Quantitative Slope Stability Mapping With ArcGIS: Prioritize Highway Maintenance

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Abstract

Use of GIS in hazard zonation mapping is popular. However, quantitative hazard assessment is still not well practiced. AcrGIS was used to calculate the safety factor of the slopes along 16 km highway stretch of Nepal that used to be closed for several weeks in rainy season every year due to landslides. Automated 3D FOS (factor of safety) of slope, calculated by using ArcGIS extensions, was used to prepare roadside protection priority map for the studied stretch. Input of soil test data, geological distribution, hydrological information and topographical information with automated algorithm to estimate realistic slope instability coefficient was the basis for the preparation of roadside maintenance priority map. Likewise, average FOS along each slope unit of the stream was used to predict the bridges and other cross drainage structures at danger. The roadside maintenance and bridge protection priority map is a handy tool for the highway maintenance authorities in the developing countries.

1 BACKGROUND INFORMATION

Various types of mass movements such as landslides, slope failures, debris flows and so on are some of the major natural disasters that frequently occur in the hilly and mountainous terrains. Precipitation is supposed to be the major triggering factor for such hazards. Anthropogenic activities such as deforestation for settlements, cultivations on sloping terrain, quarrying and toe cutting for roadways also enhance their occurrences.

Although the occurrence of these disasters cannot be prevented completely, the magnitude of impact in terms of loss of lives and destruction of properties can be lessened through proper considerations on the causes and application of appropriate countermeasures against such disasters.

Investigation of geology and geomorphology of the area before the planning of infrastructure and preparation of hazard susceptibility map using GIS are quite popular. Those maps ease in planning of infrastructures before the construction. However, in many countries majority of the infrastructures, especially highway alignments are or have already been established considering various obligatory aspects, taking or without taking such hazard maps into consideration. Blockade of such highways due to mass movement obviously malfunction the transportation network and possess high risk of damage to lives and properties. Deterministic hazard susceptibility analysis method based on shear strength of soil in such area is beneficial to plan the counter measures against such movements. Thanking to the present development in the multidimensional use of ArcGIS tools, we can easily conduct such deterministic analyses using ArcGIS tools, although it has not been practiced yet. Considering such necessity and possibilities, a slope instability mapping based on geomorphological characteristics and soil strength properties was carried out in Jogimara area, which covers about 16 Km length of Prithiwi Highway, Nepal (Fig. 1). The main objectives of this study are: to develop the simplified model for the stability analysis based on actual 3D failure mechanism to prepare instability potential mapping of large area using ArcGIS tools; and to recommend the risk bility potential mapping of large area using ArcGIS tools; and to recommend the risk prone area for the planning of the countermeasures with priorities to the concerned organization.

2 STUDY AREA

Krishanabhir-Kurintar sector of Prithvi highway of Nepal (Fig. 1), which is suffered from frequent slope failure problems every year, has been considered for this study. This sector is a part of two hundred kilometers long Prithvi highway of Nepal, which connects Kathmandu, the capital with the tourist city, Pokhara. Landslides and other mass movements in every rainy season, which block the highway, sometimes for several days (Bhattarai et. al, 2001), are the chronic problems of this highway (Photo 1). Due to the lack of information on potential failure sites, road clearance equipments are neither properly placed nor the pre-monsoon failure prevention strategies are well considered.

Photo 1: Krishnabhir landslide one of the troublesome landslides along study stretch

The study of geological map shows the rocks of Midland group (Upper Precambrian to late Paleozoic) of Lakharpata sub group (Lakharpata formation, Syanja formation, Sangram formation and Galyang formation) underlie the study area. Limestone, shale, slate, phyllites and dolomites are the main dominant rocks along the alignment. Several major fault/thrust lines pass over the area.

The average drainage density of the study area is about 3.26Km/Km^2. Many large small streams along both side of highway dissect the area. There are numerous slope failures along the catchments of these streams. Those slope failures are responsible for huge volume of mass movements downstream.

Figure 1 Prithiwi highway and study area of this research

3 SLOPE STABILITY MODEL

Owing to the complex nature of mass movement, the exact configuration of the movement and its volume is very difficult to predict. However, depending on the ground condition and with some analytical assumptions, suitable theoretical models could be generated for the analysis. In many investigations of natural slope stability, infinite slope analysis had frequently been used because of its relative simplicity (Wu et al., 1995), particularly where the thickness of the soil is much smaller than the length of the slope. However, for realistic modeling, 3D failure mechanism should be considered. Use of ArcGIS advantageously allows calculations based on the square cells. However, 3D circular failure includes different depth of sliding surface throughout the slope failure mass. Therefore, some concept should be developed to allocate the equivalent depth of 1D plane failure based on the same value of safety factor. This research was followed with this concept. Use of Monte Carlo random search throughout the study area may give the cells with analytical factor of safety. However, this necessitates very complicated programming and a large number of input parameters for the accurate results. In order to simplify the stability analysis process in GIS, geometry of more than 100 numbers of existing slope failures were recorded. The geometrical information in 3D for these slope failures were input in the ArcGIS analytical tool. Assessing factor of safety of these slopes equal to unity, average 1D depth of the sliding surface of 3D slope failures were back calculated. These depths were grouped according to the geological and geomorphological conditions of the study area.

Soeters and Westen (1996) recommended to use infinite slope stability analysis of each cell in order to conduct the large area deterministic analysis. However, such average calculated factor of safety may not represent the factor of safety of actual 3D failure surface. Besides, due to the complication in establishing vertical depth of failure in using Monte Carlo method, a simplified approach, as explained above has been considered by reducing 3D depth to 2D equivalent depth based on equal factor of safety. However, for automated calculation in wide area, it is not that simple even to analyze 2D rotational slide due to variation in depth of sliding surface. Hence, 2D depth of rotational slide was then converted to equivalent translational depth keeping the same factor of safety as shown in fig. 2.

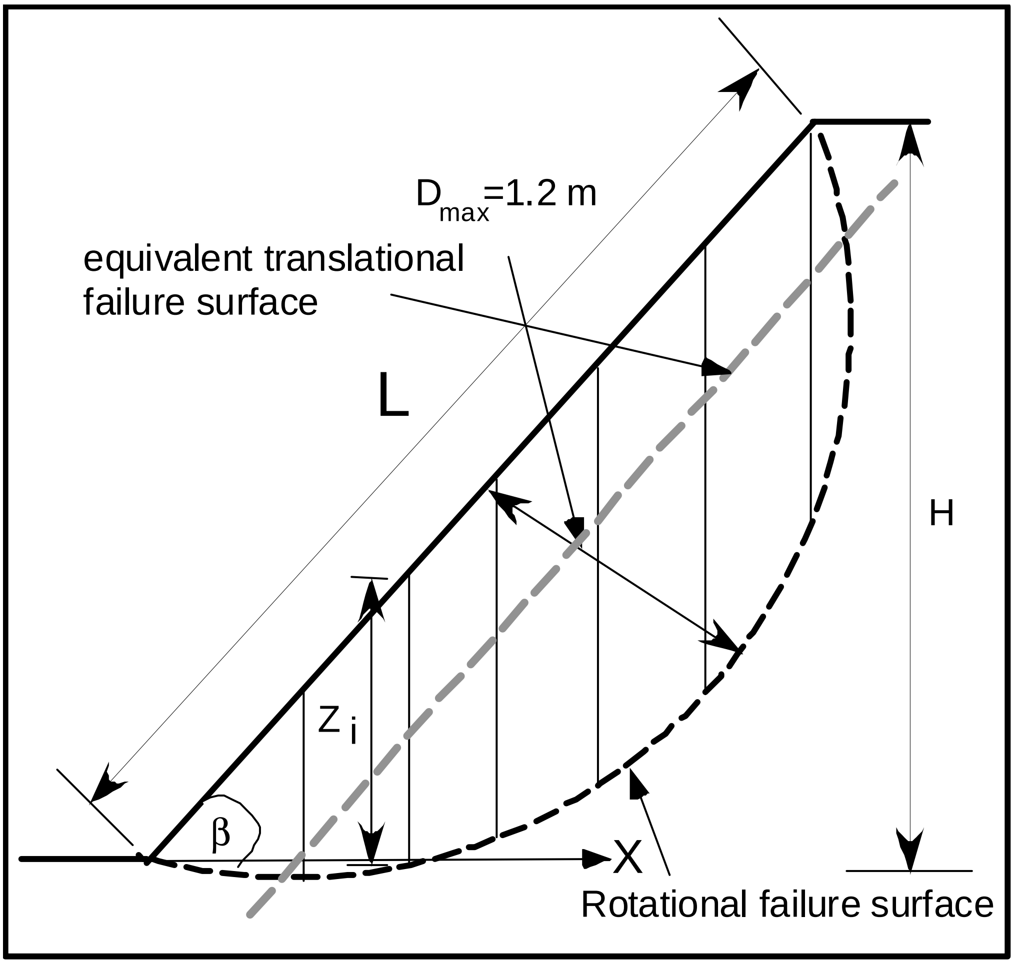

Figure 2 Conversion of depth of rotational failure (2D analysis) to the depth of equivalent translational failure (1D analysis)

$$FS(rotational) = \frac{c + \gamma.\tan\phi \sum_{i-1}^{x} z_i * \cos^2 \beta}{\gamma \sum_{i-1}^{x} z_i .\sin\beta * \cos\beta}$$

$$FS(translational) = \frac{c + \gamma.z.\cos^2 \beta * \tan\varphi}{\gamma.z.\sin\beta * \cos\beta}$$

Where,

γ unit weight of soil
z depth of failure surface below the terrain surface
γ_w unit weight of water
β the terrain surface inclination
ϕ angle of internal friction
c cohesion

3.1 Acquisition of the Slope Stability Parameters

The necessary input parameters in the above model are slope (β), the soil properties (c, ϕ, γ), depth of failure surface and ground water depth/soil thickness ratio (m). The concept of acquisition for those parameters has been briefed below.

3.1.1 Cohesion and internal frictional angle

Soil samples as well as rock pieces were collected from 176 different locations throughout the study area, dividing the area into equally spaced sampling grids as far as possible. As the types of rock in the study area were briefly understood from the geological map, emphasis was given to collect the residual soil samples representing all of the rock types. At least one sample was collected from the recorded existing slope failure areas. Likewise, at least one sample was collected from one petrological region. A series of different soil tests were conducted to find the densities (field, saturated and dry), consistency limits, water content, particle size distribution, specific gravity, shear strength (peak and residual), and mineralogical composition of the sampled specimens. Several researchers, Marui and Tiwari (2004), Tiwari and Marui (2004, 2003, 2001), Stark and Eid (1994), Mesri and Diaz (1986), Skempton (1985), Lupini et al. (1981), argued on strong relationship between residual ϕ and the index properties of soil. Tiwari and Marui (2004), Lupini (1981), Kenny (1977), mentioned that residual ϕ depends on mineralogy and Mitchel (1993) mentioned that mineralogy depends on parent rocks type. Therefore, after measuring the index properties the values were compared with rock types of each sampling location. All test results of the soil samples could be clearly divided into 10 groups according to liquid limit and rock types. Shear strength was measured by simple shear device. The tests were conducted under drained condition using 100mm diameter and 25mm thick specimen. Samples were mixed with water content 10% higher than plastic limit and kept at least 72 hours for saturation. Due to the limitation of the device, the residual shear strength has been considered for 20mm displacement although in some cases, the shear strength measured were observed to be in between fully softened and residual values. Value of c and ϕ for peak and fully softened stages were also measured. There was very good agreement between the values of c and ϕ in each petrological region. Therefore, average value of ϕ was was calculated for each type of rock. From available 1:250,000 scale geological map, distribution of each rock was identified and the distribution map for ϕ was prepared based on the average ϕ. The distribution map of cohesion was also prepared similarly.

Unlike landslides, undisturbed peak shear strength plays a significant role in slope failures during failures. However, due to the field investigation in dry season undisturbed sampling may not represent the field condition during rainy season. As the soil samples were low plasticity silts, the variation of measured peak and residual shear strength was not considerably high. This agreed with the concept postulated by Tiwari and Marui (2002), Bromhead (1992), Skempton (1985), Lupini et al. (1981). It was verified in almost all of the soil test results (Table 1). There were less than 10% variation between residual and peak ϕ. Therefore, for the analysis to be in safer side, residual shear strength has been considered. Residual ϕ had very good correlation with liquid limit and mineralogical composition.

Table 1: Values of residual and peak internal friction angle (ϕ) for 10 petrological regions

Petrological zone	ϕ(peak), deg	ϕ(residual), deg
Zone 1	24	22
Zone 2	32	31
Zone 3	28	26
Zone 4	28	27
Zone 5	21	20
Zone 6	35	33
Zone 7	27	26
Zone 8	28	28
Zone 9	26	24
Zone 10	26	23

3.1.2 Soil Density (γ) and Density of water (γ_w)

The density of soil varies from place to place. It depends on in situ condition. In this study, the value of γ was mapped according to the γ of each soil sampling point. Value of γ was then distributed according to the equi-γ line made by using ArcGIS Spatial Analyst and 3D Analyst. The Unit weight of water was taken as 9.81 KN/m^3.

3.1.3 Slope Gradient (β)

The value of the slope (β) was derived from digital elevation model (DEM). A 1:25,000 scale topographic map of the study area with 20 m contour interval was geo-referenced and digitized. This digitized contour map was then utilized to make DEM through the preparation of Triangulated Integrated Network (TIN) using Arc GIS 3D Analyst. The slope map of 1m x1m cell size was then prepared directly from Digital elevation model (DEM) using ArcGIS spatial analyst tool. This method is commonly used in generating slope map using GIS.

3.1.4 Depth of terrain surface (Z)

The average depth of the possible sliding zone based on the equal safety factor method, explained above, was grouped for each petrological region, as there was less than 18% variation in the average depth of the slides in those regions. These values at each cell were used for automated factor of safety calculation. The revised 1D slope stability model is shown in Fig. 3.

$$FS = \frac{c + (\gamma - m * \gamma w) * z * \cos^2\beta * \tan\phi}{\gamma * z * \sin\beta * \cos\beta}$$

Where,

γ	unit weight of soil
m	ground water depth/soil thickness ratio (z_w/z)
z_w	height of water table above failure surface
z	depth of failure surface below the terrain surface
γ_w	unit weight of water
β	the terrain surface inclination
ϕ	angle of internal friction
c	cohesion

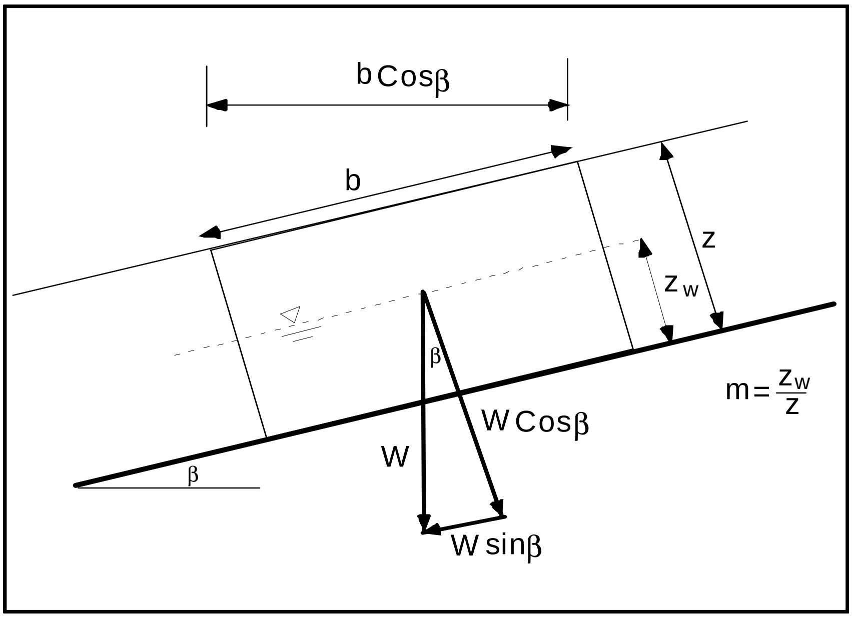

Figure 3 Slope geometry and notations for infinite slope failure surface

3.1.5 Ground water/sliding surface depth ratio (m)

It is obvious that ground water plays significant role in the occurrence of slope failures. Water decreases the stability by increasing the pore water pressure on the potential failure surface. However, there are no recorded information on the ground water table in the area. It is obvious that the ground water table is at very low level at the ridge of the mountain and ground water table at the stream is assumed to be at the water level of the stream. Cross sections of 15 slopes at different locations from the nearest ridge to the Trishuli river in the perpendicular direction was drawn using ArcGIS tool to see the impact of ground water at about 1m deep slope failure. The ground water is 1m below ground level at the distance 50m from stream in case of 500m long slopes as shown in Fig.4. This shows remaining 90% portion always has water table below the sliding depth. Value of m was interpolated from 0 to 1 according to the distance from stream up to 10% slope length. The value of m was kept 0 for the remaining portion of slope. In order to define the slope unit, reverse DEM was prepared using the DEM data and GIS analysis tool. The watershed polygon made by using ArcHydro for the DEM data had been dissected by the watershed polygon made from reverse DEM data. The divided polygons represent each slope units. Ground water analysis was done based on the buffering distance from the stream for each slope units separately.

As it had already been mentioned, rainwater during monsoon percolates down and raise the water level. However, it cannot raise the water level in such a way to saturate the whole mountain in the case of the studied terrain. There is no doubt that the percolated water increases the water content of the soil, which ultimately decreases the shear strength. This factor was considered in this analysis by conducting the soil test for saturated condition too. It does not have direct impact in m otherwise.

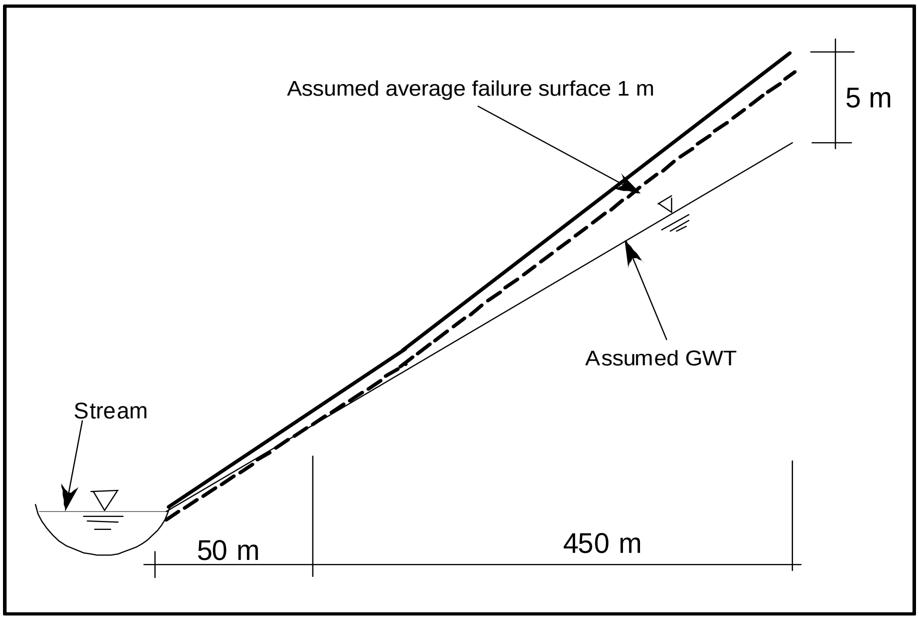

Figure 4 Distribution of groundwater level throughout the slope unit

In the way as explained above, various parameters of the stability analysis were fixed. The further step is to input the data in a GIS in the form of different vector layers.

4 PREPARATION AND ANALYSIS OF INSTABILITY MAP

As shown in the flow chart (Fig. 5) and using DEM based slope (Fig. 6), the tested shear strength parameters (Fig. 7), distance from stream for m and grid based γ slope stability analysis of each 1m x 1m cell size were done using Arc GIS. Value of factor of safety for each 1m cell was calculated automatically. The algorithm designed for the analysis based on raster calculation, using Arc GIS 8.3 spatial analyst (for the overlapped input layers of z, c, ϕ, β, γ and m), was used for the calculation. Based on the soil test results, zone for the value of c and ϕ was similar to the zone for each rock type. The map of slope instability result for 1m x 1m cell, for the study area based on the factor of safety against sliding is shown in Fig. 8. Values of factor of safety were grouped into five different classes as: Fs < 1, Fs = 1-2, Fs= 2-3, Fs=3-4, and Fs >4. The proportions of area for those groups were 6%, 24%, 54%, 10%, and 6% respectively.

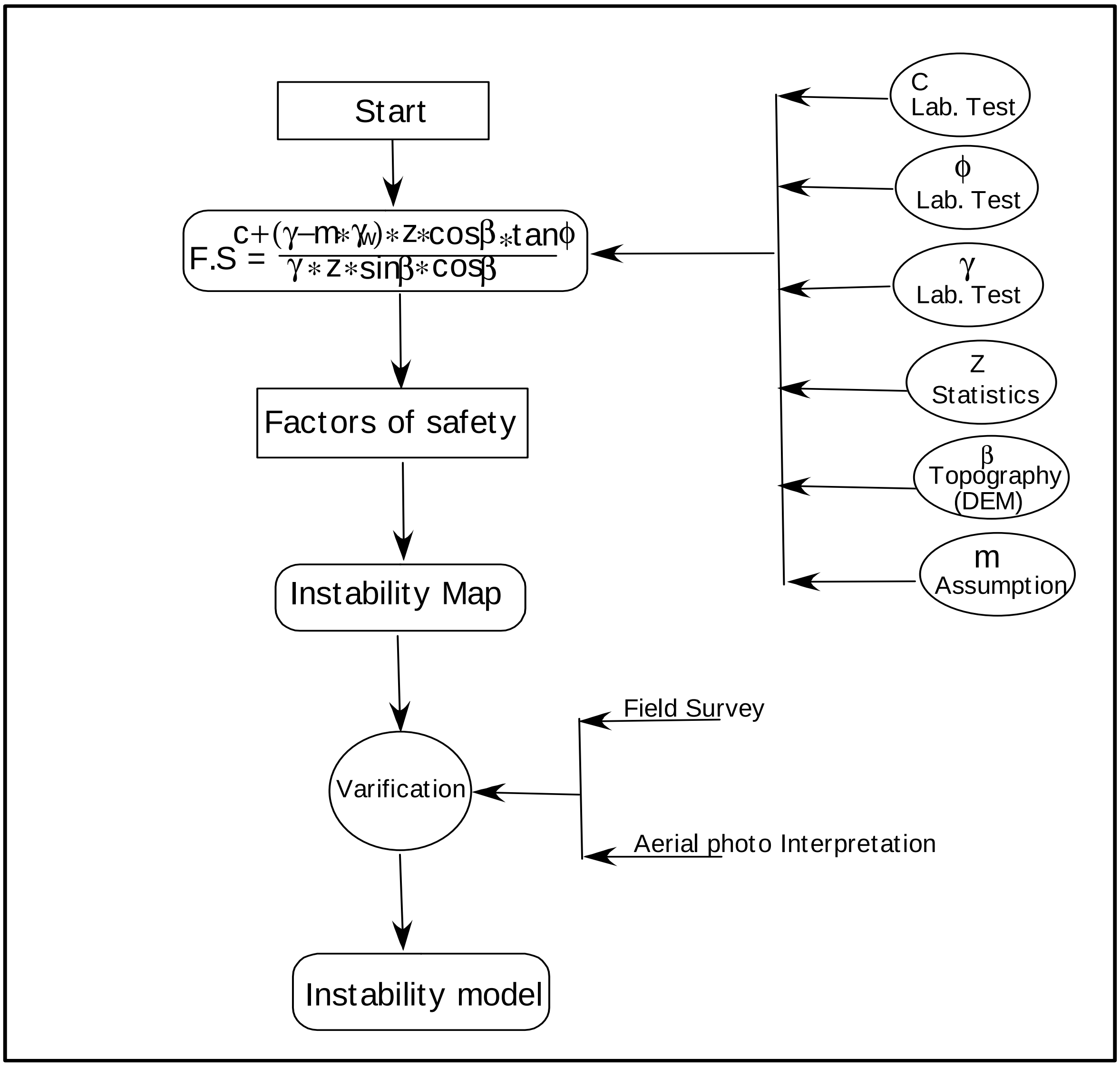

Figure 5 Flow chart for the preparation of instability map

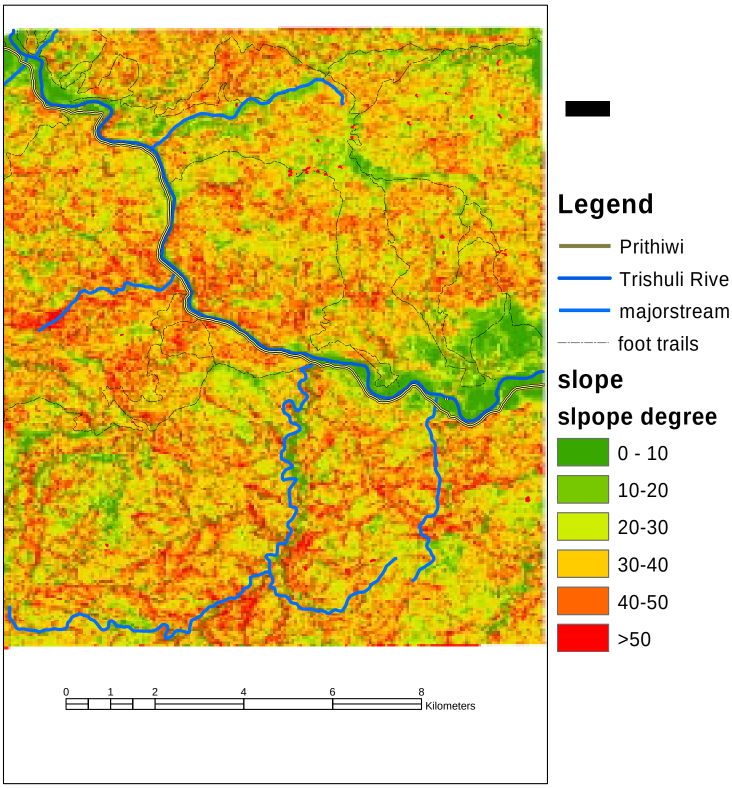

Figure 6 Slope of the study area made from DEM

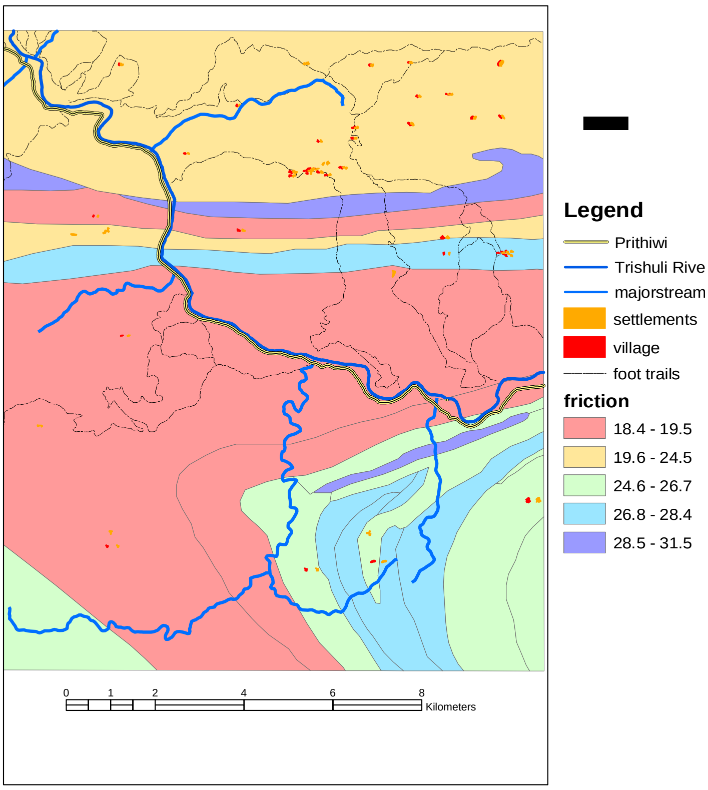

Figure 7 Distribution of friction angle throughout the area

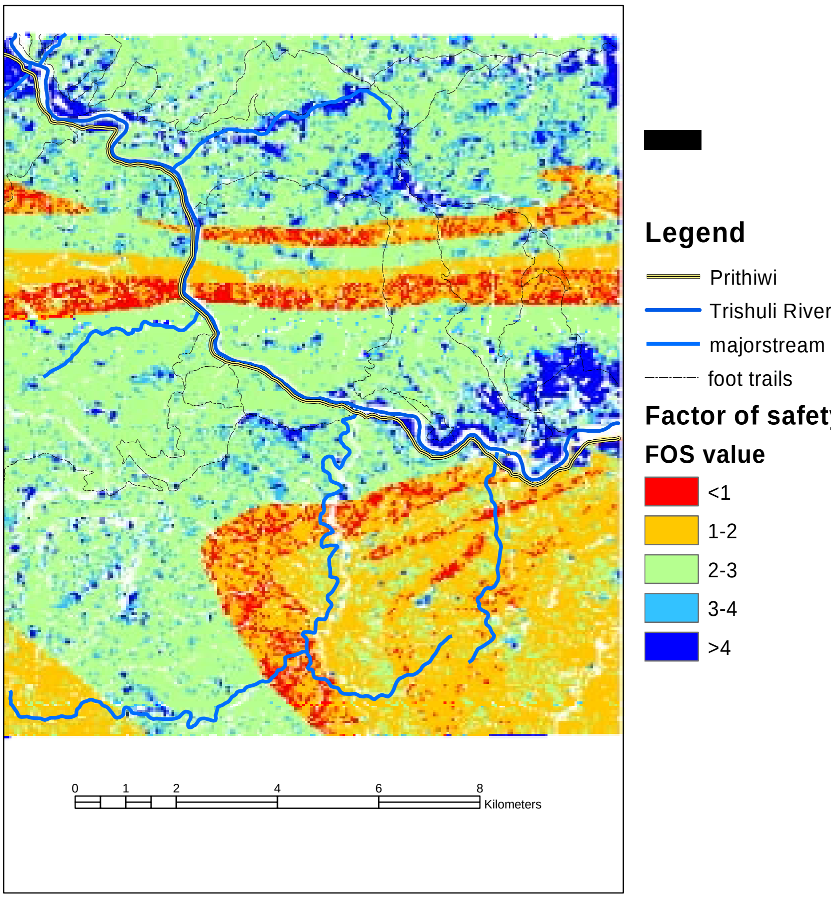

Figure 8 Result of GIS based large area automated stability calculation

5 VERIFICATION OF THE INSTABILITY ZONES

The predicted instability maps are generally verified either through distribution map of the slope failure or the detail field observation. More than 100 slope failures noted during field investigations were spatially arranged in the stability map to verify the result. Likewise, location of the collapsed sites recorded in the photographs, which were close but inaccessible, during the field study were also verified with the calculated instability zones. Besides, the predicted instability zones were tried to verify with the small and large scale failures distributed in aerial photographs. In order to verify in this way, first, specific area for the verification was chosen and slope failures, which were clearly visible in 1:50,000 scale aerial photographs were marked from the aerial photograph interpretation using stereoscope. Due to the small scale of aerial photographs that are available in Nepal, small slope failures are hardly identified. It is to be noted that large scale failures in mountainous area of Nepal, were broadened form of consecutive slope failures along the same area. Therefore, large scale slope failures were also marked from the aerial photographs. These areas were considered as a wide landslides, consisting of many small slides.

Almost 80% of the recorded slope failures were found in low stability zone and 20% were in medium stability zone. These figures indicate that predicted instability areas correspond to the actually occurred slope failures except in a few cases. Existence of landslides at the area shown as less hazardous parts in this study might due to some other causes such as geological and anthropogenic, which are out of the scope of this study.

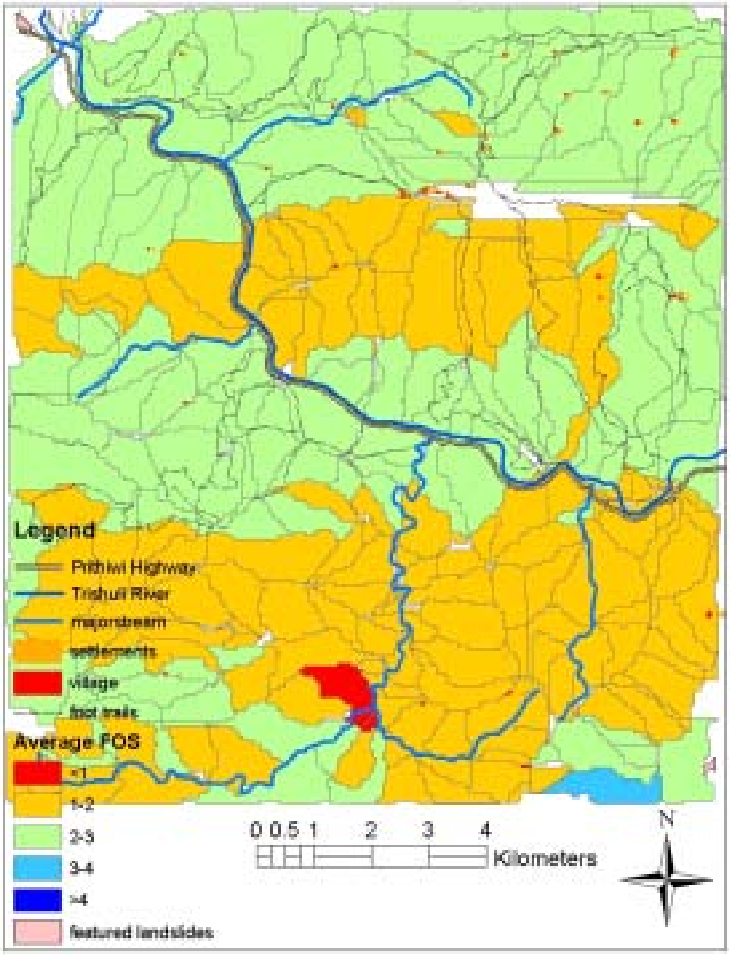

Figure 9 Average safety factor of the slope units

6 APPLICABILITY OF INSTABILITY MAP

The main objective of this study is to recommend the concerned organizations on the possibility of using ArcGIS for the prioritization of the location of the countermeasures while maintaining the highways. Prioritization should be done not only to the highway, but also to the catchments of streams and bridges, which have high possibility of being washed away due to large mass movements along the stream. It is to be noted that this sector of highway was stopped for a couple of weeks due to the mass movements at more than 30 locations and 3 bridges were washed away after heavy precipitation in July 1993 (DPTC, 1993). Therefore, the proposed instability map has been utilized to prioritize the most unstable road stretch and most vulnerable streams. In case of the highway, average instability of each 500m stretch was analyzed and 10 most vulnerable stretches ranging from low to high instability were identified. Besides, slope units of the streams longer than 200 m were made by using ArcHydro and by dissecting the watershed made of DEM data, by the catchments made by reverse DEM data. Average factor of safety of each slope unit were calculated based on the GIS based safety factor of each cell. Both slope units of some streams were found susceptible to collapse, which are potential to landslide damming (Fig. 9). Landslide damming prone streams are liable to transport large amount of debris flow, downstream and potential to wash away the bridges. Six such vulnerable streams and the respective bridges were identified prioritywise, based on the average factor of safety of the slope unit. The prioritizations of mitigation based on chainage and streams and bridges are shown in Table 2 and 3 respectively. It is well understood that the instability map prepared in this study is useful to identify unstable or potentially unstable slopes in general.

Table 2: Vulnerable locations along the 16 Km sector of Prithvi Highway.

S.N	Chainage	Place	Average Fs	priority
1	82+500	Juban Khola	0.82	1
2	83+ 000	Mahuwa Khola	0.86	2
3	81+000	Jogimara	0.88	3
4	76+500	Krishanabhir	0.93	4
5	80+500	Near Jogimara	0.97	5
6	79+500	Hugdi Khola	0.98	6
7	82+000	Near Jaban Khola	0.99	7
8	84+500	Near Phislin	1.01	8
9	84+000	Near Phislin	1.07	9
10	83+500	Near Mahuwa Khola	1.1	10

Table 3: Vulnerable streams of the study Area

S.N.	Stream	Avg. Fs	Rank	Infrastructure
1	Mahuwa Khola	0.8	1	Bridge
2	Hugdi Khola	0.85	2	Bridge
3	Jaban Khola	0.88	3	Bridge
4	Dahaki Khola	0.99	4	Bridge
5	Khatauti khola	1.07	5	Bridge
6	Barbang Khola	1.09	6	Bridge

7 CONCLUSION

From the study explained above following conclusions have been made

Unlike the prevailing practice to use the average value of shear strength throughout the study area (which gives the importance to slope gradient of the ground only), value of measured shear strength can be used directly to prepare the comprehensive slope instability map of a large area.

A comprehensive database system can be established and regularly maintained by updating various stability parameters along the highways, using ArcGIS. These data can be used for the regular maintenance program of the highways as well as in the design of the countermeasures against the landslides triggered along the highways. A GIS database system in a project will be highly beneficial for the maintenance planning of the highways.

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