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Preliminary slope instability mapping based on geo-technical and geomorphological characteristics

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Abstract

Natural and human induced mass movements are one of the most potential geo hazards that pose the severe environmental problems in the world, specially, in mountainous areas. Numerous methods and techniques have been proposed for such geo hazard susceptibility mapping using Geographical Information system (GIS). Present study is an innovative attempt in this aspect. This paper deals with the methodology of shear strength allocation, digitization of 20 m contour interval geomorphological map, preparation of digital elevation model and cell based raster calculation for the slope stability analysis in detail.
Soil samples were collected from various geological regions along the 16 km sector of Prithvi Highway, Nepal, which is suffered from various mass movements, in order to measure the residual shear strength, consistency limit, particle size distribution, mineralogical composition. The soil test result was used for slope stability analysis. Automated calculation method was developed and used in each and every segment of the study area.

Keywords : *GIS, Shear strength, Slope gradient, Consistency limit, Mineralogy, Instability map*

1. Introduction

Various types of mass movements such as landslides, slope failures, debris flows and so on are one of the major natural disasters that frequently occur in the hilly and mountainous terrains. Most of these movements are caused by heavy rainfall, though other causes may also contribute the trigger. Anthropogenic activities such as deforestation for settlements, cultivations towards the marginal slope, quarrying and toe cutting for roadways add to their frequency of occurrences.

The economic implications of these disasters are manifold. Among the direct and indirect effects of mankind are loss of life, damage to natural resources like vegetation, land soil and delay of and damage to development projects like highways, dams, communication lines and bridges. Although, the occurrence of these disasters cannot be prevented, completely the magnitude of impact in terms of loss of life and destruction of property can be kept within reasonable bounds through proper considerations on the causes and appropriate preventive measures against such disasters.

Investigation of geology and geomorphology of the area before the planning of

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infrastructure and preparation of hazard susceptibility map based on those factors are quite popular. Those maps ease in planning of infrastructures before the implementation. However, 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. In this regard, a slope instability mapping based on geo-technical characteristics and geomorphological analysis was carried out along the 16 ㎞ sector of Prithvi Highway, Nepal. Following are the objectives of the study.

1) To develop the model for stability analysis to prepare instability potential mapping of large area.
2) To study the landslide potential area with the geo-technical point of view.
3) To report the risk prone area and recommend the possible countermeasure plans to the concerned organization.

2. Study area

The study area (Krishanabhir-Kurintar) is a part of two hundred kilometers long Prithvi highway of Nepal, which connects Kathmandu, the capital with the tourist city, Pokhara (Fig. 1). This highway is suffered by landslide and other mass movements in every rainy season, that block the highway, sometimes for several days. Traffic flow was totally cut off for 24 days in total for 6 numbers of failures in this highway only in 2001. The study area lies between 27° 46' N to 27° 52' N Latitude and between 84° 37' E to 84° 45' E longitude. It is about 78㎞ towards west from Kathmandu. The study of geological map shows the rocks of Midland group (Upper Precambrian to late Paleozoic) of Lakharpata

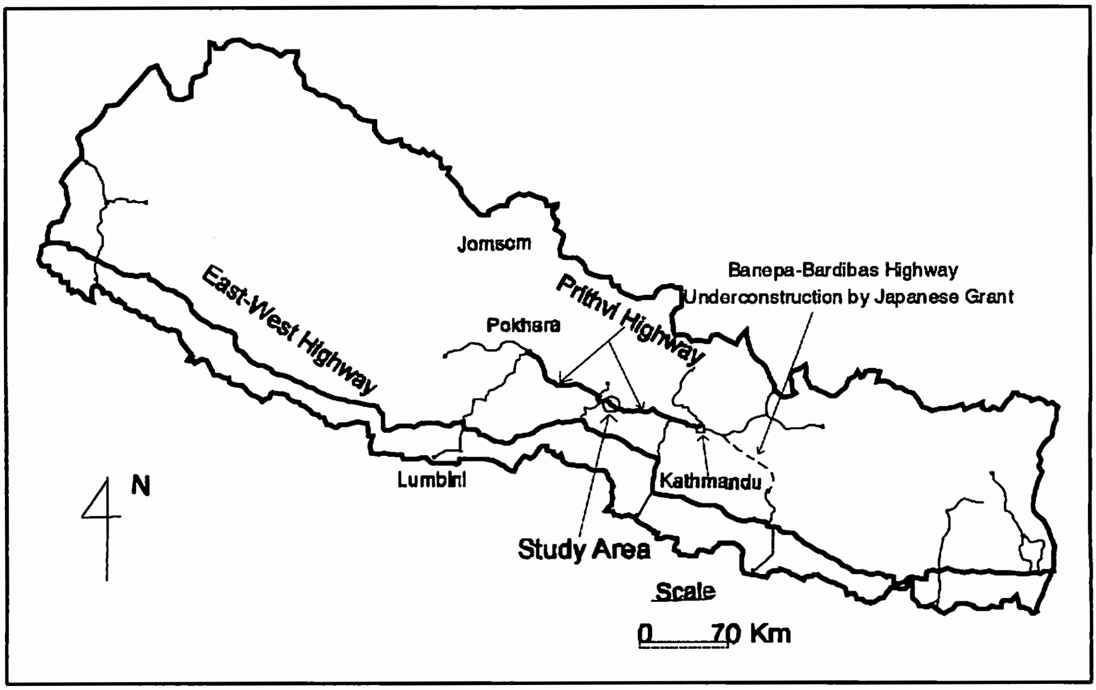

Figure 1 : Schematic Map of Nepal showing the study area.

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 study sector lies along the bank of Trushuli River, which continuously strikes on the embankment of the highway. The area is also dissected by many large small streams along both sides of highway. Among them Hugdi Khola, Mauwa Khola, Dahaki Khola and Barbang Khola are significant. There are numerous landslides along the catchments of these streams. Those landslides are responsible for huge volume of mass movements downstream. Three major landslides lie along the study area:

Photo 1 : View of Krishanabhir landslide, a chronic landslide along the Prithvi Highway.

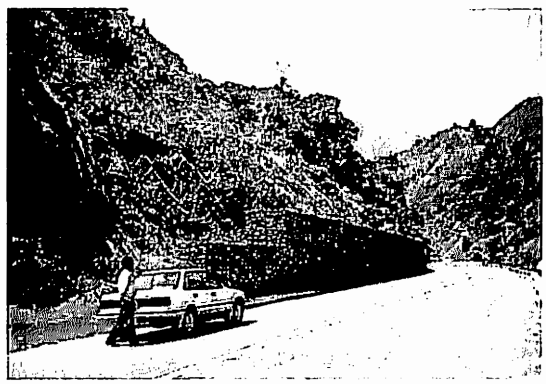

Photo 2 : View of Jogimara landslide, an old and chronic landslide along the Prithvi Highway.

Photo 3 : View of Dahakibhir landslide, a recent problem to the Prithvi Highway.

a) Krishanabhir Landslide : This massive landslide is located at about 78 ㎞ from Kathmandu towards Pokhara. It was first occurred on August 11, 2000 and blocked the traffic for 11 days. The debris buried the road up to 10 m height and excess of which had flown down which impeded the river almost 15minutes forcing the people of near by area to escape at night. The total volume of this landslide was estimated about 380,000 m^3. The total width and height was measured 200 m and 220 m respectively from road level. Last year it stopped the traffic twice for a couple of days. This year although it looked stable because of the construction work, it has already blocked the traffic for 15 hours (Photo 1).

b) Jogimara Landslide : The Jogimara Landslide, located at the slope close to the old limestone quarry, has been remained a most hazardous landslide between eighties to mid nineties. It has carried several buses and trucks into the Trishuli River and hundreds of people lost their lives. At present the Jogimara landslide is under control. The department of road HMG/N has excavated the great amount of weathered materials and constructed the huge gabion wall at the landslide site (Photo 2).

c) Dahakibhir landslide : This is the recently developed landslide along the study area, which had occurred in August, last year. Part of Prithvi highway had been washed off, when about 100 m of road sank near Dahaki Khola. In addition, landslides occurred at the hillside blocked the busy traffic for couple of hours (Photo 3).

3. Materials and Methodology

Materials

a) Topographic map of Jogimara Area, scale 1 : 25,000
b) Geological Map of Central Nepal, Scale 1 : 250,000
c) Black and white Aerial Photographs, No. 38-01～38-04
d) Computer software, including Arc View 3. 2a, Arc GIS 8. 1, Arc GIS 3D analyst and Arc GIS spatial analyst.
e) Soil testing equipments.

Methods

The study was carried out in a series of different phases as from desk study to processing and integration of data to prepare landslide hazard map. Reconnaissance survey was carried out before detail investigation and soil sampling. Soil samples were collected from 70 different sites representing each geological region. Particle size distribution and consistency tests were done in Nepal for most of the samples. On the basis of tested liquid limit, representative samples were brought to Japan for confirmative tests. Apart from some basic tests simple shear tests was done to determine the mechanical properties of the soil. X-Ray diffraction test was also done to analyze the mineralogical composition.

Landslide hazard analysis

A hazard is defined as a probability of occurrence of a potentially damaging phenomenon within a given area and in a given period of time. Over the past 25 years many methods and techniques have been proposed to evaluate the landslide hazard and produce maps portraying its spatial distribution (Landslide hazard zonation). At present, there is no agreement on the methods of producing hazard maps (Brabb, 1984 ; Carrara et al., 1995).

Many authors have classified in different ways the principal approaches to slope instability mapping. (Hansen, 1984) proposed the following distinction between different approaches.

a) Earth science approach that principally focuses the instability condition by mapping.
b) Engineering approach, that focuses the interest on the stability of a particular site or a slope. The input data derive from laboratory test and can be used to determine the safety parameters (Luzi et al., 1995). The study presented here is based on this approach.

Slope stability analysis

Limit equilibrium analysis is used to determine the magnitude of the factor of safety of a slope. Limit equilibrium methods have long been applied to the determination of natural slope stability. Infinite slope analysis has been widely applied in many investigations of natural slope stability because of its relative simplicity (Wu et al., 1995), particularly where the thickness of the soil mantle is much smaller than the length of the slope. Factor of safety of each grid cell was calculated by using the following formula :

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

Where F. S. is the factor of safety, γ is unit weight of soil (kN/㎥), m is ground water/soil thickness ratio, z is depth of failure surface below the terrain surface (m), γw is unit weight of water (kN/㎥), β is the terrain surface inclination (degree), ϕ is the angle of internal friction (degree).

Geomorphological analysis

Various themes like contour lines (20m interval), drainage networks, land use types, Infrastructures etc were digitized from a scanned base map. From the digitized contours of topographic map, a digital elevation model (DEM) was generated from Triangulated Irregular Network (TIN) model. Slope gradient, Slope aspect and elevation layers were derived from the DEM. The slope gradient obtained from DEM was used in slope stability analysis. The stereo pairs of black and white aerial photographs were interpreted to plot the landslides on the topographic map. Because of the availability of aerial photographs the landslides were picked between Mahuwa Khola and Hugdi khola in the hillside and between Kaudi Khola and Prem Khola in the valley side of the road. For samples about 169 landslides were identified which was later verified by field checking. The landslides distribution map was then digitized. This landslide distribution map was later used to verify the final slope instability hazard map.

4. Results and Discussion

The result of the physical and mechanical tests of the representative soil sample is shown in table 1. It was found very good relationship between liquid limit and residual ϕ as shown in (Fig. 2). The liquid limit and Residual ϕ depends on the type of clay minerals (Tiwari et al.,2001 ; Moore, 1991). To verify the result of liquid limit and residual ϕ, X-ray diffraction test was done and the result of the test is shown in table 2. It showed the different mineralogical patterns in all the samples. Although proportions were different, quartz, feldspar, smectite and kaolinite were present in all the samples. The higher proportion of quartz and less smectite based minerals has clearly indicated relatively higher residual ϕ.

Geomorphological Features

The study area is highly dissected by the drainage system. Average drainage density is calculated as 3.26 ㎞/㎢. The gradient of the geomorphological surfaces play an important

Table 1 : Results of soil tests.

soil sample	W(%)	Gs	LL(%)	PL(%)	PI(%)	c(residual) Kpa	ϕ (residual) degree	Particle size distribution(%)			
								Clay	silt	fine sand	coarse sand
Sample 1	26.97	2.72	35.44	25.55	9.89	19.00	22.40	22.36	20.76	36.45	20.42
Sample 2	12.31	2.73	18.60	16.37	2.23	2.50	30.80	23.99	10.55	24.69	40.76
Sample 3	15.60	2.71	30.62	24.86	5.76	9.10	26.33	10.64	9.57	13.73	66.06
Sample 4	14.58	2.69	23.23	18.87	4.36	2.60	27.03	16.72	18.67	25.12	39.47
Sample 5	19.66	2.71	40.80	28.07	12.73	18.30	19.84	26.62	20.78	15.81	36.78
Sample 6	9.07	2.71	19.15	16.98	2.17	0	33.04	7.83	4.84	11.53	75.80
Sample 7	15.88	2.68	33.39	26.10	7.29	7.90	25.66	22.45	21.89	19.03	36.62
Sample 8	15.01	2.67	25.70	24.54	1.16	6.10	28.23	9.08	16.61	68.11	6.19
Sample 9	13.08	2.76	30.92	25.61	5.31	11.50	24.42	13.84	22.58	17.64	45.93
Sample 10	19.51	2.69	39.37	30.02	9.35	9.30	23.40	14.17	12.26	33.90	39.66

W : water contents, Gs : Specific gravity, LL : Liquid limit, PL : Plastic limit, PI : plasticity index, ϕ : Internal friction angle.

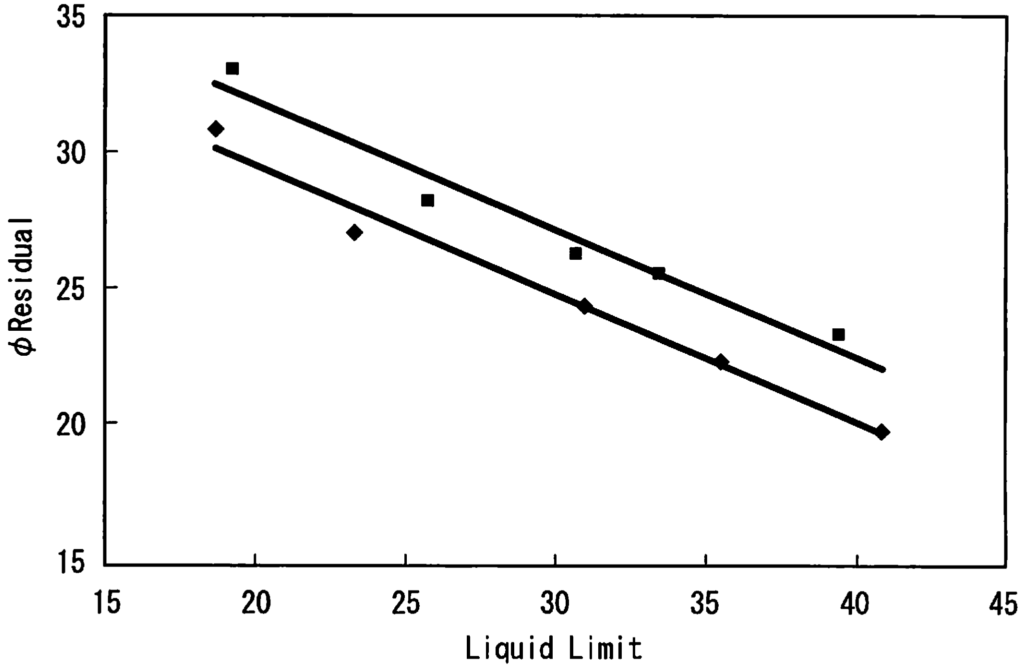

Figure 2 : Relationship between liquid limit and residual ϕ.

Table 2: Results of X-ray Diffraction Analysis

	Quartz	Mica	Feldspar	Smectite	Kaolinite	Dolomite	Calcite
Sample 1	57.1	16.0	17.1	4.7	5.1	0.0	0.0
Sample 2	78.1	5.5	6.3	2.3	7.8	0.0	0.0
Sample 3	52.1	21.9	4.2	5.7	16.1	0.0	0.0
Sample 4	71.4	10.0	7.9	3.6	7.1	0.0	0.0
Sample 5	42.6	28.1	4.6	6.4	18.3	0.0	0.0
Sample 6	69.0	20.7	7.6	0.0	2.7	0.0	0.0
Sample 7	73.5	11.8	6.6	3.7	4.4	0.0	0.0
Sample 8	84.0	8.4	4.2	3.4	0.0	0.0	0.0
Sample 9	47.6	19.0	3.7	5.7	10.0	11.0	2.9
Sample 10	64.1	12.8	2.6	3.2	6.3	10.9	0.0

role in generation of slope failures (Pachauri and Panta, 1992). More than 80 % area has slope gradient greater than 20°. No landslides were found below 10° slope gradient. The percentage nos. of landslide was very high (91%) between 30°–50° slope gradient as shown in (Fig. 3a). It shows the critical range of the shallow landslide. Relationship between slope gradient and landslide in natural slopes has been studied by many researchers in different mountainous regions and they had stated similar results. In Nepal, the natural slope with gradient 30°–40° is found to be more critical for failure (Dikshit, 1994). Similarly the occurrence of landslide was found high in the elevation ranges from 400–600 m (Fig. 3b). The correlation of landslide distribution with aspect is shown in (Fig. 3c). It can be seen that on north facing slopes the landslide distribution is very low. It increases with the orientation angle, reaching maximum

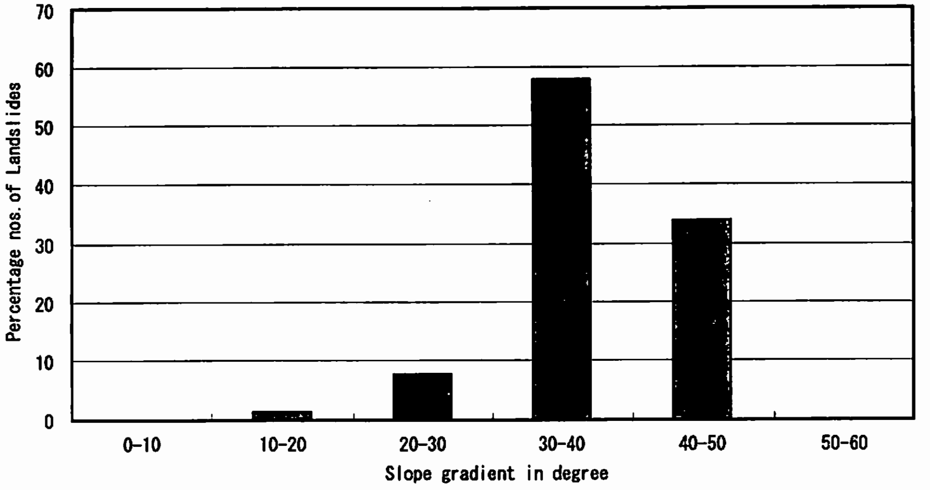

Figure 3a : Distribution of landslide with respect to slope gradient.

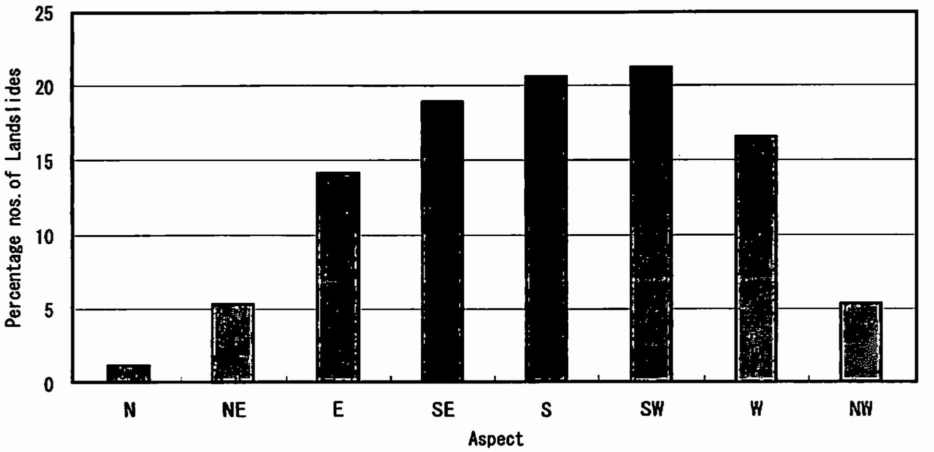

Figure 3b : Distribution of landslide with respect to aspect.

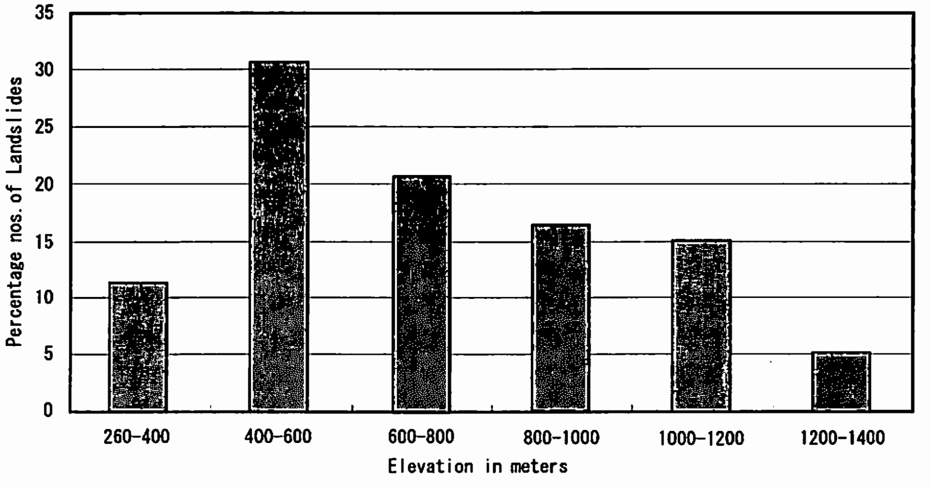

Figure 3c : Distribution of landslide with respect to elevation.

on South-West facing slopes, and then declines.

Landslide instability mapping

The slope instability map of the study area is shown in (Fig. 4). It is based on the factor of safety of the slope. Values of factor of safety were grouped into five classes and the instability ranking was carried out as follows : Fs < 1 : very high hazard ; Fs=1−1.5 : high hazard ; Fs=1.5−2.5 : medium hazard ; Fs=2.5−3.5 : low hazard and Fs > 3.5 very low hazard.

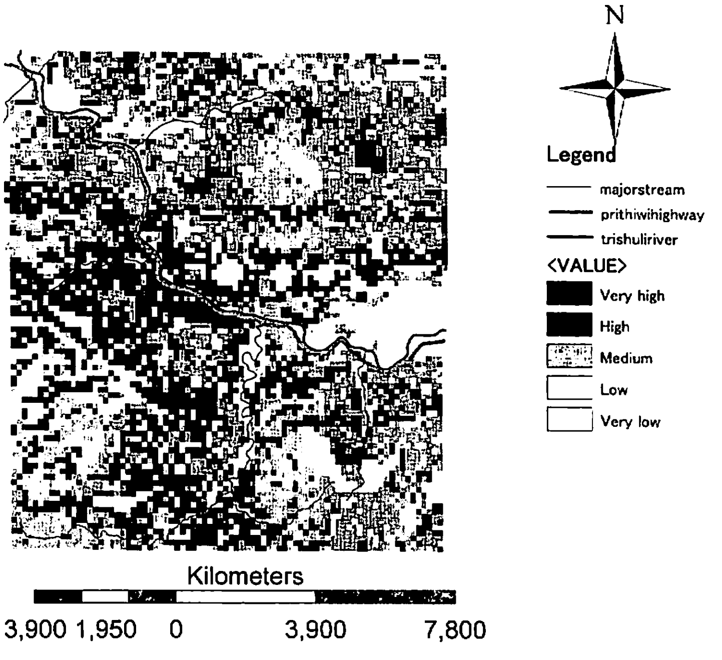

Figure 4 : Slope instability map of the study area.

5. Conclusion

The factor of safety obtained from slope stability analysis can be used to prepare the instability map of the mass movement area. This approach is helpful to identify the instable area along the road corridor and to give the proper counter measures against such failures.

Although, it required a substantial time to prepare the GIS database, GIS was invaluable in reducing the complexity associated with the hazard assessment by facilitating quick trial and error for the final product.

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