METHOD FOR LANDSLIDE RISK EVALUATION AND ROAD OPERATION MANAGEMENT: A CASE STUDY OF BHUTAN

Yokohama National University Dorji CHEKI*1
Yokohama National University Tomoya SHIBAYAMA*2

This study describes method to determine risk due to landslide and applies Certainty Factor (CF) model to determine landslide susceptible area along the most important highway in Bhutan. The quantification of the risk in terms of total duration of road blockages was done based on the data collected from eleven years eight months period Kuensel (weekly newspaper of central government). The total traffic and passenger losses determined with freight and passenger transport value losses in terms of dollar values indicated that the road operation risk would have significant impact in terms of economic value for the country. The certainty factor model that used 149 cases of the existing landslide with its affecting parameters indicated that the landslide certainty factor increases with the increase of slope value above 30° for the slopes facing towards the south. The rainfall parameter showed the increase in certainty value from the rainfall intensity of 7.76 mm/day. The lithological and land use parameters used indicated the certainty of landslides in phyllite areas and barren area with grasses. Application of the certainty factor model along the most important highway in Bhutan could delineate the susceptible areas similar to the existing landslides.

[Key Words] *Risk, Bhutan, Landslide, Blockage, GIS, Certainty Factor (CF) and Susceptibility*

1. INTRODUCTION

In landlocked country like Bhutan, effective and sustainable road transport network, are seriously affected by extreme geographic conditions. The mountainous terrain pose challenges like frequent landslides in summer that block the roads and cause major delays in movement to vehicles. The sharp curves along roads make distances two to three times the direct distance and roads become difficult to drive during rainy season. Freight rates are generally higher in the monsoon period, partly due to increased demand coinciding with the harvest season for cash crops and partly due to increased likelihood of trucks being delayed due to landslides. The people in the field of business community and construction industries are worried about the consequences of road blockages. [LEA International Ltd.2001; ABD RBP: BHU 32288 2000; Kuensel 1991-2002].

The actual planned developmental work started in Bhutan after the First Five Year Plan in 1961. Since then the emphasis was made to develop smooth road. Currently there is a total of 4392.5 km length of the road network linking important towns and villages. The Five Year Plan documents of Bhutan starting from Fourth Five Year Plan to Ninth Five Year Plan documents indicate there is urgent need to clear landslides disrupting the smooth flow of traffic and loss of money.

The present study took the most important road of Bhutan as a case study and the risk of road blockage in terms of duration of blockages resulting in disruption of economic activity are quantified. The losses due to road blockages in terms of traffic and the loss of amount per day are determined based on the total duration of blockages. The severity of the landslide problem intensifies with the increased urban development and change in land use. Landslides are rapidly becoming the focus of major scientific research, engineering study and practices, and land use policy throughout the world. Although, landslide risk evaluation can be done based on total risk (i.e expected number of live lost, people injured, damage to property and disruption of economic activity) due to landslide. This study used only the expected degree of economic activity loss due to landslide based on the traffic volume and their unit prices as the data on other events were not available. Further as risk is also associated with uncertainty, in this study risk is expressed as the expected loss caused by landslide over given period and the uncertainty of an event is predicted based on total events recorded. Thus study recognized the vulnerability and degrees of landslide risk involved in the study area and proposed the statistical landslide modeling techniques to avoid existing landslides and to predict future potential landslide areas. With such techniques, the planner and managers could

*1 Graduate Student, Department of Civil Engineering
TEL: 045-339-4035
Email: **d06sc192@ynu.ac.jp**
*2 Professor, Department of Civil Engineering
TEL: 045-339-4036
Email: **tomo@ynu.ac.jp**

reduce the losses resulting from landslide by avoiding the landslide-susceptible areas if it is deemed appropriate, or implement strategies to reduce risk.

In recent years, the assessment of landslide hazard and risk has become a topic of major interest for both geoscientists and engineers as well as for the community and the local administrations in many parts of the world (Aleotti and Chowhhury, 1999). The factors that influence landslide susceptibility and the approaches for qualitative or quantitative risk assessment in a GIS environment have been discussed by number of authors. Landslide poses a severe threat to life, property and infrastructure and becomes a major constraint for the development activities. Strategies should be made to understand landslide process, analyze threatening landslide hazard and predict the future landslide for reducing ongoing and future damage from landslides (Lan et.al, 2004). There is growing trend towards the development and use of quantitative methods for landslide hazard and risk assessment (Ko Ko et.al, 2004). The study by Dai and Lee, 2002 has indicated that research should be concentrated on improving practice by exploring more explanatory variables and more powerful techniques.

Despite the efforts by many researches, no agreement has yet been reached on the techniques and methods for landslide susceptibility mapping (Yesilnarcar and Topal, 2005). The Geographic Information System (GIS) in recent years has attracted attention in researches due to its power and versatility for processing spatial data. It provides platform to carryout geostatistical analysis and database processing. The inventory data of landslide for the area were obtained from road division, Ministry of Works and Human Settlement, google earth and land use map of Bhutan.

As the event of the landslide depends on both casual and triggering factors to occur, and often the cause is a complex phenomenon, this study used modified Certainty Factor Model (CF) of Heckerman, 1986, to relate landslide occurrences to the affecting factors. A 90m-resolution digital elevation model (DEM) was used to calculate elevation, slope and aspect. The affected location of the landslide along the road was used to compare and derive the susceptible area. The lithological unit for the study area was derived from geological map of Bhutan and the land use map of Bhutan for the year 2003 is used for deriving the land use.

The objective of this study is to quantify the road blockage risk in terms of economic activity losses and develop landslide susceptibility map of the area to assist managers, planners and designers.

2. STUDY REGION

The study area consists an area of 2667.37 sq.km covering two district, Thimphu capital city and Phuntsholing the industrial town connected by 179 km length road. This road is considered as the lifeline of Bhutan as there is no other alternate road as shown in **Fig. 1**. This is the road that brings in the consumer goods from India. When this road gets blocked, the capital gets cut of from India the single most important partner of trade for Bhutan (Kuenza et.al, 2004). The area consists of comparatively steep slopes formed from higher Himalayan belt and lesser Himalayan belt with Precambrain and Riphean geological age with gneiss, mica schist, phyllite, clay and sandstone overlain by sub tropical weathered soils and colluviums as shown in **Fig. 2**. The slopes are densely vegetated, with primary forest dominating along with subsistence agriculture in the valley bottoms where gradient allows. The landslide triggered by road cutting is quite common in Bhutan. Sorchen and Jumja landslide along Phuntsholing to Thimphu highway are very popular landslides for which a risk management has not been found for several years. These are deep-seated slide in rocks of moderate to highly weathered phyllites. The government in 1992 decided to totally do away with this landslide and built an alternative route as an avoidance strategy for Sorchen area (Kuenza et.al, 2004). The landslides in Bhutan are scale-dependent, ranging from the magnitude of mountain ranges, through lateral spreading, to the smallest slope failures.

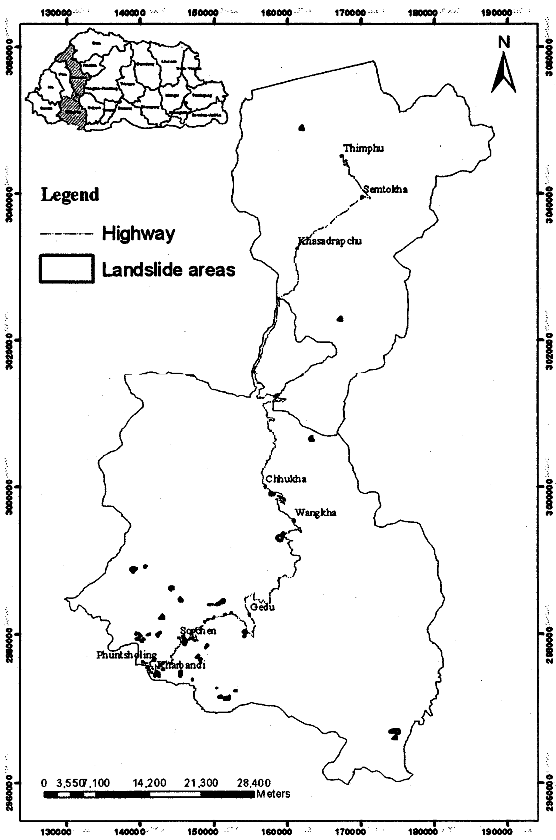

Fig.1 Location of study area and landslide

3. METHOD TO DETERMINE LOSSES DUE TO ROAD BLOCKAGES

(1) Field survey and data

The authors made the field visit from 7th to 9th June 2002, and surveyed the affected areas along the particular highway. It was learnt during the survey that the road blockages are of the concern and at some of the locations numerous redundant bypasses constructed earlier were clearly visible and still new bypass roads were been constructed in Sorchen area. The data for road blockage at various locations on the routes available in Kuensel (weekly newspaper of central government) was collected, as there were no other reliable sources of data. The data collected after reviewing the newspapers for 4258 days (Jan. 1991-Aug.2002) period indicated that the most serious months for road blockages are August and September with 43 days and 32 days respectively as shown in **Table 1**. The average daily traffic volume along Thimphu to Phuntsholing highway was collected from the traffic data recorded at Kharbandi checkpoint (point where every vehicles are required to registered at this point) from 1998 to 2002. It was recorded that an average of 950 vehicles use this particular highway daily out of which 333 are heavy vehicles that transport goods. Further it was observed during the survey that the low-lying areas towards the plains of India are more susceptible for blockages and observed that these blockages are more intense during the rainy season in Bhutan. The earlier study by the authors in Bhutan indicated that most places of the road blockages are located in places with annual rainfall of 1500mm to 4500mm. Although, independent study on the relation between the rainfall intensity and landslides has not been carried out due to lack of data. However, it agreed with the concept of more landslides in areas of higher rainfall due to higher pore pressure and thereby reducing effective stresses. Thus indicating rainfall is one of the important contributing factors to generate the cause of road blockages. Also it was observed that landslide induced by rainfall is one of the most serious problems causing road blockages along the area.

Table 1 Total blockages in months

Year	Blockage months (no.days)				Total
	July	Aug.	Sept.	Oct.	
1993	0	11	0	0	11
1996	14	15	30	15	74
1997	0	1	0	0	1
1998	0	4	0	0	4
1999	0	3	0	1	4
2000	1	9	0	0	10
2002	0	0	2	0	2
Total	15	43	32	16	106

(2) Analysis and results

In order to understand the effects of landslide risk on roads and to quantify its possible associated effects. The study determined the effects of road blockage to traffic operations on road and its loss in monetary values. The loss of traffic in terms of rate of blockage per day was determined by using the expressions below;

$$L_D = R_B \times D_V \tag{1}$$

Where L_D: traffic loss per day (Nos)
R_B: rate of blockage per day
D_V: volume of traffic per day and

$$R_B = \frac{T_A}{T_D} \tag{2}$$

T_A: total no of days blocked
T_D: total period of data in days

The loss of freight resulted from the road blockages are calculated based on the expression;

$$F_L = H_V \times F_R \times D_S \tag{3}$$

where F_L: freight loss per day (US$)
H_V: total heavy vehicle loss per day
F_R: freight rate per ton km
D_S: distance (km)

The total passenger fare losses are determined based on the following relation;

$$P_F = R_B \times D_S \times U_P \times B_L \tag{4}$$

where P_F: passenger fare loss per day (US$)
U_P: fare per km
B_L: no. of bus loss per day

The rate of blockage per day (R_B) calculated based on **Equation 2** for 4258 days period and 106 days of blockage indicated the rate of blockage of 0.0249 per day. It was indicated that at least 24 numbers from an average of 950 vehicles was blocked per day using **Equation 1**. The study used the values reported from Report TA3470-BHU, April 2001, which states that 35% of the total traffic is heavy vehicle and all the heavy vehicles carry 8 tons payload. It was determined that at least 9 heavy vehicle are blocked per day on this highway and the basis of the freight rate was taken from ADB Report RBP.BHU 32288, September 2000.pp2. The report states for payload of 8 tons and the average freight rate is Nu.2.5 to 3.5 per ton km (Nu- *Nultrum*-Bhutan Currency and Nu.47.7 = US$1). The freight rate of Nu.3.5 per ton km was taken for this study to calculate the freight loss. The freight loss due to road blockage on the road length of 179 km based on **Equation 3**, resulted to a loss of Nu.5638.50 (US$118.21). The number of passenger transport buses with their capacity was obtained from Road Safety Transport Authority, Thimphu, Bhutan and the fare per km based on the ADB report RBP.BHU 32288, September 2000 pp.2. It was determined that there was a total of 14 buss loss per day on the highway and indicated that at least 23 passengers will be blocked per day. Taking the average fare charge of Nu. 0.55 and using **Equation 4**, the total passenger fare loss per day resulted to an amount of Nu.34.32 (US$ 0.72) per day. Hence a total loss of US$ 118.93 per day was indicated due to road blockages.

(3) Discussion

Although, the total loss of US$ 118.93 per day is small in terms of amount, but for under developed country like Bhutan the loss of such amount per day is not acceptable as this amount is expected to increase as the intensity of traffic increases. Further, as the road blockage causes direct and indirect effects on to the traffic and transportation operation. In this study, the losses due to both direct and indirect effects are related to its loss in monetary values referred to as economic activity losses due to landslides. The rate of blockage per day determined from the total duration of road blockages and the number of vehicle blocked within the given period, reduces the loss of the other associated activities. This particular study used only the losses resulted due to freight transport and passenger transport losses due to the lack of data for other activities. However, the losses of other commercial activities in terms of value of goods being blocked, loss of other private vehicles and taxis could be determined in the similar manner if data are available. In this way the loss from the road blockage could be evaluated in terms of monetary value by assigning a unit value for all the economic related activities that takes place during normal traffic flow.

As indicated through the risk evaluation, there is urgent need to seek methods to avoid the areas susceptible to landslides. Further, it was observed during the survey that the alignment of the existing highway was made connecting the main town and villages without giving due consideration to landslide susceptible area. Hence to avoid such incidents in future and to reduce losses resulting from landslides, the study propose the Certainty Factor (CF) model that delineates the areas in terms of susceptibility as solution for managing and planning any future road construction works.

4. METHOD FOR LANDSLIDE MANAGEMENT AND ANALYSIS

(1) Spatial data sources and processing

Landslides are governed by several factors and it is important to recognize the conditions that caused instability of the slope and the processes that triggered the movement during landslide analysis in GIS. In the present study, six factors namely lithology, slope, slope aspect, elevation, land use and rainfall were considered for analysis. The factors considered in this study can be collected from the field and available information. The locations of landslides for the study area were obtained from Department of Road, Ministry of Works and Human Settlement, some digitized from google earth and from land use map of Bhutan. The Digital Elevation Model (DEM) was generated from SRTM elevation images from WRS2-syetem of 90m resolutions by importing and mosaicing in ERADAS IMAGINE 8.4. The terrain attributes such as slope angle, slope aspect and elevation were derived from the DEM with cell size of 100m. The study adopted the values of slope angle divided into 6 classes with slope aspect of 45° interval and elevation of 300m intervals. These data were subsequently rasterized in GIS with a cell size of 100x100m. This is the dimension used to generate geomorphological parameters, namely slope gradient and aspect and elevation. Other data layers such as lithology and land use processed from the geological map of Bhutan and land use map of Bhutan were rasterized to the same cell size. The rainfall data used was derived from the average daily rainfall recorded at the stations from 2001 to 2005 by Hydromet Service Division, Department of Energy, Ministry of Trade and Industry as point data. These data were interpolated and converted to raster using inverse distance weighted tool in GIS. The raster rainfall data layer was reclassified with 2 mm/day rainfall interval to the same cell size.

(2) Certainty Factor (CF) model

The spatial data analysis in GIS can be performed by either qualitative or quantitative techniques. While the qualitative models rely on expert knowledge and assign weights based on expert opinion or experience on the subject and the area (Anbalagan, 1992). The quantitative models use mathematics and statistics, to express the relationships between variables. Among the commonly used GIS models for landslide susceptibility, CF model has been deeply considered and experimentally investigated (Chung and Afabbri, 1993, 1999; Binnaghi et al, 1998). In this study the Certainty Factor (CF) model that uses quantitative techniques to relate landslide frequency distribution in different categories of factors to determine the susceptible areas by integrating the Certainty Factor (CF) values is used.

As the CF values are computed by comparing the conditional probability value to the prior probability value. It solves the problem of combination based on heterogeneity of different data layers. It is defined as follows:

$$CF = \begin{cases} \dfrac{pp_a - pp_s}{pp_a(1-pp_s)} & \text{if } pp_a \geq pp_s \\ \dfrac{pp_a - pp_s}{pp_s(1-pp_a)} & \text{if } pp_a < pp_s \end{cases} \quad (5)$$

Where pp_a is the conditional probability of having a number of landslide event occurring in a class of the parameter and is given by:

$$pp_a = \frac{Number\ of\ landslide\ cell\ within\ the\ class}{Number\ of\ cell\ in\ the\ class}$$

and pp_s is the prior probability of having the total number of landslide events occurring in the study area and is given by:

$$pp_s = \frac{Total\ landslide\ cell\ in\ the\ area}{Total\ cell\ in\ the\ area}$$

The CF approach transforms each class or area to specific interval varying between –1 and 1, referred to as Certainty Factors. A CF value of –1 indicates that the certainty of the proposition being true is very low, as compared with a high CF near +1 meaning that the evidence strongly supports the proposition as true. A value close to 0 means that the prior probability is similar to the conditional one, and is difficult to give any indication about the certainty of the landslide occurrence.

The favourability values (pp_a, pp_s) were determined by overlaying each parameter layer with the landslide inventory layer in ArcGIS 9.1 and landslides falling in each parameter class were determined. These values were used to determine the CF value of each classes based on **Equation 5**. After calculating the CF value of each class for all parameters, the layers were then reclassified with the value based on class value. These reclassified layers were combined using summation and this final layer was used to derive the average summation rank for the susceptibility mapping of the area. Thus, the CF model reduces to flexible quantitative method to generate independent results from the input data that transforms the thematic data into continuous data and also allow subjective assessment of the values. This advantage of subjective and objectivity is useful for decision makers to base their decision on issues for which the scientific foundations are unclear and fundamental data are lacking.

a) Combination of lithologic group and landslide

It is widely known that geology greatly influence the occurrence of landslides, as landslides are concentrated on certain lithological units and structural variations. The distribution of the lithology in the study area from **Fig. 2**, indicates that the area consists of gneiss covering the major portion of the area followed by mica schist, phyllite, sandstone and shale. The calculation process first takes the relation between the number occupied by landslide cells on a class of a certain class of lithology and the total number of cells of that class. This was repeated for up to the number of classes available in those parameters. The distribution of the landslides on certain lithology units was calculated based on **Equation 5** and the CF values are determined as shown in **Table 2**.

It can be seen that the lithologic groups can be delineated based on the CF value. The highest landslide certainty is indicated on phyllite region with CF value of 0.85. Although phyllites are suppose to have wide range of strength and durability characteristics when loaded perpendicular to the plane. The major problem in slope stability associated with phyllite in the landslide areas in Bhutan are due to the dipping of the bedding plane towards the slope of the failure plane. It was observed in most landslide area that the plane was dipping parallel to the failure plane.

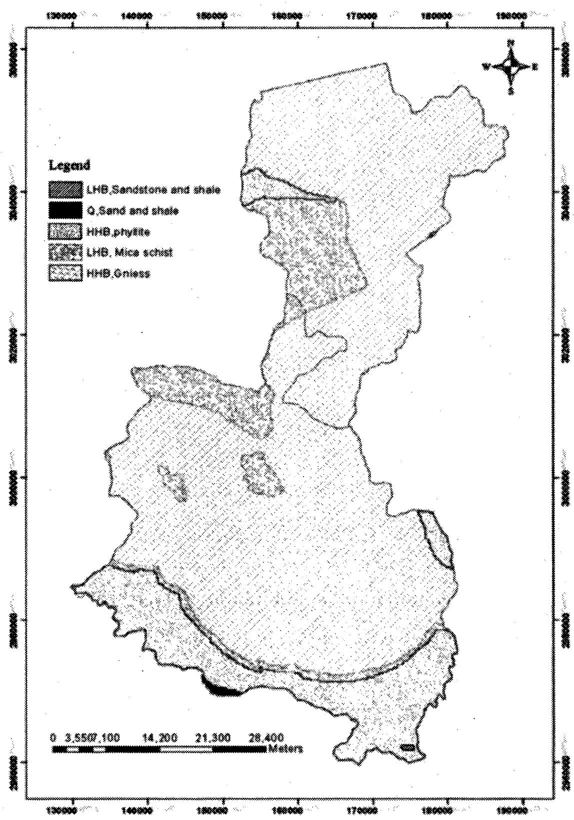

Fig.2 Distribution of lithological unit

Table 2 CF value of lithology

Class	Lithology	Lithology count	Slide count	pp_a	CF
1	Mica schist	33460	0	0.00000	-1.00
2	Phyllite	10602	90	0.00849	0.85
3	Mica schist and phyllite	28935	77	0.00266	0.52
4	Gniess	202553	185	0.00091	-0.28
5	Sand and clay	427	0	0.00000	-1.00
6	Sandstone and shale	114	0	0.00000	-1.00
pp_s = 0.00127					

b) Combination of slope angle and landslide

The study area covered slopes with angles range from 0° to 64.75°. The area was delineated based on CF values of 10° interval indicated that the failures of slope along this particular road increase with the increase in slope from 30° as shown in **Table 3**, indicating that the most probable range for failure of slope. The CF value of slope lower than 30° is negative, which means a low probability of landslide occurrence.

Table 3 CF value for slope

Class	Slope (Degree)	Slope count	Slide count	pp_a	CF
1	0 - 10	17660	11	0.00062	-0.52
2	10 - 20	74769	86	0.00115	-0.11
3	20 - 30	103581	110	0.00106	-0.17
4	30 - 40	62353	97	0.00156	0.17
5	40 - 50	16732	47	0.00281	0.54
6	50 - 64.75	1723	5	0.00290	0.56
$pp_s = 0.00129$					

c) Combination of slope aspect and landslide

The landslide is also influenced by direction of the slope as it influences the other landslide parameters. The slope aspect plays important role by exposing the topography to sun and rainfall that controls the growth of vegetation. In the study area the slope aspect facing south and southeast has CF 0.51 and 0.36 respectively, indicating the probability of occurrence of landslide as indicated in **Table 4**. Moreover the slopes facing the south are known to receive heavy rainfall during monsoon.

Table 4 CF value for aspect

Class	Aspect	Aspect count	Slide count	pp_a	CF
1	Flat	130	0	0.00000	-1.00
2	North	30728	23	0.00075	-0.42
3	Northeast	33288	24	0.00072	-0.44
4	East	36373	27	0.00074	-0.42
5	Southeast	33332	67	0.00201	0.36
6	South	38584	101	0.00262	0.51
7	Southwest	35786	65	0.00182	0.29
8	West	37237	36	0.00097	-0.25
9	Northwest	31360	13	0.00041	-0.68
$pp_s = 0.00129$					

d) Combination of elevation and landslide

Like the aspect of the slope, elevation is not the direct factor for landslide event, but it can control several other factors, especially vegetation, type of erosion and the activity of human beings. Further elevation is useful to classify the local relief and locate points of maximum heights within the terrain. For this area landslides are mostly distributed between 300-2100m and have highest CF value of 0.74 and the lowest value as 0.11 as indicated in **Table 5**. Although there are some landslides at an elevation of 3900-4200m with CF value of 0.1, it was observed that these are mostly resulted due to the melting of the snow. This indicates that landslides are certain at low and medium level elevation.

e) Combination of land use and landslide

The land use or vegetation cover plays important role on the stability of the slope. The importance of vegetation cover or land use characteristics on the stability of slopes are used by several researchers to assesses the conditioning parameters of the landslides (Uromeihy and Mahadavirfar, 2000, Anbalangan, 1992). In this area, the land use is divided into four distinct classes by reclassifying the land use map of Bhutan. The land use parameter thus divided indicated the CF value for barren land with grasses to be 0.45 as shown in **Table 6**, indicating that there are more certainty of landslide occurrence areas on barren land with grasses.

Table 5 CF value for elevation

Class	Elevation (m)	Elevation count	Slide count	pp_a	CF
1	143-300	2045	2	0.00098	-0.24
2	300-600	10239	51	0.00498	0.74
3	600-900	14313	62	0.00433	0.70
4	900-1200	17292	59	0.00341	0.62
5	1200-1500	19329	48	0.00248	0.48
6	1500-1800	18590	27	0.00145	0.11
7	1800-2100	19386	42	0.00217	0.41
8	2100-2400	25672	29	0.00113	-0.12
9	2400-2700	32056	0	0.00000	-1.00
10	2700-3000	33133	0	0.00000	-1.00
11	3000-3300	31016	11	0.00035	-0.72
12	3300-3600	23004	2	0.00009	-0.93
13	3600-3900	14372	9	0.00063	-0.51
14	3900-4200	9792	14	0.00143	0.10
15	4200-4724	6579	0	0.00000	-1.00
$pp_s = 0.00129$					

Table 6 CF value for land use

Class	Land use	Lus count	Slide count	pp_a	CF
1	Settlement with structures	1515	1	0.00066	-0.49
2	Forest	248563	305	0.00123	-0.04
3	Barren land with grasses	15809	37	0.00234	0.45
4	Agriculture land	10090	11	0.00109	-0.15
$pp_s = 0.00128$					

f) Combination of rainfall and landslide

Landslides are triggered by earthquake or rainfall. These triggering parameters cause the slope to slip from marginally stable to an actively unstable state. The CF value delineated based on 2 mm/day interval rainfall indicated that CF values increases as the intensity of rainfall increases as shown in **Table 7**. The average rain of 13.76mm to 15.76mm per day indicated highest CF value of 0.85. It also indicated the increase in certainty of landslide as rainfall intensity increases.

Table 7 CF value for rainfall

Class	Rainfall (mm/day)	Rain count	Slide count	pp_a	CF
1	1.76-3.76	93839	22	0.00023	-0.82
2	3.76-5.76	61546	65	0.00106	-0.17
3	5.76-7.76	38019	0	0.00000	-1.00
4	7.76-9.76	27980	56	0.00200	0.36
5	9.76-11.76	32860	81	0.00247	0.48
6	11.76-13.76	14247	76	0.00533	0.76
7	13.76-15.76	6386	56	0.00877	0.85
$pp_s = 0.00129$					

g) Combination of parameters

The six-parameter layers that were used were assigned with the calculated CF values by using reclassification in ArcGIS. The combinations of the cell within these six layers were based on the CF values with an array of grid cells of the parameter layer. This study used these combinations and calculations are represented with the help of an example of two raster data layers as shown in **Fig. 3**. For instance, in **Fig. 3**, each grid cell is referenced by row and column, and contains a number representing CF value on a 4x4 grid. The CF values of each cell of all the parameter layers were added and an average parameter layer was determined to represent the combined CF values of all the parameter layers in GIS.

Layer 1

	1	2	3	4
1	1.00	0.30	-0.10	0.50
2	0.20	-0.1	0.40	-0.30
3	-1.00	0.10	-0.60	0.10
4	0.10	-0.80	0.10	0.20

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Layer 2

	1	2	3	4
1	-1.00	0.30	0.10	0.20
2	0.40	-0.45	0.40	-0.76
3	0.70	0.10	-0.30	0.25
4	0.60	0.67	0.63	0.80

=

Average Layer

	1	2	3	4
1	0.00	0.30	0.00	0.35
2	0.30	-0.28	0.40	-0.53
3	-0.15	0.10	-0.45	0.18
4	0.03	-0.07	0.37	0.50

Fig.3 CF value combination model

Further, the average data layer values thus obtained was classified into six different susceptible classes based on the frequency distribution of the cells within the CF values. The boundary of the CF value was fixed based on the significant change of the frequency distribution and observing the standard deviation plot. After repeated trail of CF value grouping, the susceptible classes are classified into high stability, medium stability, uncertainty, low instability, medium instability and high instability with CF value range shown in **Table 8.** This classification gave reasonable representation of the area in terms of standard deviation plot in GIS.

Table 8 CF value with class value and susceptibility class

CF value	Class value	Description	Susceptibility class
(-1 to -0.5)	1	Very low certainity of landslide occurance	High stability
(-0.5 to -0.05)	2	Low certainity of landslide occurance	Medium stability
(-0.05 to 0.05)	3	Uncertainty.CF value within the range close to zero represent the interval in which no landsliding certainity can be expressed	Uncertainty
(0.05 to 0.3)	4	Low certainity of landslide occurance	Low instability
(0.3 to 0.8)	5	Medium certainity of landslide occurance	Medium instability
(0.8 to 1.0)	6	High certainity of landslide occurance	High instability

The CF value ranges in **Table 8** were used to derive the final susceptibility class of the area. The average susceptible layer derived from these combined layers indicated high stability, medium stability, uncertainty, low instability and medium instability class as the susceptibility class for the area. However, the final average layer was reclassified and subtracted to delete the high stability, medium stability and uncertain layer as it was of less significance to derive the required susceptibility class. The final layer thus obtained through this process indicates low instability and medium instability areas as shown in **Fig. 4**.

The susceptibility area indicated in **Fig. 4** represents the low and medium instability classes along with the landslide location. The low and medium instable areas determined by the model was validated by using landslide density by taking the ratio of existing landslide area to the area of each landslide susceptible area on the basis of the number of cells. It indicated that the low instable area covers an area of 397.88 sq. km, with 1.22 sq. km of existing landslide area while the medium instable area covered an area of 142.7 sq. km with 1.37 sq. km of existing landslide area. These values indicated the landslide density of 0.0028 and 0.0096 in low instable are and medium instable area respectively, thus suggesting higher density of landslides on higher susceptible area compared to lower susceptible area. Also **Fig. 4**, represented that all the instable areas are concentrated towards the southern region bordering to the Indian plains as observed during the field survey, thus validating the susceptible area. In order to determine the length of existing road on the susceptible areas, the Phuntsholing to Thimphu highway was overlaid over the susceptible area and it indicated that 5.7 km length of the existing highway passes over the medium instable area. Determining the location of the existing landslide within that of susceptibility class, it indicated that 249 landslide cells are located in low and medium susceptible area out of 352 landslide cells indicating that 70.7 percent of existing landslides are located inside low and medium susceptible area. This further suggested that the CF model could represent the actual landslide susceptible areas.

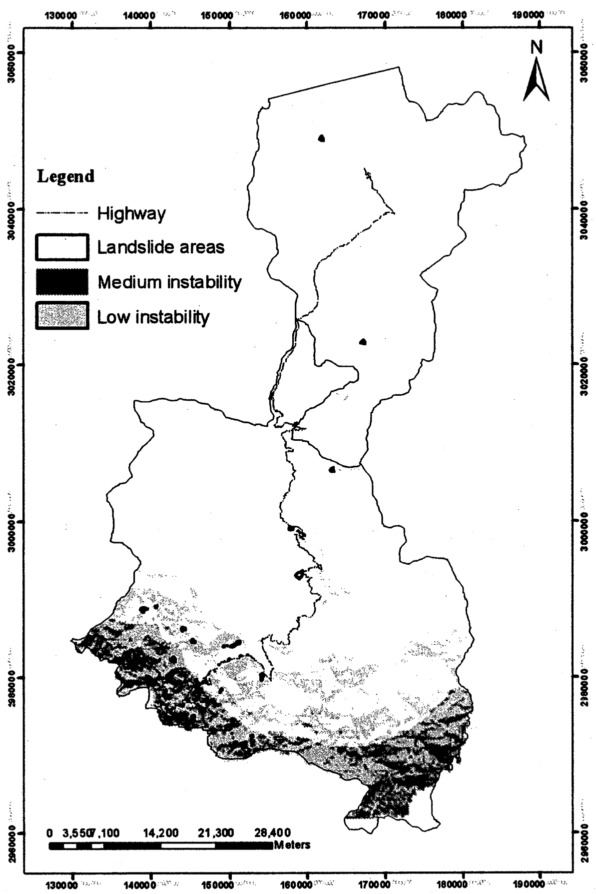

Fig.4 Susceptibility area with landslide locations

5. DISCUSSIONS AND CONCLUSION

This paper presented the method to evaluate the risk caused by rock blockages and suggests the application of GIS to manage landslide susceptible areas based on statistical approach. The method to determine losses based on unit price showed that it could determine total losses due to road blockages. Although the paper analyzed only the risk due to the landslide and could not compare with other risk on the road, however for mountainous area like Bhutan, landslides could be one of the most serious risk for road operation as it disturbs smooth flow of traffic due to road blockage. Both the site survey and study had indicated that the very high risk exists along the most important highway connecting the important industrial town Phuntsholing with Thimphu. It was indicated that the road blockage contributed to a monetary loss of $118.93 per day that too only from freight transport and passengers transport losses. It was determined that the blockages were caused mainly due to the heavy rainfall during the month of August and September.

The CF model that was validated based on landslide density was successful in representing the actual landslide susceptible areas. It indicated that the lithological group with phyllite with CF value of 0.85 has high certainty of landslide compared to other groups due to the bedding planes inclined parallel to the slope. The certainty factor value of slope indicates that the certainty of landslide in south, southeast and southwest has higher landslide certainty as the areas receive heavy relief rainfall. The elevation and land use parameters indicated that the landslides are more certain along elevation of 300-2100m along barren land with grasses compared to other classes.

The rainfall parameter indicated that the CF value increases after the rainfall intensity of 7.76mm/day and the certainty of landslide increases as the intensity of rainfall increases. The categorization of each parameter class in terms landslide susceptible area based on CF value would be useful for designers, planners and managers for selecting suitable locations of future developmental activities and road network planning in hilly regions.

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