Dynamic Model to Forecast Slope Stability A Case Study: Geradiella Lanslide Site

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Abstract: Forecasting the potential for disastrous events such as landslides has become one of the major necessities in the current world. Most of the landslides occurring in Sri Lanka are found to be triggered by intense rainfall events. This study was carried out on a landslide that occurred near Gerandiella waterfall, located in Kotmale Divisional secretariat in Sri Lanka. This project investigates the possibility of developing a dynamic model to map the spatial distribution of the slope stability using Geographic Information System (GIS). The model incorporates several theoretical models including the infinite slope model, Green Ampt infiltration model and Perched ground water flow model. A series of rainfall values can be fed to the model as the main input to simulate the dynamics of slope stability. Hydrological model developed using GIS is used to quantify the perched water table height. Infinite slope stability model is used to quantify the degree of slope stability in terms of factor of safety. DEM was built with the use of digitized contour data. Stratigraphy was modelled in Surfer software using borehole data and resistivity images. This model equipped with the predicted rainfall values can be used to forecast the slope dynamics of the area of interest.

Keywords: Factor of safety, Geographic Information System, Hydrological model, slope stability

1. Introduction

1.1 Background

A landslide occurs when part of a natural slope is unable to support its own weight. A landslide is a downward or outward movement of soil, rock or vegetation, under the influence of gravity. This movement can occur in many ways. It can be a fall, topple, slide, spread or flow. The speed of the movement may range from very slow to rapid. Landslides destroy property along its path of movement and may cause death to people and livestock. Although landslides usually occur at steep slopes, they may also occur in areas with low relief or slope gradient.

In Sri Lankan context, the research projects conducted investigating the possibility of forecasting the potential of landslides or slope instability using GIS techniques are limited. In the Global context, integrated hydrology and slope stability models have been developed using few basic GIS software like PC Raster but none has used ArcGIS.

1.2 Overview of the paper and contributions

This project investigates the possibility of developing a dynamic model to map the spatial distribution of the slope stability. A series of rainfall values can be fed to the model as the main input to simulate the dynamics of slope stability. Hydrology model developed using GIS is used to quantify the perched water table height, which is one of the most critical parameters affecting the slope stability. Infinite slope stability model is used to quantify the degree of slope stability in terms of factor of safety. DEM was built with the use of digitized contour data. Stratigraphy was modelled in Surfer using borehole data and resistivity images.

GIS is a powerful and effective tool in modelling that can be applied in a vast array of real world applications especially in emulating real world processes.

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However, the advanced applications of Geographic Information system are found to be rare in the Sri Lankan context. In the disaster management sector, there exist no available practices which exploit advanced dynamic modelling capabilities of GIS. Thereby, this research has the potential to generate exposure to high-tech landslide forecasting technique benefiting the industrial sector.

2. Literature review

2.1 Landslides

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing (USGCWebsite, 2004). Sudden movements of rock or soil mass are fairly common and are generally termed as landslides. A landslide can be a movement of either a sloping mass or the crest or the foot of a hill or even the cut surface of a slope (Bandara, 2003).

2.2 Landslides in Sri Lanka

Of the 65,000sqkm of land extent of Sri Lanka, an area of nearly 20,000sq km encompassing 10 districts is prone to landslides. It is about 30% of the Sri Lanka's land area spread into several districts namely Badulla, NuwaraEliya, Kegalle, Ratnapura, Kandy, Matale, Kalutara, Matara, Galle and Hambantota (Bandara , 2003).

2.3 Landslide triggering factors

The occurrence of landslides is dependent on geo-morphometric, tectonic, lithological and climate factors. Landslide triggered by rainfall occurs in most mountainous landscapes in Sri Lanka.

2.4 Hydrologic cycle

Earth's water is always in movement, and the natural water cycle, also known as the hydrologic cycle, describes the continuous movement of water on, above, and below the surface of the Earth. Water is always changing states between liquid, vapour, and ice. (USGS, 2013)

2.5 Ground water flow

The process of groundwater flow is generally assumed to be governed by the relations expressed in Darcy's law. Two standard laboratory tests are used to determine the hydraulic conductivity of soil the constant-head test and the falling-head test. Constant head test demonstrates the subsurface groundwater flow

2.6 Brooks-Corey Model

The unsaturated hydraulic conductivity gets its maximum when the infiltration capacity reached. Water will not flow until the water content in the soil is sufficient and the pressure head becomes less negative, when the soil is initially dry. The specific discharge (q) is then given as

Equation 1

$$q = -K(\theta)\frac{\partial h}{\partial l}$$

θ = the moisture content

$\frac{\partial h}{\partial l}$= pressure gradient

Brooks and Corey (1964) give the formula for hydraulic conductivity as

Equation 2

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{n - \theta_r}\right)^m$$

Where

K (θ)=hydraulic conductivity

Ks= saturated hydraulic conductivity
θ_r =residual water content
n = porosity and

Equation 3

$$m = 3 + \frac{2}{\lambda}$$

Where λ is pore size index.

2.7 Saturated Hydraulic conductivity

The hydraulic conductivity of a soil is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient. Hydraulic conductivity is defined by Darcy's law, which, for one-dimensional vertical flow.

2.8 Saturated volumetric moisture content

Commonly used in the description of infiltration, is a volumetric expression for the amount of moisture in a soil. It is defined as the ratio between volume of water and total volume (Delleur, 1999).

2.9 Residual volumetric moisture content

This represents the amount of water that remains in a soil mass even when a high vacuum pressure is applied to the soil

3. Methodology

3.1 Model Conception

Model Conception was the initial step in defining the actual scope of the project. Rich picture of the model was developed to identify

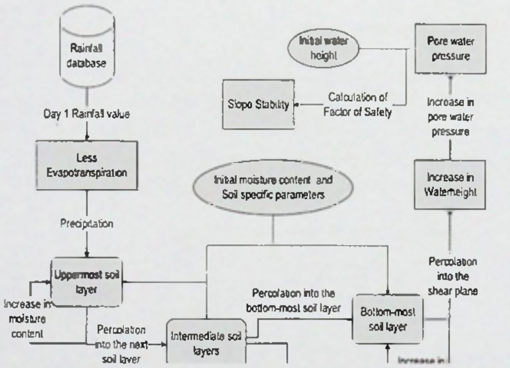

Figure 1: Rich picture of the model (not clear have to be adjust)

functional requirements of the project.

3.2 Functional requirement

The functional requirements describe the core functionality of the application including data requirement and functional process.

Data requirement- Rainfall time series, evapotranspiration and interception time series, terrain elevation data, number and type of soil strata of AOI and geotechnical parameters of underneath soil such as thickness of each soil stratum initial moisture content, initial water height, saturated hydraulic conductivity of each soil type, saturated moisture content of each soil type, residual moisture content of each soil type, cohesion between bottom most soil layer, angle of friction needed to the modelling process as inputs.

Process requirement-Model requires processes to calculate precipitation after the evapotranspiration, increase in moisture content of soil layers, percolation, pore water pressure, changes in water height and factor of safety. Model perform all calculations each pixel simultaneously.

3.3 Collection of data

Daily rainfall data for the period from 2012-06-27 to 2013-01-31 and borehole data from five boreholes within the AOI were collected by National Building Research Organization, Sri Lanka. The elevation data in the form of 1:10,000 contour maps were purchased from the Survey department, Sri Lanka. Geotechnical parameters were estimated using the borehole data and the information obtained through the literature survey.

3.4 Preparation of data input

Rain fall time series data-Selected set of daily rainfall time-series data were added to the attribute table of the shape file representing the Area of Interest.

Digital Elevation Model-Depression less DEM of the area of interest was created. DEM was required to calculate the flow direction raster and to calculate the slope angle of the terrain.

Geological unit information-Using the borehole data the elevation values were interpolated using of the upper-most surface of each geological unit (soil layer) and one separate raster for each geological unit (soil layer) was prepared, 50mX50m area on the ground

3.5 Model design

The model was designed using ArcGIS 10.1 Model Builder application. Several sub-models were created and nested within the main model to avoid the complexity.

3.6 Model Process

The dynamic input for the model is a series of rainfall data. The set of rainfall data assigned to the AOI shape file is the initial input for the model where the configuration of tools and variables as shown in figure 2 enables reading one precipitation value at a time and create a constant raster of 50mX50m resolution and assign the precipitation value to each pixel of the raster

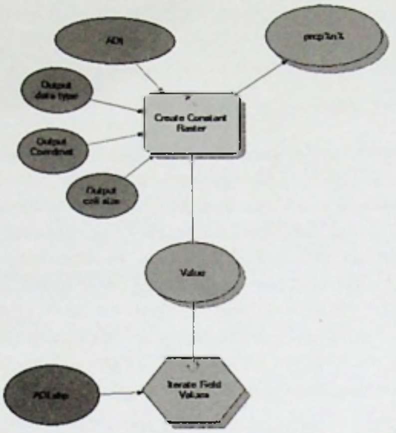

Figure 2: The total model process iterates for each rainfall value

Model reads the first precipitation value of the data set and calculates how much water (as a height) the uppermost layer absorbs to increase its moisture content and how much does it allow percolating into the next soil layer. This process is continued repetitively for all the soil layers.

Percolation-Unsaturated percolation to the ground water was assumed to take place by gravity according to the equation 1. For each soil layer the percolation flux (mm/day) was calculated using the equation.

Equation 4

$$Pr = K_s\left(\frac{\theta - \theta_s}{\theta_s - \theta_r}\right)^m$$

Where,

P_r =Percolating flux (mm /day)

K_s =Saturated hydraulic conductivity (mm/day)

θ = actual volumetric soil moisture content %

θ_p = residual volumetric moisture content %

θ_σ = saturated volumetric moisture content %

m = constant (between 3 and 8)

Change in water height-The model assumes that the total impact on the water height is due to three main components.

Equation 5

New water table=Existing water table+ Δ_1-Δ_2+Δ_3

Outflow due to groundwater flow (Δ_2)

Equation 6

$$Q = K_s z_w B \sin\beta$$

Where:

Q =Ground water flow (mm^3/day)

K_s =Saturated hydraulic conductivity (mm/day)

Z_w =Height of the ground water table (mm)

B =Width of flow (=width of pixel) (mm)

Sin =Sinus of the topographical slope

Equation 7

$$\Delta_2 = \frac{Q}{B^2(thetaMax4 + 0.01 - mc4)}$$

Inflow due to gravity flow (Δ_1)

ArcGIS software facilitates calculating the flow direction and flow accumulation using the digital elevation model and the outflow values. Using the Digital Elevation model flow direction raster was calculated

Inflow due to percolating flux(Δ_3)

Equation 8

$$\Delta_3 = \frac{Perc4}{(\theta_{max4} + 0.01 - \theta_4)}$$

Where

θ_{max4} = Saturated moisture content of the soil layer immediately above the shear plane,

θ_4 = Moisture content of the soil layer immediately above the shear plane

Perc4 = percolating flux of the soil layer immediately above the shear plane (mm/day)

Factor of Safety-The stability of the slope is calculated in terms of a Safety Factor. The Safety Factor is the ratio between the driving and the resisting forces of the slope. The infinite slope model is used to calculate the stability. In this model, it is assumed that the slip surface of the landslide is running parallel to the topographical slope. In that case the stability can be calculated for each pixel

Equation 9

$$FoS = \frac{c' + \tan\emptyset(\gamma z\cos^2\beta - u)}{\gamma z \sin\beta\cos\beta}$$

F = Factor of Safety

c'=soil cohesion (kN/m^2)

γ=unit weight of soil (kN/m^3)

Z=depth of the soil (slip surface) (m)

u=pore water pressure (kN/m^2)

β=angle of the topographical slope

$$u = \gamma_w Z_w \cos^2\beta$$

γ_ω= Unit weight of water (kN/m^3)
Z_w= Height of the water table above the slip surface (m)

3.7 Model Calibration and Validation

During calibration, the parameters were adjusted until a good fit between the simulated outputs and observed data. The parameter set fed to obtain the calibration for the period of July -Oct 2012. Hydrological model was calibrated by changing m value of Equation 4 in the range of 3-8. The extreme goodness of fit was obtained though applying m=4. Friction angle and the cohesion was taken 35^0 and 0 kPa respectively for the modeling process

The model was validated with the rainfall data for the period of Nov 2012-Jan 2014

4. Results

4.1 Results of Calibration for Groundwater levels of BH1 and BH2 piezometers

Table 1 Goodness of Fit Parameters

Bore Hole	Efficiency Index	Standard Deviation (S)	Root Mean Square Error (RMSE)	Mean Percentage Error (MPE) %
BH1	0.62	3.44	44.04	0.00
BH2	1.42	183.70	99.95	0.02

4.3 Results of Model Validation of BH1 and BH2 Piezometers

Table 2: Goodness of Fit Parameters

4.2 Results of Calibration for Factor of Safety

Bore Hole	Efficiency Index	Standard Deviation (S)	Root Mean Square Error (RMSE)	Mean Percentage Error (MPE) %
BH1	0.74	37.01	76.01	0.03
BH2	0.29	178.67	111.82	0.02

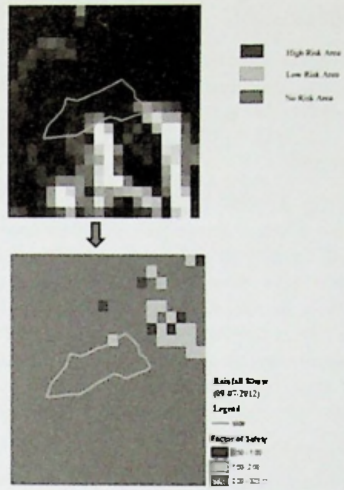

Figure 3: Raster image representing outputs of stability model

5. Discussion

There were several important factors considered during model calibration and validation. There were assumptions, input parameter values and distributions, output values and conclusions. Initial calibration attempt concentrated on the output of the model. A real system measurements to analyze the model is the most reliable and preferred method.

The main assumption of this model is that it does not encounter the entire catchment ground water flow. It represents only the ground water floor of the interested area. As this is a hilly area this will highly affect in ground water levels.

The calibration should be done in long term basis to determine invariance. Since the rainfall at Garandiella gauging station was available only for seven months and at least there should be two year data (representing two water years) set to carry out calibration and validation for consecutive years. Otherwise it does not meet the storm and dry period in Sri Lankan climate condition.

Soil layer thickness is a major parameter for this model. It should be given for the entire area by layer by layer. It cannot represent when there are interconnecting soil layers present. Sometimes they should be neglected. Therefore, the properties of subsurface could be changed and geological features such as discontinuities, fractures etc were not modelled.

6. Conclusion

This triggers the need for identifying and continuous monitoring of landslide prone areas where the model we developed has a high potential to be useful in such applications.

The model was developed to investigate the ability of using a dynamic model to forecast landslide potential of a rainfall induced landslide site using the model builder application in ArcMap10.1. Time series of rainfall values can be fed to the model to along with the site specific parameters and the model gives a time series raster indicating the factor of safety.

The modifications to the model and the execution of the model require knowledge, experience and skills developed in GIS platforms. Hence may not be user friendly for the users with no GIS knowledge.

The model requires large number of data to be fed in the form of geotechnical parameters which are not readily available and can be expensive to collect.

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