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SLOPE MORPHOLOGY MODEL DERIVED FROM DIGITAL ELEVATION DATA

In the Pacific Northwest, hillslope gradient and form (e.g. concave, convex, planar) play primary roles in governing the presence and behavior of landslides. Other physical factors such as hydrologic conditions, soil properties, bedrock geology, and land-use practices also dictate the frequency and timing of landslides. The initiation point of most such occurrences, however, may be predicted solely on the basis of slope morphology. Debris avalanches (e.g. shallow, rapid landslides, excluding those triggered by roads) often occur on steep ground, particularly in concave topography which forms a collection point for water, soils, and debris. These materials become destabilized when the forces promoting mass movement (e.g. gravity, soil saturation) overcome those resisting motion (e.g. soil shear strength). Therefore, slope gradient and form can be used as tools for locating potential sites of debris avalanches. This information is especially useful for land managers who do not have access to field inventories of mass-wasting sites.

We have developed a slope morphology model for use in land management, by combining this understanding of geomorphic processes with GIS methods for analyzing surface topography. This model is intended as a flagging tool, to be used in conjunction with field information, for making management decisions regarding protection of unstable slopes. The advantage of this model is that it relies on information currently available on the GTS system. Digital elevation data are analyzed using a modified version of the curvature tool found in the ArcInfo/GRID package. Slope-form classes derived from this analysis are assigned failure potentials based on known landslide criteria for specific geomorphic units. These criteria are set from available site-specific information and extrapolated to other parts of the region in which little or no data exist. The model may be applied generally across a geologic province in which precipitation regimes and soil properties are similar; separate model runs must be made for discrete geologic provinces. With the use of various look-up tables, the model can be more closely tailored to areas with unique topology. Model output

comprises maps in which 900 m^2 pixels (i.e. the resolution scale of the DEM data) are color-coded to degrees of failure potential. We have mapped the western portion of Washington and currently are developing GIS coverages for the state east of the Cascade Range.

INTRODUCTION

Land managers in the Pacific Northwest often have few databases available with which to evaluate landslide potential. Information on site characteristics and failure behavior typically is confined to small geographic areas or landslide sites in which case studies, mass-wasting inventories, geomorphic research, or theoretical stability analyses have been performed. In recent years, state forest-practices regulators (e.g., Washington Forest Practices Board, 1994) and private landowners (e.g., Beschta et al., 1992) have initiated watershed analyses for specific landscape units, whereby landslide inventories are compiled with the aid of aerial photographs and field reconnaissance. Watershed analyses, however, generally are conducted on tight schedules and with limited resources (e.g. , incomplete aerial-photo records, sparse soils and geology information), in order to minimize costs and meet regulatory timeframes. Computer models designed to identify landslide potential, therefore, are useful tools because model results can be used as a preliminary screen to locate potentially unstable ground and assist managers and scientists in determining where harvest or restorative efforts should be concentrated. Moreover, model results can be extrapolated to geologically similar areas in which little to no data are available for making management decisions.

The GIS-based model described herein originally was developed in 1993 as a flagging tool for assisting foresters with locating unstable ground in proposed timber sales on state-trusts lands of the western Olympic Peninsula (Hoh Tribe and Washington Department of Natural Resources (DNR), 1993). The scientific’ and technical concepts of this model are not new. For the past several decades, geologists and engineers have recognized the critical role that land topography plays in governing sedimentary and hydrologic processes. Likewise, mathematicians and geophysicists have explored the realm of describing land surfaces with complex numerical equations, in order to simulate and analyze terrain features. The contribution of this paper, therefore, is a practical application of such concepts to the analysis of landslide features, in a format that can be implemented readily by natural-resource scientists and managers.

METHODS

Summary. This computational model analyzes, on the basis of hillslope gradient and form, the susceptibility of terrain to landslide processes. The two required inputs are topographic data and a geomorphic interpretation of landforms prone to erosion by landsliding in the area of concern. Digital elevation model (DEM) data are used, because they constitute the most commonly used and readily available source of topographic data on GIS systems, although the model could equally accommodate other types of digitally formatted data. A modified version of the GRID tool, "curvature", in ArcInfo is employed to analyze slope morphology and failure potential. Modifications to the GRID software are described in this paper.

A slope-morphology matrix is formed by the union of slope gradient and form (i.e., concave, planar, convex). This matrix is based, for a given geomorphic unit, on field determinations of the characteristic hillslope configurations in which natural landslide processes occur. A geomorphic unit is an area in which the earth-surface processes (e.g., landform development, soil generation) and precipitation regimes are relatively uniform. The slope-morphology criteria are set from analyses of landslide behavior in a number of representative sites within a geomorphic unit and then extrapolated to similar units within a geologic province, or regional area with a distinct tectonic (e.g., mountain-building) history. Model output consists of maps in which pixels or cells representing $900 m^2$ on the ground (i.e., the resolution of the DEM data) are differentiated by degree of failure potential.

We first summarize the geologic basis and rationale for this method, and then discuss the GIS tools used by the model. A number of important model assumptions will be addressed, as well as the uses and limitations of applying this analytical method to management of unstable terrain.

Geologic basis and rationale

Several natural factors contribute to the intensity and frequency of landsliding in the Pacific Northwest. They include (e.g., see Sidle et al., 1985): (1) geomorphic factors, such as substrate type, bedrock structure, and slope morphology; (2) soil properties, particularly soil strength and cohesion; (3) hydrologic processes, including plant transpiration, soil saturation, and surface runoff; (4) vegetation composition and root strength; and (5) seismic activity. A principal assumption of this model is that slope morphology (i.e., slope gradient and form) constitutes the dominant driving force promoting episodic, shallow landslides in areas of similar geomorphology , hydrology, and soil genesis within Washington state. Although earthquakes have the potential for triggering catastrophic landslides and rock avalanches, these events have occurred relatively infrequently in the recent past and are hard to address from a land-management perspective. Consequently, seismically induced slope failures are not considered.

The geomorphic community remains divided on the issue of employing slope gradient and form as a simple predictor of slope stability. Independent testing of this theory with field data and historical information in Washington, however, suggests that slope morphology generally can be used to predict the initiation point of certain natural forms of mass wasting (e.g., debris avalanches and flows) in greater than 80% of known cases. Field tests on the western Olympic Peninsula indicate that 90% of all existent shallow-landslide sites can be identified with slope gradient and form criteria. Road-related failures are not treated explicitly by the model, other than those roads built on slopes naturally prone to debris avalanches or shallow landsliding.

The theory relating slope morphology to mass-wasting potential, if applied in a physically sound way to geomorphically similar portions of the landscape, proves advantageous from a land-management perspective. Many state agencies and private landowners currently lack the requisite databases for accurately predicting landslide potential, or have limited resources for collecting the quality and quantity of field information necessary to use theoretical slope-stability models or more sophisticated DEM models. Models, such as those developed by O'Loughlin (1986), Vertessy et al. (1990), and Dietrich et al. (1993), variously require detailed information on soil properties, surface and subsurface flow regimes, and bedrock geology. Hence, basing a preliminary analysis of potential landslide sites on readily available topographic information provides an efficient and cost-effective means for prioritizing further management planning and fieldwork.

The two aspects of slope morphology considered here are slope gradient and form. Gradient has been closely correlated with debris avalanches (i.e., shallow, rapid landsliding) in several geological provinces of the Pacific Northwest (Sidle et al., 1985). The threshold gradient at which mass movement occurs, however, varies with the regional geology, climate, topography, and land-use practices. This variability precludes making too many generalizations; however, it appears from field evidence that many slopes over 47 % (25") in the Pacific Northwest are susceptible to shallow, rapid landsliding. In wet climates, landslides can occur on even gentler slopes. On the western Olympic Peninsula, for example, shallow landslides are triggered on 25 % (14") slopes due to increased soil moisture and corresponding loss of soil strength during the wet winter months (Logan et al., 1991; Hoh Tribe and Wash. DNR, 1993).

Slope form influences mass-wasting processes by governing the distribution of soil water. Slopes that are convex in plan form (e.g., ridges) tend to disperse groundwater, impede the formation of perched water tables, and suppress the development of high water pressures in the pores between soil particles which contributes to slope instability (Sidle et al., 1985). Concave slopes (e.g., tributary valleys), in contrast, tend to develop perched water tables and concentrate groundwater, surface water, sediment, and organic debris. In these slope depressions, the forces promoting mass movement (e.g., gravity, soil pore pressures, material weight) can exceed those resisting movement (e.g., soil shear strength, buoyancy effects of soil pore water). It is, therefore, not a coincidence that the majority of debris avalanches and flows originate in concave slope forms like incised channels and depressions upslope of channel heads. Landslides on steep, concave slopes often recur over a period of centuries as the depressions fill, flush, and refill with sediment and other debris (Dietrich and Dunne, 1978; Swanson and Fredriksen, 1982). Shallow, rapid landslides also occur on planar slopes that exceed the angle of repose for unconsolidated materials (70 % or 35 °).

Table 1 shows a matrix relating slope gradient and form to the potential for shallow, rapid landsliding. The number and distribution of slope-gradient classes (e.g., A through E) are initially set, for a specific geomorphic unit, with the aid of mass-wasting inventories and slope-stability analyses. The matrix is then extrapolated to areas without precise landslide information. Slope-gradient classes and assignments of landslide potential are verified, and modified if necessary, with each new mass-wasting inventory performed in the region. Model matrices have been established for the Olympic Peninsula and portions of the western slopes of the Cascade Range, as well as steeper terrain in southwestern Washington. The mass-wasting potential for slopes in each gradient-form class is represented by a color that is used to identify each DEM cell in the mapping process. Red indicates those slopes most susceptible to shallow, rapid landsliding, yellow denotes moderate susceptibility, and green indicates low susceptibility. Typically, the highest density of landsliding occurs on the least stable slopes.

TABLE 1. Matrix relating slope form and gradient to shallow-landslide potential.

Slope form	Slope gradient (percent)				
	A ,	B	C	D	E
Convex	**green**	**green**	**green**	**green**	**yellow**
Planar	**green**	**green**	**green**	**yellow**	**red**
Concave	**green**	**yellow**	**red**	**red**	**red**

This slope morphology model only addresses the potential for debris avalanches, or shallow landslides. These landslides typically involve the soil mantle and underlying regolith (i.e., materials accumulated from weathering 'and erosion of the bedrock surface), which average less than 10 m. deep. In contrast, earthflows or chronic deep-seated failures occur in thick sequences of soil and regolith, and often are characterized by complex, hummocky topography with multiple failure blocks whose individual length scales are smaller than the width of a DEM cell. This model, thus, is not capable of evaluating the potential for earthflows or deep-seated failures.

GIS methods

The analysis of topographic data, with respect to the slope gradient and form criteria established for each geomorphic unit, was first accomplished with the Arc command VIP. This command was used with, a 100% selection to create a point coverage with one point for every cell of a USGS 7.5-minute DEM lattice. The following values represented a DEM surface: 2 for a local surface maximum, -2 for a minimum, 1 for a convexity or edge point, -1 for a concavity, and **0** for a point with both a local maximum and minimum (e.g., a saddle). These point values were. stored in SFCODE. A grid was then generated around the points, with the same cell size and origin as the original DEM. A polygon topology was created by merging the grid with the points coverage and dissolving the coverage around SFCODE. The resulting coverage represented the computer-generated shape of the surface. A union of the surface shape with its slope created a new coverage in which each cell could be assigned a mass-wasting potential according to the matrix presented in Table 1.

We currently use the "curvature" function in ArcInfo GRID (ESRI, 1992), which provides a somewhat more straightforward and sophisticated method for performing this slope-morphology analysis. This tool calculates the curvature of a surface at each cell center af a USGS 7.5minute DEM lattice, by evaluating slope gradient, aspect, planform curvature, and profile curvature. Slope gradient influences the rate of sediment and water transport across a slope. Aspect defines the slope direction and, therefore, the direction of transport. Planform curvature is measured transverse to the slope direction and influences flow concentration or dispersal. Profile curvature, or the rate of change of slope, governs flow acceleration and deceleration and, thereby, sediment deposition and erosion. The mathematical derivation of curvature used in the ESRI (1992) package is developed in a paper by Zevenbergen and Thome (1987; see their literature review), in which a topographic surface is described by a fourth-order polynomial equation of the form:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I. \qquad (1)$$

The four topographic indices are analyzed with respect to a central point (origin) on a 3x3 matrix of surface cells. The 9 elevations of this matrix are used to calculate parameters A through I in equation 1. Planform curvature is the second derivative of **Z** with respect to D, and profile curvature is the second derivative of Z with respect to E. The curvature of a surface at each DEM cell center is given as the LaPlacian of Z evaluated at the origin, or the divergence of the gradient (i.e., normal vector to a plane tangent to a point on the topographic surface):

$$\text{Curvature} = \nabla^2 Z = 2D + 2E. \qquad (2)$$

See Zeverbergen and Thome (1987) and Moore et al. (1991) for a full derivation of these equations.

The output of the GRID "curvature" function is given as equation 2 in the ESRI package. We found, however, that the software package did not account properly for a mathematical sign change; in addition, slope is calculated as a dimensional term by ESRI (1992), whereas equation 2 is derived analytically from (1) in terms of dimensionless slope. We, therefore, modified the equation in "curvature" to read:

$$\text{Curvature} = -2(D+E)lOO. \qquad (3)$$

The "curvature" function requires one input and two output grids (see discussion in Appendix). The input grid represents a continuous topographic surface, for example, the USGS 7.5minute DEM. The two output grids are the planform and profile curvatures for each cell in the grid. A slope grid, sliced in slope-percent classes as previously -defined (see Table l), is created from the same input grid. A curvature grid is obtained by subtracting the profile grid from the planform grid (i.e., see eqn. 3). A positive curvature at a particular grid cell indicates that the surface is upwardly convex, whereas a negative curvature corresponds to an upwardly concave surface. A curvature value of zero signifies a flat or planar surface. Planform and profile grids at a particular cell have different signs, that is, one is convex and the other concave, in 80% to 90% of all cases. Planform and profile grids in the remaining cases, however, have like signs due to the local landform characteristics (e.g., ridgelines saddles, sinks in flat terrain). Grids, therefore, are added rather than subtracted, to accurately preserve these features in the slope-morphology analysis. The resulting three shape grids are merged to form a corrected curvature grid. This grid is then sliced into three classes (i.e., concave, convex, and planar) according to criteria based on field evaluations of slope morphology in a given geomorphic unit. Nondimensional values are assigned to these criteria, ranging from -4 (highly concave) to 4 (highly convex). The sliced curvature grid can then be added to the sliced slope grid to yield a grid or 3xN matrix, where N represents the number of slope classes selected. In the example given in Table 1, a 3x5 matrix results from this union. Classes of mass-wasting susceptibility are assigned through a remap table, as described in the Appendix.

DISCUSSION

The results of applying this GIS method to the preliminary analysis of slope stability are shown in the examples below. Figure 1 displays the GIS-defined areas of high susceptibility to mass wasting on a shaded relief map of the Willoughby Creek watershed on the western Olympic Peninsula. [Field maps used by foresters and managers in this area would indicate these areas in red, for example as denoted in Table 1.] Areas of highest susceptibility to shallow landsliding in this landscape are the steepest, most concave portions of the slope. Figure 2 shows the locations of shallow landslides as determined by field and aerial-photo analyses in the watershed. Comparison of Figures 1 and 2 demonstrates a high degree of correlation between the computer-defined areas of high mass-wasting potential and the actual, field-verified landslide sites. Furthermore, red pixels not matched with landslide sites in Figure 2 correlate well with unstable ground, as identified by field analyses.

The cells identified in Figure 1 generally correspond to areas of high landslide potential. This does not mean, however, that the entire area of the pixel represents a landslide; unstable ground may be present in all or' only a small fraction of the 900 m^2 area. Hence, pixel size does not accurately reflect the magnitude of the slide-prone area. The latter must be determined from field information or analyses. The output of this slope-morphology model, therefore, does not substitute for on-the-ground slope evaluations. Rather, it should be used as a preliminary screen, supplemented by other sources of information (e.g., geologic and soils maps, aerial photos, and other technical tools of the field analyst).

FIGURE 1. GIS-defined areas of high susceptibility to mass wasting (i.e., shallow landslides) in the 2000-acre Willoughby Creek watershed on the western Olympic Peninsula, Washington.

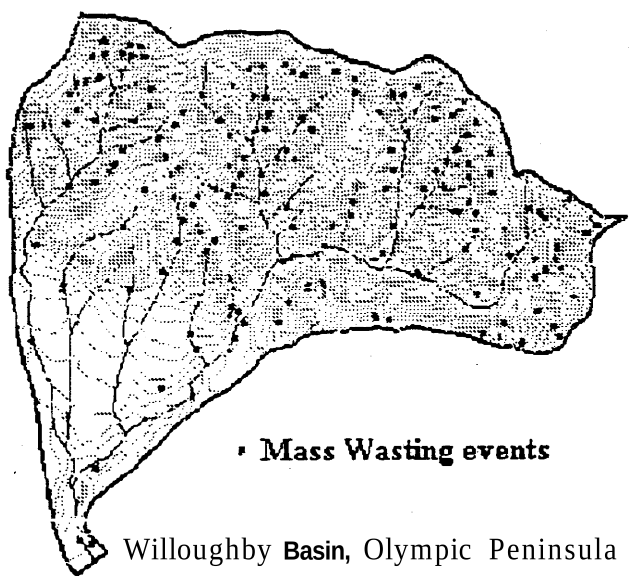

FIGURE 2. Mapped inventory of shallow landslides in the Willoughby Creek watershed, western Olympic Peninsula. The inventory is based on field slope-stability analyses and aerial-photo interpretation. Compare with Figure 1..

As with any predictive model, the output is only as accurate as the input information used to generate or run the model. There are two primary sources of error with this model. The first is the DEM data. The quality of these data vary considerably over some portions of the landscape, leading to anomalous slope gradient and form calculations. Furthermore, the resolution of the data (i.e., 900 m^2 grid cells) precludes analyzing the finest scale features of the landscape, including the exact location of channel heads and the smallest channel orders in low-relief terrain. Also, topographic contours developed from DEM data have not been calibrated across map quadrangle boundaries, resulting in spurious straight lines in the model output. These errors, however, should not unduly influence forest-management practices because model output is only intended as a preliminary guide for planning and fieldwork.

An additional limitation of the model is that it cannot account for artificial slope features that are susceptible to mass wasting, including road fills, quarries, reservoir walls, and stream-crossing structures. These objects rarely are indicated as three-dimensional in the DEM data. Furthermore, the slope-morphology model cannot predict earthflows or deep-seated movement over complex topography.

This model has been used primarily on the Olympic Peninsula and has been tested extensively over the past two years with independently generated mass-wasting inventories and site studies. The Washington DNR currently is conducting field tests throughout the state to determine the range of applicability of the model to areas with diverse land form, climate, topographic, and land-use conditions.

CONCLUSIONS

This paper describes the application of a GIS method for evaluating digital terrain information (e.g., USGS DEM data) to the analysis of landslide potential. A modified version of the "curvature" function in ArcInfo GRID (ESRI, 1992) is used to calculate slope gradient and form (i.e., concave, planar, convex surfaces). This information is merged with a geomorphic interpretation of slope morphologies prone to landslide processes, to yield a map of areas prone to shallow landsliding and debris flows. This method is advantageous for land managers because it only requires information that typically is readily available: (1) topographic data (e.g., DEM), and (2) a knowledge of the mass-wasting characteristics for selected areas within a given geomorphic unit. The latter may be determined from representative mass-wasting inventories of the type normally produced during watershed analysis. The model is intended as a preliminary planning tool only, and a field analysis must be performed to locate actual landslides within the areas of mass-wasting susceptibility identified by the model. Until more sophisticated and accurate models become available in the land-management arena, this simple method allows managers to evaluate the potential costs and physical impacts of land-use activities prior to investing in more detailed analyses and planning efforts.

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APPENDIX

The model program contains the following grid manipulations:

```
1:   crvgrd = curvature( < demgrd > , {progrd} , { plangrd})
2:   slopegrd = slope( < demgrd > , {percentrise})
3:   slpsligrd = slice( < slopegrd > , < table > , < slo_sli.rmt > )
4:   planprogrd = (plangrd - progrd)
5:   concavegrd = con(plangrd lt 0 and progrd lt O,plangrd + progrd)
6:   convexgrd = con(plangrd gt 0 and progrd gt 0, plangrd + progrd)
7:   cavevexgrd = merge(concavegrd,convexgrd,planprogrd)
8:   cavevexgrd 1 = (slice( < cavevexgrd > , < table > , < curvature.rmt > ) +
            slpsligrd)
9:   geogrd = slice( < cavevexgrd 1 > , c table > , < rgy_sli. rmt > )
```

Line 1: The curvature function is used to create three grids. “Crvgrd” is a standard output grid not used in this version of the model; c demgrd > is the input grid representing a continuous surface; {progrd} is the output grid representing the profile curvature; (plangrd} is the output grid representing the planform curvature.

Line 2: “Slopegrd” is created from the same DEM grid as the curvature/shape grids. The {percentrise} option is used to correspond with the slope percent classes identified in Table 1.

Line 3: “Slosligrd” is the result of slicing the slope grid into slope percent classes identified by a geomorphic evaluation of the area of concern (see Table 1). Slicing employs a remap table, for example:

(slo_sli.rmt)

AB:10	/* relatively flat
BC:20	/* low gradient
CD:30	/* moderate gradient
DE:40	/* high gradient
E 00: 50	/* extreme gradient

This produces a grid with 5 gradient classes that can be assigned numbers (e.g., 10,20…50) for use later in the curvature grid.

Line 4: "Planprogrd" is created by subtracting {progrd} from {plangrd}. See text for explanation. For cases where (progrd} and {plangrd} have opposite signs.

Line 5: For cases where {progrd} and {plangrd} have like signs. Concave cells are added together.

Line 6: For cases where (progrd} and {plangrd} have like signs. Convex cells are added together.

Line 7: The three curvature grids are merged to form a corrected curvature grid, “cavevexgrd”.

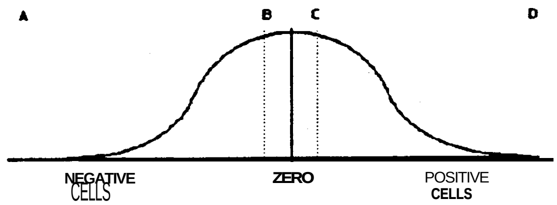
Line 8: “Cavevexgrd” is sliced into three classes (i.e., concave, convex, planar) using a remap table similar to the following:

(curvature.rmt)

-a -b : 1	/* concave surface
-b c : 2	/* planar surface

c d : 3 /* convex surface

The numerical criteria for defining slices must be determined **on the basis of local** knowledge regarding slope form. Very few grid manipulations result in values of zero, and there are few planar slopes. The histogram below illustrates a sample distribution of cell values for the corrected curvature grid:



Line **9: The** sliced "Cavevexgrd" is added to the sliced slope table from above to create a grid with N classes, or a 3xN matrix as shown in Table 1, where N is the number of specified slope-percent classes:

Slope form	**Slope gradient (percent)**				
	A	**B**	**C**	**D**	**E**
(a-b) Convex	**11**	**21**	**31**	**41**	**51**
(b-c) Planar	**12**	**22**	**32**	**42**	**52**
(c-d) Concave	**13**	**23**	**33**	**43**	**53**

The matrix can then be sliced into slope-stability-potential classes with, for example, the following remap table and map color codes:

(rgy_sli.rmt)

```
11 13 : 1      /* green, stable
21 21 : 2      /* yellow, moderately unstable
22 23 : I      /* green, stable
31 31 :3       /* red, highly unstable
32 33 : 1      /* green, stable
41 41 : 3      /* red, highly unstable
42 42 : 2      /* yellow, moderately unstable
43 43 : 1      /* green, stable
51 52 : 3      /* red, highly unstable
53 53 : 2      /* yellow, moderately unstable
```

as shown in Table 1.

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```
&severity &error &ignore
/*&echo &on
/*
/*  +-----------------------------------------------------------------+
/*  |  ***   ***  January 1994, Forks, Washington.  ***   ***   ***   |
/*  | This model developed by Susan Shaw and David Johnson            |
/*  | of the Olympic Region, Department of Natural Resources,         |
/*  | for the purpose of detection of possible instabilities due to   |
/*  | slope, shape and form of the landscape. This is only a tool     |
/*  | to be used for a broad approach to instability detection.       |
/*      |                                                               |
/*      I Rewritten March 1995 to account for the 'incorrectness in signs |
/*      | in the ArcInfo Grid Curvature function and to eliminate the-  |
/*      | loss of important information due to the subtraction of like  |
/*      | signs. For more information contact David Johnson at the DNR  |
/*      | Olympic Region Office, (360)374-6131 or through the internet  |
/*      | at daff490@wadnr.gov
/*  +__-------------------------_--~~~~~~~~~~~~~~~~~~~~~~~~~~----------+
/*
/*
&type GEOSLOPE version 2.0
&type
&type   This program will create a grid of possible slope stability based on
&type   form, shape and slope. The input grid must be a 7.5min. USGS DEM grid
&type   with a cell size of 104.355 ft.... Name to be entered later.
&type   This ratio of x to y to z is critical for the curvature-slice table
&type   to give the correct data return.
&type
&type   This program must be executed within GRID
&type
&s continue := [response '  Would you like to continue? Y/N <Enter=Y>']
&if %continue% = N or %continue% = n &then
 &goto bottom
&else
 &type Your program is being checked
/*
/*    Checking to se if the program is in grid
/*
&s .pro %:program%
&if %.pro% eq GRID &then
 &goto next
&else
 &do
  &type You must execute this program within GRID
  &goto bottom
 &end
/*
/*  Finding the mapextents
/*
&label.next
&type Your mapextent is being checked
&S .xmin [extract 1 [show mapex]]
&S .ymin [extract 2 [show mapex]]
&s .xmax [extract 3 [show mapex]]
&s .ymax [extract 4 [show mapex]]
&s xmaxt -1 * %.xmax%
/*
/*  Checking to se if the mapextents are valid
/*
&if %.xmin% ne %.ymin% ~
 and %.xmin% ne %xmaxt% &then
 &type your mapextent has been analyzed.
&else
```

```
 &do
  &type Your mapextent is not defined, please define it and start again
  &goto bottom
 &end

&s demgrd := [response 'Enter name of DEM grid']          /*
&s geogrd := [response 'Enter name for output grid']      /*   User input
fields
&type The following curvature slice tables are available:
&type cur_Ol.rmt  cur_  02.rmtcur_05.rmt  cur_1_05.rmt  cur l.rmt  cur_2.rmt
cur 5.rmt-
&type cur 1 05.rmt is being recommended by the DNR Geomorphologist Susan Shaw
&s currmt := [response' 'Enter name of slice table']      /*
/*
/*
setwindow %.xmin% %.ymin% %.xmax% %.ymax%           /*   Set Grid window
/*   ----------------------------------------
/*
&type
&type   This program can create a combination grid with many items in the VAT
file.
&type   These items will be Curvature, Slope, and the Geocode for slope
stability.
&type                                   CAUTION!!
&type   This process takes a great deal of time and makes a very large output
grid.
&type

&s comb := [response '  Would you like to create this combination grid? Y/N
<Enter=Y>']
&if %comb% = N or %comb% = n &then
  &type
 &else
  &s comgrd := [response '  Enter output name for combination grid']
&type

&type   Would you like to fill sinks in the input grid?
&s fill := [response |  This will also take additional time! Y/N <Enter=Y>']
/*
/*  To fill or not to fill the sinks
/*
&if %fill% = N or %fill% = n &then
  &do
   /*   Creating the curvature and slope grid
   &sy date
   &type Creating the slope grid...
   slope = slope(%demgrd%,percentrise)
   &type Creating the Profile and the Planform grid.
   crvgrd = curvature(%demgrd%,progrd,plangrd)
   kill crvgrd
  &end
 &else
  &do
   &s sink := [response 'enter the depth of the sinks desired to be filled']
   &sy date
   &type Filling input grid to create the elevation grid...
   fill %demgrd% elevgrd sink %sink%
   &type Creating the slope grid...
   slope = slope(elevgrd,percentrise)
   &type Creating the Profile and the Planform grid...
   crvgrd = curvature(elevgrd,progrd,plangrd)
   kill elevgrd
   kill crvgrd
```

```
  &end

&type Slicing slope grid...
slpsligrd = slice(slope,table,slo_sli.rmt~
/*
&type Creating base curvature grid...
planprogrd = (plangrd - progrd)
/*
/*  reconfiguration  portion
/*
&type Entering reconfiguration portion of program
&type Creating concave only grid...              /*
concavegrd = con(plangrd It 0 and progrd lt 0,plangrd + progrd) /*  Creating
concave and
&type Creating convex only grid....              /*  convex grids
convexgrd = con(plangrd gt 0 and progrd' gt 0,plangrd + progrd)  /*
kill progrd
kill plangrd
&type Merging reconfiguration grids...              /*  Merging curvature
grids
cavevexgrd =  merge(concavegrd,convexgrd,planprogrd)     /*
kill concavegrd
kill convexgrd
kill planprogrd
&type Slicing with curvature remap table...         /*
cavevexgrdl = (slice(cavevexgrd,table,%currmt%)  +  slpsligrd)  /*
kill slpsligrd                            /*  Slicing grids with
%geogrd% = slice(cavevexgrdl,table,rgy_sli.rmt)          /*  various remap
tables
kill cavevexgrdl                          /*
&type Finished with reconfiguration portion          /*
/*
/*  end reconfiguration portion
/*
&if %comb% = N or %comb% = n &then
  &type skipping combination grid
 &else
  &do
   &sy date
   &type     Configuring combination grids
   curvature = cavevexgrd * 100
   geocode = %geogrd%
   &type     Refiguring the elevation grid...
   elevation = %demgrd%
   &type     Creating combination grid with Geocode,  Curvature and Slope
   %comgrd% = combine(geocode,slope,curvature)
   kill geocode
   kill curvature
   kill elevation
  &end
/*
&type Killing un-needed grids
kill cavevexgrd
kill slope
&sy date
/*
gridpaint %geogrd% # # # geoslo.cmf
/*
&label bottom
&return

rgy sli.rmt
11  13  :1    /* green, stable
```

```
21 21 : 2     /*  yellow, caution
22 23 : 1     /*  green, stable
31 31 : 3     /*  red, unstable
32 33 : 1     /*  green, stable
41 41 : 3     /* red, unstable
42 42 : 2     /* yellow, caution
43 43 : 1     /* green, stable
51 52 : 3     /* red, unstable
53 53 : 2     /* yellow, caution

==== cur 5.rmt
-4 -.5 :-1
-.5 .5 : 2
.54:3
===== slo sli.rmt
0 15 : 10       /* relatively flat
15 24 : 20      /* low steepness
24 47 : 30      /* moderate steepness
47 70 : 40      /* very steep
70 9999 : 50 /* extreamly steep
===== cur.2.rmt
-4 -.2 : 1
-.2 .2 : 2
.2 4 : 3
===== cur_1_05.rmt
-9  -.1:1
-.1 .05 : 2
.05 9 : 3
==== cur 1.rmt
-4 -.1 :-1
-.1 .1: 2
.1 4 : 3
==== cur05.rmt
-4 -.05 : 1
-.05 .05: 2
.05 4 : 3
==== cur_02.rmt
-4 -.02 : 1
-.02  .02 : 2
.02 4 ; 3
==== cur_01.rmt
-4 -.01 : 1
-.01 .01: 2
.01 4 : 3
```