSTMAX, TIMEMAX
    REAL IN(100,100), KW, KS
C
C  Read in the initial data
C
    OPEN (10, FILE = 'Z.DAT')
    OPEN (13, FILE = 'SD.DAT')
    OPEN (14, FILE = 'EVOLVE.DAT')
    OPEN (20, FILE = 'EVOLVEZ.DAT')
    OPEN (23, FILE = 'EVOLVESD.DAT')
    WRITE(*,*)'NAME OF SUMMARY OUTPUT FILE?'
    OPEN (51, FILE = ' ')
    READ (14,*) DUFFACUM, WP, KW, KS, TSTMAX, TIMEMAX
     REWIND 10
     REWIND 13
     READ (10,*) N, M, ANGLE, DIST, EPS
     READ (13,*) N, M, ANGLE, DIST, EPS
     DO 5 I=1,M
     READ (10,*) (Z(I,J),J=1,N)
     READ (13,*) (SD(I,J),J=1,N)
  5  CONTINUE
    WRITE(51,*)
```

```
      WRITE(51,*)'Program EVOLVE'
      WRITE(51,*)'Douglas S. Chandler, Dept. of Civil Engineering'
      WRITE(51,*)'Dr. Terrence W. Cundy, College of Forest Resources'
      WRITE(51,*)'University of Washington'
      WRITE(51,*)'Seattle, Washington'
      WRITE(51,*)'April, 1991'
      WRITE(51,*)
      WRITE(51,*)
C
      WRITE(51,*)
      WRITE(51,500)'N = number of grid columns = ', N
      WRITE(51,500)'M = number of grid rows =    ', M
      WRITE(51,400)'DIST = grid cell dimension = ', DIST
      WRITE(51,400)'ANGLE = angle grid rotated ccw from North = ', ANGLE
      WRITE(51,*)
      WRITE(51,*)'RUN DATA'
      WRITE(51,*)
      WRITE(51,400)'ACCUMULATION RATE OF FOREST DUFF = ',DUFFACUM
      WRITE(51,400)'POTENTIAL WEATHERING RATE ON BARE ROCK = ', WP
      WRITE(51,400)'WEATHERING CONSTANT (DIMENSIONLESS) = ', KW
      WRITE(51,400)'SLOPE TRANSPORT CONSTANT (LENGTH SQUARED/TIME) =',KS
      WRITE(51,500)'TIME INTERVAL FOR RECALCULATING TOPOGRAPHY =',TSTMAX
      WRITE(51,500)'TIME PERIOD TO RUN THE ANALYSIS = ',TIMEMAX
      WRITE(51,*)
      WRITE(51,*)
      WRITE(51,*)'INITIAL ELEVATIONS AT EACH GRID CELL'
      DO 4 I=1,M
    4 WRITE(51,300) (Z(I,J), J=1,N)
      WRITE(51,*)
      WRITE(51,*)
      WRITE(51,*)'INITIAL SOIL DEPTHS AT EACH GRID CELL'
      DO 8 I=1,M
    8 WRITE(51,300) (SD(I,J), J=1,N)
      WRITE(51,*)
      DO 100 TIME = 0, TIMEMAX, TSTMAX
      CALL TOPOGS
C
C     OUT(I,J) = THE TOTAL AMOUNT OF OUTGOING SEDIMENT FOR EACH
C              CELL (DURING EACH TIME PERIOD OF TSTMAX).  SINCE
C              GRID CELL SIZE IS CONSTANT, 'OUT' IS
C              EXPRESSED AS A DEPTH COVERING THE ENTIRE CELL AREA.
C              'OUT' IS FROM CREEP AND SLOPE WASH AND IS A FUNCTION
C              OF THE SIN OF THE SLOPE ANGLE.  'OUT' CAN BE NO MORE
C              THAN THE EXISTING SOIL DEPTH OF THE CELL.
C
```

```
      DO 10 I=1,M
        DO 10 J=1,N
        OUT(I,J) = TSTMAX*KS*SIN(SLOPE(I,J))/DIST
        IF(OUT(I,J).GT.SD(I,J)) OUT(I,J) = SD(I,J)
        IN(I,J) = 0.0
 10   CONTINUE
C
C     IN(I,J) = THE TOTAL AMOUNT OF INCOMING SEDIMENT FOR EACH
C               CELL.  AS FOR 'OUT', 'IN' IS EXPRESSED AS A DEPTH
C               OVER THE ENTIRE CELL AREA.  'IN' EQUALS THE SUM OF ALL
C               THE 'OUTS' OF CONTRIBUTING NEIGHBOR CELLS PLUS THE
C               ACCUMULATION OF FOREST DUFF.
C
C
      DO 100 I=1,M
        DO 100 J=1,N
        IF (I.EQ.1.OR.J.EQ.1) GO TO 20
        IF (ASPECT(I-1,J-1).GT.112.5.AND.ASPECT(I-1,J-1).LE.157.5)
     #  IN(I,J) = IN(I,J) + OUT(I-1,J-1)
 20     IF (I.EQ.1) GO TO 30
        IF (ASPECT(I-1,J).GT.157.5.AND.ASPECT(I-1,J).LE.202.5)
     #  IN(I,J) = IN(I,J) + OUT(I-1,J)
 30     IF (I.EQ.1.OR.J.EQ.N) GO TO 40
        IF (ASPECT(I-1,J+1).GT.202.5.AND.ASPECT(I-1,J+1).LE.247.5)
     #  IN (I,J) = IN(I,J) + OUT(I-1,J+1)
 40     IF (J.EQ.N) GO TO 50
        IF (ASPECT(I,J+1).GT.247.5.AND.ASPECT(I,J+1).LE.292.5)
     #  IN(I,J) = IN(I,J) + OUT(I,J+1)
 50     IF (I.EQ.M.OR.J.EQ.N) GO TO 60
        IF (ASPECT(I+1,J+1).GT.292.5.AND.ASPECT(I+1,J+1).LE.337.5)
     #  IN(I,J) = IN(I,J) + OUT(I+1,J+1)
 60     IF (I.EQ.M) GO TO 70
        IF (ASPECT(I+1,J).GT.337.5.OR.ASPECT(I+1,J).LE.22.5)
     #  IN (I,J) = IN(I,J) + OUT(I+1,J)
 70     IF (I.EQ.M.OR.J.EQ.1) GO TO 80
        IF (ASPECT(I+1,J-1).GT.22.5.AND.ASPECT(I+1,J-1).LE.67.5)
     #  IN(I,J) = IN(I,J) + OUT(I+1,J-1)
 80     IF (J.EQ.1) GO TO 90
        IF (ASPECT(I,J-1).GT.67.5.AND.ASPECT(I,J-1).LE.112.5)
     #  IN(I,J) = IN(I,J) + OUT(I,J-1)
 90     IN(I,J) = IN(I,J) + DUFFACUM*TSTMAX
        Z(I,J) = Z(I,J) + IN(I,J) - OUT(I,J)
        WA = WP*2.718**(-KW*SD(I,J))
        SD(I,J) = SD(I,J) + IN(I,J) - OUT(I,J) + WA
 100    CONTINUE
```

```
   WRITE (20,200) N, M, ANGLE, DIST, EPS
   WRITE (23,200) N, M, ANGLE, DIST, EPS
    DO 105 I = 1,M
     WRITE (20,300) (Z(I,J), J=1,N)
105   WRITE (23,300) (SD(I,J), J=1,N)
   WRITE(51,*)
   WRITE(51,*)'RUN RESULTS (FINAL SOIL DEPTHS & ELEVATIONS)'
   WRITE(51,*)
   WRITE(51,*)'FINAL ELEVATIONS AT EACH GRID CELL'
    DO 110 I=1,M
110  WRITE(51,300) (Z(I,J), J=1,N)
   WRITE(51,*)
   WRITE(51,*)
    WRITE(51,*)'FINAL SOIL DEPTHS AT EACH GRID CELL'
    DO 120 I=1,M
120  WRITE(51,300) (SD(I,J), J=1,N)
   WRITE(51,*)
   WRITE(51,*)
200 FORMAT (I7, 2X, I7, 2X, F7.2, 2X, F7.2, 2X, F7.2)
300 FORMAT (100(F7.2, 2X))
400 FORMAT(2X,A60,F9.6)
500 FORMAT(2X,A60,I10)
   RETURN
   END
```

```
c**********************************************************************
c  Program PROBFAIL
c  Douglas S. Chandler, Dept. of Civil Engineering
c  University of Washington
c  Seattle, Washington
c
c**********************************************************************
c This program calculates the probability of failure by landsliding
c for a forested location using a Monte Carlo simulation of the
c infinite slope equation.  The most important input variables are
c normally distributed random variables of given means and variances.
c**********************************************************************
C
C DESCRIPTION OF NECESSARY INPUT DATA
C
C PRIMARY INPUT TO THIS PROGRAM IS BY READING FROM EXTERNAL FILES BUILT
C PRIOR TO THE EXECUTION OF THE PROGRAM.  ALTHOUGH THERE IS EXTRANEOUS
C DATA PRESENT, THE SAME INPUT FILES USED BY THE FASSA PROGRAM ARE USED
C FOR THIS PROGRAM.  IN ADDITION, THE OUTPUT DATA FILES "SAT.DAT, RC.DAT,
C QO.DAT & SD.DAT FROM THE FASSA2 PROGRAM ARE USED TO DETERMINE THE
C MEAN VALUES AND COEFICIENTS OF VARIATION OF THOSE VARIABLES.
C
C ALTHOUGH SEVERAL COMBINATIONS OF UNITS CAN BE USED, THE FOLLOWING
C UNITS ARE SUGGESTED:
C
C  - USE DEGREES FOR ANGLE INPUT AND OUTPUT, PROGRAM WORKS IN RADIANS.
C
C  - SHEAR STRENGTHS & PRESSURES (COHESION & TREE LOADING)
C      USE NEWTONS/SQUARE METER  'OR'  POUNDS/SQUARE FOOT
C
C  - UNIT WEIGHTS
C      USE NEWTONS/CUBIC METER 'OR'  POUNDS/CUBIC FOOT
C      UNIT WEIGHT OF WATER = 9810 NCM  OR  62.4 PCF
C
C**********************************************************************
C
C
      PROGRAM PROBFAIL
$debug
      DIMENSION VALUE(200), SLOPE(60,60)
      REAL INT11, INT21, INT12, INT22, L1, L2, MEAN
      CHARACTER*50 RUNID
C
      WRITE(*,*)'Program PROBFAIL'
      WRITE(*,*)'Douglas S. Chandler, Dept. of Civil Engineering'
```

```
      WRITE(*,*)'University of Washington'
      WRITE(*,*)'Seattle, Washington'
      WRITE(*,*)'November, 1992'
      WRITE(*,*)
      WRITE(*,*)
C
      WRITE(*,*)'THE FOLLOWING INPUT FILES ARE NEEDED TO BEGIN'
      WRITE(*,*)'EXECUTION OF THE PROGRAM:'
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)'SOIL.PAR - PARAMETERS DEFINING THE SOIL PROPERTIES'
      WRITE(*,*)'QO.DAT - PLANT SURCHARCH DATA FROM FASSA2'
      WRITE(*,*)'RC.DAT - ROOT COHESION DATA FROM FASSA2'
      WRITE(*,*)'SAT.DAT - WATER LEVEL DATA FROM FASSA2'
      WRITE(*,*)'SD.DAT - SOIL DEPTH DATA FROM FASSA2'
      WRITE(*,*)'SLOPE.DAT - SLOPE DATA FROM FASSA2'
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)'THESE FILES SHOULD BE IN THE DEFAULT DIRECTORY'
      WRITE(*,*)'PRIOR TO EXECUTION OF THE PROGRAM'
      WRITE(*,*)
      WRITE(*,*)'FILE NAME OF OUTPUT SUMMARY FILE?'
C
C  OPEN ALL DATA FILES NEEDED IN THE ANALYSIS
C
c      OPEN (10, FILE = 'Z.DAT')
c      OPEN (11, FILE = 'ASPECT.DAT')
      OPEN (12, FILE = 'SLOPE.DAT')
      OPEN (13, FILE = 'SD.DAT')
c      OPEN (14, FILE = 'UPDIST.DAT')
c      OPEN (15, FILE = 'UPAREA.DAT')
      OPEN (16, FILE = 'RC.DAT')
      OPEN (17, FILE = 'QO.DAT')
c      OPEN (18, FILE = 'K.DAT')
c      OPEN (19, FILE = 'FA.DAT')
c      OPEN (20, FILE = 'C.DAT')
c      OPEN (21, FILE = 'SUW.DAT')
      OPEN (22, FILE = 'SAT.DAT')
c      OPEN (23, FILE = 'SDM.DAT')
c      OPEN (30, FILE = 'VEG.PAR')
      OPEN (31, FILE = 'HYDRO.PAR')
      OPEN (32, FILE = 'SOIL.PAR')
      OPEN (40, FILE = 'FS.DAT')
      OPEN (42, FILE = 'PROBFAIL.DAT')
      OPEN (50, FILE = ' ')
```

```
      WRITE(*,*)
      WRITE(*,*)'RUN IDENTIFICATION? (50 CHARACTERS OR LESS)'
      READ(*,1100) RUNID
      WRITE(*,*)
      WRITE(*,*) 'UNIT WEIGHT OF WATER?'
      WRITE(*,*) '(62.4 for U.S. units, 9810 for metric units)'
      READ (*,*)  UWW
      WRITE(*,*)
      WRITE(*,*) 'INPUT RANDOM NUMBER SEED VALUE!'
      READ (*,*)  SEED
      WRITE(*,*)
      WRITE(50,*)'Program PROBFAIL'
      WRITE(50,*)'Douglas S. Chandler, Dept. of Civil Engineering'
      WRITE(50,*)'University of Washington'
      WRITE(50,*)'Seattle, Washington'
      WRITE(50,*)'November, 1992'
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,1100) RUNID
      WRITE(50,*)
      IF(UWW.EQ.62.4) WRITE(50,*)'U.S. units (lbs, feet, days)'
      IF(UWW.EQ.9810) WRITE(50,*)'Metric units (Newtons, meters, days)'
      READ(13,*) N, M, NOTRIAL, TIMEMAX
c
c First read SD.DAT and find mean and std. dev. of numbers
c
      NOLINES = NOTRIAL*TIMEMAX*M
      TOTAL = 0
      DO 10 L =1,NOLINES
       READ(13,*) (VALUE(J),J=1,N)
       DO 10 J = 1,N
   10  TOTAL = TOTAL + VALUE(J)
      REWIND 13
      READ(13,*) N, M, NOTRIAL, TIMEMAX
      MEAN = TOTAL/(NOLINES*N)
      SUMSUB = 0
      DO 20 L =1,NOLINES
       READ(13,*) (VALUE(J),J=1,N)
       DO 20 J = 1,N
       SUB = (VALUE(J)-MEAN)**2
   20  SUMSUB =  SUMSUB + SUB
      VAR = SUMSUB/(NOLINES*N-1)
      STDEV = VAR**.5
      SDMEAN = MEAN
      SDSTDEV = STDEV
```

```
      WRITE (50,*)'MEAN SD = ', SDMEAN
      WRITE(50,*)'STANDARD DEVIATION OF SD = ', SDSTDEV
      WRITE (*,*)'MEAN SD = ', SDMEAN
      WRITE(*,*)'STANDARD DEVIATION OF SD = ', SDSTDEV
c Now do the same thing for RC.DAT
      TOTAL = 0
      DO 30 L =1,NOLINES
       READ(16,*) (VALUE(J),J=1,N)
       DO 30 J = 1,N
   30 TOTAL = TOTAL + VALUE(J)
      MEAN = TOTAL/(NOLINES*N)
      SUMSUB = 0
      REWIND 16
      DO 40 L =1,NOLINES
       READ(16,*) (VALUE(J),J=1,N)
       DO 40 J = 1,N
       SUB = (VALUE(J)-MEAN)**2
   40 SUMSUB =  SUMSUB + SUB
      VAR = SUMSUB/(NOLINES*N-1)
      STDEV = VAR**.5
      RCMEAN = MEAN
      RCSTDEV = STDEV
      WRITE(50,*)'MEAN RC = ', RCMEAN
      WRITE(50,*)'STANDARD DEVIATION OF RC = ', RCSTDEV
      WRITE(*,*)'MEAN RC = ', RCMEAN
      WRITE(*,*)'STANDARD DEVIATION OF RC = ', RCSTDEV
c Now QO.DAT
      TOTAL = 0
      DO 50 L =1,NOLINES
       READ(17,*) (VALUE(J),J=1,N)
       DO 50 J = 1,N
   50 TOTAL = TOTAL + VALUE(J)
      MEAN = TOTAL/(NOLINES*N)
      SUMSUB = 0
      REWIND 17
      DO 60 L =1,NOLINES
       READ(17,*) (VALUE(J),J=1,N)
       DO 60 J = 1,N
       SUB = (VALUE(J)-MEAN)**2
   60 SUMSUB =  SUMSUB + SUB
      VAR = SUMSUB/(NOLINES*N-1)
      STDEV = VAR**.5
      QOMEAN = MEAN
      QOSTDEV = STDEV
      WRITE(50,*)'MEAN QO = ', QOMEAN
```

```
      WRITE(50,*)'STANDARD DEVIATION OF QO = ', QOSTDEV
      WRITE(*,*)'MEAN QO = ', QOMEAN
      WRITE(*,*)'STANDARD DEVIATION OF QO = ', QOSTDEV
c Now SAT.DAT
      TOTAL = 0
      DO 70 L =1,NOLINES
       READ(22,*) (VALUE(J),J=1,N)
       DO 70 J = 1,N
   70  TOTAL = TOTAL + VALUE(J)
      MEAN = TOTAL/(NOLINES*N)
      SUMSUB = 0
      REWIND 22
      DO 80 L =1,NOLINES
       READ(22,*) (VALUE(J),J=1,N)
       DO 80 J = 1,N
       SUB = (VALUE(J)-MEAN)**2
   80  SUMSUB =  SUMSUB + SUB
      VAR = SUMSUB/(NOLINES*N-1)
      STDEV = VAR**.5
      SATMEAN = MEAN
      SATSTDEV = STDEV
      WRITE(50,*)'MEAN SAT = ', SATMEAN
      WRITE(50,*)'STANDARD DEVIATION OF SAT = ', SATSTDEV
      WRITE(*,*)'MEAN SAT = ', SATMEAN
      WRITE(*,*)'STANDARD DEVIATION OF SAT = ', SATSTDEV
c Now find the mean and standard deviation of the slopes
       READ(12,*) N, M, ANGLE, DIST, EPS
       DO 90 I=1,M
        READ (12,*) (SLOPE(I,J), J=1,N)
   90 CONTINUE
      TOTAL = 0
       DO 100 I=1,M
        DO 100 J=1,N
  100   TOTAL = TOTAL + SLOPE(I,J)
      MEAN = TOTAL/(N*M)
      SUMSUB = 0
      DO 110 I=1,M
       DO 110 J=1,N
       SUB = (SLOPE(I,J)-MEAN)**2
  110 SUMSUB =  SUMSUB + SUB
      VAR = SUMSUB/(N*M-1)
      STDEV = VAR**.5
      SLOPEMEAN = MEAN
      SLOPESTDEV = STDEV
C Convert from radians to degrees temporarily for output to file.
```

```
      TEMP1 = SLOPEMEAN * 57.3
      TEMP2 = SLOPESTDEV * 57.3
      WRITE(50,*)'MEAN SLOPE = ', TEMP1
      WRITE(50,*)'STANDARD DEVIATION OF SLOPE = ', TEMP2
      WRITE(*,*)'MEAN SLOPE = ', TEMP1
      WRITE(*,*)'STANDARD DEVIATION OF SLOPE = ', TEMP2
c Now read the means and covariances of the soil parameters.
      OPEN(32,FILE = 'SOIL.PAR')
      READ(32,*) N, M, ANGLE, DIST
      READ(32,*) FAM, FACOVAR
      READ(32,*) CM, CCOVAR
      READ(32,*) SUWM, SUWCOVAR
      FASD = FAM * FACOVAR
      CSD =CM * CCOVAR
      IF(CM.LT.40) CSD = 40 * CCOVAR
      SUWSD = SUWM * SUWCOVAR
      WRITE(50,*)'MEAN FA = ', FAM
      WRITE(50,*)'STANDARD DEVIATION OF FA = ', FASD
      WRITE(50,*)'MEAN C = ', CM
      WRITE(50,*)'STANDARD DEVIATION OF C = ', CSD
      WRITE(50,*)'MEAN SATURATED UNIT WEIGHT = ', SUWM
      WRITE(50,*)'STANDARD DEVIATION OF SAT. UNIT WT. = ', SUWSD
      WRITE(*,*)'MEAN FA = ', FAM
      WRITE(*,*)'STANDARD DEVIATION OF FA = ', FASD
      WRITE(*,*)'MEAN C = ', CM
      WRITE(*,*)'STANDARD DEVIATION OF C = ', CSD
      WRITE(*,*)'MEAN SATURATED UNIT WEIGHT = ', SUWM
      WRITE(*,*)'STANDARD DEVIATION OF SAT. UNIT WT. = ', SUWSD
      FAM = FAM/57.2958
      FASD = FASD/57.2958
c Now have means and standard deviations of all the variables and can
c perform the Monte Carlo simulation.
      TOTFAIL = 0
      FSAVG = 0
      FSMIN = 1000
      FSMAX = 0
      TRIALS = NOTRIAL*TIMEMAX*N*M/2
       DO 120 TRIAL = 1,TRIALS
         CALL RANGEN(SEED, RAN, R2)
         RAN1 = RAN
         CALL RANGEN(SEED, RAN, R2)
         RAN2 = RAN
         DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
         DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
         FA1 = FAM + FASD * DF1
```

```
IF(FA1.LT.0.227) FA=0.227
FA2 = FAM + FASD * DF2
IF(FA2.LT.0.227) FA2=0.227
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
C1 = CM - CSD * DF1
IF(C1.LT.0.0) C1=0.0
C2 = CM - CSD * DF2
IF(C2.LT.0.0) C2=0.0
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
SUW1 = SUWM + SUWSD * DF1
IF(SUW1.LE.0.0) SUW1=.1*SUWM
SUW2 = SUWM + SUWSD * DF2
IF(SUW2.LE.0.0) SUW2=.1*SUWM
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
SD1 = SDMEAN + SDSTDEV * DF1
IF(SD1.LE.0.0) SD1=.001
SD2 = SDMEAN + SDSTDEV * DF2
IF(SD2.LE.0.0) SD2=.001
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
RC1 = RCMEAN - RCSTDEV * DF1
IF(RC1.LT.0.0) RC1=0.0
RC2 = RCMEAN - RCSTDEV * DF2
IF(RC2.LT.0.0) RC2=0.0
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
```

```
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
QO1 = QOMEAN - QOSTDEV * DF1
IF(QO1.LT.0.0) QO1=0.0
QO2 = QOMEAN - QOSTDEV * DF2
IF(QO2.LT.0.0) QO2=0.0
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
SAT1 = SATMEAN - SATSTDEV * DF1
IF(SAT1.LT.0.0) SAT1 = 0.0
IF(SAT1.GT.1.0) SAT1 = 1.0
SAT2 = SATMEAN - SATSTDEV * DF2
IF(SAT2.LT.0.0) SAT2 = 0.0
IF(SAT2.GT.1.0) SAT2 = 1.0
CALL RANGEN(SEED, RAN, R2)
RAN1 = RAN
CALL RANGEN(SEED, RAN, R2)
RAN2 = RAN
DF1 = SQRT(2*LOG(1/RAN1))*COS(2*3.14159*RAN2)
DF2 = SQRT(2*LOG(1/RAN1))*SIN(2*3.14159*RAN2)
SLOPE1 = SLOPEMEAN - SLOPESTDEV * DF1
IF(SLOPE1.LE.0.0) SLOPE1=0.00001
IF(SLOPE1.GE.3.14159) SLOPE1 = 3.14
SLOPE2 = SLOPEMEAN - SLOPESTDEV * DF2
IF(SLOPE2.LE.0.0) SLOPE2 = 0.00001
IF(SLOPE2.GE.3.14159) SLOPE2 = 3.14
 L1 = QO1/(UWW*SD1)+(SUW1/UWW)*SAT1+(.9*SUW1/UWW)*(1-SAT1)
 INT11=2*(C1+RC1)/(UWW*SD1*SIN(2*(SLOPE1)))
 INT21=(L1-SAT1)*TAN(FA1)/TAN (SLOPE1)
 FS1 = (INT11 + INT21)/L1
 IF(FS1.LE.1.0) TOTFAIL = TOTFAIL + 1
 IF(FS1.LT.FSMIN) FSMIN = FS1
 IF(FS1.GT.FSMAX) FSMAX = FS1
 FSAVG = FSAVG + FS1
 L2 = QO2/(UWW*SD2)+(SUW2/UWW)*SAT2+(.9*SUW2/UWW)*(1-SAT2)
 INT12=2*(C2+RC2)/(UWW*SD2*SIN(2*(SLOPE2)))
 INT22=(L2-SAT2)*TAN(FA2)/TAN (SLOPE2)
 FS2 = (INT12 + INT22)/L2
 IF(FS2.LE.1.0) TOTFAIL = TOTFAIL + 1
```

```
          IF(FS2.LT.FSMIN) FSMIN = FS2
          IF(FS2.GT.FSMAX) FSMAX = FS2
          FSAVG = FSAVG + FS2
 120  CONTINUE
       CALCS = TRIALS * 2
       FSAVG = FSAVG/(CALCS)
       FAILPROB = TOTFAIL/(CALCS)
      WRITE(50,*)
      WRITE(50,*)
      WRITE(50,*)'TOTAL NUMBER OF CALCULATIONS = ', CALCS
      WRITE(50,*)
      WRITE(50,*)'TOTAL NUMBER OF FAILURES = ', TOTFAIL
      WRITE(50,*)
      WRITE(50,*)'AVERAGE FACTOR OF SAFETY = ', FSAVG
      WRITE(50,*)
      WRITE(50,*)'MINIMUM FACTOR OF SAFETY = ', FSMIN
      WRITE(50,*)
      WRITE(50,*)'MAXIMUM FACTOR OF SAFETY = ', FSMAX
      WRITE(50,*)
      WRITE(50,*)'PROBABILITY OF FAILURE = ', FAILPROB
      WRITE(50,*)
 200 FORMAT(100(F6.5,2X))
 300 FORMAT(2X,A50,I4)
 400 FORMAT(2X,A50,F9.3)
 500 FORMAT(2X,A20,2X,A30)
 600 FORMAT(10X,F7.3,15X,F6.2)
 700 FORMAT(2X,A6,5X,A25,2X,A25)
 800 FORMAT(2X,I4,14X,F8.2,17X,F8.2)
 900 FORMAT(2X,A12,I4,A20,I4)
1000 FORMAT(1X,I8,12X,F8.2)
1100 FORMAT(A50)
1200 FORMAT(A1)
     RETURN
     END
```

```
PROGRAM MAKESOIL
DIMENSION SDM(100,100)
REAL KM, KCOVAR
OPEN(23,FILE = 'SDM.DAT')
OPEN(32,FILE = 'SOIL.PAR')
WRITE(*,*)'THIS PROGRAM PROMPTS THE USER FOR THE NEEDED SOIL'
WRITE(*,*)'INFORMATION, THEN BUILDS THE FILE "SOIL.PAR".'
WRITE(*,*)
WRITE(*,*) 'NUMBER OF COLUMNS IN GRID MATRICES?'
READ(*,*) N
WRITE(*,*) 'NUMBER OF ROWS IN GRID MATRICES?'
READ(*,*) M
WRITE(*,*)'ANGLE (DEGREES) THE GRID IS ROTATED CCW?'
READ(*,*) ANGLE
WRITE(*,*)
WRITE(*,*)'GRID CELL DIMENSION?'
READ(*,*) DIST
WRITE(*,*)
WRITE(*,*)'THE MEAN SOIL FRICTION ANGLE?'
READ(*,*)FAM
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF FRIC. ANGL? (TYP=.06 TO.25)'
READ(*,*)FACOVAR
WRITE(*,*)
WRITE(*,*)'THE MEAN SOIL COHESION?'
READ(*,*)CM
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF COHESION? (TYP=.3 TO .5)'
READ(*,*)CCOVAR
WRITE(*,*)
WRITE(*,*)'THE MEAN SOIL SATURATED UNIT WEIGHT?'
READ(*,*)SUWM
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF UNIT WEIGHT? (TYP=.1 TO .2)'
READ(*,*)SUWCOVAR
WRITE(*,*)
WRITE(*,*)'THE MEAN SOIL SATURATED HYDRAULIC CONDUCTIVITY (K)?'
READ(*,*)KM
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF K? (TYP=.3 TO 1.5)'
READ(*,*)KCOVAR
WRITE(*,*)
WRITE(*,*)'THE MEAN SOIL DEPTHS CAN EITHER BE INPUT AS A SINGLE'
WRITE(*,*)'VALUE TO BE APPLIED TO THE ENTIRE GRID, OR AS A'
WRITE(*,*)'MATRIX OF SOIL DEPTHS WITH A SINGLE COEFICIENT OF'
```

```
   WRITE(*,*)'VARIATION.  PUSH Y TO USE A MATRIX OF MEAN DEPTHS, OR'
   WRITE(*,*)'N TO USE A SINGLE MEAN SOIL DEPTH OVER THE GRID AREA.'
   READ(*,100) ANSWER
   IF(ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y') GO TO 30
   WRITE(*,*)
   WRITE(*,*)'INPUT THE MEAN SOIL DEPTH.'
   READ(*,*)SD
   WRITE(*,*)
   WRITE(*,*)'THE COEF. OF VARIATION OF SOIL DEPTH? (TYP=.1 TO .3)'
   READ(*,*)SDCOVAR
   WRITE(23,*) N, M, ANGLE, DIST, SDCOVAR
    DO 10, I = 1,M
     DO 10, J = 1,N
10   SDM(I,J)=SD
    DO 20, I = 1,M
20  WRITE(23,200)(SDM(I,J), J=1,N)
   WRITE(*,*)'THE MEAN SOIL DEPTH IS WRITTEN TO GRID FILE SDM.DAT'
   GO TO 40
   WRITE(*,*)
30 WRITE(*,*)'YOU MUST PREPARE A GRID FILE NAMED SDM.DAT WITH THE'
   WRITE(*,*)'GRID CELL VALUES OF THE MEAN SOIL DEPTHS.'
   WRITE(*,*)'INPUT COEF. OF VAR. OF SOIL DEPTHS? (TYP=.1 TO .2)'
   READ(*,*)SDCOVAR
40 WRITE(32,*) N, M, ANGLE, DIST
   WRITE(32,*) FAM, FACOVAR
   WRITE(32,*) CM, CCOVAR
   WRITE(32,*) SUWM, SUWCOVAR
   WRITE(32,*) KM, KCOVAR
   WRITE(32,*) SDCOVAR
   WRITE(*,*)
   WRITE(*,*)'YOU ARE DONE, DATA IS WRITTEN TO SOIL.PAR.'
100 FORMAT(A1)
200 FORMAT(100(F7.1,2X))
   RETURN
   END
```

```
PROGRAM MAKEVEG
DIMENSION T(50), LRC(50)
OPEN(40,FILE = 'VEG.PAR')
WRITE(*,*)'THIS PROGRAM PROMPTS THE USER FOR THE CORRECT'
WRITE(*,*)'INFORMATION THEN BUILDS THE FILE "VEG.PAR".'
WRITE(*,*)
WRITE(*,*) 'NUMBER OF COLUMNS IN GRID MATRICES?'
WRITE(*,*)
READ(*,*) N
WRITE(*,*) 'NUMBER OF ROWS IN GRID MATRICES?'
READ(*,*) M
WRITE(*,*)
WRITE(*,*)'ANGLE (DEGREES) THE GRID IS ROTATED CCW?'
READ(*,*) ANGLE
WRITE(*,*)
WRITE(*,*)'GRID CELL DIMENSION?'
READ(*,*) DIST
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF RC (TYPICAL = 0.3)'
READ(*,*)RCCOVAR
WRITE(*,*)
WRITE(*,*)'THE COEF. OF VARIATION OF QO (TYPICAL = 0.3)'
READ(*,*)QOCOVAR
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)'THE APPARENT COHESION DUE TO ROOT REINFORCEMENT IS'
WRITE(*,*)'DUE TO BOTH THE DECAYING DEAD ROOTS AND THE GROWING'
WRITE(*,*)'LIVE ROOTS.  THE DEAD ROOT COHESION IS APPROXIMATED'
WRITE(*,*)'BY A DECAYING FUNCTION SIMILAR TO ZIEMER, 1981.'
WRITE(*,*)' '
WRITE(*,*)'DECAY TIME (YEARS) TO GET MINIMUM DRC? (TYP = 25)'
READ(*,*) DECAYTIME
WRITE(*,*)
WRITE(*,*)'INITIAL (MAXIMUM) COHESION FROM DEAD ROOTS?'
READ(*,*) DRCMAX
WRITE(*,*)
WRITE(*,*)'MINIMUM COHESION FROM DEAD ROOTS?'
READ(*,*) DRCMIN
WRITE(*,*)
WRITE(40,*) N, M, ANGLE, DIST, RCCOVAR, QOCOVAR
WRITE(40,*) DRCMAX, DRCMIN, DECAYTIME
WRITE(*,*)
WRITE(*,*)'THE LIVE ROOT COHESION VARIES WITH TIME FROM PLANTING.'
WRITE(*,*)'PUSH Y IF YOU WANT TO SPECIFY THE TIME RELATIONSHIP OF'
WRITE(*,*)'ZIEMER (1981), SCALED TO A MAXIMUM LIVE ROOT COHESION'
```

```
   WRITE(*,*)'THAT YOU SPECIFY.'
   WRITE(*,*)
   WRITE(*,*)'PUSH N IF YOU WANT TO SPECIFY YOUR OWN CURVE.'
   WRITE(*,*)
   READ(*,100) ANSWER
   IF(ANSWER.EQ.'Y'.OR.ANSWER.EQ.'y') GO TO 20
   WRITE(*,*)
   WRITE(*,*)
   WRITE(*,*)'YOU HAVE OPTED TO SPECIFY YOUR OWN SERIES OF POINTS'
   WRITE(*,*)'ON A CURVE OF LIVE ROOT REINFORCEMENT VRS. YEARS'
   WRITE(*,*)'AFTER LOGGING.  HOW MANY POINTS?'
   WRITE(*,*)
   READ(*,*)NUMPTS
   WRITE(40,*) NUMPTS
    DO 10, L = 1, NUMPTS
    WRITE(*,*)'TIME, LIVE ROOT COHESION?'
    WRITE(*,*)
    READ(5,*) T(L), LRC(L)
10  WRITE(40,*) T(L), LRC(L)
   GO TO 30
20 WRITE(*,*)'MAXIMUM LIVE ROOT COHESION?'
   READ(*,*)LRCMAX
   LRC3=.04*LRCMAX
   LRC8=.06*LRCMAX
   LRC14=.6*LRCMAX
   LRC25=.4*LRCMAX
   LRC50=LRCMAX
   WRITE(40,*) 5
   WRITE(40,*) 3, LRC3
   WRITE(40,*) 8, LRC8
   WRITE(40,*) 14, LRC14
   WRITE(40,*) 25, LRC25
   WRITE(40,*) 50, LRC50
30 WRITE(*,*)'THE WEIGHT OF VEGETATION (QO) MUST BE CONSIDERED AS'
   WRITE(*,*)'A LOAD ON THE SLOPE.  IT IS ASSUMED THAT THE LOAD'
   WRITE(*,*)'INCREASES TO A USER SPECIFIED MAXIMUM ACCORDING TO'
   WRITE(*,*)'THE FOLLOWING LOGISTICS FUNCTION:'
   WRITE(*,*)
   WRITE(*,*)'QO = QOMAX/(1+C*e**(-kT))'
   WRITE(*,*)
   WRITE(*,*)'QOMAX? (SUGGEST ABOUT 300 NSM OR 7 PSF)'
   READ(*,*)QOMAX
   WRITE(*,*)
   WRITE(*,*)'WHERE T = TIME IN YEARS'
   WRITE(*,*)
```

```
   WRITE(*,*)'ENTER C?  (SUGGEST 60)'
   READ(*,*) QC
   WRITE(*,*)
   WRITE(*,*)'ENTER k?  (SUGGEST 0.07)'
   READ(*,*)QK
   WRITE(*,*)
   WRITE(40,*) QOMAX, QC, QK
   WRITE(*,*)'YOU ARE DONE, DATA IS WRITTEN TO VEG.PAR.'
100 FORMAT (A1)
   RETURN
   END
```

```
      PROGRAM MAKEHYDR
      DIMENSION R(100), T(100)
      OPEN(31, FILE = 'HYDRO.PAR')
      WRITE(*,*)'THIS PROGRAM PROMPTS USER FOR HYDROLOGIC DATA, THE'
      WRITE(*,*)'WRITES IT TO THE FILE "HYDRO.PAR" FOR USE BY THE'
      WRITE(*,*)'SUBROUTINE "HYDRO".'
      WRITE(*,*)' '
      WRITE(*,*)'YOU MUST INPUT A SERIES OF PAIRED DATA VALUES OF'
      WRITE(*,*)'24 HOUR PRECIPITATION AMOUNTS AND THE ASSOCIATED'
      WRITE(*,*)'RETURN PERIOD IN YEARS FOR EACH 24 HOUR PRECIPT.'
      WRITE(*,*)'THE NUMBER PAIRS SHOULD START WITH THE SMALLEST'
      WRITE(*,*)'RETURN PERIOD (MOST FREQUENT EVENT).'
      WRITE(*,*)' '
      WRITE(*,*)'HOW MANY DATA PAIRS OF 24 HR. RAIN, RETURN PERIOD?'
      READ(*,*) NPTS
      WRITE(*,*)' '
       DO 10, I = 1,NPTS
       WRITE(*,*)'INPUT "24 HR. RAIN","RETURN PERIOD (YEARS)"'
       READ(*,*) R(I), T(I)
       WRITE(*,*)' '
   10  CONTINUE
      WRITE(*,*)' '
      WRITE(*,*)'THESE 24 HOUR PRECIPT VALUES REPRESENT AN AVERAGE'
      WRITE(*,*)'STORM INTENSTITY OVER THE 24 HOURS.  THIS INTENSITY'
      WRITE(*,*)'IS FACTORED TO ESTIMATE A STEADY STATE INTENSITY TO'
      WRITE(*,*)'USE WITH THE KINEMATIC CASCADE APPROXIMATION.'
      WRITE(*,*)'FOR EXAMPLE, A FACTOR OF 1.5 WOULD MULTIPLY THE '
      WRITE(*,*)'AVERAGE INTENSITY CALCULATED FROM THE 24 HOUR'
      WRITE(*,*)'PRECIPT BY 1.5 TO GET THE INTENSITY FOR THE KINEMATIC'
      WRITE(*,*)'CASCADE APPROXIMATION.'
      WRITE(*,*)
      WRITE(*,*)'WHAT FACTOR SHOULD BE USED?'
      WRITE(*,*)
      READ(*,*) FACTOR
      WRITE(*,*)
      WRITE(31,100) NPTS, FACTOR
      WRITE(*,*)
       DO 20 I = 1,NPTS
       WRITE(31,*) R(I), T(I)
   20  CONTINUE
  100 FORMAT(I4, 2X, F8.2, 2X, F8.4)
      RETURN
      END
```

```
C     PROGRAM MAKEFILE.FOR
C     THIS PROGRAM MAKES A BLANK INPUT SOIL DEPTH FILE FOR THE EVOLVE PROGRAM
      WRITE (*,*) 'NAME OF OUTPUT SOIL DATA FILE?'
      OPEN (7, FILE = ' ')
      WRITE (*,*) 'N - NUMBER OF COLUMNS IN MATRIX?'
      READ (5,*) N
      WRITE (*,*) 'M - NUMBER OF ROWS IN MATRIX?'
      READ (5,*) M
      WRITE (*,*) 'ANGLE - ANGLE IN DEGREES GRID IS ROTATED CC?'
      READ (5,*) ANGLE
      WRITE (*,*) 'DIST - DIMENSION OF GRID CELLS?'
      READ (5,*) DIST
      WRITE (*,*) 'SOIL DEPTH?'
      READ (5,*) SOILDPTH
      EPS = .1*SOILDPTH
      WRITE (7,100) N, M, ANGLE, DIST, EPS
       DO 10 I = 1,M
       WRITE (7,200) (SOILDPTH, J=1,N)
 10    CONTINUE
100   FORMAT (I7, 2X, I7, 2X, F7.2, 2X, F7.2, 2X, F7.2)
200   FORMAT (100(F7.2, 2X))
      STOP
      END
```

APPENDIX C

EXAMPLE PROGRAM INPUT AND OUTPUT

LISTING OF FILE 'SOIL.PAR' (SOIL PARAMETERS) FOR EXAMPLE PROBLEM

```
19  27  270  20
36  .1
0   .2
105  .05
100  .3
.2
```

LISTING OF FILE 'VEG.PAR' (VEGETATION PARAMETERS) FOR EXAMPLE PROBLEM

```
19  27  270  20  .5  .5
80  0  .5
2
1  160
50 160
400  60  .07
```

LISTING OF FILE 'HYDRO.PAR' (HYDROLOGIC PARAMETERS) FOR EXAMPLE PROBLEM

```
8  3
8.100000E-02       1.010000
1.110000E-01       1.100000
1.690000E-01       2.000000
2.240000E-01       5.000000
2.470000E-01      10.000000
2.860000E-01      20.000000
3.220000E-01      50.000000
3.540000E-01     100.000000
```

LISTING OF FILE 'Z.DAT' (ELEVATIONS) FOR EXAMPLE PROBLEM

```
19      27    270     20      1
354.27 353.72 352.95 352.30 351.75 351.34 351.12 351.15 351.45 351.75 352.06 352.28 352.38 352.38 352.31 352.38 352.71 353.12 353.42
354.21 353.56 352.89 352.32 351.88 351.51 351.29 351.32 351.53 351.81 352.03 352.20 352.38 352.46 352.57 352.71 353.04 353.60 353.83
354.13 353.48 352.93 352.46 352.04 351.70 351.51 351.59 351.83 352.05 352.18 352.35 352.59 352.84 353.00 353.13 353.52 353.86 354.23
354.11 353.51 353.07 352.69 352.32 352.00 351.83 352.01 352.30 352.53 352.65 352.77 353.18 353.53 353.70 353.80 353.87 354.02 353.28
354.22 353.74 353.36 353.03 352.71 352.41 352.34 352.55 352.95 353.25 353.40 353.62 353.92 354.16 354.24 354.11 353.14 351.50 350.68
354.42 354.06 353.70 353.45 353.14 352.98 352.96 353.17 353.64 353.88 354.02 354.10 353.86 353.29 352.87 352.13 350.43 348.37 346.92
354.62 354.37 354.13 353.88 353.73 353.60 353.61 353.80 354.02 353.65 352.85 352.08 351.25 350.56 349.84 349.06 347.51 344.99 343.50
354.42 354.57 354.45 354.36 354.25 354.11 354.04 353.83 352.30 350.78 349.54 348.38 347.31 346.41 345.86 345.42 343.93 341.46 339.39
353.49 353.86 353.90 353.85 353.86 353.73 353.15 351.04 348.60 346.51 344.91 343.68 342.27 341.31 340.97 340.50 339.28 336.29 333.84
352.25 352.38 352.18 351.98 351.55 350.85 349.38 346.84 343.78 341.27 339.56 337.88 336.39 335.44 334.93 334.22 332.60 329.59 327.39
351.05 350.86 350.41 349.41 348.46 346.78 344.67 341.98 338.43 335.61 333.08 331.01 329.67 328.87 328.44 327.51 325.44 322.35 320.27
349.89 349.73 348.61 347.08 344.93 342.54 339.88 336.43 332.51 328.63 325.51 323.14 321.85 321.51 321.10 320.32 318.48 315.70 312.76
348.75 348.31 346.78 344.20 341.34 338.37 334.63 330.17 325.38 320.91 317.07 314.59 313.32 312.95 312.99 312.85 311.71 308.26 304.98
347.27 346.60 344.31 341.15 337.61 333.65 329.14 323.54 317.85 312.70 308.74 305.41 303.99 303.58 303.79 304.06 303.13 299.07 295.55
345.32 344.23 341.59 337.94 333.64 328.88 323.38 317.04 310.60 305.10 300.27 296.48 294.23 293.30 293.01 292.59 290.72 286.94 283.91
343.32 341.96 339.18 334.71 329.76 323.98 317.46 310.63 303.15 296.75 291.13 286.73 283.73 281.97 280.88 279.51 276.66 272.79 270.11
341.03 340.22 336.53 331.35 325.03 318.43 311.49 303.38 294.88 286.98 280.49 275.64 272.12 269.77 268.15 266.13 262.22 257.95 255.77
337.79 337.27 332.99 326.00 318.81 311.89 304.01 294.86 284.97 275.94 268.61 263.12 259.30 256.71 254.99 252.91 248.30 243.72 241.04
331.28 331.47 325.80 318.07 310.27 302.59 294.44 284.20 273.32 263.56 255.55 249.60 245.66 243.16 241.48 239.64 235.44 230.41 227.66
320.31 319.24 314.21 306.98 298.92 290.44 281.33 271.02 260.24 249.88 241.43 235.31 231.58 229.40 228.25 226.82 222.94 218.71 215.72
306.64 304.77 300.22 293.51 285.58 276.65 266.71 256.21 245.45 235.18 226.26 220.13 216.84 215.67 215.77 215.32 211.50 208.01 206.23
292.44 290.46 285.87 279.63 271.50 262.07 251.99 241.24 230.31 219.95 211.27 205.77 203.56 203.42 204.51 205.22 203.04 200.91 200.13
278.39 276.37 272.01 265.24 256.96 247.57 237.40 226.98 216.47 206.49 200.37 197.67 197.01 197.54 198.40 198.90 198.38 197.71 197.44
264.03 262.31 257.54 250.79 242.60 233.46 223.69 214.16 204.99 199.24 195.70 193.63 193.80 194.69 195.57 196.18 195.83 195.51 195.43
249.31 247.05 242.63 236.45 228.94 220.41 211.88 203.90 199.16 196.01 193.60 192.18 192.18 193.02 193.86 194.50 194.15 193.75 193.61
235.19 232.49 228.44 223.07 216.52 209.33 202.48 198.96 196.40 194.31 192.59 191.50 191.41 192.00 192.80 193.35 193.46 192.50 192.17
226.58 223.61 219.86 215.01 209.08 202.94 199.47 197.05 195.24 193.55 192.11 191.20 191.02 191.54 192.25 192.92 193.02 192.00 191.42
```

LISTING OF FILE 'SDM.DAT' (MEAN SOIL DEPTHS) FOR EXAMPLE PROBLEM

```
19     27    270    20     1
2.07   2.10   2.15   2.18   2.21   2.22   2.23   2.22   2.21   2.20   2.18   2.18   2.18   2.18   2.18   2.17   2.15   2.13   2.12
2.09   2.12   2.16   2.19   2.22   2.23   2.23   2.22   2.21   2.20   2.18   2.18   2.17   2.16   2.15   2.14   2.12   2.10   2.09
2.12   2.15   2.17   2.20   2.21   2.22   2.22   2.21   2.19   2.18   2.16   2.15   2.14   2.13   2.11   2.09   2.07   2.04   2.03
2.14   2.15   2.17   2.19   2.20   2.21   2.20   2.18   2.16   2.14   2.12   2.11   2.09   2.07   2.05   2.03   2.00   1.98   1.98
2.14   2.15   2.16   2.17   2.18   2.18   2.16   2.14   2.11   2.09   2.07   2.05   2.03   2.01   1.98   1.96   1.94   1.93   1.93
2.12   2.13   2.14   2.14   2.14   2.13   2.11   2.08   2.04   2.02   2.01   2.00   1.98   1.96   1.93   1.90   1.89   1.89   1.89
2.10   2.10   2.11   2.10   2.09   2.07   2.04   2.01   1.98   1.98   1.97   1.97   1.96   1.93   1.90   1.87   1.85   1.85   1.86
2.08   2.08   2.07   2.06   2.03   1.99   1.96   1.94   1.95   1.97   1.98   1.98   1.96   1.94   1.90   1.85   1.82   1.81   1.82
2.08   2.06   2.04   2.01   1.97   1.92   1.90   1.91   1.95   2.00   2.02   2.02   2.00   1.96   1.91   1.85   1.80   1.78   1.77
2.08   2.06   2.03   1.99   1.93   1.88   1.87   1.91   1.99   2.06   2.09   2.08   2.04   1.99   1.92   1.85   1.79   1.75   1.74
2.08   2.05   2.01   1.97   1.92   1.88   1.88   1.93   2.03   2.12   2.16   2.14   2.09   2.02   1.94   1.85   1.77   1.73   1.71
2.06   2.02   1.99   1.95   1.91   1.89   1.89   1.96   2.07   2.17   2.23   2.21   2.15   2.06   1.95   1.84   1.75   1.69   1.66
2.02   1.98   1.95   1.92   1.90   1.89   1.91   1.98   2.09   2.21   2.29   2.28   2.20   2.09   1.96   1.83   1.72   1.64   1.61
1.98   1.93   1.90   1.89   1.89   1.89   1.92   1.99   2.10   2.23   2.32   2.33   2.25   2.12   1.98   1.84   1.72   1.63   1.60
1.92   1.88   1.85   1.85   1.86   1.88   1.91   1.98   2.10   2.24   2.34   2.36   2.29   2.16   2.03   1.89   1.78   1.71   1.68
1.84   1.80   1.78   1.79   1.82   1.85   1.89   1.96   2.08   2.23   2.35   2.39   2.33   2.21   2.09   1.98   1.91   1.85   1.83
1.75   1.70   1.69   1.71   1.76   1.81   1.87   1.94   2.07   2.22   2.37   2.43   2.38   2.27   2.15   2.08   2.04   2.01   2.00
1.65   1.60   1.59   1.63   1.71   1.79   1.86   1.94   2.07   2.25   2.41   2.48   2.44   2.33   2.23   2.18   2.16   2.16   2.16
1.60   1.53   1.52   1.58   1.68   1.79   1.87   1.97   2.11   2.31   2.49   2.57   2.53   2.41   2.31   2.26   2.26   2.28   2.29
1.62   1.53   1.50   1.56   1.69   1.81   1.92   2.03   2.20   2.41   2.60   2.69   2.64   2.52   2.40   2.35   2.36   2.39   2.41
1.70   1.59   1.53   1.58   1.72   1.87   2.00   2.13   2.32   2.54   2.74   2.83   2.77   2.63   2.51   2.44   2.45   2.48   2.50
1.78   1.65   1.58   1.63   1.77   1.94   2.10   2.27   2.46   2.69   2.88   2.95   2.88   2.73   2.59   2.51   2.51   2.53   2.55
1.86   1.72   1.64   1.68   1.84   2.03   2.22   2.41   2.62   2.83   2.98   3.01   2.91   2.75   2.61   2.53   2.51   2.52   2.53
1.92   1.78   1.69   1.74   1.90   2.12   2.35   2.56   2.75   2.90   2.99   2.97   2.85   2.69   2.56   2.48   2.45   2.45   2.45
1.98   1.83   1.75   1.79   1.96   2.20   2.46   2.66   2.81   2.89   2.91   2.85   2.73   2.59   2.46   2.39   2.36   2.36   2.36
2.02   1.88   1.79   1.83   2.00   2.26   2.52   2.71   2.82   2.84   2.81   2.73   2.61   2.48   2.37   2.31   2.28   2.28   2.28
2.03   1.90   1.82   1.85   2.02   2.28   2.54   2.73   2.81   2.81   2.75   2.67   2.55   2.43   2.33   2.27   2.25   2.25   2.25
```

```
 Program FASSA
 Forest Area Slope Stability Analsyis
 Douglas S. Chandler, Dept. of Civil Engineering
 University of Washington

Run Description:

Natural conditions without drywell

GRID INDICES

N = number of grid columns =   19
M = number of grid rows =      27
DIST = grid cell dimension =    20.000
ANGLE = angle grid rotated ccw from North =   270.000


HEADER FOR DAT FILES

         19          27      270.000000       20.000000         1.000000

RUN DATA

Number of Trials = 1000
Time Period of Analysis (years) =    1
U.S. units (lbs, feet, days)


SUMMARY OF RUN RESULTS


 TOTAL NUMBER OF FACTOR OF SAFETY CALCULATIONS PERFORMED =  513000
 TOTAL NUMBER OF FAILURES =        13149



 TIME          AVERAGE NUMBER OF FAILED              PROB OF AT LEAST ONE
(YEAR)         CELLS FOR EACH YEAR                   CELL FAILING DURING YEAR
 1                       13.15                                     .290
```

```
SOIL PARAMETERS

                    Mean Friction Angle (degrees) =    36.000
               Coef. of variation of Friction Angle =    .100

                  Mean Soil Cohesion (NSM or PSF) =      .000
               Coef. of variation of Soil Cohesion =    .200

        Mean Saturated Unit Weight (NCM or PCF) =   105.000
         Coef. of variation of Sat. Unit Weight =      .050

       Mean Hydrualic Conductivity (MPD or FPD) =   100.000
       Coef. of variation of Hydr. Conductivity =      .300

                Coef. of variation of Soil Depths =     .200
Array of Mean Soil Depths listed later


HYDRAULIC PARAMETERS

The rainfall data is presented in a curve of the
24 hour rainfall (in Meters or Feet) verses the
recurrence interval (in years).

               Number of points defining the curve =   8


24 HOUR RAINFALL               RECURRENCE INTERVAL (YEARS)
      .081                            1.01
      .111                            1.10
      .169                            2.00
      .224                            5.00
      .247                           10.00
      .286                           20.00
      .322                           50.00
      .354                          100.00

                 Factor Applied to Intensities =     3.000

                   Maximum Factored Intensity =     1.146
```

VEGETATION PARAMETERS

Vegetation parameters are calculated for each year of analysis based on data given in the file "veg.par". The resulting mean root cohesion and vegetation surcharge for each year are presented below.

```
YEAR          TOTAL ROOT COHESION                  VEGETATION SURCHARGE
 1                  160.00                                 7.02
```

Coefficient of Variation of root cohesion = 0.5
Coefficient of Variation of vegetation surcharge = 0.5

Grid Variables

Z (ELEVATION)

```
354.27 353.72 352.95 352.30 351.75 351.34 351.12 351.15 351.45 351.75 352.06 352.28 352.38 352.38 352.31 352.38 352.71 353.12 353.42
354.21 353.56 352.89 352.32 351.88 351.51 351.29 351.32 351.53 351.81 352.03 352.20 352.38 352.46 352.57 352.71 353.04 353.60 353.83
354.13 353.48 352.93 352.46 352.04 351.70 351.51 351.59 351.33 352.05 352.18 352.35 352.59 352.84 353.00 353.13 353.52 353.86 354.23
354.11 353.51 353.07 352.69 352.32 352.00 351.83 352.01 352.30 352.53 352.65 352.77 353.18 353.53 353.70 353.80 353.87 354.02 353.28
354.22 353.74 353.36 353.03 352.71 352.41 352.34 352.55 352.95 353.25 353.40 353.62 353.92 354.16 354.24 354.11 353.14 351.50 350.68
354.42 354.06 353.70 353.45 353.14 352.98 352.96 353.17 353.64 353.88 354.02 354.10 353.86 353.29 352.37 352.13 350.43 348.37 346.92
354.62 354.37 354.13 353.88 353.73 353.60 353.61 353.80 354.02 353.65 352.85 352.08 351.25 350.56 349.84 349.06 347.51 344.99 343.50
354.42 354.57 354.45 354.36 354.25 354.11 354.04 353.83 352.30 350.78 349.54 348.38 347.31 346.41 345.36 345.42 343.93 341.46 339.39
353.49 353.86 353.90 353.85 353.86 353.73 353.15 351.04 348.60 346.51 344.91 343.68 342.27 341.31 340.97 340.50 339.28 336.29 333.84
352.25 352.38 352.18 351.98 351.55 350.85 349.38 346.84 343.78 341.27 339.56 337.88 336.39 335.44 334.93 334.22 332.60 329.59 327.39
351.05 350.86 350.41 349.41 348.46 346.78 344.67 341.98 338.43 335.61 333.08 331.01 329.67 328.87 328.44 327.51 325.44 322.35 320.27
349.89 349.73 348.61 347.08 344.93 342.54 339.88 336.43 332.51 328.63 325.51 323.14 321.85 321.51 321.10 320.32 318.48 315.70 312.76
348.75 348.31 346.78 344.20 341.34 338.37 334.63 330.17 325.38 320.91 317.07 314.59 313.32 312.95 312.99 312.85 311.71 308.26 304.98
347.27 346.60 344.31 341.15 337.61 333.65 329.14 323.54 317.85 312.70 308.74 305.41 303.99 303.58 303.79 304.06 303.13 299.07 295.55
345.32 344.23 341.59 337.94 333.64 328.88 323.38 317.04 310.60 305.10 300.27 296.48 294.23 293.30 293.01 292.59 290.72 286.94 283.91
343.32 341.96 339.18 334.71 329.76 323.98 317.46 310.63 303.15 296.75 291.13 286.73 283.73 281.97 280.88 279.51 276.66 272.79 270.11
341.03 340.22 336.53 331.35 325.03 318.43 311.49 303.38 294.88 286.98 280.49 275.64 272.12 269.77 268.15 266.13 262.22 257.95 255.77
337.79 337.27 332.99 326.00 318.81 311.89 304.01 294.86 284.97 275.94 268.61 263.12 259.30 256.71 254.99 252.91 248.30 243.72 241.04
331.28 331.47 325.80 313.07 310.27 302.59 294.44 284.20 273.32 263.56 255.55 249.60 245.66 243.16 241.48 239.64 235.44 230.41 227.66
320.31 319.24 314.21 306.98 298.92 290.44 281.33 271.02 260.24 249.88 241.43 235.31 231.58 229.40 228.25 226.82 222.94 218.71 215.72
306.64 304.77 300.22 293.51 285.58 276.65 266.71 256.21 245.45 235.18 226.26 220.13 216.84 215.67 215.77 215.32 211.50 208.01 206.23
292.44 290.46 285.37 279.63 271.50 262.07 251.99 241.24 230.31 219.95 211.27 205.77 203.56 203.42 204.51 205.22 203.04 200.91 200.13
278.39 276.37 272.01 265.24 256.96 247.57 237.40 225.98 216.47 206.49 200.37 197.67 197.01 197.54 198.40 198.90 198.38 197.71 197.44
264.03 262.31 257.54 250.79 242.60 233.46 223.69 214.16 204.99 199.24 195.70 193.63 193.80 194.69 195.57 196.18 195.83 195.51 195.43
249.31 247.05 242.63 236.45 228.94 220.41 211.88 203.90 199.16 196.01 193.60 192.18 192.18 193.02 193.86 194.50 194.15 193.75 193.61
235.19 232.49 228.44 223.07 216.52 209.33 202.48 198.96 196.40 194.31 192.59 191.50 191.41 192.00 192.80 193.35 193.46 192.50 192.17
226.58 223.61 219.86 215.01 209.08 202.94 199.47 197.05 195.24 193.55 192.11 191.20 191.02 191.54 192.25 192.92 193.02 192.00 191.42
```

```
SLOPE IN DEGREES

  2.   2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   0.   1.   1.   1.   2.   2.   2.
  2.   2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   0.   1.   1.   1.   2.   2.   2.
  2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   1.   1.   2.   2.   2.   2.   1.   1.
  2.   2.   1.   1.   1.   1.   1.   2.   2.   2.   2.   2.   2.   2.   2.   1.   1.   3.   3.
  1.   1.   1.   1.   1.   2.   2.   2.   2.   2.   2.   2.   1.   1.   1.   3.   6.   9.   9.
  1.   1.   1.   1.   2.   2.   2.   2.   2.   1.   1.   2.   4.   5.   6.   8.  10.  10.  10.
  1.   1.   1.   1.   2.   2.   2.   1.   2.   5.   7.   8.  10.  10.  10.  10.  11.  11.  11.
  1.   1.   0.   0.   0.   0.   1.   5.   9.  11.  12.  12.  13.  13.  13.  12.  13.  14.  14.
  3.   3.   3.   3.   4.   5.   8.  12.  14.  14.  15.  15.  16.  15.  15.  16.  17.  18.  18.
  4.   4.   5.   6.   8.  10.  13.  15.  16.  16.  17.  18.  18.  17.  17.  18.  20.  20.  20.
  4.   4.   6.   8.  10.  13.  15.  17.  18.  19.  20.  21.  20.  19.  19.  20.  21.  20.  20.
  4.   4.   6.   9.  12.  14.  16.  19.  21.  22.  23.  23.  22.  22.  21.  20.  20.  21.  21.
  5.   5.   8.  11.  13.  16.  19.  22.  23.  24.  24.  24.  24.  24.  23.  22.  22.  24.  24.
  7.   7.  11.  13.  15.  18.  21.  23.  25.  25.  25.  25.  26.  26.  27.  27.  28.  29.  29.
  8.   8.  11.  14.  17.  19.  23.  24.  25.  25.  26.  26.  27.  28.  30.  32.  34.  34.  34.
  8.   8.  12.  16.  19.  22.  24.  26.  28.  29.  29.  29.  29.  31.  32.  34.  36.  37.  37.
  9.   9.  15.  20.  23.  24.  27.  30.  31.  32.  32.  32.  32.  33.  33.  34.  36.  37.  37.
 14.  14.  21.  26.  27.  28.  31.  34.  36.  36.  35.  35.  34.  34.  34.  34.  35.  35.  35.
 25.  25.  30.  32.  32.  34.  36.  39.  39.  38.  37.  36.  35.  35.  34.  34.  34.  33.  33.
 34.  34.  35.  36.  37.  38.  40.  41.  41.  40.  39.  38.  36.  35.  33.  32.  32.  30.  30.
 36.  36.  37.  38.  39.  40.  42.  42.  42.  42.  40.  38.  35.  33.  31.  29.  28.  25.  25.
 36.  36.  37.  38.  40.  41.  42.  42.  42.  41.  36.  31.  27.  24.  24.  22.  19.  15.  15.
 36.  36.  37.  39.  40.  41.  41.  41.  39.  33.  24.  17.  14.  12.  13.  13.  10.   8.   8.
 37.  37.  38.  39.  39.  40.  39.  37.  30.  19.  12.   8.   7.   7.   7.   6.   6.   6.   6.
 37.  37.  38.  38.  37.  36.  34.  26.  16.  11.   7.   4.   4.   5.   4.   4.   4.   4.   4.
 31.  31.  32.  32.  31.  29.  22.  13.   9.   6.   5.   2.   2.   3.   3.   2.   2.   3.   3.
 31.  31.  32.  32.  31.  29.  22.  13.   9.   6.   5.   2.   2.   3.   3.   2.   2.   3.   3.
```

```
UPAREA

  400.   800.  1200.  1600.  2000.  2400.  9600. 15200.  5200.  1600.  1200.   800.   400.  1600.  3200.  1200.  1200.   800.   400.
  400.   800.  1200.  1600.  6000.  8400. 13200.   800.  1600.  4800.  2000.   800.   400.  1200.  2000.   800.   800.   800.   400.
  400.   800.  1200.  4000.  2000.  2000. 10000.   800.   400.  1200.  2400.   800.   400.   800.   800.   800.   400.   400.   400.
  400.  1200.  2400.  1600.  1600.  4800.  3600.  1200.   400.   800.   800.  1200.   400.   400.   400.   400.   400.   400.   400.
  400.   800.  1200.  1200.  1200.  3200.  2400.   800.   800.   400.   400.   400.   400.   400.   400.   800.   400.   800.   800.
  400.   800.   800.   800.  1200.  1600.  1600.   400.   400.   400.   400.   400.   800.   400.   800.   400.  1200.   800.  1200.
  400.   400.   400.   400.   400.  1200.   800.   400.   400.   400.   800.   800.  1200.   800.  1200.   400.   800.  1600.  1200.
  400.   400.   400.   400.   800.   400.   400.   400.   800.   800.  1200.  1200.  1600.  1200.  1600.   800.   400.  1200.  2000.
  800.   800.   400.   800.   400.   400.   400.   800.   800.  2000.  1600.  1600.  2000.  1600.  2000.  1200.   400.   800.  1600.
 1200.  1200.   800.  1200.   800.   800.   400.   800.  1200.  3200.  2000.  2000.  2400.  2000.  2400.  1600.   800.   400.  1200.
 1600.  1600.  1200.  1600.  1200.  1200.   400.   800.  1200.  4800.  2400.  2400.  2800.  2400.  2800.  2000.  1200.   800.  1600.
 2000.  2000.  1600.  2000.  1600.   400.  1600.   800.  1200.  1600.  7600.  2800.  3200.  2800.  3200.  2400.  1600.  1200.  2000.
  400.  2400.  2400.  2000.  2400.  2000.   800.  2000.  1200.  1600.  9600.  3200.  3600.  3200.  3600.  2800.  2000.  1600.  2400.
  400.   800.  2800.  2800.  2400.  2800.  2400.  1200.  2400.  1600. 11600.  3600.  4000.  3600.  4000.  3200.  2400.  2000.  2800.
  400.   800.  1200.  3200.  3200.  2800.  3200.  2800.  1600.  2800.  2000. 15600.  4400.  4000.  4400.  3600.  2800.  2400.  3200.
  400.   800.  1200.  1600.  3600.  3600.  3200.  3600.  3200.  2000.  3200. 18000.  4800.  4400.  4800.  4000.  3200.  2800.  3600.
  400.   800.  1200.  1600.  2000.  4000.  4000.  3600.  4000.  3600.  2400. 21600.  5200.  4800.  5200.  4400.  3600.  3200.  4000.
  400.   800.  1200.  1600.  2000.  2400.  4400.  4400.  4000.  4400.  4000. 24400.  5600.  5200.  5600.  4800.  4000.  3600.  4400.
  400.   800.  1200.  1600.  2000.  2400.  2800.  4800.  4800.  4400.  4800. 28800.  6000.  5600.  6000.  5200.  4400.  4000.  4800.
  800.  1200.   400.  1600.  2000.  2400.  2800.  3200.  5200.  5200.  4800. 34000.  6400.  6000.  6400.  5600.  4800.  4400.  5200.
 1200.  1600.   400.   800.  2000.  2400.  2800.  3200.  3600.  5600.  5600. 39200.  6800.  6400.  6800.  6000.  5200.  4800.  5600.
 1600.  2000.   800.   400.  1200.  2400.  2800.  3200.  3600.  4000.  6000. 45200.  7200.  6800.  7200.  6400.  5600.  5200.  6000.
 2000.  2400.  1200.   400.   800.  1600.  2800.  3200.  3600.  4000.  4400. 51600.  7600.  7200.  7600.  6800.  6000.  5600.  6400.
 2400.  2800.  1600.   400.   800.  1200.  2000.  3200.  3600.  4000.  4400. 56400.  8000.  7600.  8000.  7200.  6400.  6000.  6800.
 2800.  3200.  2000.   400.   800.  1200.  1600.  2400.  3600.  4000.  4400. 61200.  8400.  8000.  8400.  7600.  6800.  6400.  7200.
 3200.  3600.  2400.   400.   800.  1200.  1600.  2000.  2800.  4000.  4400.  4800. 78000.  8800.   400.  8000.  7200.  6800.  7600.
 3600.  4000.  2800.   400.   800.  1200.  1600.  2000.  2400.  3200.  4400. 32800. 14000.   800.  8400.   400.   400.  7600.  7200.
```

ASPECT

```
 190.  190.  181.  171.  160.  149.  116.   61.   38.   31.   17.   11.   39.   68.   70.   58.   42.   43.   43.
 190.  190.  181.  171.  160.  149.  116.   61.   38.   31.   17.   11.   39.   68.   70.   58.   42.   43.   43.
 182.  182.  170.  157.  150.  137.  102.   65.   59.   64.   64.   54.   59.   69.   76.   64.   49.   31.   31.
 166.  166.  152.  143.  136.  125.   89.   64.   65.   74.   79.   67.   60.   68.   78.   80.  300.  256.  256.
 147.  147.  138.  131.  127.  111.   83.   62.   62.   72.   75.   69.   52.  323.  267.  237.  233.  246.  246.
 139.  139.  128.  123.  115.   99.   81.   61.   56.   46.  292.  264.  253.  255.  255.  244.  236.  242.  242.
 134.  134.  123.  114.  104.   96.   80.   58.  264.  249.  251.  254.  257.  258.  258.  251.  238.  240.  240.
 273.  273.  228.  189.  153.  148.  239.  238.  241.  249.  253.  255.  258.  261.  264.  257.  244.  242.  242.
 281.  281.  270.  269.  267.  258.  240.  237.  242.  249.  254.  256.  258.  263.  266.  261.  250.  245.  245.
 269.  269.  263.  262.  258.  253.  245.  238.  241.  249.  254.  256.  259.  263.  264.  260.  252.  250.  250.
 256.  256.  248.  248.  248.  245.  243.  239.  241.  247.  252.  257.  262.  265.  264.  258.  250.  250.  250.
 243.  243.  234.  235.  237.  239.  239.  238.  239.  245.  251.  257.  264.  267.  266.  260.  251.  248.  248.
 238.  238.  226.  227.  231.  233.  233.  234.  238.  242.  249.  258.  265.  269.  270.  265.  253.  248.  248.
 234.  234.  224.  223.  226.  228.  228.  229.  234.  240.  247.  255.  265.  269.  271.  268.  257.  250.  250.
 231.  231.  219.  219.  221.  223.  225.  225.  231.  237.  244.  252.  261.  267.  268.  265.  258.  255.  255.
 224.  224.  215.  215.  219.  220.  222.  224.  229.  236.  243.  250.  258.  263.  264.  261.  257.  257.  257.
 226.  226.  215.  217.  220.  222.  222.  224.  228.  235.  243.  250.  256.  261.  262.  257.  254.  257.  257.
 241.  241.  224.  223.  226.  227.  225.  225.  229.  235.  243.  250.  256.  261.  262.  256.  251.  255.  255.
 253.  253.  234.  231.  232.  234.  231.  228.  230.  236.  243.  250.  257.  261.  263.  257.  250.  253.  253.
 257.  257.  244.  238.  236.  236.  235.  233.  233.  236.  244.  252.  258.  263.  264.  258.  251.  252.  252.
 257.  257.  248.  242.  238.  236.  235.  234.  235.  237.  243.  252.  261.  268.  269.  259.  250.  254.  254.
 257.  257.  249.  243.  238.  236.  235.  233.  234.  236.  241.  251.  263.  273.  276.  265.  252.  254.  254.
 257.  257.  249.  242.  239.  236.  234.  232.  231.  232.  240.  255.  269.  279.  279.  270.  261.  260.  260.
 258.  258.  249.  243.  238.  235.  233.  231.  229.  228.  230.  251.  282.  291.  288.  273.  261.  264.  264.
 257.  257.  250.  244.  238.  235.  232.  230.  227.  222.  219.  236.  289.  302.  298.  276.  252.  260.  260.
 254.  254.  248.  241.  235.  231.  230.  228.  220.  213.  208.  220.  293.  313.  310.  293.  233.  234.  234.
 254.  254.  248.  241.  235.  231.  230.  228.  220.  213.  208.  220.  293.  313.  310.  293.  233.  234.  234.
```

MEAN SOIL DEPTH AT EACH GRID CELL

```
2.07  2.10  2.15  2.18  2.21  2.22  2.23  2.22  2.21  2.20  2.18  2.18  2.18  2.18  2.18  2.17  2.15  2.13  2.12
2.09  2.12  2.16  2.19  2.22  2.23  2.23  2.22  2.21  2.20  2.18  2.18  2.17  2.16  2.15  2.14  2.12  2.10  2.09
2.12  2.15  2.17  2.20  2.21  2.22  2.22  2.21  2.19  2.18  2.16  2.15  2.14  2.13  2.11  2.09  2.07  2.04  2.03
2.14  2.15  2.17  2.19  2.20  2.21  2.20  2.18  2.16  2.14  2.12  2.11  2.09  2.07  2.05  2.03  2.00  1.98  1.98
2.14  2.15  2.16  2.17  2.18  2.18  2.16  2.14  2.11  2.09  2.07  2.05  2.03  2.01  1.98  1.96  1.94  1.93  1.93
2.12  2.13  2.14  2.14  2.14  2.13  2.11  2.08  2.04  2.02  2.01  2.00  1.98  1.96  1.93  1.90  1.89  1.89  1.89
2.10  2.10  2.11  2.10  2.09  2.07  2.04  2.01  1.98  1.98  1.97  1.97  1.96  1.93  1.90  1.87  1.85  1.85  1.86
2.08  2.08  2.07  2.06  2.03  1.99  1.96  1.94  1.95  1.97  1.98  1.98  1.96  1.94  1.90  1.85  1.82  1.81  1.82
2.08  2.06  2.04  2.01  1.97  1.92  1.90  1.91  1.95  2.00  2.02  2.02  2.00  1.96  1.91  1.85  1.80  1.78  1.77
2.08  2.06  2.03  1.99  1.93  1.88  1.87  1.91  1.99  2.06  2.09  2.08  2.04  1.99  1.92  1.85  1.79  1.75  1.74
2.08  2.05  2.01  1.97  1.92  1.88  1.88  1.93  2.03  2.12  2.16  2.14  2.09  2.02  1.94  1.85  1.77  1.73  1.71
2.06  2.02  1.99  1.95  1.91  1.89  1.89  1.96  2.07  2.17  2.23  2.21  2.15  2.06  1.95  1.84  1.75  1.69  1.66
2.02  1.98  1.95  1.92  1.90  1.89  1.91  1.98  2.09  2.21  2.29  2.28  2.20  2.09  1.96  1.83  1.72  1.64  1.61
1.98  1.93  1.90  1.89  1.89  1.89  1.92  1.99  2.10  2.23  2.32  2.33  2.25  2.12  1.98  1.84  1.72  1.63  1.60
1.92  1.88  1.85  1.85  1.86  1.88  1.91  1.98  2.10  2.24  2.34  2.36  2.29  2.16  2.03  1.89  1.78  1.71  1.68
1.84  1.80  1.78  1.79  1.82  1.85  1.89  1.96  2.08  2.23  2.35  2.39  2.33  2.21  2.09  1.98  1.91  1.85  1.83
1.75  1.70  1.69  1.71  1.76  1.81  1.87  1.94  2.07  2.22  2.37  2.43  2.38  2.27  2.15  2.08  2.04  2.01  2.00
1.65  1.60  1.59  1.63  1.71  1.79  1.86  1.94  2.07  2.25  2.41  2.48  2.44  2.33  2.23  2.18  2.16  2.16  2.16
1.60  1.53  1.52  1.58  1.68  1.79  1.87  1.97  2.11  2.31  2.49  2.57  2.53  2.41  2.31  2.26  2.26  2.28  2.29
1.62  1.53  1.50  1.56  1.69  1.81  1.92  2.03  2.20  2.41  2.60  2.69  2.64  2.52  2.40  2.35  2.36  2.39  2.41
1.70  1.59  1.53  1.58  1.72  1.87  2.00  2.13  2.32  2.54  2.74  2.83  2.77  2.63  2.51  2.44  2.45  2.48  2.50
1.78  1.65  1.58  1.63  1.77  1.94  2.10  2.27  2.46  2.69  2.88  2.95  2.88  2.73  2.59  2.51  2.51  2.53  2.55
1.86  1.72  1.64  1.68  1.84  2.03  2.22  2.41  2.62  2.83  2.98  3.01  2.91  2.75  2.61  2.53  2.51  2.52  2.53
1.92  1.78  1.69  1.74  1.90  2.12  2.35  2.56  2.75  2.90  2.99  2.97  2.85  2.69  2.56  2.48  2.45  2.45  2.45
1.98  1.83  1.75  1.79  1.96  2.20  2.46  2.66  2.81  2.89  2.91  2.85  2.73  2.59  2.46  2.39  2.36  2.36  2.36
2.02  1.88  1.79  1.83  2.00  2.26  2.52  2.71  2.82  2.84  2.81  2.73  2.61  2.48  2.37  2.31  2.28  2.28  2.28
2.03  1.90  1.82  1.85  2.02  2.28  2.54  2.73  2.81  2.81  2.75  2.67  2.55  2.43  2.33  2.27  2.25  2.25  2.25
```

```
AVERAGE NUMBER OF FAILURES PER YEAR AT EACH GRID CELL DURING THE ANALYZED PERIOD

 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .00  .00  .00  .00  .00  .00  .00
 .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .01  .01  .00  .00  .00  .00  .00  .00  .01
 .00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .01  .01  .01  .01  .01  .01  .03  .02  .03
 .00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .01  .02  .03  .03  .04  .07  .07  .06  .06
 .00  .00  .00  .00  .00  .00  .00  .02  .01  .03  .04  .04  .04  .06  .06  .08  .09  .09  .09
 .00  .00  .00  .00  .00  .00  .02  .03  .05  .07  .07  .08  .07  .07  .08  .10  .12  .10  .09
 .00  .00  .00  .01  .01  .02  .04  .08  .10  .12  .11  .11  .08  .08  .10  .11  .09  .09  .10
 .00  .00  .02  .03  .05  .05  .08  .13  .14  .16  .16  .16  .13  .13  .10  .10  .10  .09  .07
 .03  .05  .04  .06  .06  .10  .13  .17  .20  .23  .21  .19  .17  .12  .07  .08  .07  .06  .05
 .05  .06  .03  .03  .07  .12  .14  .18  .22  .26  .23  .23  .17  .11  .06  .04  .03  .01  .01
 .06  .07  .03  .02  .07  .10  .15  .17  .19  .21  .19  .06  .02  .01  .00  .00  .00  .00  .00
 .05  .07  .06  .03  .05  .08  .16  .17  .18  .08  .01  .00  .00  .00  .00  .00  .00  .00  .00
 .09  .08  .08  .03  .04  .06  .10  .13  .04  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .10  .09  .08  .03  .05  .06  .04  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .05  .05  .05  .02  .03  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .07  .06  .05  .01  .03  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
```

```
NUMBER OF FAILURES AT EACH GRID CELL DIVIDED
BY THE TOTAL NUMBER OF FAILURES FOR THE WHOLE GRID

.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00008 .00000 .00000 .00008 .00000 .00000 .00000 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00008 .00046 .00008 .00015 .00008 .00023 .00015 .00000 .00015 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00015 .00023 .00008 .00068 .00046 .00038 .00030 .00000 .00000 .00008 .00023 .00061
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00023 .00053 .00015 .00068 .00076 .00046 .00106 .00076 .00091 .00228 .00152 .00228
.00000 .00000 .00000 .00000 .00000 .00000 .00008 .00030 .00068 .00038 .00106 .00160 .00221 .00190 .00304 .00555 .00502 .00494 .00494
.00000 .00000 .00000 .00000 .00000 .00000 .00015 .00122 .00106 .00213 .00274 .00297 .00266 .00472 .00426 .00639 .00722 .00707 .00692
.00000 .00000 .00000 .00000 .00000 .00038 .00122 .00243 .00365 .00510 .00502 .00586 .00525 .00563 .00608 .00761 .00897 .00791 .00715
.00000 .00000 .00015 .00068 .00091 .00160 .00281 .00586 .00761 .00890 .00844 .00829 .00639 .00586 .00783 .00806 .00654 .00654 .00768
.00008 .00038 .00175 .00259 .00365 .00380 .00578 .00958 .01103 .01202 .01240 .01186 .01011 .01004 .00768 .00738 .00730 .00646 .00517
.00251 .00365 .00266 .00441 .00494 .00738 .00973 .01316 .01521 .01749 .01612 .01483 .01331 .00935 .00555 .00578 .00548 .00433 .00403
.00388 .00441 .00259 .00243 .00563 .00875 .01027 .01361 .01643 .01985 .01780 .01726 .01285 .00844 .00433 .00335 .00228 .00084 .00084
.00464 .00525 .00236 .00183 .00563 .00761 .01156 .01235 .01415 .01628 .01453 .00479 .00167 .00076 .00030 .00000 .00008 .00000 .00000
.00403 .00525 .00456 .00228 .00380 .00601 .01179 .01270 .01346 .00608 .00046 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00707 .00578 .00570 .00236 .00335 .00441 .00745 .01019 .00289 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00753 .00669 .00593 .00213 .00342 .00494 .00304 .00106 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00418 .00388 .00350 .00122 .00190 .00084 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00517 .00433 .00350 .00068 .00198 .00114 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
```

```
AVERAGE RATIO OF WATER DEPTH/SOIL DEPTH FOR EACH CELL

 .99  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .99  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99  1.00  1.00  1.00   .98   .99   .99  1.00  1.00   .91   .91
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99   .99   .99  1.00  1.00  1.00  1.00   .70   .85   .85
1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99  1.00  1.00  1.00   .99   .99   .76   .94   .59   .95   .78   .93
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99   .81   .93   .85   .95   .80   .94   .49   .78   .98   .92
1.00  1.00  1.00  1.00  1.00  1.00  1.00   .83   .84   .76   .90   .87   .94   .86   .96   .72   .40   .87   .98
1.00  1.00   .92  1.00   .89   .82   .59   .72   .66   .96   .91   .91   .95   .90   .96   .80   .32   .58   .90
1.00  1.00   .98   .99   .88   .80   .38   .63   .77   .99   .92   .91   .96   .93   .97   .87   .54   .28   .73
1.00  1.00  1.00   .99   .94   .88   .35   .57   .72  1.00   .92   .92   .97   .95   .98   .93   .73   .55   .86
1.00  1.00  1.00  1.00   .96   .37   .90   .51   .65   .73  1.00   .94   .96   .96   .98   .96   .36   .74   .94
 .75  1.00  1.00   .99   .99   .96   .52   .88   .58   .69  1.00   .95   .97   .96   .99   .97   .92   .82   .96
 .61   .92  1.00  1.00   .99   .98   .95   .62   .89   .69  1.00   .96   .98   .97   .99   .97   .92   .86   .96
 .54   .88   .93  1.00  1.00   .98   .98   .95   .70   .91   .75  1.00   .98   .97   .98   .97   .92   .89   .96
 .58   .90   .91   .92  1.00   .99   .97   .98   .94   .76   .90  1.00   .98   .97   .99   .97   .93   .90   .97
 .54   .88   .86   .88   .90   .99   .99   .97   .98   .94   .77  1.00   .98   .98   .99   .98   .94   .92   .97
 .40   .73   .76   .83   .87   .90   .99   .98   .96   .96   .93  1.00   .98   .98   .99   .98   .95   .93   .97
 .26   .52   .66   .77   .84   .88   .91   .99   .98   .95   .96  1.00   .98   .98   .99   .98   .97   .95   .98
 .42   .64   .23   .75   .81   .85   .88   .90   .98   .97   .95  1.00   .99   .99   .99   .99   .97   .97   .99
 .56   .73   .22   .41   .79   .83   .86   .89   .90   .97   .97  1.00   .99   .99   .99   .99   .98   .99   .99
 .68   .82   .42   .21   .53   .81   .84   .86   .88   .88   .97  1.00   .99  1.00  1.00  1.00  1.00  1.00  1.00
 .78   .88   .57   .19   .35   .61   .82   .85   .87   .89   .96  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .85   .92   .70   .20   .34   .45   .64   .84   .89   .97  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .88   .94   .79   .19   .34   .46   .54   .76   .98  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .94   .97   .89   .19   .36   .48   .66   .92  1.00  1.00  1.00  1.00  1.00  1.00   .91  1.00  1.00  1.00  1.00
 .96   .98   .93   .20   .36   .47   .66   .92   .99  1.00  1.00  1.00  1.00  1.00  1.00   .96   .98  1.00  1.00
```

```
AVERAGE FACTOR OF SAFETY AT EACH GRID CELL

27.09  27.35  29.01  34.89  41.51  50.69  81.06  70.74  57.33  60.80  88.27 100.46 107.10  72.07  48.56  40.65  29.78  33.73  32.83
27.22  26.83  29.16  35.49  41.51  51.24  31.40  70.66  56.89  62.41  87.90  98.53 107.47  72.24  48.69  41.01  30.34  33.65  33.53
30.45  29.68  34.63  36.78  39.67  49.09  64.52  46.80  39.79  45.01  51.98  51.35  38.59  31.60  30.94  30.22  33.24  44.35  44.85
33.56  33.97  38.82  37.63  37.27  41.10  42.56  33.50  29.48  28.87  29.33  26.30  24.08  25.97  29.02  36.94  84.64  16.00  15.90
35.47  34.77  37.94  36.11  35.18  34.57  31.60  27.75  23.63  26.05  25.35  25.88  42.79  92.27  44.82  18.62  10.54   6.70   6.73
37.51  37.71  36.42  35.32  32.30  30.36  28.56  26.02  28.77  66.36  62.99  24.09  13.57  11.65   8.50   8.93   5.82   5.94   5.42
51.38  50.87  40.43  36.81  31.74  32.32  33.78  48.15  28.00  12.52   8.13   6.92   5.75   6.06   5.47   7.83   5.84   4.93   5.07
71.08  71.34 118.18 181.08 130.74 152.38  68.36  12.68   6.63   5.68   4.87   4.69   4.31   4.42   4.45   5.39   6.92   4.47   4.03
16.54  16.59  16.64  15.42  14.76  12.65   9.19   5.43   4.92   3.79   3.86   3.71   3.50   3.70   3.68   4.01   5.94   4.17   3.33
12.24  12.23  10.48   8.36   7.30   6.08   6.77   4.72   3.31   3.28   3.21   3.04   3.09   3.23   3.21   3.31   4.01   5.43   3.38
13.51  13.52   9.66   7.19   5.51   4.53   6.20   4.33   3.54   2.81   2.67   2.63   2.69   2.87   2.89   2.98   3.29   3.99   3.11
12.81  12.97   8.32   5.88   4.65   6.56   3.58   4.04   3.21   2.78   2.25   2.32   2.43   2.49   2.62   2.81   3.12   3.38   3.00
11.70  10.07   6.44   4.31   4.17   3.65   4.09   2.66   2.95   2.63   2.09   2.16   2.20   2.25   2.35   2.59   2.81   2.76   2.56
 9.45   7.89   5.15   4.30   3.66   3.14   2.73   2.99   2.30   2.59   2.07   2.06   2.03   2.04   2.08   2.19   2.22   2.30   2.16
 8.83   6.94   5.00   3.89   3.35   2.91   2.45   2.33   2.55   2.14   2.23   1.89   1.90   1.90   1.84   1.84   1.84   1.90   1.86
 8.85   7.16   4.77   3.70   2.98   2.57   2.35   2.14   2.03   2.13   1.86   1.79   1.77   1.74   1.72   1.70   1.68   1.73   1.67
 8.46   6.80   4.14   3.17   2.69   2.36   2.14   1.92   1.79   1.68   1.31   1.56   1.59   1.63   1.64   1.63   1.58   1.61   1.62
 6.84   5.10   3.36   2.67   2.39   2.21   1.88   1.70   1.61   1.54   1.52   1.45   1.51   1.57   1.56   1.59   1.59   1.60   1.55
 4.75   3.63   2.74   2.38   2.14   1.92   1.73   1.52   1.47   1.44   1.39   1.38   1.43   1.49   1.54   1.58   1.58   1.62   1.61
 2.98   2.53   4.08   2.19   1.95   1.77   1.59   1.47   1.34   1.32   1.32   1.31   1.36   1.44   1.58   1.63   1.61   1.70   1.68
 2.42   2.18   3.93   2.91   1.90   1.70   1.54   1.43   1.36   1.25   1.26   1.26   1.38   1.49   1.61   1.77   1.81   1.99   1.98
 2.12   1.97   2.93   3.91   2.28   1.65   1.52   1.43   1.36   1.31   1.32   1.50   1.74   1.92   2.03   2.18   2.53   3.22   3.20
 1.94   1.86   2.36   3.75   2.77   1.94   1.52   1.41   1.38   1.50   1.92   2.56   3.34   3.77   3.72   3.80   4.64   6.19   6.22
 1.77   1.75   2.07   3.79   2.76   2.23   1.76   1.50   1.69   2.41   3.66   5.49   6.53   6.81   7.11   7.75   8.05   8.62   8.62
 1.65   1.70   1.90   3.69   2.77   2.28   2.09   2.08   2.91   4.36   6.46  12.71  12.92  10.44  10.87  12.16  13.83  11.32  11.17
 1.84   1.34   2.03   4.07   3.05   2.55   2.71   3.79   5.31   7.12  10.19  21.46  26.20  16.70  17.35  20.24  25.07  16.17  15.98
 1.79   1.82   1.94   3.99   3.07   2.60   2.74   3.76   5.28   7.11  10.18  21.47  26.32  16.82  16.38  20.75  24.51  16.40  16.01
```

```
MINIMUM FACTOR OF SAFETY AT EACH GRID CELL

 9.44  11.94  13.15  14.35  18.02  23.26  36.27  29.29  23.37  25.48  35.88  46.51  42.76  27.22  17.86  17.04  12.68  14.07  14.03
11.01  11.78  12.69  13.74  18.25  23.84  34.50  27.47  25.60  26.44  37.50  45.71  43.86  30.57  18.95  17.86  12.59  14.50  14.54
12.22  12.30  14.98  15.58  19.23  21.78  27.63  18.98  17.76  16.38  21.92  20.39  16.46  13.77  11.89  14.00  12.40  19.67  17.06
14.07  14.25  17.65  15.58  14.50  17.21  17.56  15.10  12.33  12.19  11.89  11.54  11.52  11.05  11.01  15.68  31.60   6.20   6.07
14.35  15.97  16.09  14.51  15.03  14.93  12.95  12.71  10.44  11.62   9.30  11.30  18.56  42.03  19.03   7.22   3.93   2.83   2.23
15.45  15.03  16.11  14.22  13.80  13.71  11.43  11.58  12.43  27.08  25.31  10.47   5.25   4.23   3.48   2.56   2.12   1.99   2.12
24.65  21.41  15.13  15.36  11.30  13.40  12.80  19.15  10.79   4.42   3.37   2.34   2.39   2.03   2.07   2.54   2.21   2.04   2.11
28.57  30.79  52.06  74.68  48.79  64.07  28.30   5.11   2.53   2.07   2.07   1.92   1.89   1.76   1.55   1.72   1.96   1.52   1.73
 7.52   7.03   6.43   6.74   6.29   4.56   3.02   2.01   1.70   1.25   1.60   1.34   1.39   1.41   1.54   1.41   1.62   1.25   1.24
 4.92   5.29   3.99   3.24   2.84   2.07   2.02   1.58   1.36   1.34   1.23   1.07   1.18   1.25   1.19   1.14   1.07   1.21   1.00
 5.50   5.49   3.57   2.89   2.15   1.52   1.67   1.29   1.05   1.01   1.11    .99   1.01   1.17   1.00   1.09   1.06   1.02    .90
 5.05   4.98   3.49   2.33   1.70   1.76   1.44   1.22   1.13    .97    .93    .99    .90    .98    .94    .96   1.17    .97    .94
 4.11   4.53   2.86   1.84   1.63   1.44   1.19    .94    .83    .86    .87    .97    .95    .91   1.04   1.03    .98    .77    .87
 2.79   3.14   2.20   1.74   1.36   1.27   1.11    .96    .87    .86    .81    .84    .78    .74    .88    .76    .73    .75    .69
 2.77   2.71   1.68   1.57   1.37   1.13    .94    .90    .81    .84    .73    .31    .71    .80    .69    .66    .60    .60    .58
 2.75   2.77   1.66   1.50   1.19   1.07    .88    .79    .67    .69    .75    .68    .66    .73    .61    .59    .49    .49    .53
 2.39   2.05   1.48   1.00   1.02    .92    .78    .62    .68    .60    .62    .59    .65    .60    .56    .56    .49    .52    .44
 1.76   1.48    .95    .84    .85    .81    .57    .58    .55    .57    .51    .58    .54    .52    .61    .64    .59    .60    .50
  .99    .94    .77    .57    .66    .58    .57    .55    .43    .52    .57    .47    .46    .56    .50    .49    .58    .60    .63
  .60    .53    .64    .54    .49    .52    .46    .47    .44    .48    .46    .48    .52    .51    .65    .56    .57    .63    .74
  .53    .53    .65    .58    .47    .47    .38    .43    .47    .39    .49    .45    .49    .59    .67    .75    .82    .86    .75
  .59    .56    .56    .53    .53    .47    .42    .46    .44    .47    .59    .67    .77    .83    .90   1.01    .97   1.51   1.59
  .52    .62    .50    .52    .57    .50    .51    .47    .51    .51    .92   1.16   1.57   1.61   1.77   1.75   2.18   2.26   2.65
  .54    .51    .48    .58    .60    .46    .55    .51    .69   1.15   1.61   2.63   3.14   3.45   3.05   3.28   3.57   3.98   3.84
  .60    .55    .51    .59    .61    .55    .64    .81   1.29   2.29   2.98   5.93   6.30   4.70   4.64   5.39   6.08   5.34   5.23
  .60    .60    .67    .76    .70    .77   1.08   1.60   2.26   3.46   5.20   9.86  12.18   7.34   7.57   9.15  10.95   6.54   6.67
  .65    .63    .60    .77    .62    .77   1.10   1.73   2.61   3.11   4.25   9.44  11.66   7.47   7.49   3.09  10.67   7.09   6.58


MAXIMUM FACTOR OF SAFETY AT EACH GRID CELL

 65.40   62.10   55.80   74.08   96.79   98.59  209.87  161.05  120.29  114.03  204.42  246.70  247.61  160.47   92.29   92.25   58.87   63.29   77.83
 60.71   54.03   73.51   70.83   76.45  127.67  170.39  173.54  108.29  145.87  218.51  272.31  222.29  161.00  104.53   92.66   69.73   73.46   67.19
 64.52   30.25   66.71   92.82  110.85  120.43  128.19  131.16   80.32   93.79  116.48  102.42  132.89   66.61   79.09   73.99   73.12   93.49  106.38
 76.57   73.04   77.44   77.90   81.62  113.87   98.54   72.05   83.43   65.84   60.46   61.10   47.68   60.60   65.22   80.67  167.07   37.71   35.79
 77.56   66.83   74.53   99.72   91.18   89.84   62.85   61.48   49.25   54.64   47.45   59.64   82.48  250.34   97.34   41.12   24.96   15.55   16.74
 93.30   77.65   81.31   68.59   65.83   66.97   61.31   57.13   53.10  165.72  124.26   47.29   37.91   30.11   18.41   24.56   13.84   14.68   10.93
134.16   96.14   83.06   72.45   65.39   68.82   71.20  108.88   52.29   29.03   17.43   19.69   13.04   14.30   13.09   19.25   14.95   11.70   10.65
151.90  156.80  264.81  468.12  269.67  308.95  160.10   30.61   16.44   13.61   10.42   10.65    8.68   10.57    9.75   11.77   16.05   12.00    9.37
 35.70   32.56   35.54   31.22   32.79   32.13   18.95   14.02   11.36    7.83    7.77    8.74    7.61    8.09    7.05   11.06   16.79   11.76    8.05
 26.07   26.56   23.22   16.78   14.77   13.46   17.83   11.45    8.49    7.27    8.04    6.97    6.16    9.30    7.80    8.12   10.29   12.76    7.57
 30.78   28.67   24.36   15.47   11.47   12.37   15.62   10.92    8.69    6.63    5.59    5.10    7.18    6.85    6.21    7.88    8.47   10.70    7.40
 28.29   32.21   16.29   11.89   10.21   22.00    8.53   10.68    8.44    7.90    5.53    5.87    5.16    5.08    6.16    6.47    8.24    7.34    7.90
 26.62   30.34   13.36   11.29    9.89    6.93    9.06    5.49    7.41    6.14    5.01    4.92    4.96    5.07    5.46    5.28    6.34    6.45    6.87
 22.06   16.31   11.48    9.08    7.71    6.68    5.46    8.82    5.44    6.38    4.58    5.06    4.02    4.36    4.64    4.56    4.83    5.55    4.99
 26.28   17.71   13.22    9.40    7.80    6.95    5.28    4.87    7.51    5.70    5.35    3.55    4.38    4.04    4.96    4.57    5.60    4.68    4.77
 22.60   15.69   11.78    7.49    6.38    5.81    5.01    5.09    4.59    5.16    4.10    3.84    3.49    4.68    4.04    4.08    4.13    4.31    3.79
 21.37   13.93   12.74    6.97    6.17    5.10    5.10    4.48    4.65    4.44    4.99    4.07    4.05    3.87    3.58    3.95    3.74    3.78    3.61
 17.57   14.24    9.17    6.02    5.93    5.45    4.28    3.97    3.99    3.59    3.71    3.42    3.63    3.47    3.60    4.21    3.06    3.26    3.40
 12.56    9.38    7.30    5.64    5.42    5.16    4.39    3.50    3.36    3.64    3.11    3.11    3.14    3.49    3.25    3.59    3.63    3.78    3.29
  6.87    7.10   11.97    6.53    6.17    4.24    4.21    4.09    2.83    3.17    2.66    3.48    3.16    3.15    3.40    2.95    3.22    3.70    3.72
  6.78    5.35   10.19    7.57    5.49    4.45    3.50    4.62    3.25    3.98    3.22    3.15    3.55    5.01    3.27    4.21    4.44    4.29    4.40
  5.55    5.70    8.41    9.01    7.70    3.99    3.95    3.68    3.11    2.71    3.06    2.93    3.23    4.09    5.41    4.94    5.86    8.29    6.02
  5.33    4.39    3.88    9.56    7.12    5.43    3.80    3.30    2.91    2.88    3.75    5.84    7.63    7.94    7.11    7.23    9.02   13.55   11.85
  4.90    3.74    6.07   11.11    7.32    5.62    5.01    3.35    3.48    6.11    6.76   12.63   13.52   14.62   14.73   16.53   16.74   17.02   17.90
  4.30    4.05    4.73    9.67    7.60    6.76    4.71    4.61    5.87    8.82   13.07   24.11   27.11   20.70   21.13   24.86   29.36   22.84   20.75
  5.40    4.33    6.54   12.07    9.00    7.56    6.97    7.88   10.66   15.18   20.70   43.38   35.70   33.07   41.17   41.37   50.88   36.96   31.94
  4.17    4.69    4.45    9.68    8.55    5.93    6.46   10.94   15.48   15.01   25.21   45.46   65.75   36.31   32.75   55.77   55.93   35.60   33.29
```

Program FASSA
Forest Area Slope Stability Analsyis
Douglas S. Chandler, Dept. of Civil Engineering
University of Washington

Run Description:

Simulated drywell by adding a total of about 5000 square feet of uparea to the drywell location (833 square feet to 6 cells).

GRID INDICES

N = number of grid columns = 19
M = number of grid rows = 27
DIST = grid cell dimension = 20.000
ANGLE = angle grid rotated ccw from North = 270.000

HEADER FOR DAT FILES

```
        19        27     270.000000      20.000000       1.000000
```

RUN DATA

Number of Trials = 1000
Time Period of Analysis (years) = 1

U.S. units (lbs, feet, days)

THE FOLLOWING DRAINAGE AREAS WERE MANUALLY ADDED TO THE FOLLOWING GRID CELL LOCATIONS TO SIMULATE A MAN MADE DISCHARGE POINT

I	J	Drainage Area Added
9	4	833
9	5	833
9	6	833
9	7	833
9	8	833
9	9	833

```
          SUMMARY OF RUN RESULTS

 TOTAL NUMBER OF FACTOR OF SAFETY CALCULATIONS PERFORMED = 513000
 TOTAL NUMBER OF FAILURES =      13166

 TIME        AVERAGE NUMBER OF FAILED           PROB OF AT LEAST ONE
(YEAR)       CELLS FOR EACH YEAR                CELL FAILING DURING YEAR
 1                13.17                                   .290

SOIL PARAMETERS

                 Mean Friction Angle (degrees) =   36.000
            Coef. of variation of Friction Angle =    .100

                Mean Soil Cohesion (NSM or PSF) =      .000
            Coef. of variation of Soil Cohesion =     .200

       Mean Saturated Unit Weight (NCM or PCF) =  105.000
        Coef. of variation of Sat. Unit Weight =     .050

      Mean Hydrualic Conductivity (MPD or FPD) =  100.000
      Coef. of variation of Hydr. Conductivity =     .300

               Coef. of variation of Soil Depths =     .200
Array of Mean Soil Depths listed later

HYDRAULIC PARAMETERS

The rainfall data is presented in a curve of the
24 hour rainfall (in Meters or Feet) verses the
recurrence interval (in years).

          Number of points defining the curve =   8

24 HOUR RAINFALL          RECURRENCE INTERVAL (YEARS)
      .081                        1.01
      .111                        1.10
      .169                        2.00
      .224                        5.00
      .247                       10.00
      .286                       20.00
      .322                       50.00
      .354                      100.00

              Factor Applied to Intensities =    3.000
                Maximum Factored Intensity =     1.146
```

VEGETATION PARAMETERS

Vegetation parameters are calculated for each year of analysis based on data given in the file "veg.par". The resulting mean root cohesion and vegetation surcharge for each year are presented below.

Coefficient of Variation of root cohesion = 0.5
Coefficient of Variation of vegetation surcharge = 0.5

YEAR	TOTAL ROOT COHESION	VEGETATION SURCHARGE
1	160.00	7.02

Coefficient of Variation for root cohesion = 0.5
Coefficient of Variation for vegetation surcharge = 0.5

Grid Variables

Z (ELEVATION)

```
354.27 353.72 352.95 352.30 351.75 351.34 351.12 351.15 351.45 351.75 352.06 352.28 352.38 352.38 352.31 352.38 352.71 353.12 353.42
354.21 353.56 352.89 352.32 351.88 351.51 351.29 351.32 351.53 351.81 352.03 352.20 352.38 352.46 352.57 352.71 353.04 353.60 353.83
354.13 353.48 352.93 352.46 352.04 351.70 351.51 351.59 351.83 352.05 352.18 352.35 352.59 352.84 353.00 353.13 353.52 353.86 354.23
354.11 353.51 353.07 352.69 352.32 352.00 351.83 352.01 352.30 352.53 352.65 352.77 353.18 353.53 353.70 353.80 353.87 354.02 353.28
354.22 353.74 353.36 353.03 352.71 352.41 352.34 352.55 352.95 353.25 353.40 353.62 353.92 354.16 354.24 354.11 353.14 351.50 350.68
354.42 354.06 353.70 353.45 353.14 352.98 352.96 353.17 353.64 353.88 354.02 354.10 353.86 353.29 352.87 352.13 350.43 348.37 346.92
354.62 354.37 354.13 353.88 353.73 353.60 353.61 353.80 354.02 353.65 352.85 352.08 351.25 350.56 349.84 349.06 347.51 344.99 343.50
354.42 354.57 354.45 354.36 354.25 354.11 354.04 353.83 352.30 350.78 349.54 348.38 347.31 346.41 345.86 345.42 343.93 341.46 339.39
353.49 353.86 353.90 353.85 353.86 353.73 353.15 351.04 348.60 346.51 344.91 343.68 342.27 341.31 340.97 340.50 339.28 336.29 333.84
352.25 352.38 352.18 351.98 351.55 350.85 349.38 346.84 343.78 341.27 339.56 337.88 336.39 335.44 334.93 334.22 332.60 329.59 327.39
351.05 350.86 350.41 349.41 348.46 346.78 344.67 341.98 338.43 335.61 333.08 331.01 329.67 328.87 328.44 327.51 325.44 322.35 320.27
349.89 349.73 348.61 347.08 344.93 342.54 339.88 336.43 332.51 328.63 325.51 323.14 321.85 321.51 321.10 320.32 318.48 315.70 312.76
348.75 348.31 346.78 344.20 341.34 338.37 334.63 330.17 325.38 320.91 317.07 314.59 313.32 312.95 312.99 312.85 311.71 308.26 304.98
347.27 346.60 344.31 341.15 337.61 333.65 329.14 323.54 317.85 312.70 308.74 305.41 303.99 303.58 303.79 304.06 303.13 299.07 295.55
345.32 344.23 341.59 337.94 333.64 328.88 323.38 317.04 310.60 305.10 300.27 296.48 294.23 293.30 293.01 292.59 290.72 286.94 283.91
343.32 341.96 339.18 334.71 329.76 323.98 317.46 310.63 303.15 296.75 291.13 286.73 283.73 281.97 280.88 279.51 276.66 272.79 270.11
341.03 340.22 336.53 331.35 325.03 318.43 311.49 303.38 294.88 286.98 280.49 275.64 272.12 269.77 268.15 266.13 262.22 257.95 255.77
337.79 337.27 332.99 326.00 318.81 311.89 304.01 294.86 284.97 275.94 268.61 263.12 259.30 256.71 254.99 252.91 248.30 243.72 241.04
331.28 331.47 325.80 318.07 310.27 302.59 294.44 284.20 273.32 263.56 255.55 249.60 245.66 243.16 241.48 239.64 235.44 230.41 227.66
320.31 319.24 314.21 306.98 298.92 290.44 281.33 271.02 260.24 249.88 241.43 235.31 231.58 229.40 228.25 226.82 222.94 218.71 215.72
306.64 304.77 300.22 293.51 285.58 276.65 266.71 256.21 245.45 235.18 226.26 220.13 216.84 215.67 215.77 215.32 211.50 208.01 206.23
292.44 290.46 285.87 279.63 271.50 262.07 251.99 241.24 230.31 219.95 211.27 205.77 203.56 203.42 204.51 205.22 203.04 200.91 200.13
278.39 276.37 272.01 265.24 256.96 247.57 237.40 226.98 216.47 206.49 200.37 197.67 197.01 197.54 198.40 198.90 198.38 197.71 197.44
264.03 262.31 257.54 250.79 242.60 233.46 223.69 214.16 204.99 199.24 195.70 193.63 193.30 194.69 195.57 196.18 195.83 195.51 195.43
249.31 247.05 242.63 236.45 228.94 220.41 211.88 203.90 199.16 196.01 193.60 192.18 192.18 193.02 193.86 194.50 194.15 193.75 193.61
235.19 232.49 228.44 223.07 216.52 209.33 202.48 198.96 196.40 194.31 192.59 191.50 191.41 192.00 192.80 193.35 193.46 192.50 192.17
226.58 223.61 219.86 215.01 209.08 202.94 199.47 197.05 195.24 193.55 192.11 191.20 191.02 191.54 192.25 192.92 193.02 192.00 191.42
```

```
SLOPE IN DEGREES

  2.   2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   0.   1.   1.   1.   2.   2.   2.
  2.   2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   0.   1.   1.   1.   2.   2.   2.
  2.   2.   1.   1.   1.   1.   1.   1.   1.   1.   1.   1.   1.   2.   2.   2.   2.   1.   1.
  2.   2.   1.   1.   1.   1.   1.   2.   2.   2.   2.   2.   2.   2.   2.   1.   1.   3.   3.
  1.   1.   1.   1.   1.   2.   2.   2.   2.   2.   2.   2.   1.   1.   1.   3.   6.   9.   9.
  1.   1.   1.   1.   2.   2.   2.   2.   2.   1.   1.   2.   4.   5.   6.   8.  10.  10.  10.
  1.   1.   1.   1.   2.   2.   2.   1.   2.   5.   7.   8.  10.  10.  10.  10.  11.  11.  11.
  1.   1.   0.   0.   0.   0.   1.   5.   9.  11.  12.  12.  13.  13.  13.  12.  13.  14.  14.
  3.   3.   3.   3.   4.   5.   8.  12.  14.  14.  15.  15.  16.  15.  15.  16.  17.  18.  18.
  4.   4.   5.   6.   8.  10.  13.  15.  16.  16.  17.  18.  18.  17.  17.  18.  20.  20.  20.
  4.   4.   6.   8.  10.  13.  15.  17.  18.  19.  20.  21.  20.  19.  19.  20.  21.  20.  20.
  4.   4.   6.   9.  12.  14.  16.  19.  21.  22.  23.  23.  22.  22.  21.  20.  20.  21.  21.
  5.   5.   8.  11.  13.  16.  19.  22.  23.  24.  24.  24.  24.  24.  23.  22.  22.  24.  24.
  7.   7.  11.  13.  15.  18.  21.  23.  25.  25.  25.  25.  26.  26.  27.  27.  28.  29.  29.
  8.   8.  11.  14.  17.  19.  23.  24.  25.  25.  26.  26.  27.  28.  30.  32.  34.  34.  34.
  8.   8.  12.  16.  19.  22.  24.  26.  28.  29.  29.  29.  29.  31.  32.  34.  36.  37.  37.
  9.   9.  15.  20.  23.  24.  27.  30.  31.  32.  32.  32.  32.  33.  33.  34.  36.  37.  37.
 14.  14.  21.  26.  27.  28.  31.  34.  36.  36.  35.  35.  34.  34.  34.  34.  35.  35.  35.
 25.  25.  30.  32.  32.  34.  36.  39.  39.  38.  37.  36.  35.  35.  34.  34.  34.  33.  33.
 34.  34.  35.  36.  37.  38.  40.  41.  41.  40.  39.  38.  36.  35.  33.  32.  32.  30.  30.
 36.  36.  37.  38.  39.  40.  42.  42.  42.  42.  40.  38.  35.  33.  31.  29.  28.  25.  25.
 36.  36.  37.  38.  40.  41.  42.  42.  42.  41.  36.  31.  27.  24.  24.  22.  19.  15.  15.
 36.  36.  37.  39.  40.  41.  41.  41.  39.  33.  24.  17.  14.  12.  13.  13.  10.   8.   8.
 37.  37.  38.  39.  39.  40.  39.  37.  30.  19.  12.   8.   7.   7.   7.   6.   6.   6.   6.
 37.  37.  38.  38.  37.  36.  34.  26.  16.  11.   7.   4.   4.   5.   4.   4.   4.   4.   4.
 31.  31.  32.  32.  31.  29.  22.  13.   9.   6.   5.   2.   2.   3.   3.   2.   2.   3.   3.
 31.  31.  32.  32.  31.  29.  22.  13.   9.   6.   5.   2.   2.   3.   3.   2.   2.   3.   3.
```

```
UPAREA

  400.   800.  1200.  1600.  2000.  2400.  9600. 15200.  5200.  1600.  1200.   800.   400.  1600.  3200.  1200.  1200.   800.   400.
  400.   800.  1200.  1600.  6000.  8400. 13200.   800.  1600.  4800.  2000.   800.   400.  1200.  2000.   800.   800.   800.   400.
  400.   800.  1200.  4000.  2000.  2000. 10000.   800.   400.  1200.  2400.   800.   400.   800.   800.   800.   400.   400.   400.
  400.  1200.  2400.  1600.  1600.  4800.  3600.  1200.   400.   800.   800.  1200.   400.   400.   400.   400.   400.   400.   400.
  400.   800.  1200.  1200.  1200.  3200.  2400.   800.   800.   400.   400.   400.   400.   400.   400.   800.   400.   800.   800.
  400.   800.   800.   800.  1200.  1600.  1600.   400.   400.   400.   400.   400.   800.   400.   800.   400.  1200.   800.  1200.
  400.   400.   400.   400.   400.  1200.   800.   400.   400.   400.   800.   800.  1200.   800.  1200.   400.   800.  1600.  1200.
  400.   400.   400.   400.   800.   400.   400.   400.   800.   800.  1200.  1200.  1600.  1200.  1600.   800.   400.  1200.  2000.
  800.   800.   400.  1633.  1233.  1233.  1233.  1633.  1633.  2000.  1600.  1600.  2000.  1600.  2000.  1200.   400.   800.  1600.
 1200.  1200.   800.  2033.  1633.  1633.   400.  1633.  2033.  4033.  2000.  2000.  2400.  2000.  2400.  1600.   800.   400.  1200.
 1600.  1600.  1200.  2433.  2033.  2033.   400.   800.  2033.  6466.  2400.  2400.  2800.  2400.  2800.  2000.  1200.   800.  1600.
 2000.  2000.  1600.  2833.  2433.   400.  2433.   800.  1200.  2433.  9266.  2800.  3200.  2800.  3200.  2400.  1600.  1200.  2000.
  400.  2400.  2400.  2000.  3233.  2833.   800.  2833.  1200.  1600. 12099.  3200.  3600.  3200.  3600.  2800.  2000.  1600.  2400.
  400.   800.  2800.  2800.  2400.  3633.  3233.  1200.  3233.  1600. 14099.  3600.  4000.  3600.  4000.  3200.  2400.  2000.  2800.
  400.   800.  1200.  3200.  3200.  2800.  4033.  3633.  1600.  3633.  2000. 18099.  4400.  4000.  4400.  3600.  2800.  2400.  3200.
  400.   800.  1200.  1600.  3600.  3600.  3200.  4433.  4033.  2000.  4033. 20499.  4800.  4400.  4800.  4000.  3200.  2800.  3600.
  400.   800.  1200.  1600.  2000.  4000.  4000.  3600.  4833.  4433.  2400. 24932.  5200.  4800.  5200.  4400.  3600.  3200.  4000.
  400.   800.  1200.  1600.  2000.  2400.  4400.  4400.  4000.  5233.  4833. 27732.  5600.  5200.  5600.  4800.  4000.  3600.  4400.
  400.   800.  1200.  1600.  2000.  2400.  2800.  4800.  4800.  4400.  5633. 32965.  6000.  5600.  6000.  5200.  4400.  4000.  4800.
  800.  1200.   400.  1600.  2000.  2400.  2800.  3200.  5200.  5200.  4800. 38998.  6400.  6000.  6400.  5600.  4800.  4400.  5200.
 1200.  1600.   400.   800.  2000.  2400.  2800.  3200.  3600.  5600.  5600. 44198.  6800.  6400.  6800.  6000.  5200.  4800.  5600.
 1600.  2000.   800.   400.  1200.  2400.  2800.  3200.  3600.  4000.  6000. 50198.  7200.  6800.  7200.  6400.  5600.  5200.  6000.
 2000.  2400.  1200.   400.   800.  1600.  2800.  3200.  3600.  4000.  4400. 56598.  7600.  7200.  7600.  6800.  6000.  5600.  6400.
 2400.  2800.  1600.   400.   800.  1200.  2000.  3200.  3600.  4000.  4400. 61398.  8000.  7600.  8000.  7200.  6400.  6000.  6800.
 2800.  3200.  2000.   400.   800.  1200.  1600.  2400.  3600.  4000.  4400. 66198.  8400.  8000.  8400.  7600.  6800.  6400.  7200.
 3200.  3600.  2400.   400.   800.  1200.  1600.  2000.  2800.  4000.  4400.  4800. 32998.  8800.   400.  8000.  7200.  6800.  7600.
 3600.  4000.  2800.   400.   800.  1200.  1600.  2000.  2400.  3200.  4400. 87798. 14000.   800.  8400.   400.   400.  7600.  7200.
```

```
ASPECT

190.  190.  181.  171.  160.  149.  116.   61.   38.   31.   17.   11.   39.   68.   70.   58.   42.   43.   43.
190.  190.  181.  171.  160.  149.  116.   61.   38.   31.   17.   11.   39.   68.   70.   58.   42.   43.   43.
182.  182.  170.  157.  150.  137.  102.   65.   59.   64.   64.   54.   59.   69.   76.   64.   49.   31.   31.
166.  166.  152.  143.  136.  125.   89.   64.   65.   74.   79.   67.   60.   68.   78.   80.  300.  256.  256.
147.  147.  138.  131.  127.  111.   83.   62.   62.   72.   75.   69.   52.  323.  267.  237.  233.  246.  246.
139.  139.  128.  123.  115.   99.   81.   61.   56.   46.  292.  264.  253.  255.  255.  244.  236.  242.  242.
134.  134.  123.  114.  104.   96.   80.   58.  264.  249.  251.  254.  257.  258.  258.  251.  238.  240.  240.
273.  273.  228.  189.  153.  148.  239.  238.  241.  249.  253.  255.  258.  261.  264.  257.  244.  242.  242.
281.  281.  270.  269.  267.  258.  240.  237.  242.  249.  254.  256.  258.  263.  266.  261.  250.  245.  245.
269.  269.  263.  262.  258.  253.  245.  238.  241.  249.  254.  256.  259.  263.  264.  260.  252.  250.  250.
256.  256.  248.  248.  248.  245.  243.  239.  241.  247.  252.  257.  262.  265.  264.  258.  250.  250.  250.
243.  243.  234.  235.  237.  239.  239.  238.  239.  245.  251.  257.  264.  267.  266.  260.  251.  248.  248.
238.  238.  226.  227.  231.  233.  233.  234.  238.  242.  249.  258.  265.  269.  270.  265.  253.  248.  248.
234.  234.  224.  223.  226.  228.  228.  229.  234.  240.  247.  255.  265.  269.  271.  268.  257.  250.  250.
231.  231.  219.  219.  221.  223.  225.  225.  231.  237.  244.  252.  261.  267.  268.  265.  258.  255.  255.
224.  224.  215.  215.  219.  220.  222.  224.  229.  236.  243.  250.  258.  263.  264.  261.  257.  257.  257.
226.  226.  215.  217.  220.  222.  222.  224.  228.  235.  243.  250.  256.  261.  262.  257.  254.  257.  257.
241.  241.  224.  223.  226.  227.  225.  225.  229.  235.  243.  250.  256.  261.  262.  256.  251.  255.  255.
253.  253.  234.  231.  232.  234.  231.  228.  230.  236.  243.  250.  257.  261.  263.  257.  250.  253.  253.
257.  257.  244.  238.  236.  236.  235.  233.  233.  236.  244.  252.  258.  263.  264.  258.  251.  252.  252.
257.  257.  248.  242.  238.  236.  235.  234.  235.  237.  243.  252.  261.  268.  269.  259.  250.  254.  254.
257.  257.  249.  243.  238.  236.  235.  233.  234.  236.  241.  251.  263.  273.  276.  265.  252.  254.  254.
257.  257.  249.  242.  239.  236.  234.  232.  231.  232.  240.  255.  269.  279.  279.  270.  261.  260.  260.
258.  258.  249.  243.  238.  235.  233.  231.  229.  228.  230.  251.  282.  291.  288.  273.  261.  264.  264.
257.  257.  250.  244.  238.  235.  232.  230.  227.  222.  219.  236.  289.  302.  298.  276.  252.  260.  260.
254.  254.  248.  241.  235.  231.  230.  228.  220.  213.  208.  220.  293.  313.  310.  293.  233.  234.  234.
254.  254.  248.  241.  235.  231.  230.  228.  220.  213.  208.  220.  293.  313.  310.  293.  233.  234.  234.


MEAN SOIL DEPTH AT EACH GRID CELL

2.07  2.10  2.15  2.18  2.21  2.22  2.23  2.22  2.21  2.20  2.18  2.18  2.18  2.18  2.18  2.17  2.15  2.13  2.12
2.09  2.12  2.16  2.19  2.22  2.23  2.23  2.22  2.21  2.20  2.18  2.18  2.17  2.16  2.15  2.14  2.12  2.10  2.09
2.12  2.15  2.17  2.20  2.21  2.22  2.22  2.21  2.19  2.18  2.16  2.15  2.14  2.13  2.11  2.09  2.07  2.04  2.03
2.14  2.15  2.17  2.19  2.20  2.21  2.20  2.18  2.16  2.14  2.12  2.11  2.09  2.07  2.05  2.03  2.00  1.98  1.98
2.14  2.15  2.16  2.17  2.18  2.18  2.16  2.14  2.11  2.09  2.07  2.05  2.03  2.01  1.98  1.96  1.94  1.93  1.93
2.12  2.13  2.14  2.14  2.14  2.13  2.11  2.08  2.04  2.02  2.01  2.00  1.98  1.96  1.93  1.90  1.89  1.89  1.89
2.10  2.10  2.11  2.10  2.09  2.07  2.04  2.01  1.98  1.98  1.97  1.97  1.96  1.93  1.90  1.87  1.85  1.85  1.86
2.08  2.08  2.07  2.06  2.03  1.99  1.96  1.94  1.95  1.97  1.98  1.98  1.96  1.94  1.90  1.85  1.82  1.81  1.82
2.08  2.06  2.04  2.01  1.97  1.92  1.90  1.91  1.95  2.00  2.02  2.02  2.00  1.96  1.91  1.85  1.80  1.78  1.77
2.08  2.06  2.03  1.99  1.93  1.88  1.87  1.91  1.99  2.06  2.09  2.08  2.04  1.99  1.92  1.85  1.79  1.75  1.74
2.08  2.05  2.01  1.97  1.92  1.88  1.88  1.93  2.03  2.12  2.16  2.14  2.09  2.02  1.94  1.85  1.77  1.73  1.71
2.06  2.02  1.99  1.95  1.91  1.89  1.89  1.96  2.07  2.17  2.23  2.21  2.15  2.06  1.95  1.84  1.75  1.69  1.66
2.02  1.98  1.95  1.92  1.90  1.89  1.91  1.98  2.09  2.21  2.29  2.28  2.20  2.09  1.96  1.83  1.72  1.64  1.61
1.98  1.93  1.90  1.89  1.89  1.89  1.92  1.99  2.10  2.23  2.32  2.33  2.25  2.12  1.98  1.84  1.72  1.63  1.60
1.92  1.88  1.85  1.85  1.86  1.88  1.91  1.98  2.10  2.24  2.34  2.36  2.29  2.16  2.03  1.89  1.78  1.71  1.68
1.84  1.80  1.78  1.79  1.82  1.85  1.89  1.96  2.08  2.23  2.35  2.39  2.33  2.21  2.09  1.98  1.91  1.85  1.83
1.75  1.70  1.69  1.71  1.76  1.81  1.87  1.94  2.07  2.22  2.37  2.43  2.38  2.27  2.15  2.08  2.04  2.01  2.00
1.65  1.60  1.59  1.63  1.71  1.79  1.86  1.94  2.07  2.25  2.41  2.48  2.44  2.33  2.23  2.18  2.16  2.16  2.16
1.60  1.53  1.52  1.58  1.68  1.79  1.87  1.97  2.11  2.31  2.49  2.57  2.53  2.41  2.31  2.26  2.26  2.28  2.29
1.62  1.53  1.50  1.56  1.69  1.81  1.92  2.03  2.20  2.41  2.60  2.69  2.64  2.52  2.40  2.35  2.36  2.39  2.41
1.70  1.59  1.53  1.58  1.72  1.87  2.00  2.13  2.32  2.54  2.74  2.83  2.77  2.63  2.51  2.44  2.45  2.48  2.50
1.78  1.65  1.58  1.63  1.77  1.94  2.10  2.27  2.46  2.69  2.88  2.95  2.88  2.73  2.59  2.51  2.51  2.53  2.55
1.86  1.72  1.64  1.68  1.84  2.03  2.22  2.41  2.62  2.83  2.98  3.01  2.91  2.75  2.61  2.53  2.51  2.52  2.53
1.92  1.78  1.69  1.74  1.90  2.12  2.35  2.56  2.75  2.90  2.99  2.97  2.85  2.69  2.56  2.48  2.45  2.45  2.45
1.98  1.83  1.75  1.79  1.96  2.20  2.46  2.66  2.81  2.89  2.91  2.85  2.73  2.59  2.46  2.39  2.36  2.36  2.36
2.02  1.88  1.79  1.83  2.00  2.26  2.52  2.71  2.82  2.84  2.81  2.73  2.61  2.48  2.37  2.31  2.28  2.28  2.28
2.03  1.90  1.82  1.85  2.02  2.28  2.54  2.73  2.81  2.81  2.75  2.67  2.55  2.43  2.33  2.27  2.25  2.25  2.25
```

AVERAGE NUMBER OF FAILURES PER YEAR AT EACH GRID CELL DURING THE ANALYZED PERIOD

```
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .00  .00  .00  .00  .00  .00  .00
.00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .01  .01  .00  .00  .00  .00  .00  .00  .01
.00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .01  .01  .01  .01  .01  .01  .03  .02  .03
.00  .00  .00  .00  .00  .00  .00  .00  .01  .00  .01  .02  .03  .03  .04  .07  .07  .06  .06
.00  .00  .00  .00  .00  .00  .00  .02  .01  .03  .04  .04  .04  .06  .06  .08  .09  .09  .09
.00  .00  .00  .00  .00  .00  .02  .03  .05  .07  .07  .08  .07  .07  .08  .10  .12  .10  .09
.00  .00  .00  .01  .01  .02  .04  .08  .10  .12  .12  .11  .08  .08  .10  .11  .09  .09  .10
.00  .00  .02  .03  .05  .05  .08  .13  .14  .16  .17  .16  .13  .13  .10  .10  .10  .09  .07
.03  .05  .04  .06  .06  .10  .13  .17  .20  .23  .21  .19  .17  .12  .07  .08  .07  .06  .05
.05  .06  .03  .03  .07  .12  .14  .18  .22  .26  .23  .23  .17  .11  .06  .04  .03  .01  .01
.06  .07  .03  .02  .07  .10  .15  .17  .19  .21  .19  .06  .02  .01  .00  .00  .00  .00  .00
.05  .07  .06  .03  .05  .08  .16  .17  .18  .08  .01  .00  .00  .00  .00  .00  .00  .00  .00
.09  .08  .08  .03  .04  .06  .10  .13  .04  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.10  .09  .08  .03  .05  .06  .04  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.05  .05  .05  .02  .03  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
.07  .06  .05  .01  .03  .01  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
```

NUMBER OF FAILURES AT EACH GRID CELL DIVIDED
BY THE TOTAL NUMBER OF FAILURES FOR THE WHOLE GRID

```
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00008 .00000 .00000 .00008 .00000 .00000 .00000 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00015 .00046 .00008 .00015 .00008 .00023 .00015 .00000 .00015 .00008
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00023 .00023 .00008 .00068 .00046 .00038 .00030 .00000 .00000 .00008 .00023 .00061
.00000 .00000 .00000 .00000 .00000 .00000 .00000 .00023 .00053 .00015 .00068 .00076 .00046 .00106 .00076 .00091 .00228 .00152 .00228
.00000 .00000 .00000 .00000 .00000 .00000 .00015 .00030 .00068 .00038 .00106 .00160 .00220 .00190 .00304 .00554 .00501 .00494 .00494
.00000 .00000 .00000 .00000 .00000 .00000 .00015 .00122 .00106 .00213 .00273 .00296 .00266 .00471 .00425 .00638 .00722 .00706 .00691
.00000 .00000 .00000 .00000 .00000 .00038 .00122 .00243 .00365 .00532 .00501 .00585 .00524 .00562 .00608 .00760 .00896 .00790 .00714
.00000 .00000 .00015 .00068 .00091 .00160 .00231 .00585 .00760 .00896 .00881 .00828 .00638 .00585 .00702 .00805 .00653 .00653 .00767
.00008 .00038 .00175 .00258 .00365 .00380 .00577 .00957 .01101 .01200 .01276 .01135 .01010 .01003 .00767 .00737 .00729 .00646 .00516
.00251 .00365 .00266 .00441 .00494 .00737 .00972 .01314 .01519 .01747 .01610 .01481 .01329 .00934 .00554 .00577 .00547 .00433 .00403
.00387 .00441 .00258 .00243 .00562 .00873 .01025 .01360 .01641 .01982 .01777 .01724 .01284 .00843 .00433 .00334 .00228 .00084 .00084
.00463 .00524 .00235 .00182 .00562 .00760 .01154 .01284 .01413 .01625 .01451 .00479 .00167 .00076 .00030 .00000 .00008 .00000 .00000
.00403 .00524 .00456 .00228 .00380 .00600 .01177 .01268 .01344 .00608 .00046 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00706 .00577 .00570 .00235 .00334 .00441 .00744 .01018 .00289 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00752 .00668 .00592 .00213 .00342 .00494 .00304 .00106 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00418 .00387 .00349 .00122 .00190 .00084 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
.00516 .00433 .00349 .00068 .00197 .00114 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000 .00000
```

AVERAGE RATIO OF WATER DEPTH/SOIL DEPTH FOR EACH CELL

```
 .99  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .99  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99  1.00  1.00  1.00   .98   .99   .99  1.00  1.00   .91   .91
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99   .99   .99  1.00  1.00  1.00  1.00   .70   .85   .85
1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99  1.00  1.00  1.00   .99   .99   .76   .94   .59   .95   .78   .93
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00   .99   .81   .93   .85   .95   .80   .94   .49   .78   .98   .92
1.00  1.00  1.00  1.00  1.00  1.00  1.00   .83   .84   .76   .90   .87   .94   .86   .96   .72   .40   .37   .98
1.00  1.00   .92  1.00  1.00  1.00   .98   .97   .94   .96   .91   .91   .95   .90   .96   .80   .32   .58   .90
1.00  1.00   .98  1.00  1.00   .98   .38   .92   .95  1.00   .92   .91   .96   .93   .97   .87   .54   .28   .73
1.00  1.00  1.00  1.00  1.00   .99   .35   .57   .93  1.00   .92   .92   .97   .95   .98   .93   .73   .55   .86
1.00  1.00  1.00  1.00   .99   .37   .98   .51   .65   .91  1.00   .94   .96   .96   .98   .96   .86   .74   .94
 .75  1.00  1.00   .99  1.00   .99   .52   .97   .58   .69  1.00   .95   .97   .96   .99   .97   .92   .82   .96
 .61   .92  1.00  1.00   .99  1.00   .99   .62   .96   .69  1.00   .96   .98   .97   .99   .97   .92   .86   .96
 .54   .88   .93  1.00  1.00   .98  1.00   .98   .70   .96   .75  1.00   .98   .97   .98   .97   .92   .89   .96
 .58   .90   .91   .92  1.00   .99   .97   .99   .98   .76   .96  1.00   .98   .97   .99   .97   .93   .90   .97
 .54   .88   .86   .88   .90   .99   .99   .97   .99   .98   .77  1.00   .98   .98   .99   .98   .94   .92   .97
 .40   .73   .76   .83   .87   .90   .99   .98   .96   .98   .97  1.00   .98   .98   .99   .98   .95   .93   .97
 .26   .52   .66   .77   .84   .88   .91   .99   .98   .95   .98  1.00   .98   .98   .99   .98   .97   .95   .98
 .42   .64   .23   .75   .81   .85   .88   .90   .98   .97   .95  1.00   .99   .99   .99   .99   .97   .97   .99
 .56   .73   .22   .41   .79   .83   .86   .89   .90   .97   .97  1.00   .99   .99   .99   .99   .98   .99   .99
 .68   .82   .42   .21   .53   .81   .84   .86   .88   .88   .97  1.00   .99  1.00  1.00  1.00  1.00  1.00  1.00
 .78   .88   .57   .19   .35   .61   .82   .85   .87   .89   .96  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .85   .92   .70   .20   .34   .45   .64   .84   .89   .97  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .88   .94   .79   .19   .34   .46   .54   .76   .98  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 .94   .97   .89   .19   .36   .48   .66   .92  1.00  1.00  1.00  1.00  1.00  1.00   .91  1.00  1.00  1.00  1.00
 .96   .98   .93   .20   .36   .47   .66   .92   .99  1.00  1.00  1.00  1.00  1.00  1.00   .96   .98  1.00  1.00
```

AVERAGE FACTOR OF SAFETY AT EACH GRID CELL

```
27.09  27.35  29.01  34.89  41.51  50.69  81.06  70.74  57.33  60.80  88.27 100.46 107.10  72.07  48.56  40.65  29.78  33.73  32.83
27.22  26.83  29.16  35.49  41.51  51.24  81.40  70.66  56.89  62.41  87.90  98.53 107.47  72.24  48.69  41.01  30.34  33.65  33.53
30.45  29.68  34.63  36.78  39.67  49.09  64.52  46.80  39.79  45.01  51.98  51.35  38.59  31.60  30.94  30.22  33.24  44.35  44.85
33.56  33.97  38.82  37.63  37.27  41.10  42.56  33.50  29.48  28.87  29.33  26.30  24.08  25.97  29.02  36.94  84.64  16.00  15.90
35.47  34.77  37.94  36.11  35.18  34.57  31.60  27.75  23.63  26.05  25.85  25.88  42.79  92.27  44.82  18.62  10.54   6.70   6.73
37.51  37.71  36.42  35.32  32.30  30.36  28.56  26.02  28.77  66.36  62.99  24.09  13.57  11.65   8.50   8.93   5.82   5.94   5.42
51.38  50.87  40.43  36.31  31.74  32.32  33.78  48.15  28.00  12.52   8.13   6.92   5.75   6.06   5.47   7.83   5.34   4.93   5.07
71.08  71.34 118.18 181.08 130.74 152.38  68.86  12.68   6.63   5.68   4.87   4.69   4.31   4.42   4.45   5.39   6.92   4.47   4.03
16.54  16.59  16.64  15.40  13.95  11.43   7.09   4.68   4.08   3.79   3.86   3.71   3.50   3.70   3.68   4.01   5.94   4.17   3.33
12.24  12.23  10.48   8.33   6.86   5.44   6.77   3.85   3.41   3.27   3.21   3.04   3.09   3.23   3.21   3.31   4.01   5.43   3.38
13.51  13.52   9.66   7.18   5.36   4.27   6.20   4.38   3.09   2.80   2.67   2.63   2.69   2.87   2.89   2.98   3.29   3.99   3.11
12.81  12.97   8.32   5.87   4.57   6.56   3.41   4.04   3.21   2.48   2.25   2.32   2.43   2.49   2.62   2.81   3.12   3.38   3.00
11.70  10.07   6.44   4.81   4.15   3.59   4.09   2.53   2.95   2.63   2.09   2.16   2.20   2.25   2.35   2.59   2.81   2.76   2.56
 9.45   7.39   5.15   4.30   3.66   3.12   2.67   2.99   2.21   2.59   2.07   2.06   2.03   2.04   2.08   2.19   2.22   2.30   2.16
 8.83   6.94   5.00   3.89   3.35   2.91   2.44   2.29   2.55   2.08   2.23   1.89   1.90   1.90   1.84   1.84   1.84   1.90   1.86
 8.35   7.16   4.77   3.70   2.98   2.57   2.35   2.12   1.99   2.13   1.80   1.79   1.77   1.74   1.72   1.70   1.68   1.73   1.67
 8.46   6.80   4.14   3.17   2.69   2.36   2.14   1.92   1.77   1.64   1.81   1.56   1.59   1.63   1.64   1.63   1.58   1.61   1.62
 6.84   5.10   3.36   2.67   2.39   2.21   1.88   1.70   1.61   1.52   1.49   1.45   1.51   1.57   1.56   1.59   1.59   1.60   1.55
 4.75   3.63   2.74   2.38   2.14   1.92   1.73   1.52   1.47   1.44   1.38   1.38   1.43   1.49   1.54   1.58   1.58   1.62   1.61
 2.98   2.53   4.08   2.19   1.95   1.77   1.59   1.47   1.34   1.32   1.32   1.31   1.36   1.44   1.58   1.63   1.61   1.70   1.68
 2.42   2.13   3.93   2.91   1.90   1.70   1.54   1.43   1.36   1.25   1.26   1.26   1.38   1.49   1.61   1.77   1.81   1.99   1.98
 2.12   1.97   2.93   3.91   2.28   1.65   1.52   1.43   1.36   1.31   1.32   1.50   1.74   1.92   2.03   2.18   2.53   3.22   3.20
 1.94   1.86   2.36   3.75   2.77   1.94   1.52   1.41   1.38   1.50   1.92   2.56   3.34   3.77   3.72   3.80   4.64   6.19   6.22
 1.77   1.75   2.07   3.79   2.76   2.23   1.76   1.50   1.69   2.41   3.66   5.49   6.53   6.31   7.11   7.75   8.05   8.62   8.62
 1.65   1.70   1.90   3.69   2.77   2.28   2.09   2.08   2.91   4.36   6.46  12.71  12.92  10.44  10.87  12.16  13.83  11.32  11.17
 1.84   1.84   2.03   4.07   3.05   2.55   2.71   3.79   5.31   7.12  10.19  21.46  26.20  16.70  17.35  20.24  25.07  16.17  15.98
 1.79   1.82   1.94   3.99   3.07   2.60   2.74   3.76   5.28   7.11  10.18  21.47  26.32  16.82  16.38  20.75  24.51  16.40  16.01
```

```
MINIMUM FACTOR OF SAFETY AT EACH GRID CELL

  9.44  11.94  13.15  14.35  18.02  23.26  36.27  29.29  23.37  25.48  35.88  46.51  42.76  27.22  17.86  17.04  12.68  14.07  14.03
 11.01  11.78  12.69  13.74  18.25  23.84  34.50  27.47  25.60  26.44  37.50  45.71  43.86  30.57  18.95  17.86  12.59  14.50  14.54
 12.22  12.30  14.98  15.58  19.23  21.78  27.63  18.98  17.76  16.38  21.92  20.39  16.46  13.77  11.89  14.00  12.40  19.67  17.06
 14.07  14.25  17.65  15.58  14.50  17.21  17.56  15.10  12.33  12.19  11.89  11.54  11.52  11.05  11.01  15.68  31.60   6.20   6.07
 14.35  15.97  16.09  14.51  15.03  14.93  12.95  12.71  10.44  11.62   9.30  11.30  18.56  42.03  19.03   7.22   3.93   2.83   2.23
 15.45  15.03  16.11  14.22  13.80  13.71  11.43  11.58  12.43  27.08  25.31  10.47   5.25   4.23   3.48   2.56   2.12   1.99   2.12
 24.65  21.41  15.13  15.36  11.30  13.40  12.80  19.15  10.79   4.42   3.37   2.34   2.39   2.03   2.07   2.54   2.21   2.04   2.11
 28.57  30.79  52.06  74.68  48.79  64.07  28.30   5.11   2.53   2.07   2.07   1.92   1.89   1.76   1.55   1.72   1.96   1.52   1.73
  7.52   7.03   6.43   6.74   6.29   4.55   2.90   1.97   1.63   1.25   1.60   1.34   1.39   1.41   1.54   1.41   1.62   1.25   1.24
  4.92   5.29   3.99   3.24   2.84   2.07   2.02   1.51   1.35   1.34   1.23   1.07   1.18   1.25   1.19   1.14   1.07   1.21   1.00
  5.50   5.49   3.57   2.89   2.12   1.49   1.67   1.29   1.05   1.01   1.11    .99   1.01   1.17   1.00   1.09   1.06   1.02    .90
  5.05   4.98   3.49   2.33   1.70   1.76   1.44   1.22   1.13    .95    .93    .99    .90    .98    .94    .96   1.17    .97    .94
  4.11   4.53   2.86   1.84   1.63   1.44   1.19    .94    .83    .86    .87    .97    .95    .91   1.04   1.03    .98    .77    .87
  2.79   3.14   2.20   1.74   1.36   1.27   1.11    .96    .86    .86    .81    .84    .78    .74    .88    .76    .73    .75    .69
  2.77   2.71   1.68   1.57   1.37   1.13    .94    .90    .81    .84    .73    .81    .71    .80    .69    .66    .60    .60    .58
  2.75   2.77   1.66   1.50   1.19   1.07    .88    .79    .66    .69    .75    .68    .66    .73    .61    .59    .49    .49    .53
  2.39   2.05   1.48   1.00   1.02    .92    .78    .62    .68    .59    .62    .59    .65    .60    .56    .56    .49    .52    .44
  1.76   1.48    .95    .84    .85    .81    .57    .58    .55    .57    .51    .58    .54    .52    .61    .64    .59    .60    .50
   .99    .94    .77    .57    .66    .58    .57    .55    .43    .52    .57    .47    .46    .56    .50    .49    .58    .60    .63
   .60    .53    .64    .54    .49    .52    .46    .47    .44    .48    .46    .48    .52    .51    .65    .56    .57    .63    .74
   .53    .53    .65    .58    .47    .47    .38    .43    .47    .39    .49    .45    .49    .59    .67    .75    .82    .86    .75
   .59    .56    .56    .53    .53    .47    .42    .46    .44    .47    .59    .67    .77    .83    .90   1.01    .97   1.51   1.59
   .52    .62    .50    .52    .57    .50    .51    .47    .51    .51    .92   1.16   1.57   1.61   1.77   1.75   2.18   2.26   2.65
   .54    .51    .48    .58    .60    .46    .55    .51    .69   1.15   1.61   2.63   3.14   3.45   3.05   3.28   3.57   3.98   3.84
   .60    .55    .51    .59    .61    .55    .64    .81   1.29   2.29   2.98   5.93   6.30   4.70   4.64   5.39   6.08   5.34   5.23
   .60    .60    .67    .76    .70    .77   1.08   1.60   2.26   3.46   5.20   9.86  12.18   7.34   7.57   9.15  10.95   6.54   6.67
   .65    .63    .60    .77    .62    .77   1.10   1.73   2.61   3.11   4.25   9.44  11.66   7.47   7.49   8.09  10.67   7.09   6.58
```

```
MAXIMUM FACTOR OF SAFETY AT EACH GRID CELL

 65.40  62.10  55.80  74.08  96.79  98.59 209.87 161.05 120.29 114.03 204.42 246.70 247.61 160.47  92.29  92.25  58.87  63.29  77.83
 60.71  54.03  73.51  70.83  76.45 127.67 170.39 173.54 108.29 145.87 218.51 272.81 222.29 161.00 104.53  92.66  69.73  73.46  67.19
 64.52  80.25  66.71  92.82 110.85 120.43 128.19 131.16  80.32  93.79 116.48 102.42 132.89  66.61  79.09  73.99  73.12  93.49 106.38
 76.57  73.04  77.44  77.90  81.62 113.87  98.54  72.05  83.43  65.84  60.46  61.10  47.68  60.60  65.22  80.67 167.07  37.71  35.79
 77.56  66.83  74.53  99.72  91.18  89.84  62.85  61.48  49.25  54.64  47.45  59.64  82.48 250.34  97.34  41.12  24.96  15.55  16.74
 93.30  77.65  81.31  68.59  65.83  66.97  61.31  57.13  53.10 165.72 124.26  47.29  37.91  30.11  18.41  24.56  13.84  14.68  10.93
134.16  96.14  83.06  72.45  65.39  68.82  71.20 108.88  52.29  29.03  17.43  19.69  13.04  14.30  13.09  19.25  14.95  11.70  10.65
151.90 156.80 264.81 468.12 269.67 308.95 160.10  30.61  16.44  13.61  10.42  10.65   8.68  10.57   9.75  11.77  16.05  12.00   9.37
 35.70  32.56  35.54  31.22  31.25  29.02  15.53  13.65  11.36   7.83   7.77   8.74   7.61   8.09   7.05  11.06  16.79  11.76   8.05
 26.07  26.56  23.22  16.78  14.77  12.25  17.83   7.83   7.97   7.27   8.04   6.97   6.16   9.30   7.80   8.12  10.29  12.76   7.57
 30.78  28.67  24.86  15.47  11.06   9.59  15.62  10.92   6.50   6.63   5.59   5.10   7.18   6.85   6.21   7.88   8.47  10.70   7.40
 28.29  32.21  16.29  11.89  10.21  22.00   8.53  10.68   8.44   6.30   5.53   5.37   5.16   5.08   6.16   6.47   8.24   7.84   7.90
 26.62  30.34  13.36  11.29   9.89   6.93   9.06   5.06   7.41   6.14   5.01   4.92   4.96   5.07   5.46   5.28   6.34   6.45   6.37
 22.06  16.31  11.48   9.08   7.71   6.68   5.46   8.82   5.44   6.88   4.58   5.06   4.02   4.36   4.64   4.56   4.83   5.55   4.99
 26.28  17.71  13.22   9.40   7.80   6.95   5.28   4.63   7.51   5.70   5.85   3.55   4.38   4.04   4.96   4.57   5.60   4.68   4.77
 22.60  15.69  11.78   7.49   6.38   5.31   5.01   5.09   4.50   5.16   4.10   3.84   3.49   4.68   4.04   4.08   4.13   4.31   3.79
 21.37  13.93  12.74   6.97   6.17   5.10   5.10   4.48   4.65   3.96   4.99   4.07   4.05   3.87   3.58   3.95   3.74   3.78   3.61
 17.57  14.24   9.17   6.02   5.93   5.45   4.28   3.97   3.99   3.59   3.34   3.42   3.63   3.47   3.60   4.21   3.06   3.26   3.40
 12.56   9.38   7.30   5.64   5.42   5.16   4.39   3.50   3.36   3.64   3.11   3.11   3.14   3.49   3.25   3.59   3.63   3.78   3.29
  6.87   7.10  11.97   6.53   6.17   4.24   4.21   4.09   2.83   3.17   2.66   3.48   3.16   3.15   3.40   2.95   3.22   3.70   3.72
  6.78   5.35  10.19   7.57   5.49   4.45   3.50   4.62   3.25   3.98   3.22   3.15   3.55   5.01   3.27   4.21   4.44   4.29   4.40
  5.55   5.70   8.41   9.01   7.70   3.99   3.95   3.68   3.11   2.71   3.06   2.93   3.23   4.09   5.41   4.94   5.36   8.29   6.02
  5.33   4.39   8.88   9.56   7.12   5.43   3.80   3.30   2.91   2.88   3.75   5.84   7.63   7.94   7.11   7.23   9.02  13.55  11.85
  4.90   3.74   6.07  11.11   7.32   5.62   5.01   3.35   3.48   6.11   6.76  12.63  13.52  14.62  14.73  16.53  16.74  17.02  17.90
  4.30   4.05   4.73   9.67   7.60   6.76   4.71   4.61   5.87   8.82  13.07  24.11  27.11  20.70  21.13  24.86  29.36  22.84  20.75
  5.40   4.33   6.54  12.07   9.00   7.56   6.97   7.88  10.66  15.18  20.70  43.38  85.70  33.07  41.17  41.37  50.88  36.96  31.94
  4.17   4.69   4.45   9.68   8.55   5.93   6.46  10.94  15.48  15.01  25.21  45.46  65.75  36.31  32.75  55.77  55.93  35.60  33.29
```

```
 Program PROBFAIL
 Douglas S. Chandler, Dept. of Civil Engineering
 University of Washington
 Seattle, Washington
 November, 1992


natural conditions - from run192 of FASSA2

 U.S. units (lbs, feet, days)
 MEAN SD =        2.113835
 STANDARD DEVIATION OF SD =    5.223338E-01
 MEAN RC =      160.888400
 STANDARD DEVIATION OF RC =       78.669620
 MEAN QO =        7.063334
 STANDARD DEVIATION OF QO =        3.454183
 MEAN SAT =    8.945265E-01
 STANDARD DEVIATION OF SAT =    2.136417E-01
 MEAN SLOPE =       17.122890
 STANDARD DEVIATION OF SLOPE =       13.710510
 MEAN FA =      36.000000
 STANDARD DEVIATION OF FA =        3.600000
 MEAN C =    0.000000E+00
 STANDARD DEVIATION OF C =        8.000000
 MEAN SATURATED UNIT WEIGHT =      105.000000
 STANDARD DEVIATION OF SAT. UNIT WT. =        5.250000


 TOTAL NUMBER OF CALCULATIONS =   513000.000000

 TOTAL NUMBER OF FAILURES =    12448.000000

 AVERAGE FACTOR OF SAFETY =    12269.030000

 MINIMUM FACTOR OF SAFETY =    1.627408E-01

 MAXIMUM FACTOR OF SAFETY =  9818675.000000

 PROBABILITY OF FAILURE =    2.426511E-02
```

APPENDIX D

SLOPE STABILITY CALCULATIONS

Summary Table

Failure Surface	Changed Parameter	Calculated Factor of Safety		
		Infinite sl.	Bishops	OMS
1	ave	1.57	1.56	1.53
	c+ = [illegible]	1.87	1.73	1.70
	c- [illegible]	1.37	1.39	1.36
	φ+ [illegible]	2.06	2.08	2.03
	φ- 24.5'	1.20	1.16	1.14
	γ+ 18.7	1.53	1.52	1.49
	γ- 15.3	1.63	1.61	1.58
2	ave	1.19	1.74	1.50
	c+	1.24	1.85	1.62
	c-	1.15	1.66	1.42
	φ+	1.68	2.44	2.09
	φ-	.82	1.20	1.04
	γ+	1.18	1.72	1.48
	γ-	1.21	1.76	1.52
3	ave	1.37	1.50	1.42
	c+	1.55	1.67	1.59
	c-	1.25	1.39	1.31
	φ+	1.86	2.06	1.93
	φ-	.99	1.07	1.02
	γ+	1.34	1.48	1.39
	γ-	1.40	1.53	1.45

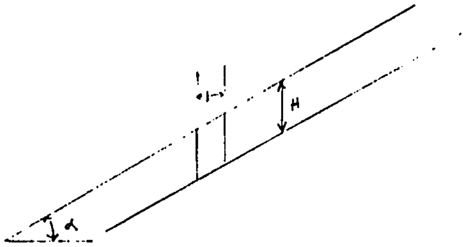
for failure surface #3			weighted w/ infinite slope = 1.00
	ave infinite slope	= 1.39	1.00
	ave. Bishops	= 1.53	1.10
	ave. OMS	= 1.44	1.04

For T.S. Cundy | Qual. Exam | Doug Chandler | 1.

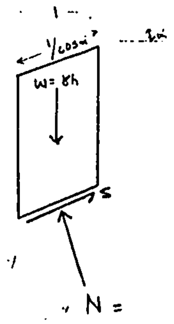
Infinite slope equation for no seepage or root strength,

1. assume failure surface is long & shallow & parrallel to slope

α = slope angle
H = depth to failure surface
c = cohesion
ϕ = friction angle
γ = unit wt of soil



consider a slice of unit width



side forces cancel in infinite slope

a.) Driving force is self wt = $W = \gamma H$

b.) Driving force in direction of slope = $\gamma H \sin\alpha$

c.) applied shear stress @ base = $\frac{\gamma H \sin\alpha}{\text{area}}$

$= \gamma H \sin\alpha \cos\alpha$

Now find shearing resistance

d.) 1st find normal stress @ base

$\Sigma F_y = 0, \quad N = \gamma h \cos\alpha$

so normal stress = $\gamma h \cos^2\alpha$

g.) available shearing resistance

$= c + \gamma h \cos^2\alpha \tan\phi$

h.) $FS = \frac{\text{Avail ss @ base}}{\text{Applied ss @ base}} = \frac{c + \gamma h \cos^2\alpha \tan\phi}{\gamma H \sin\alpha \cos\alpha}$

Wards equation reduces to $\frac{2c}{\gamma_m Z \sin 2\alpha} \quad \frac{\tan\phi}{\tan\alpha}$

for the case of no seepage, tree wts, or root strength which is same as my equation when you use double angle trig identity

$\sin 2\alpha = \sin\alpha \cos\alpha$

Failure Surface # 1

$c = 5 \ KN/m^2$
$\phi = 35°$
$\gamma = 17 \ KN/m^3$

Use infinite slope equation from page 1

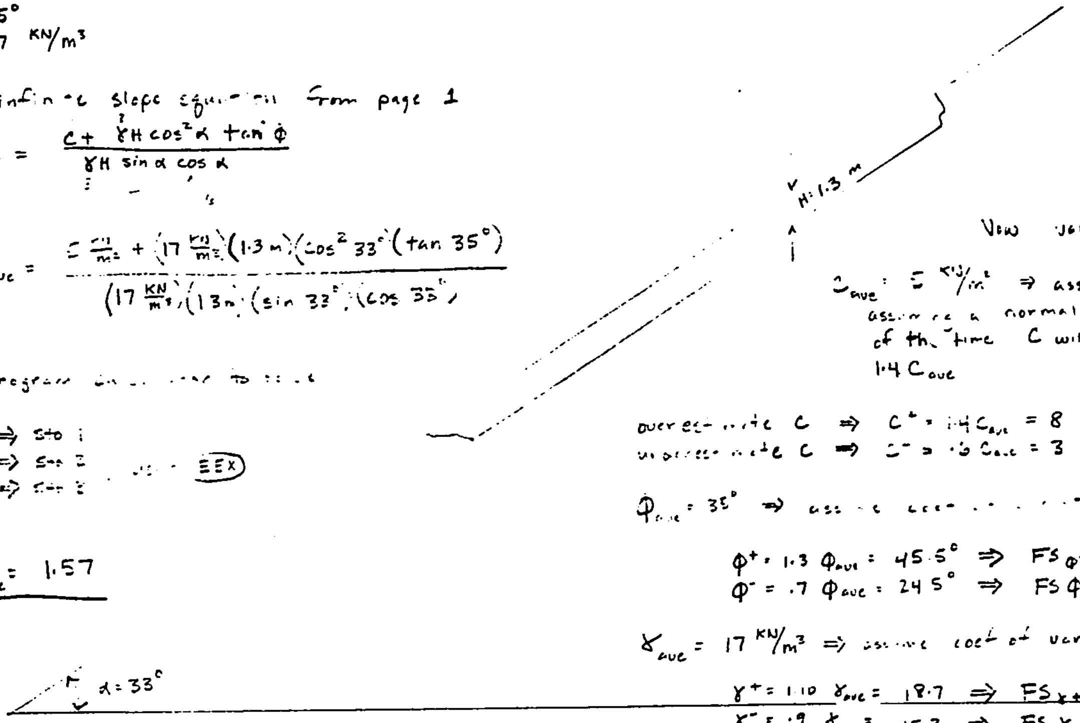
$$F.S. = \frac{c + \gamma H \cos^2\alpha \tan\phi}{\gamma H \sin\alpha \cos\alpha}$$

$$FS_{ave} = \frac{5 \frac{KN}{m^2} + (17 \frac{KN}{m^3})(1.3 m)(\cos^2 33°)(\tan 35°)}{(17 \frac{KN}{m^3})(1.3 m)(\sin 33°)(\cos 33°)}$$

program in [illegible] to solve

$C \Rightarrow$ sto 1
$\phi \Rightarrow$ sto 2
$\gamma \Rightarrow$ sto 3 [illegible] $\boxed{EEX}$

$\underline{FS_{ave} = 1.57}$



Now vary the parameters [illegible]

$C_{ave} = 5 \ KN/m^2$ ⇒ assume coef of variation .2
assuming a normal distribution, 95% of the time C will fall between .6 C_{ave} and 1.4 C_{ave}

overestimate C ⇒ $C^+ = 1.4 C_{ave} = 8 \Rightarrow FS_{c+} = 1.87$
underestimate C ⇒ $C^- = .6 C_{ave} = 3 \Rightarrow FS_{c-} = 1.37$

$\phi_{ave} = 35° \Rightarrow$ assume coef of variation = .15

$\phi^+ = 1.3 \phi_{ave} = 45.5° \Rightarrow FS_{\phi+} = 2.06$
$\phi^- = .7 \phi_{ave} = 24.5° \Rightarrow FS_{\phi-} = 1.20$

$\gamma_{ave} = 17 \ KN/m^3 \Rightarrow$ assume coef of variation = .05

$\gamma^+ = 1.10 \gamma_{ave} = 18.7 \Rightarrow FS_{\gamma+} = 1.53$
$\gamma^- = .9 \gamma_{ave} = 15.3 \Rightarrow FS_{\gamma-} = 1.63$

scale 1" = 5 m

For T.S. Cundy Qual Exam Doug Chandler

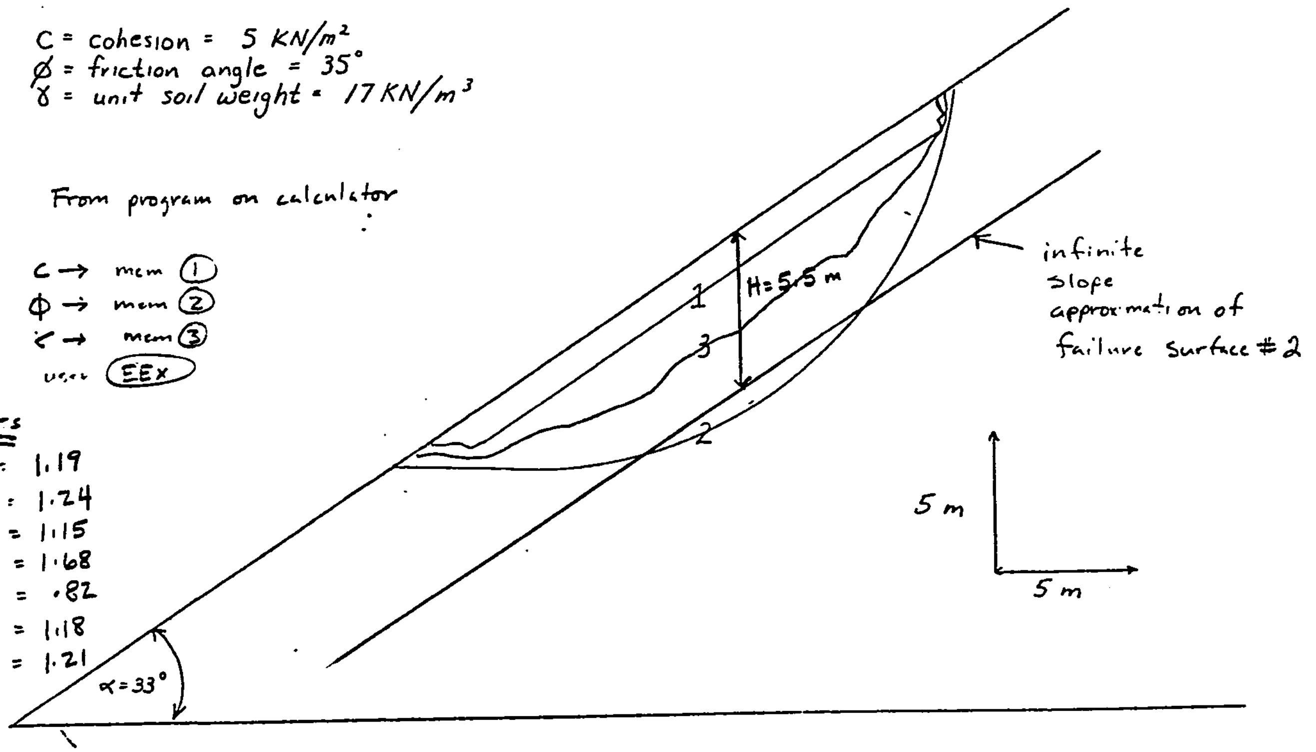
C = cohesion = 5 KN/m²
Ø = friction angle = 35°
γ = unit soil weight = 17 KN/m³

From program on calculator:

C → mem ①
Φ → mem ②
γ → mem ③
uses EEx

results

F_{ave} = 1.19
C+ = 1.24
C- = 1.15
Φ+ = 1.68
Φ- = .82
γ+ = 1.18
γ- = 1.21



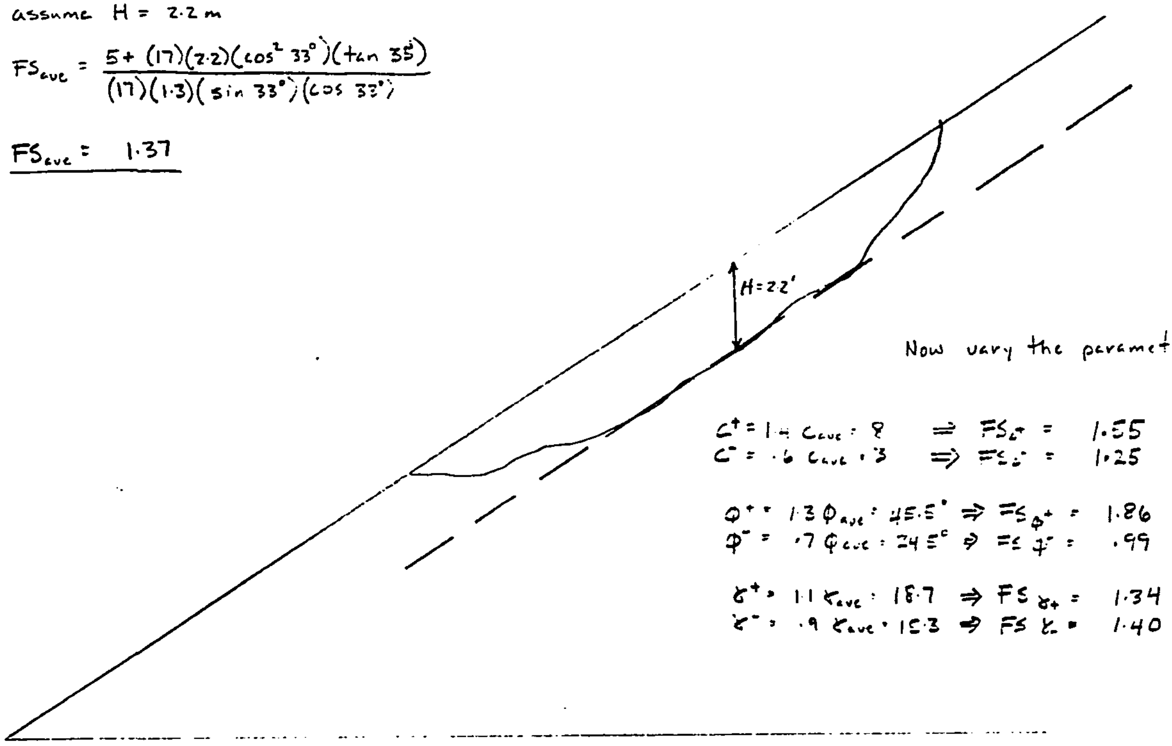
infinite slope approximation of failure surface #2

Failure surface # 3 → infinite slope approximation

assume $H = 2.2\,m$

$$FS_{ave} = \frac{5 + (17)(2.2)(\cos^2 33^\circ)(\tan 35^\circ)}{(17)(1.3)(\sin 33^\circ)(\cos 33^\circ)}$$

$\underline{FS_{ave} = 1.37}$



Now vary the parameters

$c^+ = 1.4\, c_{ave} = 8 \Rightarrow FS_{c^+} = 1.55$
$c^- = .6\, c_{ave} = 3 \Rightarrow FS_{c^-} = 1.25$

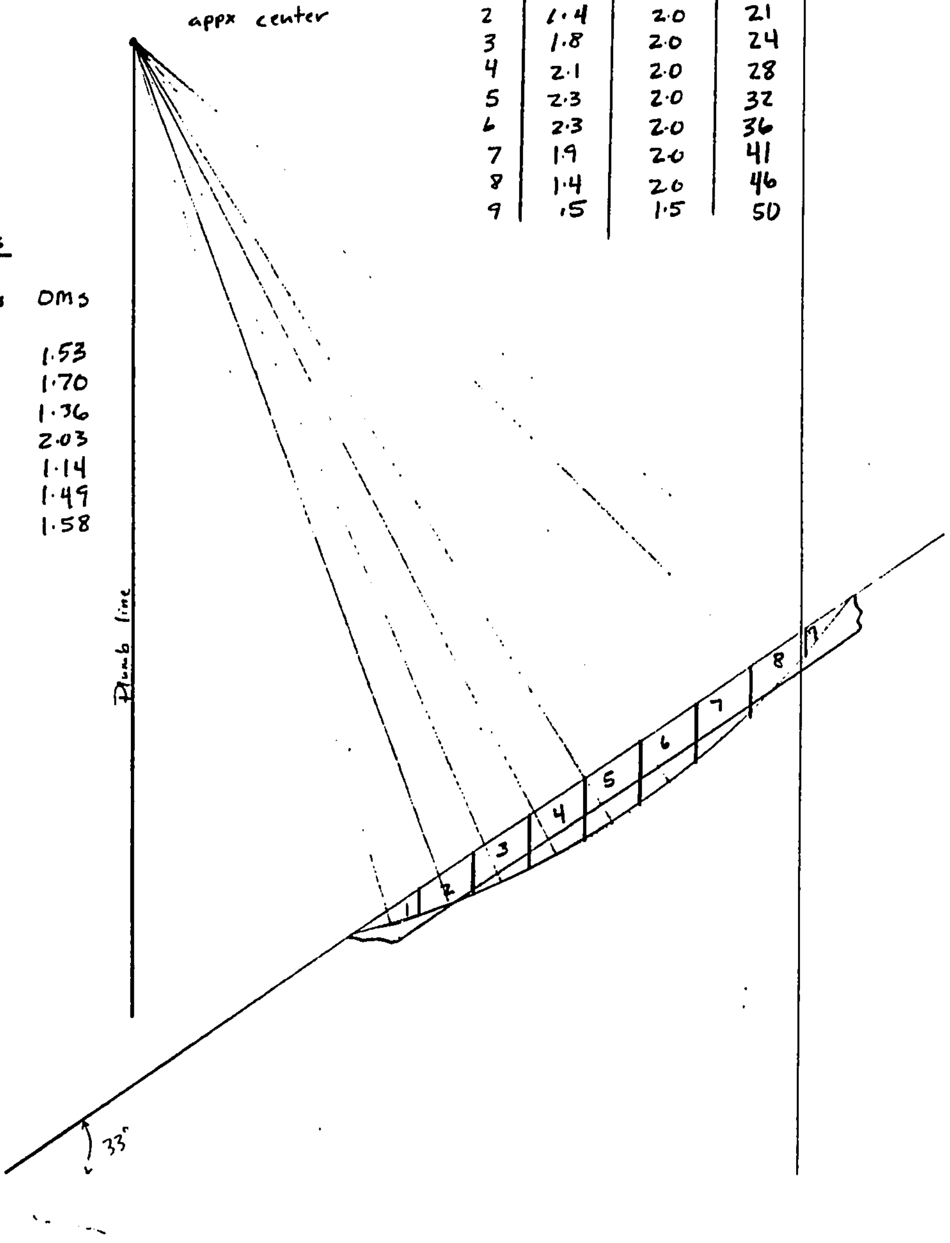
$\phi^+ = 1.3\, \phi_{ave} = 45.5^\circ \Rightarrow FS_{\phi^+} = 1.86$
$\phi^- = .7\, \phi_{ave} = 24.5^\circ \Rightarrow FS_{\phi^-} = .99$

$\gamma^+ = 1.1\, \gamma_{ave} = 18.7 \Rightarrow FS_{\gamma^+} = 1.34$
$\gamma^- = .9\, \gamma_{ave} = 15.3 \Rightarrow FS_{\gamma^-} = 1.40$

For T.W. Cundy	Qual Exam	Doug Chandler

Circular failure surface approximation for failure surface # 1

Slice	mid height	width	θ_i
1	.5	2.3	17
2	1.4	2.0	21
3	1.8	2.0	24
4	2.1	2.0	28
5	2.3	2.0	32
6	2.3	2.0	36
7	1.9	2.0	41
8	1.4	2.0	46
9	.5	1.5	50



results

		Bishops	OMS
	Ave.	1.56	1.53
c: 7	c^+	1.73	1.70
c: 3	c^-	1.39	1.36
θ: 45.5	θ^+	2.08	2.03
θ: 24.5	θ^-	1.16	1.14
18.7	γ^+	1.52	1.49
15.3	γ^-	1.61	1.58

```
DOUG CHANDLER                 QUAL EXAM FOR C.E. CONST
7-10-86
BISHOPS AND ORDINARY METHODS OF SLICES

                                              ave

         NUMBER OF SLICES =          9
                 COHESION =          5 KN/SQ.M
           FRICTION ANGLE =         35 DEGREES       =          0.61
              UNIT WIEGHT =         17 KN/CU.M

TRIAL 1   FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.56 (for Bishops method)

 SLICE #  HEIGHT     WIDTH     VOLUME    WEIGHT      THETA     THETA
           (M)        (M)      (CU M)     (KN)       (DEG)     (RADS)

     1     0.50       2.30      1.15      19.55        17       0.30
     2     1.40       2.00      2.80      47.60        21       0.37
     3     1.80       2.00      3.60      61.20        24       0.42
     4     2.10       2.00      4.20      71.40        28       0.49
     5     2.30       2.00      4.60      78.20        32       0.56
     6     2.30       2.00      4.60      78.20        36       0.63
     7     1.90       2.00      3.80      64.60        41       0.72
     8     1.40       2.00      2.80      47.60        46       0.80
     9     0.50       1.50      0.75      12.75        50       0.87


       FACTOR OF SAFETY BY BISHOPS METHOD                          1.55

       FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               1.53
```

```
DOUG CHANDLER                    QUAL EXAM FOR I.S. CLNG)
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES



        NUMBER OF SLICES =           9
                COHESION =           7 KN/SQ.M
          FRICTION ANGLE =          35 DEGREES        =          0.61
             UNIT WIEGHT =          17 KN/CU.M

TRIAL 1  FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.73 (for Bishops method)

 SLICE #  HEIGHT     WIDTH    VOLUME    WEIGHT     THETA    THETA
            M)        (M)     (CU M)     (KN)      (DEG)    (RADS)

      1     0.50      2.30      1.15     19.55        17      0.30
      2     1.40      2.00      2.80     47.60        21      0.37
      3     1.80      2.00      3.60     61.20        24      0.42
      4     2.10      2.00      4.20     71.40        28      0.49
      5     2.30      2.00      4.60     78.20        32      0.56
      6     2.30      2.00      4.60     78.20        36      0.63
      7     1.90      2.00      3.80     64.60        41      0.72
      8     1.40      2.00      2.80     47.60        46      0.80
      9     0.50      1.50      0.75     12.75        50      0.87


      FACTOR OF SAFETY BY BISHOPS METHOD                       1.73

      FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES            1.70
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          9
               COHESION =           5 KN/Sq.M
         FRICTION ANGLE =        45.5 DEGREES        =          0.79
            UNIT WIEGHT =          17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       2.08 (for bishops method)

 SLICE #  HEIGHT       WIDTH     VOLUME     WEIGHT      THETA     THETA
            (M)         (M)      (CU M)      (KN)       (DEG)     (RADS)

       1      0.50       2.30       1.15      19.55          17       0.30
       2      1.40       2.00       2.80      47.60          21       0.37
       3      1.80       2.00       3.60      61.20          24       0.42
       4      2.10       2.00       4.20      71.40          28       0.49
       5      2.30       2.00       4.60      78.20          32       0.56
       6      2.30       2.00       4.60      78.20          36       0.63
       7      1.90       2.00       3.80      64.60          41       0.72
       8      1.40       2.00       2.80      47.60          46       0.80
       9      0.50       1.50       0.75      12.75          50       0.87


        FACTOR OF SAFETY BY BISHOPS METHOD                            2.08

        FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES                 2.03
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. LUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =           9
                COHESION =           5 kN/Sq.M
          FRICTION ANGLE =        24.5 DEGREES        =          0.43
             UNIT WIEGHT =          17 kN/Cu.M

TRIAL 1  FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.16 (for Bishops method)

 SLICE #  HEIGHT      WIDTH     VOLUME     WEIGHT      THETA      THETA
            (M)        (M)      (CU M)      (kN)       (DEG)      (RADS)

       1    0.50       2.30       1.15      19.55         17       0.30
       2    1.40       2.00       2.80      47.60         21       0.37
       3    1.80       2.00       3.60      61.20         24       0.42
       4    2.10       2.00       4.20      71.40         28       0.49
       5    2.30       2.00       4.60      78.20         32       0.56
       6    2.30       2.00       4.60      78.20         36       0.63
       7    1.90       2.00       3.80      64.60         41       0.72
       8    1.40       2.00       2.80      47.60         46       0.80
       9    0.50       1.50       0.75      12.75         50       0.87


        FACTOR OF SAFETY BY BISHOPS METHOD                          1.16

        FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               1.14
```

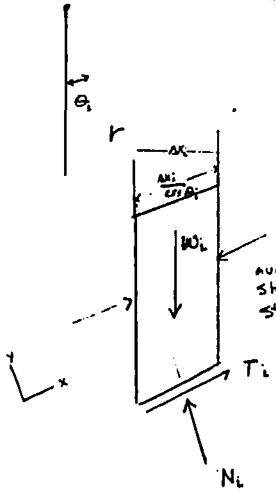
```
DOUG CHANDLER                QUAL EXAM FOR T.S. COND)
7-10-82
BISHOPS AND ORDINARY METHODS OF SLICES


         NUMBER OF SLICES =         9
                 COHESION =         5 KN/Sq.M
           FRICTION ANGLE =        35 DEGREES       =          0.61
              UNIT WIEGHT =      18.7 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.52 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)    (RADS)

      1     0.50       2.30      1.15     21.51         17      0.30
      2     1.40       2.00      2.80     52.36         21      0.37
      3     1.80       2.00      3.60     67.32         24      0.42
      4     2.10       2.00      4.20     78.54         28      0.44
      5     2.30       2.00      4.60     86.02         32      0.56
      6     2.30       2.00      4.60     86.02         36      0.63
      7     1.90       2.00      3.80     71.06         41      0.72
      8     1.40       2.00      2.80     52.36         46      0.80
      9     0.50       1.50      0.75     14.03         50      0.87


          FACTOR OF SAFETY BY BISHOPS METHOD                  1.52

          FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES       1.49
```

```
DOUG CHANDLER                QUAL EXAM FOR T.S. CUNDY
7-10-89
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          9
                COHESION =          5 KN/Sq.M
          FRICTION ANGLE =         35 DEGREES        =          0.61
             UNIT WIEGHT =       15.3 KN Cu.M

TRIAL 1  FAILURE SURFACE # 1. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.61 (for Bishops method)

 SLICE #  HEIGHT      WIDTH     VOLUME     WEIGHT       THETA      THETA
           (M)         (M)      (CU M)      (KN)        (DEG)     (RADS)

       1    0.50        2.30       1.15      17.60         17       0.30
       2    1.40        2.00       2.80      42.64         21       0.37
       3    1.80        2.00       3.60      55.08         24       0.42
       4    2.10        2.00       4.20      64.26         28       0.49
       5    2.30        2.00       4.60      70.38         32       0.56
       6    2.30        2.00       4.60      70.38         36       0.63
       7    1.90        2.00       3.80      58.14         41       0.72
       8    1.40        2.00       2.80      42.84         46       0.80
       9    0.50        1.50       0.75      11.48         50       0.87


        FACTOR OF SAFETY BY BISHOPS METHOD                          1.61

        FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               1.58
```

For T.S. Cundy	Qual Exam	Doug Chandler	5.

Failure surface #2

Ordinary method of slices – assumes the resultant of the side forces acts parrallel to the base of the slice
– doesn't satisfy force or moment equilibrium, but is one of the most conservative methods



$\Sigma F_y = 0$

$N_i = W_i \cos\theta_i$

available shear strength $\} \rightarrow T_{i_{avail}} = W_i \cos\theta_i \tan\phi + c\left(\frac{\Delta x_i}{\cos\theta_i}\right)$

$\Sigma F_x = 0$ for entire mass ⇒ side forces cancel

$T_{i_{applied}} = W_i \sin\theta_i$

$$FS = \frac{\text{avail. s.s.}}{\text{applied s.s.}} = \frac{\Sigma W_i \cos\theta_i \tan\phi + c\left(\frac{\Delta x_i}{\cos\theta_i}\right)}{\Sigma W_i \sin\theta_i}$$

I made a spread sheet to solve by both of these methods, see attached sheets for results of spread sheet calc. As expected, the OMS is slightly more conservative.

Bishops & OMS.

Vary the parameter for Both methods same as was done for infinite slope.

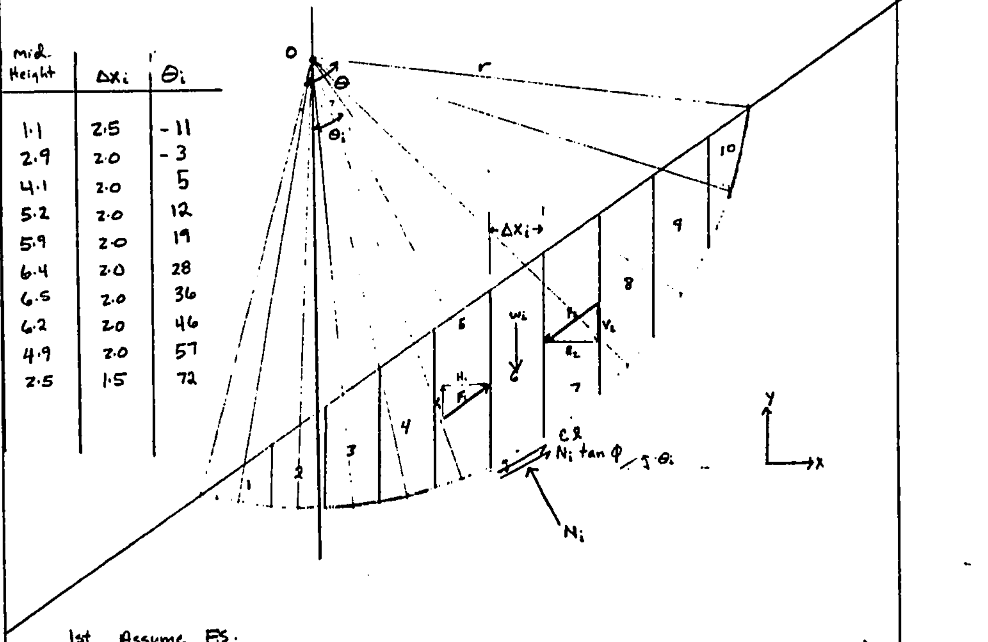
$C_{ave} = 5\ \text{kN/m}^2$ $C^+ = 8$, $C^- = 3$
$\phi_{ave} = 35°$ $\phi^+ = 45.5$, $\phi^- = 24.5$
$\gamma_{ave} = 17\ \text{kN/m}^3$ $\gamma^+ = 18.7°$, $\gamma^- = 15.3°$

see computer printouts & summary sheet for results

Failure Surface #2 -

Modified Bishops method - assumes the resultant of the side forces on each slice is horizontal (no vert. component)
- satisfies vertical & moment equilibrium

Slice	mid. Height	Δx_i	θ_i
1	1.1	2.5	-11
2	2.9	2.0	-3
3	4.1	2.0	5
4	5.2	2.0	12
5	5.9	2.0	19
6	6.4	2.0	28
7	6.5	2.0	36
8	6.2	2.0	46
9	4.9	2.0	57
10	2.5	1.5	72



1st Assume FS.
2nd on ea. slice, solve for N_i by $\Sigma F_y = 0 \Rightarrow$ (eq. 24.11 Lamb & Whitman)

$$N_i = \frac{W_i - u_i \Delta x_i - \left(c/FS\right) \Delta x_i \tan \theta_i}{\cos \theta_i \left[1 + \left(\frac{\tan \theta_i \tan \phi}{FS} \right) \right.} \Rightarrow \text{see spread sheet}$$

3rd Sum moment about O, solve for $FS_{mom} = \frac{M \text{ resist Avail}}{M \text{ actuating}}$

$$FS_{mom} = \frac{r \sum_{i=1}^{n} c_i \Delta l + r \sum_{i=1}^{n} \bar{N}_i \tan \phi}{\sum \bar{x} w} = \frac{\cancel{r} \sum c_i \frac{\Delta x}{\cos \theta} + \cancel{r} \sum N_i \tan \phi}{\sum \cancel{r}_i \sin \theta_i w}$$

Trial & Error until $FS_{assumed} = FS_{mom}$.

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. COND.
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES

                                          ave.

        NUMBER OF SLICES =         10
                COHESION =          5 KN/Sq.M
          FRICTION ANGLE =         35 DEGREES        =         0.61
             UNIT WIEGHT =         17 KN Cu.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY.
ASSUMED FACTOR OF SAFETY =      1.74 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)     (RADS)

      1     1.10       2.50      2.75     46.75        -11     -0.19
      2     2.90       2.00      5.80     98.60         -3     -0.05
      3     4.10       2.00      8.20    139.40          5      0.09
      4     5.20       2.00     10.40    176.80         12      0.21
      5     5.90       2.00     11.80    200.60         19      0.33
      6     6.40       2.00     12.80    217.60         28      0.49
      7     6.50       2.00     13.00    221.00         36      0.63
      8     6.20       2.00     12.40    210.80         46      0.80
      9     4.90       2.00      9.80    166.60         57      0.99
     10     2.50       1.50      3.75     63.75         72      1.26


          FACTOR OF SAFETY BY BISHOPS METHOD                    1.74

          FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES         1.50
```

```
DOUG CHANDLER                    QUAL EXAM FOR T.S. COND)
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


       NUMBER OF SLICES =           10
               COHESION =            8 KN/Sq.M
         FRICTION ANGLE =           35 DEGREES       =          0.61
            UNIT WIEGHT =           17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.85 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)     (RADS)

     1      1.10       2.50      2.75     46.75        -11     -0.19
     2      2.90       2.00      5.80     98.60         -3     -0.05
     3      4.10       2.00      8.20    139.40          5      0.09
     4      5.20       2.00     10.40    176.80         12      0.21
     5      5.90       2.00     11.80    200.60         19      0.33
     6      6.40       2.00     12.80    217.60         28      0.49
     7      6.50       2.00     13.00    221.00         36      0.63
     8      6.20       2.00     12.40    210.80         46      0.80
     9      4.90       2.00      9.80    166.60         57      0.99
    10      2.50       1.50      3.75     63.75         72      1.26


      FACTOR OF SAFETY BY BISHOPS METHOD                         1.85

      FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES              1.62
```

```
DOUG CHANDLER                    QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =         10
                COHESION =          3 KN/SQ.M
          FRICTION ANGLE =         35 DEGREES        =          0.61
             UNIT WIEGHT =         17 KN/CU.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.65 (for bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)     (RADS)

      1     1.10       2.50      2.75     46.75        -11     -0.19
      2     2.90       2.00      5.80     98.60         -3     -0.05
      3     4.10       2.00      8.20    139.40          5      0.09
      4     5.20       2.00     10.40    176.80         12      0.21
      5     5.90       2.00     11.80    200.60         19      0.33
      6     6.40       2.00     12.80    217.60         28      0.49
      7     6.50       2.00     13.00    221.00         36      0.63
      8     6.20       2.00     12.40    210.80         46      0.80
      9     4.90       2.00      9.80    166.60         57      0.99
     10     2.50       1.50      3.75     63.75         72      1.26


       FACTOR OF SAFETY BY BISHOPS METHOD                           1.66

       FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES                1.42
```

```
DOUG CHANDLER                QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          10
                COHESION =           5 KN/SQ.M
          FRICTION ANGLE =        45.5 DEGREES        =           0.79
             UNIT WIEGHT =          17 KN/CU.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =        2.44 (for Bishops method)

 SLICE #  HEIGHT      WIDTH     VOLUME    WEIGHT       THETA     THETA
            (M)        (M)      (CU M)     (KN)        (DEG)     (RADS)

       1     1.10       2.50       2.75     46.75        -11     -0.19
       2     2.90       2.00       5.80     98.60         -3     -0.05
       3     4.10       2.00       8.20    139.40          5      0.09
       4     5.20       2.00      10.40    176.80         12      0.21
       5     5.90       2.00      11.80    200.60         19      0.33
       6     6.40       2.00      12.80    217.60         28      0.49
       7     6.50       2.00      13.00    221.00         36      0.63
       8     6.20       2.00      12.40    210.80         46      0.80
       9     4.90       2.00       9.80    166.60         57      0.99
      10     2.50       1.50       3.75     63.75         72      1.26


         FACTOR OF SAFETY BY BISHOPS METHOD                          2.44

         FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               2.09
```

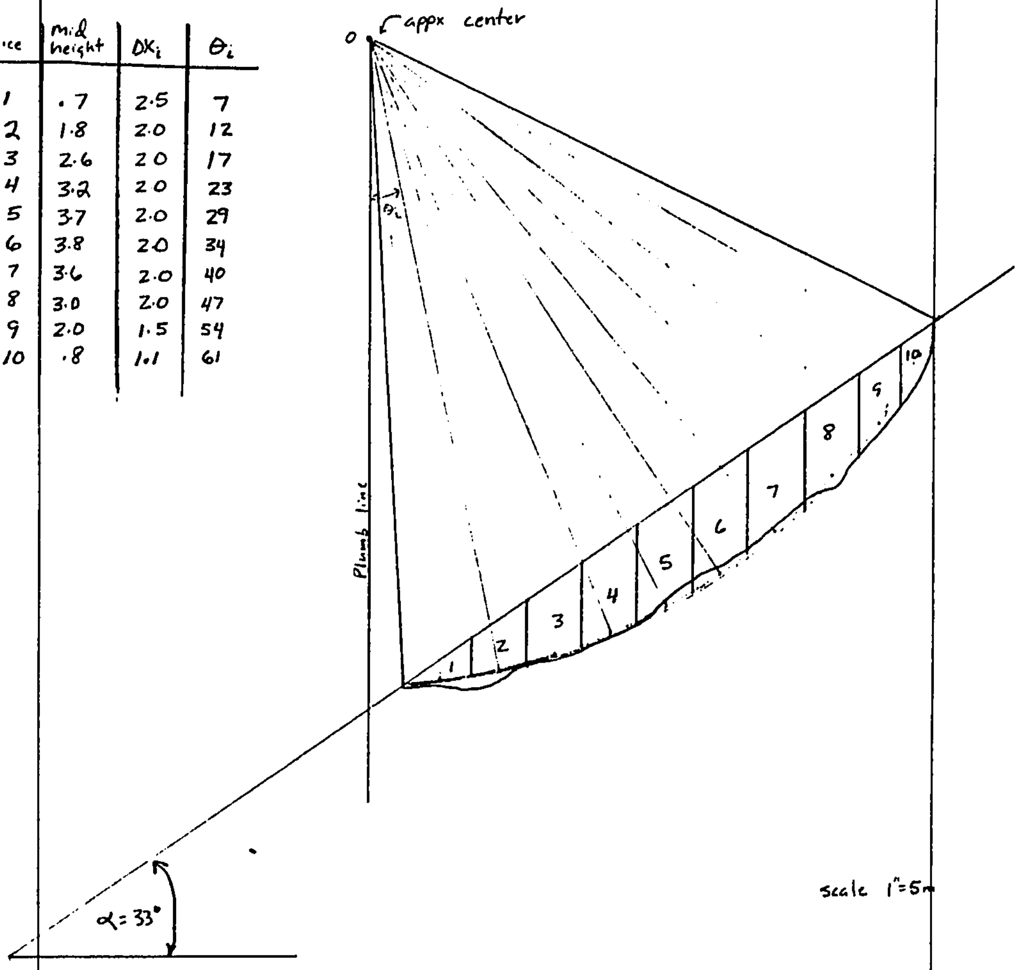
```
DOUG CHANDLER                 QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =        10
                COHESION =         5 KN/Sq.M
          FRICTION ANGLE =      24.5 DEGREES        =          0.43
            UNIT WIEGHT =        17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.2 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)    (CU M)     (KN)       (DEG)    (RADS)

      1      1.10       2.50      2.75     46.75        -11     -0.19
      2      2.90       2.00      5.80     98.60         -3     -0.05
      3      4.10       2.00      8.20    139.40          5      0.09
      4      5.20       2.00     10.40    176.80         12      0.21
      5      5.90       2.00     11.80    200.60         19      0.33
      6      6.40       2.00     12.80    217.60         28      0.49
      7      6.50       2.00     13.00    221.00         36      0.63
      8      6.20       2.00     12.40    210.80         46      0.80
      9      4.90       2.00      9.80    166.60         57      0.99
     10      2.50       1.50      3.75     63.75         72      1.26


      FACTOR OF SAFETY BY BISHOPS METHOD                          1.20

      FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               1.04
```

```
DOUG CHANDLER                QUAL EXAM FOR T.S. CUND.
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =        10
                COHESION =         5 KN/Sq.M
          FRICTION ANGLE =        35 DEGREES        =          0.61
             UNIT WIEGHT =      18.7 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.72 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)     (RADS)

      1     1.10       2.50      2.75     51.43        -11     -0.19
      2     2.90       2.00      5.80    108.46         -3     -0.05
      3     4.10       2.00      8.20    153.34          5      0.09
      4     5.20       2.00     10.40    194.48         12      0.21
      5     5.60       2.00     11.20    209.44         19      0.33
      6     6.40       2.00     12.80    239.36         28      0.49
      7     6.50       2.00     13.00    243.10         36      0.63
      8     6.20       2.00     12.40    231.88         46      0.80
      9     4.90       2.00      9.80    183.26         57      0.99
     10     2.50       1.50      3.75     70.13         72      1.26


      FACTOR OF SAFETY BY BISHOPS METHOD                         1.72

      FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES              1.48
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. LUND
7-10-89
BISHOPS AND ORDINARY METHODS OF SLICES


          NUMBER OF SLICES =        10
                  COHESION =         5 KN/Sq.M
            FRICTION ANGLE =        35 DEGREES       =          0.61
               UNIT WIEGHT =      15.3 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 2. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.76 (for Bishops method)

 SLICE #  HEIGHT     WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)       (M)     (CU M)     (KN)       (DEG)     (RADS)

      1     1.10      2.50      2.75     42.08        -11     -0.19
      2     2.90      2.00      5.80     88.74         -3     -0.05
      3     4.10      2.00      8.20    125.46          5      0.09
      4     5.20      2.00     10.40    159.12         12      0.21
      5     5.90      2.00     11.80    180.54         19      0.33
      6     6.40      2.00     12.80    195.84         28      0.49
      7     6.50      2.00     13.00    198.90         36      0.63
      8     6.20      2.00     12.40    189.72         46      0.80
      9     4.90      2.00      9.80    149.94         57      0.99
     10     2.50      1.50      3.75     57.38         72      1.26


          FACTOR OF SAFETY BY BISHOPS METHOD                    1.76

          FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES         1.52
```

Failure Surface #3 - circular slope failure approximation

Slice	mid height	DX_i	θ_i
1	.7	2.5	7
2	1.8	2.0	12
3	2.6	2.0	17
4	3.2	2.0	23
5	3.7	2.0	29
6	3.8	2.0	34
7	3.6	2.0	40
8	3.0	2.0	47
9	2.0	1.5	54
10	.8	1.1	61



```
DOUG CHANDLER                    QUAL EXAM FOR T.S. CUNDY
7-10-86
BISHOPS AND ORDINARY METHODS OF SLICES

                                            ave.

          NUMBER OF SLICES =          10
                  COHESION =           5 kN/Sq.M
            FRICTION ANGLE =          35 DEGREES         =          0.61
               UNIT WIEGHT =          17 kN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOF OF SAFETY
ASSUMED FACTOR OF SAFETY =        1.5 (for Bishops method)

 SLICE #  HEIGHT      WIDTH     VOLUME    WEIGHT      THETA    THETA
            (M)        (M)      (CU M)     (kN)       (DEG)    (RADS)

      1     0.70       2.50      1.75      29.75          7      0.12
      2     1.80       2.00      3.60      61.20         12      0.21
      3     2.60       2.00      5.20      88.40         17      0.30
      4     3.20       2.00      6.40     108.80         23      0.40
      5     3.70       2.00      7.40     125.80         29      0.51
      6     3.80       2.00      7.60     129.20         34      0.59
      7     3.60       2.00      7.20     122.40         40      0.70
      8     3.00       2.00      6.00     102.00         47      0.82
      9     2.00       1.50      3.00      51.00         54      0.94
     10     0.80       1.10      0.88      14.96         61      1.06


          FACTOR OF SAFETY BY BISHOPS METHOD                      1.50

          FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES           1.42
```

```
DOUG CHANDLER                   QUAL EXAM FOR T.S. CUND:
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          10
                COHESION =           9 KN/Sq.M
          FRICTION ANGLE =          35 DEGREES        =          0.61
             UNIT WIEGHT =          17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.67 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)    (RADS)

      1      0.70       2.50      1.75     29.75          7      0.12
      2      1.80       2.00      3.60     61.20         12      0.21
      3      2.60       2.00      5.20     88.40         17      0.30
      4      3.20       2.00      6.40    108.80         23      0.40
      5      3.70       2.00      7.40    125.80         29      0.51
      6      3.80       2.00      7.60    129.20         34      0.59
      7      3.60       2.00      7.20    122.40         40      0.70
      8      3.00       2.00      6.00    102.00         47      0.82
      9      2.00       1.50      3.00     51.00         54      0.94
     10      0.80       1.10      0.88     14.96         61      1.06


         FACTOR OF SAFETY BY BISHOPS METHOD                       1.67

         FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES            1.59
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          10
                COHESION =           3 KN/Sq.M
          FRICTION ANGLE =          35 DEGREES        =         0.61
             UNIT WIEGHT =          17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.39 (for bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)        (M)     (CU M)     (KN)       (DEG)     (RADS)

       1     0.70      2.50      1.75     29.75          7      0.12
       2     1.80      2.00      3.60     61.20         12      0.21
       3     2.60      2.00      5.20     88.40         17      0.30
       4     3.20      2.00      6.40    108.80         23      0.40
       5     3.70      2.00      7.40    125.80         29      0.51
       6     3.80      2.00      7.60    129.20         34      0.59
       7     3.60      2.00      7.20    122.40         40      0.70
       8     3.00      2.00      6.00    102.00         47      0.82
       9     2.00      1.50      3.00     51.00         54      0.94
      10     0.80      1.10      0.88     14.96         61      1.06


       FACTOR OF SAFETY BY BISHOPS METHOD                       1.39

       FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES            1.31
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. COND.
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          10
                COHESION =           5 kN/Sq.M
          FRICTION ANGLE =        45.5 DEGREES        =          0.79
             UNIT WIEGHT =          17 kN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      2.06 (for Bishops method)

 SLICE #  HEIGHT     WIDTH    VOLUME    WEIGHT      THETA     THETA
            (M)       (M)    (CU M)     (KN)       (DEG)    (RADS)

      1     0.70      2.50      1.75     29.75          7      0.12
      2     1.60      2.00      3.20     51.20         12      0.21
      3     2.60      2.00      5.20     88.40         17      0.30
      4     3.20      2.00      6.40    108.80         23      0.40
      5     3.70      2.00      7.40    125.80         29      0.51
      6     3.80      2.00      7.60    129.20         34      0.59
      7     3.60      2.00      7.20    122.40         40      0.70
      8     3.00      2.00      6.00    102.00         47      0.82
      9     2.00      1.50      3.00     51.00         54      0.94
     10     0.80      1.10      0.88     14.96         61      1.06


         FACTOR OF SAFETY BY BISHOPS METHOD                      2.06

         FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES           1.93
```

```
DOUG CHANDLER                    QUAL EXAM FOR T.S. CUNDY
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =        10
                COHESION =         5 KN/Sq.M
          FRICTION ANGLE =      24.5 DEGREES        =          0.43
             UNIT WIEGHT =        17 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =      1.07 (for Bishops method)

 SLICE #  HEIGHT      WIDTH    VOLUME    WEIGHT       THETA     THETA
            (M)        (M)     (CU M)     (KN)        (DEG)    (RADS)

      1     0.70      2.50      1.75     29.75           7      0.12
      2     1.80      2.00      3.60     61.20          12      0.21
      3     2.60      2.00      5.20     88.40          17      0.30
      4     3.20      2.00      6.40    108.80          23      0.40
      5     3.70      2.00      7.40    125.80          29      0.51
      6     3.80      2.00      7.60    129.20          34      0.59
      7     3.60      2.00      7.20    122.40          40      0.70
      8     3.00      2.00      6.00    102.00          47      0.82
      9     2.00      1.50      3.00     51.00          54      0.94
     10     0.80      1.10      0.88     14.96          61      1.06


        FACTOR OF SAFETY BY BISHOPS METHOD                      1.07

        FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES           1.02
```

```
DOUG CHANDLER                   QUAL EXAM FOR T.E. COND.
7-10-88
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =          10
                COHESION =           5 KN.Sq.M
          FRICTION ANGLE =          35 DEGREES        =          0.61
             UNIT WIEGHT =        18.7 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. ARE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =        1.45 (for Bishops method)

 SLICE #  HEIGHT       WIDTH     VOLUME     WEIGHT       THETA      THETA
            (M)         (M)      (CU M)      (KN)        (DEG)     (RADS)

      1     0.70        2.50       1.75      32.73           7       0.12
      2     1.80        2.00       3.60      67.32          12       0.21
      3     2.60        2.00       5.20      97.24          17       0.30
      4     3.20        2.00       6.40     119.68          23       0.40
      5     3.70        2.00       7.40     138.38          29       0.51
      6     3.80        2.00       7.60     142.12          34       0.59
      7     3.60        2.00       7.20     134.64          40       0.70
      8     3.00        2.00       6.00     112.20          47       0.82
      9     2.00        1.50       3.00      56.10          54       0.94
     10     0.80        1.10       0.88      16.46          61       1.06


      FACTOR OF SAFETY BY BISHOPS METHOD                           1.48

      FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES                1.39
```

```
DOUG CHANDLER                  QUAL EXAM FOR T.S. LUND)
7-10-86
BISHOPS AND ORDINARY METHODS OF SLICES


        NUMBER OF SLICES =         10
                COHESION =          5 KN/Sq.M
          FRICTION ANGLE =         35 DEGREES        =          0.61
             UNIT WIEGHT =       15.3 KN/Cu.M

TRIAL 1  FAILURE SURFACE # 3. AVE FACTOR OF SAFETY
ASSUMED FACTOR OF SAFETY =       1.53 (for Bishops method)

 SLICE #  HEIGHT      WIDTH     VOLUME     WEIGHT       THETA      THETA
            (M)        (M)      (CU M)      (KN)        (DEG)     (RADS)

       1     0.70       2.50       1.75      26.78           7       0.12
       2     1.80       2.00       3.60      55.08          12       0.21
       3     2.60       2.00       5.20      79.56          17       0.30
       4     3.20       2.00       6.40      97.92          23       0.40
       5     3.70       2.00       7.40     113.22          29       0.51
       6     3.80       2.00       7.60     116.28          34       0.59
       7     3.60       2.00       7.20     110.16          40       0.70
       8     3.00       2.00       6.00      91.80          47       0.82
       9     2.00       1.50       3.00      45.90          54       0.94
      10     0.80       1.10       0.88      13.46          61       1.06


        FACTOR OF SAFETY BY BISHOPS METHOD                          1.53

        FACTOR OF SAFETY BY ORDINARY METHOD OF SLICES               1.45
```

VITA

DOUGLAS SCOTT CHANDLER

Biographical Sketch

I was born on September 24, 1959 in Portland, Oregon. My family moved shortly thereafter to Bozeman, Montana, where my parents still live. After recieving a BSCE in 1982 and an MSCE in 1985 from Montana State University, I moved to Billings, Montana where I worked as a geotechnical engineer. I applied and was accepted to the PhD program in the Civil Engineering Department at the University of Washington in the spring of 1987. I was married to Sonja in July of 1987, and we moved shortly afterward to Bainbridge Island.

The first year in Washington, I attended school full-time under a Valle Scholarship. I worked for Shannon & Wilson, Inc. (geo-science consultants) from June of 1988 until October, 1991 while continuing my work towards a PhD. Sonja worked as a Junior High math and science teacher in Port Orchard, Washington until our first child, Alex, was born on April 1, 1991. We moved back to Bozeman, Montana in November, 1991, where I presently work for HKM Associates as a consulting geotechnical engineer.

Committee Members and Program

The appointment of a supervisory committee was completed in December, 1988. The supervisory committee consists of the faculty members:

J.E. Colcord	CETS program	Chairman
T.W. Cundy	Forest Resources	
S.A. Veress	CETS program	
J.B. Adams	Geology	Graduate Faculty Representative

My general examination was completed on July 12, 1990 and I was accepted as a Candidate in Philosophy by the Graduate School on August 17, 1990.

Summary of Course Work

My course work has included: all of the graduate level geotechnical courses offered in the CESM program; a variety of photogrammetry, engineering measurements, remote sensing, soil improvement, and individual study from the CETS program; a hazardous waste class from the CEWA program; forest hillslope stability courses from the Forestry Department; geological remote sensing and image interpretation courses from the Geology Department; a geographic information class from the Geography Department; and a Reading German class from the Germanics Department. A reading knowledge of the german language was demonstrated to Committee member S.A. Veress by translating a technical article from a German surveying publication.