USE OF A DETERMINISTIC SLOPE STABILITY PREDICTING TOOL FOR LANDSLIDE VULNERABILITY ASSESSMENT IN RATNAPURA AREA, SRI LANKA

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ABSTRACT

This study was carried out to map the landslide susceptibility of Ratnapura town area located at 6^0 43' N and 80^0 25' E using the deterministic slope stability analysis model SINMAP The selected study area covers about 153 sq. km. of land area within the southern part of the central highlands of Sri Lanka and the landslides observed in this region are induced by low intensity long duration rainfall. With the increase of population and other infrastructure facilities, utilization of land on hill slopes is unavoidable and it is very important to map the landslide potential of hilly area, to assure the safety of the people delineate the suitable land for development.

A landslide inventory point theme, a Digital Elevation Model (DEM) grid theme derived from 1: 10,000 scale contour data, Soil strength parameters and hydrological parameters such as steady state recharge and transmitivity were the input data for this model. A polygon theme, which represents regions with different geotechnical and hydrological properties, was used as a calibration regions theme during the execution of this model. The major output of the SINMAP model is the Stability Index grid theme, which can be used as a landslide hazard zonation map. The model also provides slope area plot charts and statistical summary for each calibration region in the study area facilitating the data interpretation. The results of this study indicate about 72% reliability in predicting slope instability in the selected study area. The predictability of the model can be further improved by developing it to incorporate the heterogeneous nature of the soil and by increasing the accuracy of the DEM grid data.

1. INTRODUCTION

Slope instability is a geo-dynamic process that naturally shapes up the geo-morphology of the earth. However, they are a major concern when those unstable slopes would have an effect on the safety of people and property. In Sri Lanka, where 14,000 sq.km of the 65,525 sq km of total land area comprises mountains, slope instability has become a major concern with the increased demand for development and expansion of human settlements in that region.
Existing slopes that have been stable over years can experience significant movements when natural or man-induced conditions change the forces ensuring slope equilibrium. Earthquakes, weathering of bedrock that reduce its strength, formation of underground caverns, surface erosion, development of tension cracks or shrinkage cracks followed by water intrusions can be identified as natural conditions that could change these forces. Development of a wetting front and elevation of the ground water table due to prolonged or heavy rainfall also naturally change the hydro-static and hydro-dynamic forces at the slope and often facilitate most of the Sri Lankan slope failures. Typical man-induced conditions such as removal of vegetation, removal of vegetation's root structure, steepening a slope by cuts, loading a slope near its crest, removal of earth below the toe, and construction of water retaining structures upstream of a slope would also change the slope's natural equilibrium.

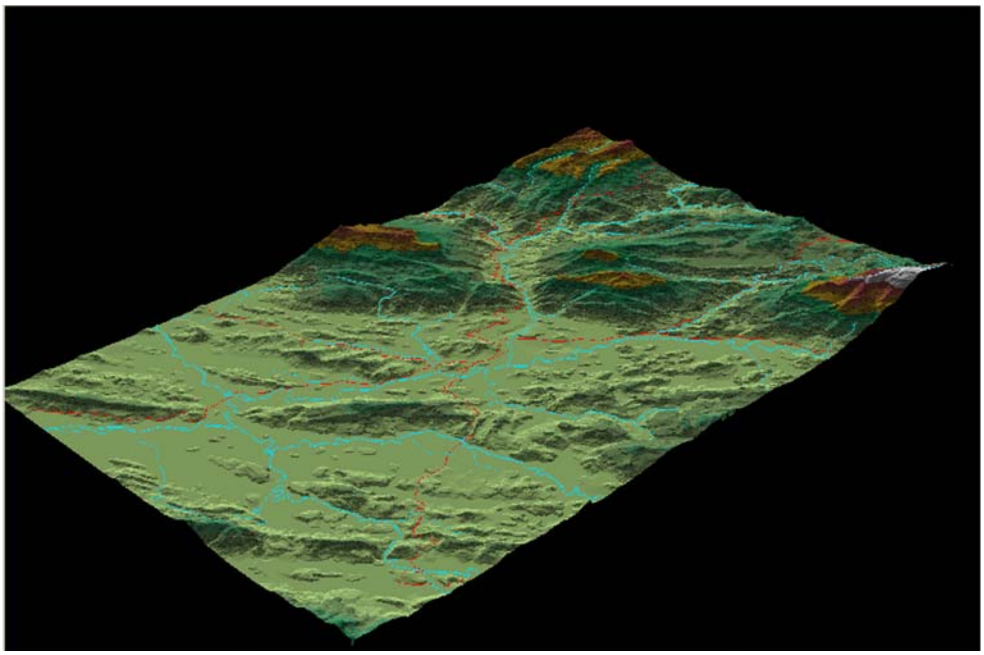
With the growth of population, there is an increasing demand for land that is suitable for housing, necessary infrastructure and other services such as health care and education. Therefore, in a country where 20% of the total land area is mountainous, utilization of land on hill slopes is unavoidable and it is extremely important to map the landslide potential of hilly area, in order to ensure the safety of the people and to delineate the suitable land for development.

2. OBJECTIVE

The objective of this study is to

- generate a landslide hazard zonation map of the selected study area utilizing a deterministic slope stability model
- study landslide hazard map produced above with the landslide hazard zonation map prepared by the National Building Research Organisation (NBRO) of Sri Lanka.
- propose guideline for development within identified hazard zones, in order to make the product more meaningful to the end user.

Figure 1 Digital terrains Model of the study area



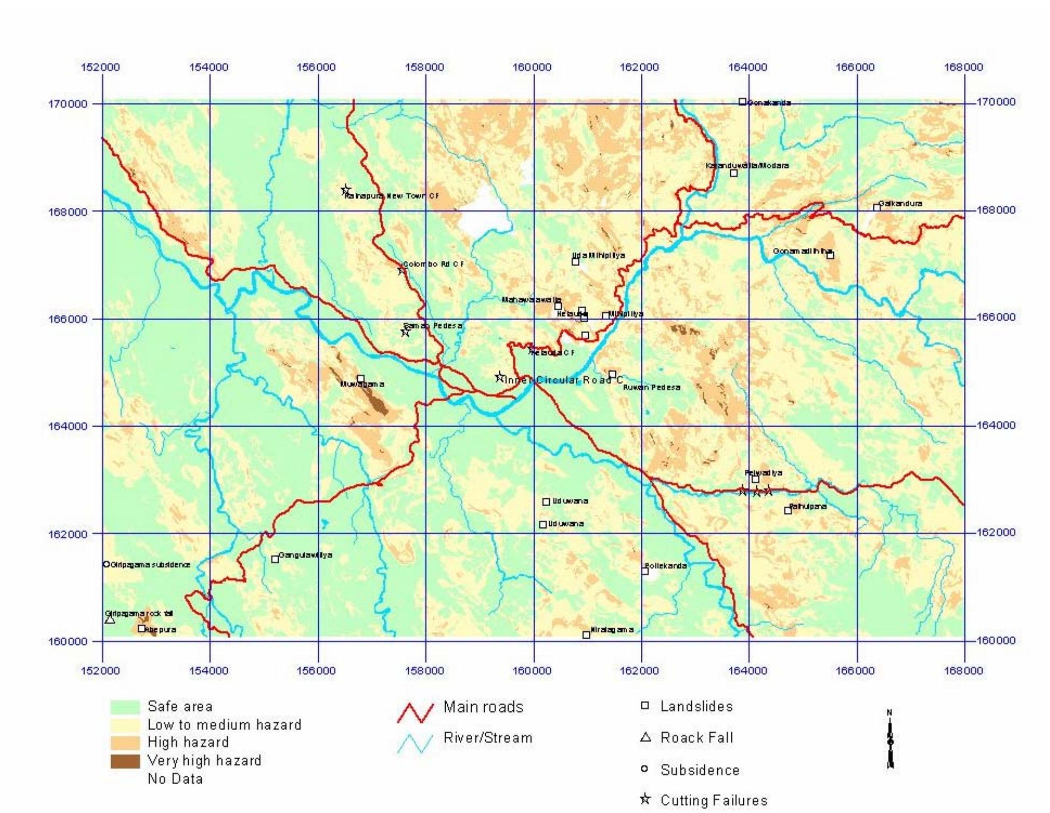
3. STUDY AREA

Ratnapura town area, which is the study area selected for this mini project, is located at 6^0 43' N and 80^0 25' E and covers about 153 sq. km (Fig. 1). of land area within the southern part of the central highlands of Sri Lanka. This region is world famous for gems such as Sapphires, Rubies, Cat's eye and Tourmaline and because of the abundance of this wealth; the area is becoming highly populated. Unfortunately, the same area has a recorded history of landsliding, which causes a serious damage to life, property and infrastructure. These landslides are induced by low intensity long duration rainfall. However, growth of population, which force to move settlements towards the highlands and inappropriate land use practices also have a major influence in increasing the frequency of landslides in this area.

During the past two decades, this area experienced many devastating landslides such as the slides that occurred in Pathulpana, Helauda, Abepura, Pelwadiya, and Muwagama. Including these 5 major slides, there are many landslides and other forms of slope failures such as rock fall, subsidence and cutting failures recorded within this area. Most of these landslides have been occurred due to natural causes while a few have been occurred on slopes modified by humans.

Under its Landslide Hazard Mapping Project (LHMP), NBRO has prepared a landslide hazard zonation map for this area based on a probabilistic method (Fig. 2). Considering the time and the cost required for mapping, the scale of 1:10000 was selected for this mapping programme (NBRO User Manual, 1995). The availability of topographic maps at the same scale has also contributed to this adoption of scale. Based on their experience on studying 863 landslides in Nuwara Eliya district and 213 landslides in Badulla district, the NBRO researchers have identified (a) Bedrock geology, (b) Spread of overburden deposits, (c) Slope angle range, (d) Hydrology, e) Land Use and (f) Land Forms as the predominance of factors towards initiating or progressing a landslide

Figure 2 NBRO's existing landslide hazard zonation map



The contributions of each of these factors towards initiating a landslide is different and therefore, the relative importance of these causative factors have quantified by studying the statistics of landslides against each of these factor attributes and assigning subjective severity levels based on the probability of occurrence. As a part of this effort, NBRO currently uses a numerical evaluation system to assess the overall landslide hazard of a given site (NBRO User Manual, 1995). Performing detailed slope stability evaluation based on analytical methods has been excluded from NBRO's mapping programme, since it is uneconomical at the selected scale of mapping.

4. METHODOLOGY

The deterministic slope stability model used in this study to assess the instability conditions and to establish a landslide hazard zonation map is called Stability INdex MAPping (SINMAP), which was developed by Pack et al. (1995). SINMAP is a raster based slope stability predictive tool based on coupled hydrological-infinite slope stability model. This approach applies to shallow translational landsliding phenomena controlled by shallow ground water convergence (SINMAP User Manual, 1998). Figure 2 shows a schematic diagram of the methodology used for this study.

The input data required for this model are

- (i) inventory of past landslides in a point vector format,
- (ii) Digital Elevation Model (DEM) of the study area,
- (iii) geotechnical data such as soils strength properties, thickness of soil above the failure plane, and
- (iv) hydrological data such as soils hydraulic conductivity and the rainfall.

A part of the required data was available within various organizations of the country and in order to collect the data that was not already available, a field reconnaissance study was carried out within the study area under the sponsorship of Japan Aerospace Exploration Agency (JAXA).

4.1. DATA COLLECTION

4.1.1 Inventory of Past Landslides

Accurate positioning of the initiation zones of known landslides is important for the accuracy of the output of this model. As part of its Landslide Hazard Mapping Project (LHMP), NBRO had prepared a 1: 10,000 scale landslide inventory map for the Ratnapura area in 1998. During the JAXA sponsored field study, a GPS survey was carried out to locate the landslides and other forms of slope failures that occurred recently (Table 1) and to update the existing landslide inventory map.

4.1.2 Digital Elevation Model (DEM) grid theme

The accuracy of the output is highly dependent on the accuracy of the DEM also. In order to generate a digital elevation model, satellite data such as ALOS, Aster, SRTM were searched for and as cloud free, recent, high-resolution satellite images of the study area were not available during the time of study, 1: 10,000 scale contour map with 10m contour intervals prepared by the Survey Department of Sri Lanka was used for Digital Elevation Model (DEM) (Figure 3). According to the Survey Department, these contour data is derived from 1:20,000 Aerial photographs using photogrammetry. Arc View 3D Analyst extension was used for creating the DEM grid.

Figure 2 Schematic diagram of the methodology used

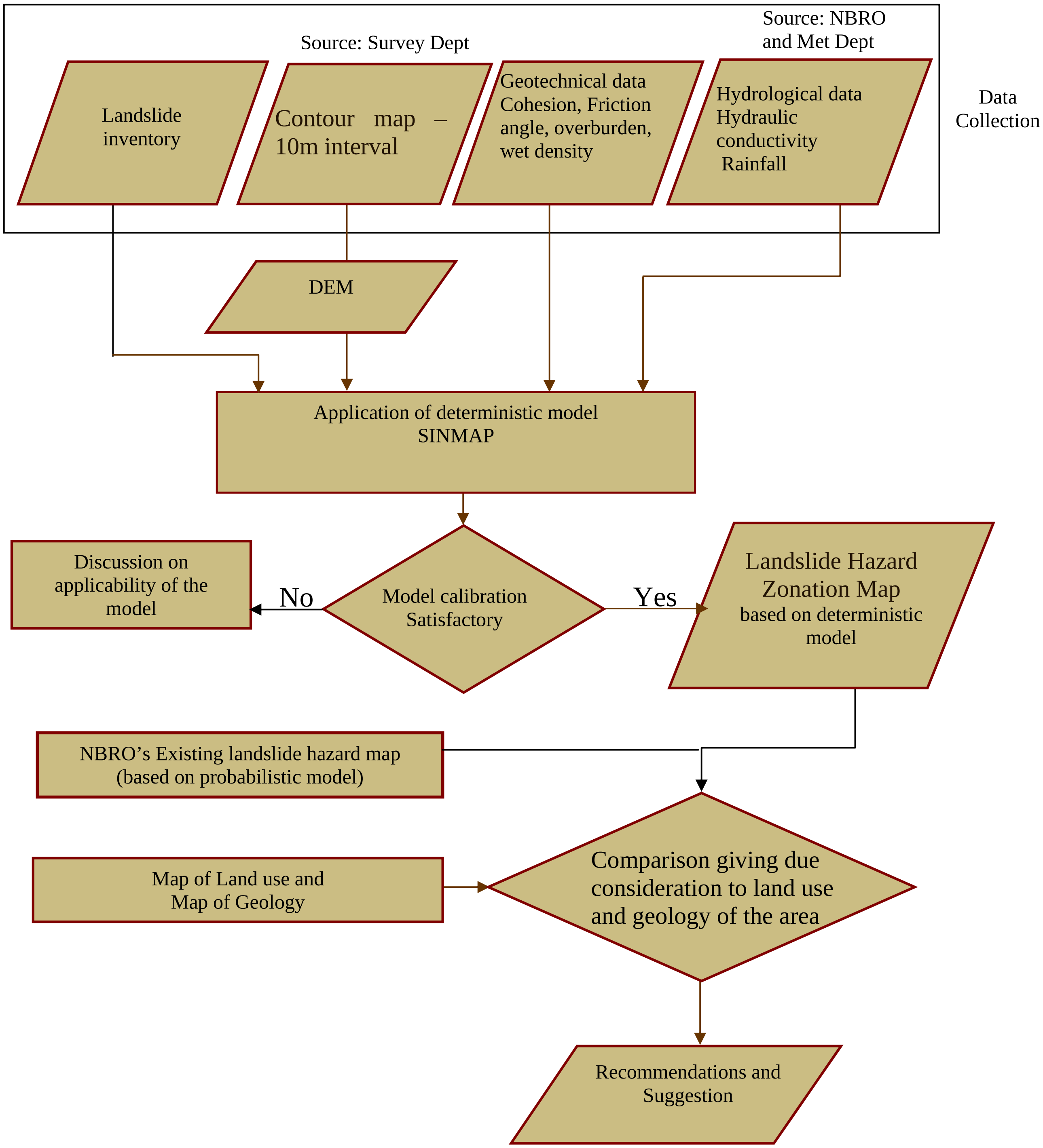
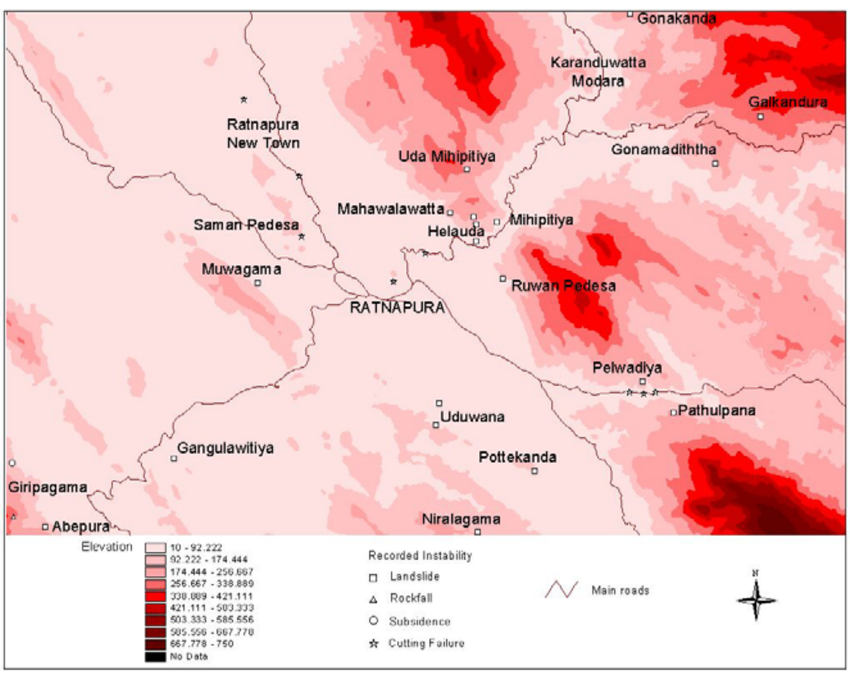


Table 1. Inventory of slope failures recorded within the study area

Ref	Location	Lattitude			Longitude			Type	Code
		d	m	s	d	m	s		
1	Uda Mihipitiya	80	25	8	6	42	7	Landslide	1
2	Mahawalawatta	80	24	58	6	41	40	Landslide	1
3	Helauda	80	25	12	6	41	38	Landslide	1
4	Helauda	80	25	14	6	41	22	Landslide	1
5	Helauda	80	25	14	6	41	33	Landslide	1
6	Mihipitiya	80	25	27	6	41	35	Landslide	1
7	Gonakanda	80	26	49	6	43	44	Landslide	1
8	Karanduwatta/Modara	80	26	44	6	43	1	Landslide	1
9	Galkandura	80	28	10	6	42	40	Landslide	1
10	Gonamadiththa	80	27	42	6	42	11	Landslide	1
11	Ruwan Pedesa	80	25	30	6	40	59	Landslide	1
12	Uduwana	80	24	49	6	39	28	Landslide	1
13	Uduwana	80	24	51	6	39	42	Landslide	1
14	Pottekanda	80	25	50	6	39	0	Landslide	1
15	Kolandagala, Pathulpana	80	27	16	6	39	36	Landslide	1
16	Abepura	80	20	46	6	38	25	Landslide	1
17	Gangulawitiya/Elapath	80	22	7	6	39	7	Landslide	1
18	Giripagama rock fall	80	20	27	6	38	31	Rock fall	2
19	Giripagama subsidence	80	20	25	6	39	4	Subsidence	3
20	Niralagama	80	25	15	6	38	21	Landslide	1
21	Saman Pedesa CF	80	23	25	6	41	25	Cutting Failure	4
22	Pelwadiya CF1	80	26	49	6	39	49	Cutting Failure	4
23	Pelwadiya CF2	80	26	58	6	39	48	Cutting Failure	4
24	Pelwadiya	80	26	57	6	39	55	Landslide	1
25	Pathulpana CF	80	27	5	6	39	49	Cutting Failure	4
26	Helauda CF	80	24	42	6	41	15	Cutting Failure	4
27	Inner Circular Road C	80	24	23	6	40	58	Cutting Failure	4
28	Colombo Rd CF	80	23	23	6	42	3	Cutting Failure	4
29	Ratnapura New Town CF	80	22	49	6	42	51	Cutting Failure	4
30	Muwagama	80	22	58	6	40	56	Landslide	1

Figure 3 Digital Elevation Model of the Study Area



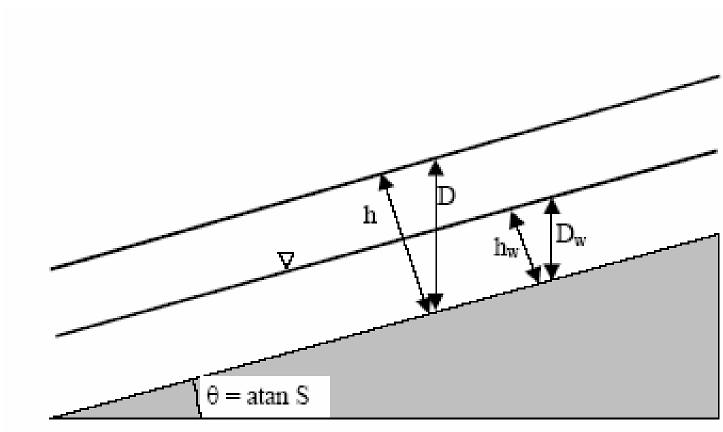
4.1.3 Geotechnical Data

Cohesion index (dimensionless cohesion factor) and the soils internal friction angle are the geotechnical data input into the model. Cohesion index is the relative contribution of soil and root cohesive forces combined to slope stability. During the above mentioned field study, observations on past landslides revealed that, the failure surfaces of almost all the landslides within the study area were found below the root zone. Therefore, for this study, cohesive forces of soil (C_s) only were considered.

$$\text{Cohesion Index (C)} = C_s / (h\rho_s g)$$

Where, h is the thickness of the soil above the failure surface (Figure 4). Due to the time limitations, performing triaxial or direct sheer tests to determine the strength properties of soil was difficult. Therefore, during the JAXA sponsored field study, disturbed soil samples were taken at the locations of failed slopes, and laboratory tests were performed to determine the soil classifications. The resulted index properties were then correlated with the shear strength parameters given in the report on "Detailed Assessment of Unsupported Earth Cuttings in the Residual Soils and Colluviums at the Ratnapura Municipal Council Area" (SLUMDMP, 1998). As the geotechnical data input into the model are considered to be highly variable in both space and time, they are input to SINMAP in terms of upper and lower bounds on the range of values they may take. Table 2 indicates the lower and upper bound parameter values used for this SINMAP model.

FIGURE 4 Scematic diagram of slope stability model (SINMAP User Manual, 1998)



4.1.4 Hydrological data

Hydrological data are input into the model in the form of a wetness index (T/R) parameter. According to the SINMAP Manual (1998), this parameter (T/R) is considered as the length of hill slope required to develop saturation in the critical wet period. T is the transmitivity or the vertical integral of the hydraulic conductivity of soil and is determined by

$$T = (k_S)^* h$$

Where k_S is the hydraulic conductivity or the permeability of the soils and h is the thickness of the soil above the failure surface (Figure 4). The SLUMDMP Report (1998) lists the upper and lower bound permeability values of the soil for Ratnapura town area and those values were used for computation of transmitivity values. As also observed during the field study, the thickness of the soil above the failure surface varies within the study area and therefore, different calibration regions with different h values (Table 2 and Figure 5) were used in the model.

The steady state recharge (R) can be defined as

Rainfall – (Evapo-transpiration + Infiltration)

For this study, evapo-transpiration and infiltration are assumed as negligible. Previous landslide studies in Sri Lanka reveal that, Sri Lankan landslides are activated by low intensity longer duration rainfall. The established threshold rainfall value that triggers Sri Lankan landslides is 200 mm per 3 days. In order to find out suitable values for steady state recharge, the daily rainfall values issued by the Meteorological Department of Sri Lanka were studied. After studying the landslide inventory and the rainfall data within 10 years (year 1996 – year 2005) average daily rainfall within six days from May 12, 2003 to May 17, 2003, which was the maximum six-day average within above 10 years, was used as the upper bound value of R. The six- day average daily rainfall from Aug 3, 2000 to Aug. 9, 2000, which was the minimum six-day average within the above 10 years, was used as the lower bound value of R. (Table 3).

Table 2. Parameter values used for each region of the multi-region calibration theme

Region	Type	h	Sat. Density	Combined Cohesion		Dimensionless Cohesion		Friction Angle		Hydraulic Conductivity ks		Transmitivity T = ks * Ob		Recharge R		T/R	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
		m	kg/m^3	Kpa	Kpa			deg	deg	m/sec	m/sec	m^2/day	m^2/day	mm/day	mm/day	m	m
1	FA	1	1800	10	20	0.566	1.133	20.8	36	1.00E-06	1.00E-05	0.086	0.864	23	100	0.86	37.57
2	Residual	2	1800	10	20	0.283	0.566	20.8	36	1.00E-06	1.00E-05	0.173	1.728	23	100	1.73	75.13
3	Residual	8	1800	10	20	0.071	0.142	20.8	36	1.00E-06	1.00E-05	0.691	6.912	23	100	6.91	300.52
4	Coluvium	1	1750	2	12	0.116	0.699	20.8	36	1.00E-06	1.00E-05	0.086	0.864	23	100	0.86	37.57
5	Coluvium	3	1750	2	12	0.039	0.233	20.8	36	1.00E-06	1.00E-05	0.259	2.592	23	100	2.59	112.70
6	Coluvium	8	1750	2	12	0.015	0.087	20.8	36	1.00E-06	1.00E-05	0.691	6.912	23	100	6.91	300.52

4.2. EXECUTION OF SINMAP

4.2.1.Calibration regions theme

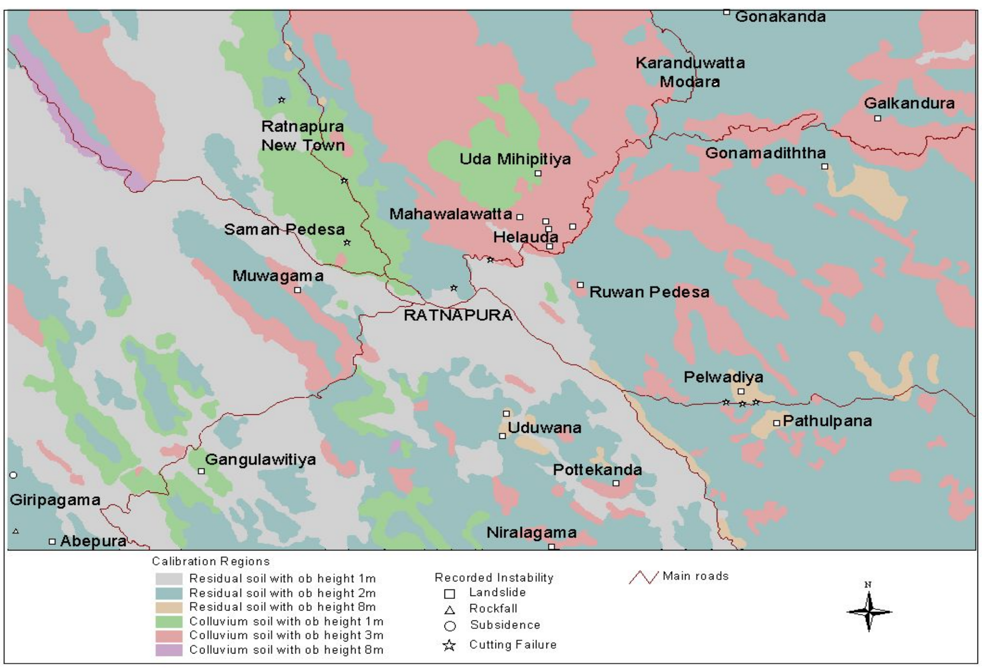
The calibration regions are areas within which single lower bound and upper bound calibration parameter values can represent wetness index (T/R), cohesion index (C), and friction angle (ϕ).

The basic properties of soil found in this region indicate that the study area consists of residual soil, which is formed by in-situ weathering of the bedrock and colluviums, which are formed by the transported debris of past slope instability. Colluviums are considered to be geotechnically weaker than residual soil. The thickness of the soil above the failure surface also varies within the study area. As part of NBRO's LHMP, a state of nature map of soil overburden deposits had been prepared for this study area. This map reflects the distribution of different soil types and different soil thickness values within the study area and was used as the calibration region grid theme for this model (Figure 5).

Table 3. 6-day average of daily rainfall from the year 1996 to the year 2005

Year		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Dates		June 16-22	Sep10-16	May7-13	April 14 - 20	Aug 3 - 9	Nov 18 - 24	Oct 19 - 25	May 12 - 17	Oct 1 - 7	Oct 6 - 12
Rainfall mm/day		3.1	7.7	9.9	5.6	22	0.6	65.6	135.8	104.8	22
		392.5	6	5.5	7.6	9.5	31.8	60.9	8.6	2.4	24.5
		31.5	39.2	3.1	17.2	16	28.2	4.6	8	30.6	28.5
		52.2	118.6	16.8	42.3	55.8	100.2	2.1	0.9	11.7	27.4
		2.6	7.1	79.1	75.9	21.6	1.6	26.8	99.6	23.8	4.4
		8.8	169.7	34.3	1.3	13.2	21.1	12.4	345.2	0.3	104.7
Average		81.78	58.05	24.78	24.98	23.02	30.58	28.73	99.68	28.93	35.25
						Selected lower bound R			Selected upper bound R		

Figure 5 Calibrations regions theme



4.3. COMPARISON WITH NBRO'S LANDSLIDE HAZARD ZONATION MAP

The landslide hazard zonation map prepared by this deterministic SINMAP model was compared with the landslide hazard zonation map prepared by NBRO to validate the applicability of SINMAP model to the selected study area.

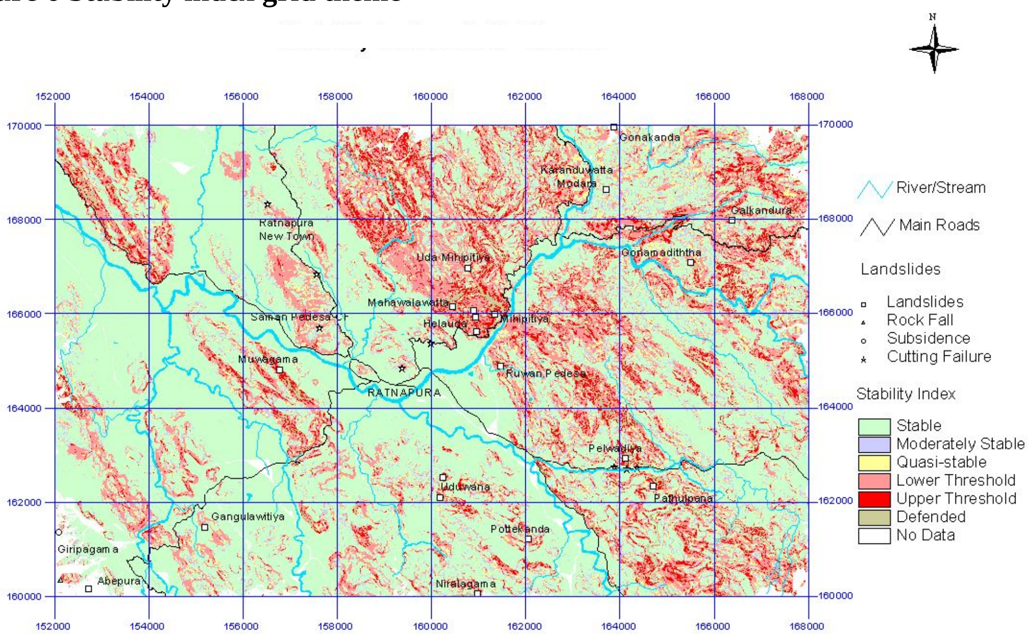
5. RESULTS AND DISCUSSION

5.1 Stability Index Grid Theme

The primary output of the model is a stability index, which is a numerical value, which is used to classify the terrain stability for each grid cell of the study area. The stability index (SI) is defined as the probability that a location is stable assuming uniform distribution of the parameters over their uncertainty ranges. This SI value ranges between 0 (most unstable) and 1 (least unstable). Table 4 shows the, broad stability classes defined in terms of SI values.

The Stability Index Grid theme (Figure 6) can be used as the landslide hazard zonation map, which defines the potential areas of slope instability. The grid cells found within the stability classes identified as lower threshold, upper threshold and defended have SI values less than 1 and can be considered as naturally unstable. The grid cells found within quasi-stable zone have SI values between 1.0 and 1.25 and indicate marginal instability. The grid cells found within moderately stable and stable zones have SI values higher than 1.25 and can be considered as stable.

Figure 6 Stability index grid theme



As the NBRO's existing landslide hazard zonation map (Figure 2) represent only four hazard zones, the stability classes found in this Stability Index grid theme were regrouped into four stability classes as shown in Figure 7, only to compare this map with the NBRO's map. Table 5 indicates the methodology used to regroup the Stability Index grid theme into four stability classes.

Table 4 Stability Class Definition (SINMAP User Manual, 1998)

Conditions	Class	Predicted State	Parameter Range	Possible Influence of Factors Not Modeled
SI > 1.5	1	Stable slope zone	Range cannot model instability	Significant destabilizing factors are required for instability
1.5 > SI > 1.25	2	Moderately Stable zone	Range cannot model instability	Moderate destabilizing factors are required for instability
1.25 > SI > 1.0	3	Quasi-stable slope zone	Range cannot model instability	Minor destabilizing factors could lead to instability
1.0 > SI > 0.5	4	Lower threshold slope zone	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
0.5 > SI > 0.0	5	Upper threshold slope zone	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
0.0 > SI	6	Defended slope zone	Range cannot model stability	Stabilizing factors are required for stability

To compare the NBRO's Landslide Hazard Zonation map (Figure 2) with reclassified Stability Index grid theme (Figure 7), only the instabilities recorded after 1998 were considered, because the NBRO's methodology which is mainly based on field observations automatically assign the highest hazard ratings to the existing failures by the time of mapping. Table 6 indicates predicted hazard zones of the grid cells/polygons where instability has been recorded after 1998.

Figure 7 Stability index grid theme classified into four stability classes

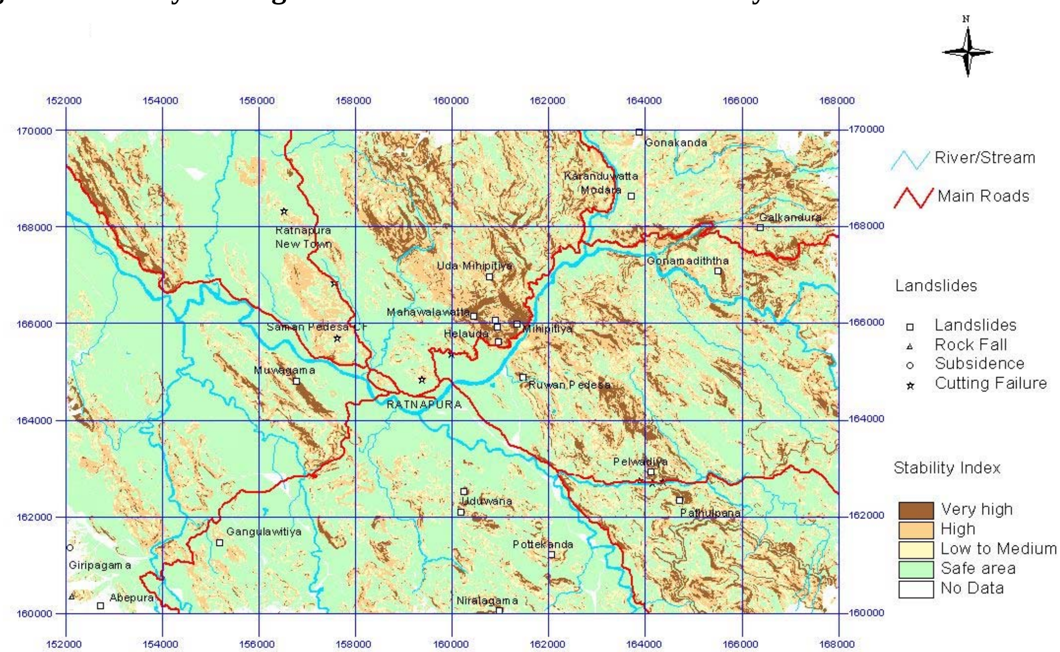


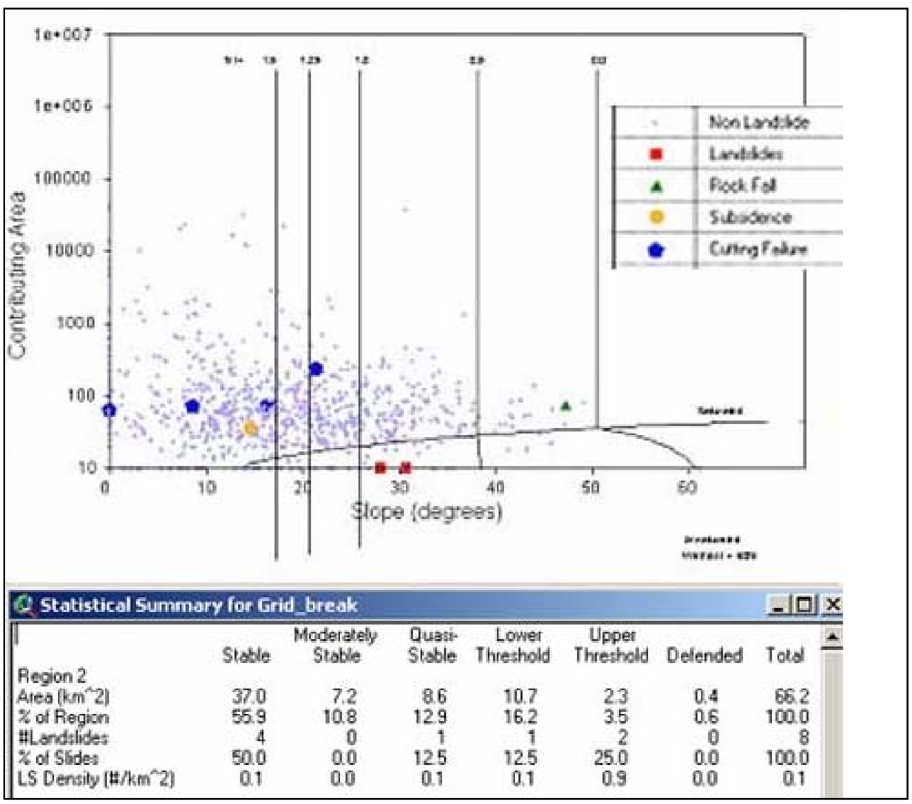
Table 5. The methodology used to regroup the Stability Index grid theme into four stability classes

Conditions	Class	Predicted State as indicated in Table 4	Reclassified predicted sate
SI > 1.5	1	Stable slope zone	Safe area
1.5 > SI > 1.25 and 1.25 > SI > 1.0	2	Moderately Stable zone and Quasi-stable slope zone	Low to medium level hazard
1.0 > SI > 0.5	3	Lower threshold slope zone	High hazard
0.5 > SI > 0.0 and 0.0 > SI	4	Upper threshold slope zone and Defended slope zone	Very high hazard

5.2 Slope-Area Plot Chart (SA)

As part of the outputs, the software also generates a slope area chart (SA plot) and a statistical summary for each region of the study area to aid in the data interpretation and parameter calibration. The SA Plot provides a view of study data in slope area space. As an example, the resulted SA plot and the statistical summary for calibration region 2 only are shown in Figure 8. Results of the execution of SINMAP model are summarized in Table 7 and Table 8.

Figure 8. SA plot and statistical summary for Region 2 of the study area



	Stable	Moderately Stable	Quasi-Stable	Lower Threshold	Upper Threshold	Defended	Total
Region 2							
Area (km^2)	37.0	7.2	8.6	10.7	2.3	0.4	66.2
% of Region	55.9	10.8	12.9	16.2	3.5	0.6	100.0
#Landslides	4	0	1	1	2	0	8
% of Slides	50.0	0.0	12.5	12.5	25.0	0.0	100.0
LS Density (#/km^2)	0.1	0.0	0.1	0.1	0.9	0.0	0.1

Table 7 indicates that about 65% of the study area has been identified as stable by the SINMAP model and about 26% of the study area has been identified as unstable. Another 9%

of the study area shows marginal instability as this area can become unstable due to minor destabilizing forces. Table 8 indicates that this model has predicted the past landslides and other forms of slope failures found in the landslide inventory with 72% accuracy. Another 7% of such failures have been predicted with marginal reliability by this model. The model has failed to predict 21% of the inventoried slope instability

Table 6. A comparison of hazard levels predicted by NBRO's methodology and the SINMAP model in the areas associated with slope instabilities that occurred after 1998

Place of instability	Type of instability	Date of Occurrence	Predicted Instability	
			NBRO's map	SINMAP
Muwagama	Landslide	May 17, 2003	High hazard	Very high hazard
Abepura	Landslide	May 17, 2003	High hazard	No data region
Niralagama	Landslide	May 17, 2003	High hazard	High hazard
Pelwadiya	Landslide	May 17, 2003	Low to medium	Very high hazard
Gangulawitiya	Landslide	May 17, 2003	Low to medium	High hazard
Pelwadiya	Cutting failure - 1	May 17, 2003	Low to medium	Safe area
Pelwadiya	Cutting failure - 2	May 17, 2003	Safe area	Safe area
Pelwadiya	Cutting failure - 3	May 17, 2003	Safe area	Safe area
Hela Uda	Cutting failure	May 17, 2003	Low to medium	Low to medium
Ratnapura town	Cutting failure - 1	May 17, 2003	Low to medium	Safe area
Ratnapura town	Cutting failure - 2	May 17, 2003	Low to medium	High hazard
Ratnapura town	Cutting failure - 3	May 17, 2003	Low to medium	Low to medium
Saman Pedesa	Cutting failure - 3	May 17, 2003	Low to medium	High hazard
Giripagama	Rock fall	May 17, 2003	Safe	Very high hazard
Giripagama	Subsidence	May 17, 2003	Low to medium	Safe area
Predicted overall Reliability			20%	50%

Table 7. Summary of statistics of the area (in sq km) found in different stability classes

Region	Stability Class						Total Area in the Region
	Stable	Moderately Stable	Quasi Stable	Lower threshold	Upper threshold	Defended	
1	37.9	0.2	0.1	0.0	0.0	0.0	38.3
2	37.0	7.2	8.6	10.7	2.3	0.4	66.2
3	0.5	0.1	0.2	0.5	0.7	0.1	2.3
4	5.3	0.9	1.5	5.3	0.3	0.0	13.4
5	8.4	1.8	3.0	11.4	6.0	1.4	32.0
6	0.2	0.0	0.1	0.4	0.3	0.1	1.1
Total area in the Stability class	89.5	10.2	13.5	28.4	9.6	2.0	153.3
% area in the Stability class	58.40%	6.67%	8.83%	18.51%	6.28%	1.31%	100.00%
General stability	65% Stable		9% Marginal	26% Unstable			

Table 8. Summary of statistics of the area (in sq km) found in different stability classes

Region	Stability Class						Total Landslides in the Region
	Stable	Moderately Stable	Quasi Stable	Lower threshold	Upper threshold	Defended	
1	0	0	0	0	0	0	0
2	4	0	1	1	2	0	8
3	1	0	0	0	2	3	6
4	0	0	0	3	0	0	3
5	1	0	1	4	3	3	12
6	0	0	0	0	0	0	0
Total landslides in the Stability class	6	0	2	8	7	6	29
% landslides in the Stability class	20.69%	0.00%	6.90%	27.59%	24.14%	20.69%	100.00%
General reliability	21% in Stable		7% Marginal	72% in Unstable			

Out of the 6 inventoried slope instabilities that the model has failed to predict, 1 is a very old landslide recorded before 1993 in Helauda area and, as a result, the morphology of the surrounding terrain has become flat and the slide has become relict at present. Therefore, the predicted stability of the model for this location can be considered as acceptable. Out of the remaining 5 slope instabilities found within the stable zone, 1 is a subsidence and the location of the same is not the location of the point of initiation of this instability. During the field reconnaissance study, the point of initiation of this subsidence could not be recorded, due to the difficulty in access to the steeper slopes above. These difficulties could have been overcome, if high-resolution satellite images such as ALOS were available. The remaining 4 instabilities, which the SINMAP model has failed to predict, are cutting failure i.e. failures on modified slopes. The reason that those 4 cutting failures have been fallen within stable zone can be assumed as that these man made slopes are not well represented in the DEM at the 10 m accuracy level.

The comparison in Table 6 indicates that the SINMAP model has predicted 50% the landslides that occurred in the study area after 1998, whereas NBRO's model had predicted only 20% of the same. Therefore, it seems that SINMAP model has better reliability in predicting slope instabilities in this area. Therefore, it can be assumed that the natural causative factors such as Geology, Thickness of soil layer above bedrock, Slope angle range, Hydrology, and Land forms are reasonably represented in SINMAP model also. Therefore, it is reasonable to assume that the SINMAP model can be utilized as a tool for identification of landslide hazard zones in this area. The results of this model can be further improved by developing it to incorporate anisotropic heterogeneous nature of the material, improving the accuracy of DEM by using high-resolution data such as ALOS, and accurately mapping the points of initiation of observed slope failures.

6.0 CONCLUSION

The deterministic slope stability evaluation tool, SINMAP was successfully used for assessment of landslide hazards in Ratnapura town area in Sri Lanka. This area is often subjected to severe landslides during the rainy season. The results of this study show that 72% of the recorded instabilities in the study area are found within the zones that are predicted as unstable. 28% of the observed failures are located within areas classified as stable and quasi-stable zones. These results reflect that, SINMAP model has its own limitations in modeling the highly complex and variable landslide phenomena and the impact of slope modifications that are not represented in the mapped level of accuracy or other human activities such as inappropriate land use practices, which have reduced the stabilizing forces of the slopes leading to landslides.

The comparison SINMAP model with NBRO's existing model indicates that SINMAP model has better reliability in predicting slope instabilities in this area. Therefore, it can be assumed that the natural causative factors such as Geology, Thickness of soil layer above bedrock, Slope angle range, Hydrology, and Land forms are reasonably represented in SINMAP model also. Therefore, it is reasonable to assume that the SINMAP model can be utilized as a tool for identification of landslide hazard zones in this area. The results of this model can be further improved by developing it to incorporate anisotropic heterogeneous nature of the material, improving the accuracy of DEM by using high-resolution data such as ALOS, and accurately mapping the points of initiation of observed slope failures.

Based on this analysis, it is reasonable to take that SINMAP would be a practical tool for identification of landslide hazard zones within the study area. However, the output of this model should be complemented with a detailed geotechnical and geological evaluation of the site. Remedial measures should be taken to minimize the risk at areas that have been delineated as Unstable. Restricted land use practices should strictly be imposed in these areas. The areas that have been identified as Quasi-stable or Moderately stable can be developed with controlled land use practices and well-engineered construction practices. No regulations are required for developing the stable regions. However, it is important to increase the awareness of people who utilize the mountainous areas, in general, regarding the possible causes of slope instability and the importance of applying better land use practices and construction practices.

ACKNOWLEDGEMENT

Authors would like to acknowledge the financial and technical support provided by the Japan Aerospace Exploration Agency (JAXA) and the Geo Informatics Center (GIC) of the Asian Institute of Technology (AIT) in executing this study. They also acknowledge the support provided in collecting necessary data by the Survey Department of Sri Lanka and the National Building Research Organisation (NBRO) of Sri Lanka.

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