LOGISNET: A TOOL FOR MULTIMETHOD, MULTILAYER SLOPE STABILITY ANALYSIS

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Abstract: Shallow landslides or slope failures have been studied from several points of view. In particular, numerous methods have been developed to assess slope stability. However, little work has been done on the systematic comparison of different techniques, and the incorporation of vertical contrasts of geotechnical properties in multiple soil layers. In this research, stability is modeled by using LOGISNET, an acronym for logistic regression, Geographic Information System and Neural Network. LOGISNET is a project of which the main purpose is to provide government planners and decision makers a tool to assess landslide susceptibility. The system is fully operational for models handling an enhanced cartographic-hydrologic model (SINMAP) and logistic regression. The enhanced implementation of SINMAP was tested and found to have improved factor of safety estimates base on comparison with landslide inventory maps. The enhanced SINMAP and logistic regression subsystems have functions that allow the user to include vertical variation in geotechnical properties through summation of forces in specific layers, acting on failure planes on a local or regional scale. The working group of LOGISNET foresees the development of an integrated tool system to handle and support the prognostic studies of slope instability, and to communicate the results to the public through maps.

Keywords: Franciscan Complex; GIS; hillslope stability; landslides; landslide susceptibility; logistic regression; neural network; modeling; Redwood National and State Parks, California; SINMAP.

1. INTRODUCTION

Triggered by extrinsic factors (such as earthquakes or unusual rainfall) and intrinsic factors (such as geology, slope, vegetation, and geotechnical parameters), landslides can cause significant damage themselves and generate often more destructive debris flows (Ohlmacher and Davis, 2003; Dai and Lee, 2002; Atkinson and Massari, 1998). In spite of the efforts made by local authorities and scientists to monitor and forecast landslides, it has been difficult to evaluate landslide potential or susceptibility accurately due to large spatial and temporal variability. Several GIS approaches to assess landslide susceptibility have been proposed (Saro-Lee et al., 2004; Zhou et al., 2003); however, few studies take full account of topographic control through shallow subsurface water flow in landslide generation (Pack et al., 2001; Montgomery and Dietrich, 1994). Based on a hydrologic model developed by O'Loughlin (1986), Montgomery and Dietrich (1994) developed a new model that combines topographic and hydrographic variables to predict potential landslide zones with sparse information. Using a similar approach, Pack et al. (1998) developed a cartographic/hydrologic model (Stability Index Mapping: SINMAP) in which poorly constrained parameters are incorporated through the use of uniform probability distributions. However, little work has been done in clarifying the importance of geotechnical properties of material in different soil layers to produce landslides, and in the systematic comparison of models to outline advantages and limitations of the methods (Guzzetti et al., 1999; Morrissey et al., 2001). Simon et al. (2000) developed a 2-D streambank failure model that allows for a slip plane crossing multiple soil layers with differing friction angle and cohesion. The model worked well in post-diction of failure events along Goodwin Creek, MS, USA. As the water table varied in height through time with stream level and rainfall, periods during which the factor of safety was calculated to approach unity from larger values were the times during which bank failure occurred.

As an attempt to develop a 3-D model allowing for soil layering, SINMAP, Multiple Logistic Regression (MLR), and Neural Network (NN) approaches are being modified to accept geotechnical parameters for multiple soil layers and from them assess landslide potential. A new computer system is proposed using geographic information system (GIS) resources. The system, called LOGISNET is developed by using arc macro language (AML) under ArcInfo GIS software. LOGISNET is used to integrate, compare, and visualize results after using the three approaches. This paper describes development, implementation, and testing of the first two approaches as methods for delineating landslide potential. Pilot tests are performed by using LOGISNET for an area on Highway 101 in the northern Coast Ranges, California.

2. BACKGROUND AND PHYSICAL BASIS

Three approaches for landslide susceptibility are used: 1) SINMAP, which expresses the stability of the slope in terms of a factor of safety, a ratio between the forces that make the slope fail and those that prevent the slope from failing, 2) MLR, which has the advantage over other multivariate statistical techniques for this application in that the dependent variable can have only two values—an event occurring or not occurring (Ohlmacher and Davis, 2003), and 3) NN, which has the advantage of independence from the statistical distribution, compared to statistical methods. NN calculate an output stability index based on the summation of weights from each of the input variables. The weights to reinforce correct decisions are made by reducing the difference between the output of the NN and a target value as given by a landslide inventory map (Saro-Lee et al., 2004). The first two approaches are fully integrated in LOGISNET. Using the functions of GIS technology, LOGISNET carried out the analysis and visualization of landslide susceptibility for a multilayer factor of safety calculation.

2.1. The Cartographic-Hydrologic Approach And Its Implementation In LOGISNET

The first approach, Stability Index Mapping (SINMAP) was developed by Pack, Tarboton, and Goodwin (1998). The model expresses the terrain stability by using six broad classes with subjective breakpoints (Table 1).

Table 1. SINMAP, Stability class definition.

Class	Condition	Predicted State
1	SI > 1.5	Stable slope zone
2	1.5 > SI > 1.25	Moderately stable zone
3	1.25 > SI > 1.0	Quasi-stable slope zone
4	1.0 > SI > 0.5	Lower threshold slope zone
5	0.5 > SI > 0.0	Upper threshold slope zone
6	SI < 0	Defended slope zone

SINMAP combines the theory of a hydrologic model (O'Laughlin, 1986; Beven and Kirkby, 1979) and the infinite slope stability model factor of safety (Hammond et al, 1992) to produce the stability index.

The hydrologic model uses wetness, W, to map the spatial pattern of soil saturation (Pack et al., 1999):

(1)

$$W = \frac{RA}{bT\sin\theta} = \frac{R}{T}\frac{a}{\sin\theta} = \frac{\text{Runoff at a rainfall rate}}{\text{Soil profile saturation}}$$

Where R is the net rainfall (mm/day), A is the contributing area (m^2), b is the length of the lower boundary (m) of A, a is the specific catchment area (A/b in m), T is the soil transmissivity, and Θ is the local slope angle (°) (Figure 1). The wetness is kept at unity in SINMAP, to avoid saturation overland flow.

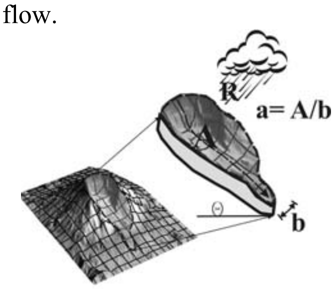

Figure1. Definition of topographic elements used in the hydrologic model.

The factor of safety for the infinite slope stability model is given as:

(2)

$$FS = \frac{C_r + C_s + \cos^2\theta[(\rho_s g Z - z_w) + (\rho_s g - \rho_w g) z_w)]\tan\phi}{\rho_s g Z \sin\theta\cos\theta}$$

Where C_r and C_s are root strength and soil cohesion, respectively, Z is the vertical soil thickness, z_w is the vertical thickness of the phreatic layer, ρ_s multiplied by g (soil density and gravitational acceleration respectively) is the unit weight of soil, and ρ_w (water density) multiplied by g is the unit weight of water. Angles θ and ϕ are the slope and friction angles. SINMAP reduces the factor of safety to a dimensionless form:

(3)

$$FS = \frac{C + \cos\theta[1 - wr)]\tan\phi}{\sin\theta}$$

Where w is relative wetness (h_w /H), C is a dimensionless cohesion ($C_r + C_s /(H\rho_s g)$, and r the density ratio (ρ_w/ρ_s) (Figure 2). In essence, Eqns 1 and 3 are coupled in SINMAP to define the stability index:

(4)

$$SI \equiv FS = \frac{C + \cos\theta\left[1 - (\frac{R}{T}\frac{a}{\sin\theta})r\right]\tan\phi}{\sin\theta}$$

SINMAP holds the soil density ratio constant and allows variability in the soil cohesion, internal friction angle and *R/T* by using a uniform probability distribution given specification of a lower and upper limit.

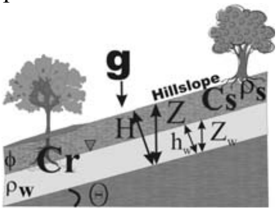

Figure 2. Definition of topographic elements used in factor of safety (adapted from Hammond et al., 1992)

Although LOGISNET-hosted SINMAP follows the same approach as standalone SINMAP, a few changes improve the cartographic/hydrologic model and help manage a multilayer dataset collected from the field. First, a multilayer slope safety factor is calculated in LOGISNET using three averaging modalities, depending on whether the input or output variables are normally distributed: (1) per layer (run the model using the values of the geotechnical properties for each layer at each sample point, then average the SI at each grid point within a region), (2) per sample point (average the geotechnical properties of layers at each sample point, then run the model for each grid point within a region), and (3) per region (average the geotechnical properties of all layers at all sample points within a region, then run the model). In these aggregation methods, the user is able to generalize from soil layers to sample points and from sample points to regions (Figure 3).

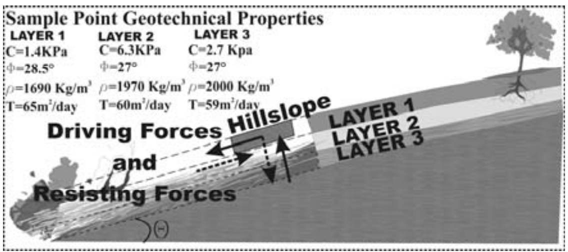

Figure 3. Flow schematic used to implement the cartographic/hydrologic model in LOGISNET per layer. Field measured parameters per layer (cohesion, soil density, internal friction angle, and soil transmissivity) are taken per sample point in a landslide head scarp. Each layer is assumed to rest on a slope of constant angle and infinite extent. For each layer the resisting and driving forces are taken as being equal and opposite in direction and magnitude. The model runs by using topographic, hydrologic, and soil geotechnical parameters per layer. Each temporal layer SI map is average at each grid point to lead the first level of abstraction (from layers to sample point). To obtain the final landslide predicted map, a second abstraction (from point to region) by average is carried out.

Although it is possible to apply manually the averaging abstraction to the dataset and/or to the maps, LOGISNET delineates simultaneously its implementation with weights and models in a systematized way. It is important to notice that the abstraction starts at the dataset level (running LOGISNET per region and per point) and from then the representation from layer beds toward regions is being done.

The results suggest that the quality in the analysis is lost by averaging in LOGISNET to aggregate and represent the information from layers to points and from points to regions. The problem is overcome by the stratigraphic column function. LOGISNET retain the basic stability calculation per layer allowing the user to access the information by using a stratigraphic column (Figure 4). The stratigraphic column shows the stability index per layer and clarifies which layer has the most significant effect on is hillslope stability.

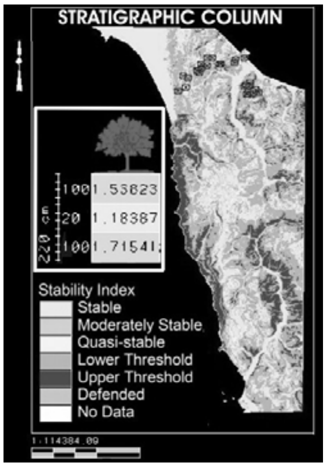

Figure 4. The stratigraphic column function (outlined with a square) allowed the evaluation of stability based on layers at a specific sample point.

Other improvements with LOGISNET are: First, soil density is not held as constant because this property not only varies in space but also along cross sectional profiles in a plane failure. Second, the user can weigh the different geotechnical soil properties involved in the model by soil thickness or by a specific user weight. Third, a correction in the C code of SINMAP was made to avoid the loss of spatial information in the borders and inside the saturation and stability index map. Fourth, the user can run the model with the default eight-neighborhood method (also called D8 method) to calculate slope and flow direction, or use the output from SINMAP, which applies the Dα method (Tarborton, 1977).

2.2. The Logistic Multiple Regression Approach And Its Implementation In LOGISNET

Among the main reasons to use the MLR in landslide susceptibility is that the model is designed to describe probability --the model estimates the probability of landslide between 0 and 1. In MLR, the landslide area outcome is a categorical dichotomy variable. The predictor variables, such as slope, contributory area, and internal friction angle, can be continuous or categorical. In this sense, when a landslide is categorized as 1 or 0, or as landslide or no-landslide, the problem of a lack of linear relationship between variables is overcome in MLR by using logarithmic transformation. Another reason for using the MLR derives from the interpretation of the sigmoidal-shape of the logistic function:

$$f(z) = \frac{1}{1+e^{-z}} \qquad (5)$$

Where $z = (\alpha+\beta_1X_{1+}\ \beta_2X_{2+\dots}\ \beta_kX_k)$ represents an index that combines the contribution of several risk factors whose values are from - α to +α, X_k are the independent variables (slope, contributory area, internal friction angle, etc.) and α and β's are coefficients that represent the intercept and slopes respectively for each input parameter. The sigmoidal shape can be interpreted by assuming that the risk of landslide is minimum for low z values until some threshold is reached. The probability of landslide increases fast over a certain range of intermediate z values and remains high once z gets large enough (Kleinbaunm and Klein, 2002).

Numerous applications of MLR have been used to assess slope stability, each one using a range of different statistical treatments (forward or backward MLR), depending on the different set of variables and how these variables are coded (binary, categorical or ordinal data) to performance the analysis (Can et al., 2005; Ayelew and Yamagishi, 2005; Ohlmacher and Davis, 2003). In our first stage of LOGISNET development, MLR is implemented to compare its output with that of the cartographic-hydrologic approach (SINMAP). MLR is already available as a set of ArcInfo geo-processing commands. LOGISNET implements a friendly graphical user interface to extract information and run the model per layer. Thirteen input variables are considered to perform the initial analysis, which is the same as that of SINMAP. These variables are: pit-filled-DEM, flow direction, slope, contributory area, saturation, soil density, soil thickness, minimum T/R, maximum T/R, minimum cohesion, maximum cohesion, minimum friction angle, and maximum friction angle. Each input variable can be treated as either continuous or binary. In a typical run, LOGISNET offers a set of sampling tools. The decision-maker can choose how to extract the information (X_k) needed to calculate the α and β's. The user can randomly resample the input dataset base on the percentage of landslide area in a landslide inventory map, or resample based on grids or points maps coded as 0 and 1. Once the user has created the sampling methodology, he/she generates the prediction report or a prediction map per layer, per point or per region. The report shows the smallest set of statistical parameters used to evaluate the model, and shows how the model was constructed. If the user wants to run different statistical treatments, LOGISNET allows him/her to save and export the needed information per layer in ASCII files. If desired, the files can be analyzed in a more sophisticated statistical package to obtain the α and β's and re-imported to LOGISNET in order to re map the information.

3. PILOT TESTS

The study area is near the Highway 101 corridor in Del Norte County, California. In the area, landslides along the coast between Wilson Creek and Crescent City create a potentially hazardous situation for people and property. More than 200 landslides have been mapped in this area by the California Geological Survey and the California Department of Transportation. The study area is prone to landslides due to the combination of several factors, such as high precipitation (101.73 in/yr), weakness of planes (rock types are mainly low strength Franciscan Complex: melange and Broken Formation), a high degree of weathering, and steep slopes (Wills, 2000; Madej et al, 1986). In light of the above situation and having knowledge of the main model and inventory map limitations, namely: a) SINMAP is designed to map only shallow translational landslides, b) The accuracy of prediction in SINMAP is highly dependent on the quality in the DEM, c) At a scale of 1:12 000, the inventory map shows that landslides tend to be deep-seated slides that affect large areas, therefore there are many small shallow slides that are obscured by thick forest cover and can not be seen (Wills, 2000), and d) Although the inventory map has database tables describing each feature map and together they can be used as a hazard map, there is little geotechnical information about rocks and deposits and their relationship to landslides.

In light of the above situation and to palliate limitations, geotechnical properties were sampled on small shallow landslides. In the field, stratigraphic columns were investigated, in which transmissivity and wetness were calculated by using a permeameter and tensiometer, respectively. A total of 107 samples (160 separate layer samples) were taken in areas with and without landslides and brought to the laboratory to perform geotechnical tests to obtain internal friction angle and cohesion. About 140 values were then integrated on the GIS dataset. Although a 10 m DEM is available from the USGS National Mapping Program, the first pilot reconnaissance test is carried out at 30m resolution to evaluate regionalization of landslides at this scale. Figure 5 shows the results at small cartographic scale. At this cartographic level, the cartographic/hydrologic approach reflects geologic conditions more than geomorphology.

A comparison of outputs by using SINMAP with default system parameters, SINMAP with field data parameters, and LOGISNET multilayer is done. The three outputs (Figure 5 b, c, d) show high instability along the coast where rock slide is the dominant process. None of the three depicts instability in areas where a large earth flow happened (southwest area in the map). By using field geotechnical data, the degree of instability increases in all regions. The most critical areas ("Upper and Lower thresholds") are even more highlighted with a multilayer test (Figures 5 and 6).

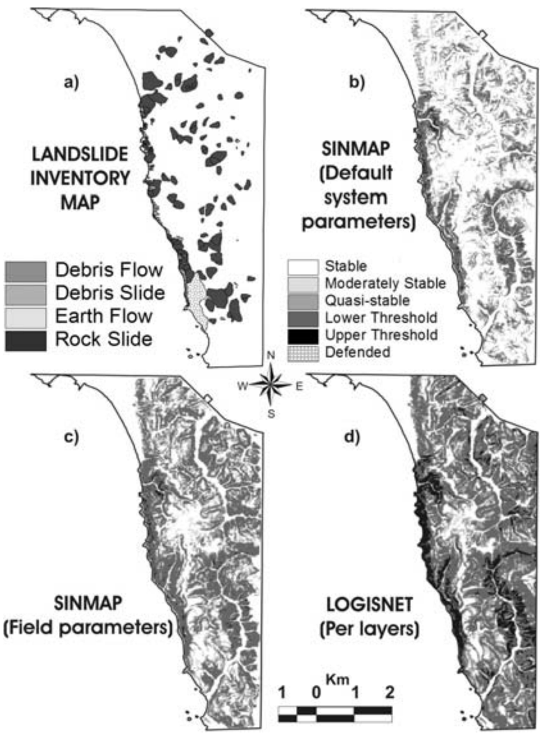

Figure 5. The inventory map of Highway 101 and three different outputs from the cartographic-hydrologic approach. (a) The inventory map from the California Geological Survey with four categories of landslides mapped at scale 1:12 000. (b) An output of SINMAP by using default parameters. (c) An output of SINMAP by using geotechnical field data only, and a fixed soil density of 2000 kg/m^3. (d) An output from LOGISNET using geotechnical field data with variable soil densities, and running layer per layer.

The LOGISNET output by layer shows high coincidence between predicted instable slopes and field observation, but also shows an overprediction. Morrissey et al, (2001), mentions that the overprediction in SINMAP may be attributed to the assumption of homogeneous and isotropic soil properties, uniform landslide thickness and spatial and temporal uniformity of rainfall. In this study we suggest that the overprediction can be justify by the abstraction and generalization of running the model at 30 m DEM resolution and may in fact better represent the pre landslide topography than does a high resolution DEM.

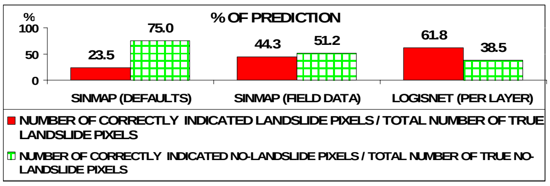

Figure 6. Shows percentage of prediction in landslides and no landslide areas by overlaying the landslide inventory map and the predicted landslide models. The low proportion of correct landslide pixel (23.5%) predicted by using system parameters is almost two and three times less than by using calibrated field data parameters and field data parameters per layer bed respectively.

4. CONCLUSIONS

We introduce the implementation of LOGISNET as a user interface and collection of functions in AML designed to facilitate the analysis and validation of cartographic-hydrologic and MLR landslide models in a multilayer fashion. The set of functions provides a toolbox that allows evaluation and calculation for prediction of landslides. The tools and methods to assess the model quality at different cartographic scales and DEM resolutions are still under development and depend on the distribution of the data. To evaluate the model by using entirely independent datasets in different regions, datasets must be obtained by using similar sampling strategies. The results from the pilot study area suggest that the predicted models are improved by using calibrated field data and by running the analysis per layer. Although LOGISNET per layer method gives more accurate prediction, it must be kept in mind, that the abstraction by average is highly influenced by extreme values. Further tests must be done to asses the influence of average and pixel size resolution on LOGISNET system.

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