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GIS aided slope instability analysis of the highway slope based on shear strength

L'analyse d'instabilité de pente d'autoroute basée sur la force de cisaillement et le SIG

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ABSTRACT

Deterministic slope stability analysis for 3D potential failure surfaces was done using GIS and the analyses of the potential slope failure area were done for a catchment of 16 Km long highway highway sector in Nepal. This study provides the guidelines for the use of soil strength parameters in the 3D deterministic analysis and mapping. About 80% of the existing slope failures were observed within the very high and high instability potential zones proposed by this study. Recommendation was done for 10 critical highway locations and 3 critical bridge sites, which are threatened by various types of mass movement activities.

RÉSUMÉ

L'analyse déterministe de stabilité de pente a 3D pour les surfaces potentiellement vulnérables a été faite en utilisant le SIG et l'analyse du secteur de pentes potentiellement vulnérables a été faite dans un bassin long de 16 kilomètres en zone d'autoroute au Népal. Cette étude fournit les directives pour l'usage des paramètres de force du sol dans l'analyse déterministe a 3D et la cartographie. Environ 80% des pentes vulnérables ont été observés dans les zones d'instabilité potentielle élevée et très élevée identifiées dans cette étude. La recommandation a été faite pour 10 zones d'autoroute et 3 emplacements de pont très exposés et menacés par de divers types d'activités de mouvement de masse.

1 INTRODUCTION

Being a mountainous country, Nepal is suffering from various kinds of geotechnical hazards. Due to the construction of hill roads along the stream banks, severe slope stability problems have been evidenced. One of these highways, suffering from slope instability problems is Prithiwi highway, which joins the capital city Kathmandu with most of the other parts of the country. A number of big landslides that have been triggered due to the topographical, the geological and the hydrological causes used to block the highway at least for a week to a month. One of them, called Jogimara landslide, which is shown in figure 1, had killed several hundreds of the people in several incidences. Although the slope at Jogimara has been temporarily stabilized, new landslides were triggered at the other portions of the highway. Krishnabhir landslide, shown in figure 2, Dahaki Khola landslide are some of the landslides that started to block the road from the last few years. Krishnabhir landslide had started to slide this year even during winter when there was no rainfall. As potential sliding stretch of the road is not known, especially near Jogimara area, highway maintenance authority is always facing the problems of allocating the most appropriate station for the debris clearance equipment. The main reason for such uncertainty is that neither there are established database on the soil strength nor the systematic study of the stability of the slope above the highway are done. It is well understood that the big landslides, creating problems are the progressive increments of the small slope failures along those slopes that have been triggering every year. Only in a big flood of 1993, three major bridges and hundreds of the other cross drainage structures were washed away by the debris mass flowing down from the upper catchments (WIDPTC, 1993). The main objective of this study is to identify the most critical locations along the highway from slope instability point of view, so that proper maintenance plan can be prepared.

2 BACKGROUND OF THE STUDY AREA

The study area covers 16 km sector of the Prithiwi highway from Krishnabhir to Kurintar, and the entire catchment of this road corridor. Location of the study area is shown in figure 3. The geological map of the study area shows that there are 10 types of petrologic regions in the catchments of the 16km sector of the highway, which is considered as most critical section along the entire highway length. 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 area is highly dissected by the dense drainage system. Average drainage density is about 3.26 Km/Km^2.

Figure 1 Jogimara landslide, one of the chronic landslides in the past

Figure 2 Krishnabhir landslide, the troublesome landslide at present

Figure 3 map of the study area in the map of Nepal

3 STUDY METHODOLOGY

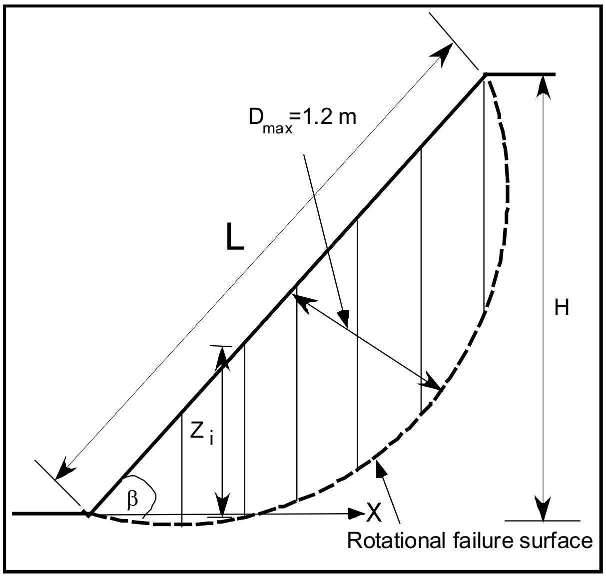

Figure 4 Typical section for the 2D stability analysis

One dimensional stability analysis for a infinite slope is generally done for the deterministic analysis of the slopes. However, the concept of 2D stability analysis for the section as shown in figure 4 was used in this study. In case of residual soil, stiff fissured clays, and non plastic clays and silts, brittleness is close to 1, and fully softened shear strength can be considered as failure criterion (Skempton, 1985). For the saturated soil sample in such conditions, shear envelope passes from the origin. The simplified equation for 2D factor of safety can then be reduced to,

$$FS = \left(\frac{\tan\phi \Sigma \sum_{ij} (\gamma \cos^2 \beta - m\gamma_w)}{\sum_{ij} \gamma \sin\beta \cos\beta} \right)$$

where, ϕ is remolded peak friction angle, γ is the unit weight of the soil mass, β is slope angle of the terrain, m is the saturation ratio, and γ_w is the unit weight of water.

Table 1 Values of measured average friction angles for the soil samples from each petrological region

Petrological region	fully softened ϕ degree	residual ϕ degree
Region 1	24	22
Region 2	32	31
Region 3	28	26
Region 4	28	27
Region 5	21	20
Region 6	35	33
Region 7	27	26
Region 8	28	28
Region 9	26	24

Residual soil samples were collected from 100 different locations throughout the study area widely distributed into an area of 140 sq. km., in such a way that at least 8 samples were collected from each petrologic region. Mechanical properties of the soil such as the particle size distribution, the consistency limit and the shear strength properties (both fully softened and residual) were measured in order to study the variation of soil properties in the petrologic regions. The test results showed that there were the similar liquid limits and shear strength of the soil in a petrologic region. Japanese soil testing practice (Japan Geotechnical Society, 1992) was followed for all types of soil testing. Both the simple shear devices as well as ring shear devices were used for the shear testing of the representative specimens. Fully softened friction angle of the samples varied from 20.7 to 35.4^0 , whereas residual friction angle varied from 19.8 to 33^0. Shown in table 1 are the average values of the friction angles (both fully softened and residual) for the tested soil samples. Bhattarai et al. (2004) did deterministic analysis based on the residual shear strength. However, the analysis presented in this study considers fully softened shear strength of the soil. Fully softened friction angle was distributed based on the petrological region in the similar manner as the residual shear strength was distributed as shown in figure 5. A set of 1:25,000 scale topographical maps was digitized to make a DEM of the study area with the help of GIS analysis tools. DEM was used to calculate the slope of the terrain (β). Spatial analyst and 3D analyst tool of a ArcGIS software was used for the entire analysis.

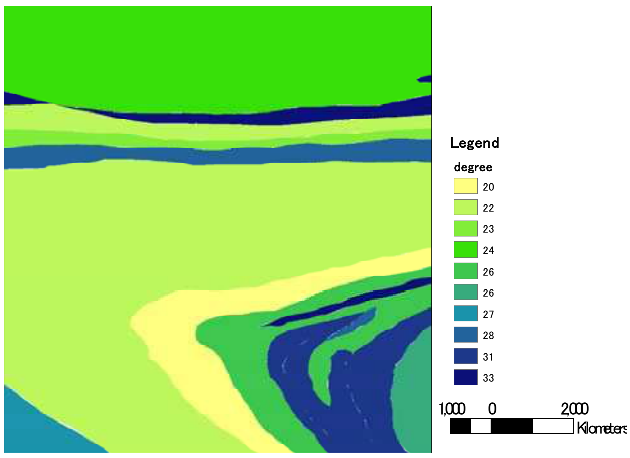

Figure 5 Distribution of residual shear strength based on petrology, similar figure was prepared for the fully softened shear strength too.

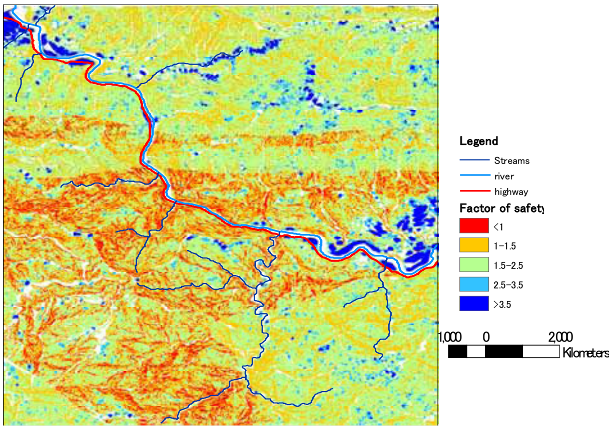

Figure 6 Distribution of hazard potential zones by stability results

4 SLOPE STABILITY ANALYSIS AND MAPPING

An automated algorithm was developed to conduct the 3D slope stability analysis of the critical ellipsoidal sliding mass throughout the area in a given slope unit with GIS as mentioned by Bhattarai et al. (2004). Bhattarai et al. (2004) have divided the entire study area into a number of catchments based on the DEM data, using ArcHydro software of ArcGIS. Then mirror image of the entire topography was created by multiplying the contour value with (-1). The mirror topography DEM was used to make the reverse catchments joining valleys. The catchments with DEM and mirror DEM were dissected with each other to divide the entire area into a number of slope units. The size and the shape of the ellipsoids to have random distribution calculation for slope stability were fixed with the average dimensions of the existing single unit shallow slope failures, recorded in the slope failure inventory that was prepared during the field survey. The value of the automatically calculated factor of safety (FS) of the slopes was used to divide the whole catchments into five different instability zones, as shown in figure 6.

Distribution of the calculated hazard potential area was compared with the existing slope failures in the areas. Shown in figure 7 are the superimposition of the slope failure areas that were detected during the field survey, on the proposed slope instability map that has been prepared based on this study results. More than 80% of the slope failures that had been marked during the field study, and the slope failures that had been located in the landslide distribution map prepared from aerial photo interpretation, were observed inside the highly instable zones. The main objective of the present study was to identify the most critical highway chainages from slope instability point of view. An entire length of the highway under study was divided into 32 different sections, each section having the length of about 500 m. Each sector was then divided into five different segments of 100 m length. Average value of safety factor for the upstream slope was calculated each 100 m segment. Each segment of each sector of the highway was assigned with a number ranging from 1 to 5 based on the value of average safety factor at that segment. The minimum average safety factor of the assigned lowest safety location of each sector was then compared to prioritize 10 topmost critical sectors based on those safety factors. According to the analysis results, chinages 82.500, 83.000, 81.000 (Jogimara), 76.500 (Krishnabhir), 80.500, 79.500, 82.500, 84.500, 84.000, and 83.500 from Kathmandu were the first 10 vulnerable locations in an increasing order. Table 2 shows the priority of the most critical 10 highway sectors, with the name of the location and average minimum safety factor of the critical segment. In order to estimate the risk to the stream due to the landslide damming or the debris flows, 144 different drainage catchments were divided into 288 slope units and average FS of those slope units were calculated. The drainages with both slope units vulnerable were identified. The potential dangers to the highway bridges or the other cross drainage structures due to the low safety factor at both the banks were prioritized based on the danger to the tributaries of each stream crossing the highway. According to the analysis results, Mahuwa Khole, Hugdi Khola, Jaban Khola, Dahaki Khola, and Katauki Khola were prioritized as five most risk prone bridges. Name of these vulnerable streams, and the average safety factor values of the endangered slope units with the type of structure at danger is shown in table 3.

Table 2 Ten most vulnerable locations along the studied sectors of the Prithiwi highway

Chainage	Place	Average FS	Ranking
82 + 500	Juban khola area	0.82	1
83 + 000	Mahuwa khola area	0.86	2
81 + 000	Jogimara	0.88	3
76 + 500	Krishnabhir	0.93	4
80 +500	Near Jogimara	0.97	5
79 + 500	Hugdi khola area	0.98	6
82 + 000	Near Jawan khola area	0.99	7
84 + 500	Near Phislin	1.01	8
84 + 000	Near Phislin	1.07	9
83 + 500	Near Mahuwa khola area	1.1	10

Table 3 Six most vulnerable streams prioritized based on the average safety factor of the slope units

Name of the stream	Average FS	Ranking	Infrastructure
Mahuwa khola	0.8	1	Bridge
Hugdi khola	0.85	2	Bridge
Jaban khola	0.88	3	Bridge
Dahaki khola	0.99	4	Bridge
Khatauti khola	1.07	5	Bridge
Barbang khola	1.09	6	Bridge

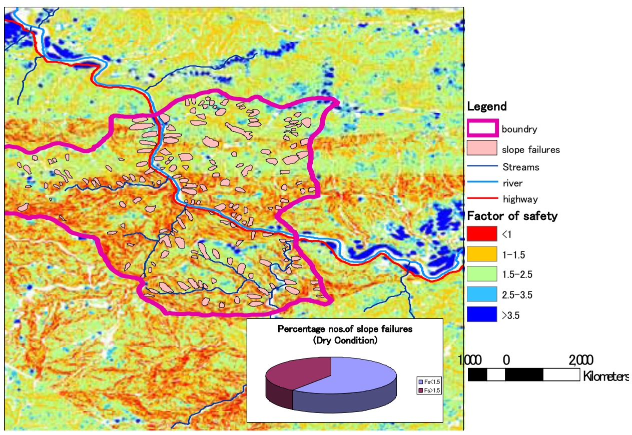

Figure 7 Superimposition of field detected slope failures in the hazard potential map

5 CONCLUSION

Until now, hazard maps are being prepared by ignoring the shear strength parameters. It was believed that the shear strength cannot be measured accurately or the shear strength data of one location cannot be used beneficially for the analysis of the other location in a slope. However, this study shows that if soil sampling and testing can be done appropriately, deterministic analysis can be done based on the available shear strength data. In order to have a good soil sampling , geological map should be studied in detail and each petrological region should be identified. Present study showed that the fully softened shear strength (and the residual shear strength as well) of the different soil samples from one petrological region are identical. This allows one to use one shear strength for one petrological region. As fully softened shear intercept of a landslide area is very close to zero if not zero, the depth component in the stability analysis can be neglected.

It is mandatory that one should use undisturbed peak shear strength for the stability analyis of the landslides. However, once the shearing occurs in heavily overconsolidated soil or in the residual soil, softening of the soil come in to action immediately. Therefore, in order to have comparison between the stable and unstable slope, fully softened shear strength can be considered as a strength parameter. This is one of the outcomes of the present study.

6 RECOMMENDATION FOR HIGHWAY MAINTENANCE PLANNING

The study was targetted to suggest the Department of Roads on the possible locations to set the debris clearing equipment. The present study shows that chainages from 82+000 to 84+000 i.e. from Jawan khola to Phislin should be given topmost priority. Second priority should be given to Jogimara area, i.e. from chainage 80+500 to 81+000. The station of the heavy equipment for mass clearance can be set at 81+500, in order to cover these vulnerable points.

Besides the locations along the road, special care should be taken to protect the stream banks in the catchment area. A stream may be seen safer at the point near the highway. However, the same stream may have potential sliding area at both sides of the stream at upstream within its catchment area. Present study had quantified the safety factor of each slope unit based on the shear strength results. Based on the study report, special care should be provided to protect the stream bank of Mahuwa khola, Hugdi khola, and Jaban khola. A second priority should be given to protect the watershed of Dahaki khola. Proper care should be taken to the watershed deteriorating condition at Dahaki khola, Khatauni khola, and Barbang khola. Failure in the anticipation of the landslide dams along the catchment area had resulted in the huge debris flow and wash out of three major bridges, i.e. Agra khola, Belkhu khola, and Malekhu khola along the Prithiwi highway in 1993. Likewise, recent earthquake at Niigata Prefecture, Japan had taught us a lesson that the locality which is vulnerable to landslides along the banks of the stream can equally be vulnerable for potential landslide damming during the earthquake, which is many times disastrous than the disaster potential of a single landslide.

7 LIMITATIONS OF THE PRESENT METHOD

The present study is very useful for the overall management of the highway sector against possible slope disaster. However, this study is not a complete tool for the highway management as it also has many limitations. Less data on the ground water level, Preparation of DEM based on the contour map of a larg scale, the inability to cover rock slope stability issues, coverage of only a shallow slope failures and not the big landslides like Krishnabhir, inability to model the effect of rainfall separately are some of the limitations of this study. However, this study has provided the overall scenario of the stability problems along the studied road corridor. Further detailed study on the effect of each of the parameters stated above should be done for a relatively smaller area so that proper countermeasure plannings can also be done. The authors recommend the academic institutions and highway management authority to have separate study on the ground water condition, underground profile of theh soil and rock, and complete hydrological study for some specific area in detail. Individual and specific study for geological, geotechnical, and hydrological information in order to design appropriate countermeasures for already slided locations such as in Krishnabhir, and Dahaki khola is also important. Undisturbed soil sampling and measurement of peak, fully softened, and residual shear strength, exploratory borings for the underground geological profile, establishment of piezometers for ground water profile, detailed instrumentation of the landslide area, geological and geomorphological study of the entire area at detailed scale are some of the investigations that should be given top priority in those area for the landslide hazard management.

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REFERENCES

Bhattarai, P., Marui, H., Aoyama, K., and Tiwari, B. 2004. Use of Soil Properties on Preliminary Slope Instability Mapping and Prioritization of Potential Failures along Prithiwi Highway, Nepal, *GeoHimal*, Nepal , 2 (1): 2-9.

Department of Survey Nepal. 1998. Topographic map of Jogimara area (1:25,000)

Department of Survey Nepal. 1993. Aerial photographs of Jogimara area (1:50,000)

Department of Survey Nepal. 1950. Land capability map of Jogimara area (1:25,000)

ESRI (2003). ArC GIS 8.3, Arc Map - software and user's manual

ESRI (2003). ArcGIS 8.3 Spatial Analyst Extension - software and usser's manual

ESRI (2003). ArcGI 8.3 3D Analyst Extension - software and user's manual

ESRI (2002). ArcHydro extension of ArcGIS- software and user's manual

Japan Geotechnical Society (1992) Soil Testing Manual

Skempton, A. W. 1985. Residual strength of clays in landslides, folded strata and the laboratory, Geotechnique, UK , 35 (1): 3-18.

Water Induced Disaster Prevention technical Center (1993). Disaspet Photo Album of 1993 flood disaster.