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The planning and design of linear infrastructures in mountainous regions must carefully take into account the geomorphology and geology of the area under consideration. Rigorous geological and geotechnical checks and engineering measures are generally carried out for major projects such as dams and tunnels. However, as yet there are no fully developed standard procedures and techniques to assess hazards and risks for linear infrastructures such as roads and irrigation canals. It is not relevant or cost-effective to carry out detailed geotechnical investigations at all stages of a project and for all types and sizes of projects. Over the past four decades, road building in Nepal's young and rugged mountain terrain has taken place under varying levels of technological and financial inputs. This paper highlights the importance of hazard and risk assessments and provides an overview of the techniques and approaches evolved to plan the construction of linear mountain infrastructures based upon experiences in Nepal.

## Introduction

Linear infrastructures are vulnerable to frequent damage from ground failures due to their spread along long lengths of a variety of terrain, geological profile, and surface and ground water conditions; and the tendency of engineers to generalise a design to save time and effort.

The instabilities of mountain slopes are a factor in the geomorphology of a site; they include the inherent material characteristics, and the forces of nature and human interventions. The problem is more severe in young mountainous areas such as the Himalayas due to the fragility caused by the steep slopes, the severe undercutting of rivers, and the continuous up thrusting from tectonic movements. The beauty and grandeur of the high Himalaya and the rich biodiversity of its lower mountain ranges, where a growing human population is increasingly exerting pressure, is a matter of pride and challenge not only for the people of this area but also for the whole world. Most of the mountain slopes in this region are only marginally stable and so any change or disturbance in the surface or subsurface drainage of slopes or the material structure may destabilise them; rainfall is the main trigger of erosion, gullying, undercutting, and landslides. The natural processes of vegetation and forest-controlled runoff, infiltration, and evapotranspiration maintain a cycle of instability and stability. Human interference can accelerate this process and pose threats to the topsoil, the fertile land, and the rich plant diversity. The indiscriminate development of infrastructures in fragile areas is inadvisable as the associated hazards pose a big risk not only to the investment but also to the precious ecology and environment.

From time to time the geomorphological processes of mountain slopes may change and so structures that were considered secure under the conditions prevailing at the time of construction may not be secure later. The potential threat of ground failure is the **hazard**, whilst the potential loss of life and property is the **risk**. Hazards and ground failures are normally of little concern unless they threaten life and property. Scientists and engineers need to understand the geological processes in

order to be able to estimate the extent of temporal and spatial instabilities; they must also assess the extent of damage that can be tolerated. When planning a construction, the hazards must be identified and their extent assessed as must possible alternatives, applicable technology, the amount of money available, the benefits, and the initial and recurring costs. This is called risk management. Minor hazards may be modified within the small area of influence of any structure after it has been built, but it is not possible to counteract major natural hazards. It is not the hazard but the risk that we have to try and manage.

Engineering is essentially an exercise dictated by the level of investments and the recovery of costs or the return on investment, normally over a 15 to 20-year period (the design life). Therefore most risk management has to be viewed over this time period, although potential damage to the environment from a structures should be considered over a longer time frame to ensure that irreversible impacts are avoided. Cost cutting measures should not increase the levels of erosion or the hazards. From an economic standpoint, the accuracy of costing is crucial. The accuracy of pre-feasibility and feasibility costing depends upon the accuracy of the hazard and risk assessments. Geologists need to be able to understand the needs of the engineers in order to assess the temporal and spatial hazards, and in turn the engineer must try and understand the natural processes and use this information to assess and manage the risk. This requires an ability to link the hazard with the potential damage to the proposed structure over the design life. An affordable level of risk can be allowed for in the design and can be built into the cost.

Until recently engineers and geologists only looked at the hazards and risks from their own subjective perspective. In many instances, their recommendations have been more academic than practical. Though many methods have been developed by geologists to assess and map landslide susceptibility and natural hazards, very few have linked the hazards to the risks and the overall impact on the cost and life of engineering structures. This has been particularly so for linear infrastructures such as roads and canals.

It is crucial that geologists and engineers co-operate in their work to facilitate a common understanding of geological and geomorphological processes and how they act upon structures. This will indicate how best to design a structure to enable it to resist these forces over its economic life by using the appropriate strength of material and adequate foundations.

## **Need to Assess Hazards and Risks**

Structures built in mountainous terrain are subject to instabilities from various natural forces, both sudden and gradual, that cause ground movement. Structures built on slopes, are subject to considerable forces from lateral earth pressure and slope movements over time due to disturbances up slope or down slope from the structure. Structures in mountainous terrain have to be designed to allow for changing conditions in the forces acting on and around them – in contrast to level terrain where both the forces and the strength of underlying materials are constant.

Assessment of hazards to a structure means trying to understand and quantify, in simple terms, the effects of geomorphic processes and thus enable designers to allow for the maximum natural forces that a structure is likely to be subjected to over its lifetime. Such assessments aren't simple, but the priority is to minimise the risk to human life and the investment (the structure) from unexpected frequent failures. The mountain environment is in many ways a fragile environment and structures that are built on it without a reasonable understanding of the impacts to and from the environment are likely to be subject to serious problems.

To summarise, hazards and risks need to be assessed and used as a decision making tool. It is important to

- understand instabilities from geomorphic processes;
- quantify and communicate uncertainties; and
- assess the probable damage from existing or potential events;

in order to

- increase the accuracy of project cost estimates;
- optimise investment efficiency;
- understand total costs over a period of time;
- develop reliable designs; and
- understand impacts on and from the environment.

## Definitions of Hazard and Risk

British Standard (BS) 4778 defines hazard as “a set of conditions in the operation of a product or system with the potential for initiating an accident sequence”. Varnes (1984) says, “Natural hazard is the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon”. Einstein (1988) defines hazard as the “Probability that a particular danger occurs within a given period of time.” Dangers include existing or potential phenomena such as landslide, creep, rock fall, debris flow, mudflow, and slope undercutting.

BS 4778 defines risk as “The probability that a potential hazard will be realised and the probability of the harm itself. ... (risk is) the combined effect of the probability of occurrence of an undesirable event and the magnitude of the event”. Varnes defines risk in terms of specific risk and total risk. Specific risk ( $R_s$ ) is the expected degree of loss due to a particular natural phenomenon and may be expressed as:

$$R_s = \text{hazard} \times \text{vulnerability}$$

He defines the **vulnerability** as “the degree of loss to a given element or a set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude”. It is expressed on a scale of 0 (no damage) to 1 (total loss).

“Total risk ( $R_t$ ) means the number of lives that could be lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon. It is therefore the product of specific risk ( $R_s$ ) and element at risk ( $E$ )”. It is expressed as:

$$R_t = R_s \times E = H \times V \times E$$

where,  $V$  = vulnerability and  $H$  = hazard

Einstein (1988) expresses risk as:

$$\text{hazard} \times \text{potential worth of loss, and} \\ R = P[\text{danger}] \cdot u(x)$$

In other words, risk is the “probability of an event multiplied by the consequences if the event occurs”. The danger can be any event that may cause damage; whilst hazard assesses the prob-

ability that this danger may occur. The probability of an event occurring can be worked out either by collecting data, or through a subjective estimation.

In many instances, the hazards and risks at any site are taken as the same, as risks are taken to be implicit and are assumed to be proportional to the hazards. The relative levels are adequate for comparisons, and it is often not necessary to quantify the physical and monetary value

## Types of Hazard and Risk

Hazards can be classified in relative, empirical, absolute, or monitoring terms.

- The relativity of a hazard is expressed as high, medium, or low with reference to a pre-determined measure of hazard attributes.
- The empirical nature of a hazard is expressed in terms of the height and the slope angle.
- The absolute nature of a hazard is expressed in terms of the factor of safety and the probability of the event happening.
- Observations from monitoring hazards are expressed in terms of changes over time including, deformation and rate of movement.

Risks may be classified in terms of physical, economic, or monetary risk, as in the following examples.

- *Physical risk*: "There would be a loss of 50% of the road in a slope area B if a large deep seated rotational soil slide occurred at B."
- *Economic risk*: "There is a 90% probability that the economic rate of return in a road project through hazardous terrain is less than 15%".
- *Monetary risk*: "If a landslide resulted in the failure of the bridge, repair costs would amount to about 100,000 dollars."

## Stages in Hazard and Risk Assessment

### *National and regional level preliminary planning stage*

Before attempting to assess the hazards of ground failure, the purpose of any assessment and its practical value to the end-user must be clearly understood. Small-scale maps are useful for preliminary planning at the macro-level. For example, a 1:1,000,000 hazard map is useful to indicate the risks of locating major projects at different locations. Such hazard maps can be prepared by overlaying and picking out the relevant information from separate hazard maps of tectonic/seismic hazards, rainfall hazards, and slope hazards. For regional level planning for a mountainous country such as Nepal a 1:50,000 scale map is appropriate.

### *Project level and pre-feasibility level planning stage*

Existing hazard maps of 1:50,000 scale or larger should be used to make preliminary comparisons of alternatives and to determine the extent of further investigations of proposed sites. If such maps are not available, they need to be prepared by overlaying 1:50,000 scale seismicity, rainfall, landslide, land use, geological, and terrain maps. Alternatively, strip maps can be made for the proposed paths of linear infrastructure projects from walk over surveys. Such maps will indicate the geomorphologic, land use, and engineering geological features within the watershed areas that will influence the structure. Relative hazards can be assessed by rating the characteristics such as slope, soil type and depth, lithology, structure, relief, land use, and drainage, and calculating the total rating and predicting landslides, gullying, and erosion.



A simple approach for directly assessing hazards and risks along road alignments is by doing field surveys and marking hazards onto topographical maps. The first step is to mark the proposed alignment of the road on 1:50,000 or 1:25,000 scale topographical maps and divide into one kilometre sections. Next the following should be marked on in a field survey: rock or soil types; existing dangers such as landslides, debris flow, major gullying, major erosion, and river undercutting; and potential dangers. Probabilities may be assigned to each type of potential failure on the basis of the subjective judgement of the survey geologists and engineers. The extent of damage to the proposed structure if the danger occurred once the structure was built should also be rated based on judgement.

### ***Project level feasibility, hazard assessment, stage***

At the project feasibility stage, indicative designs need to be prepared to allow cost estimates of about  $\pm 10\%$  accuracy to be prepared. This means assessing both hazards and risks to the proposed structure. All the maps and any aerial photographs need to be at a scale of 1:25,000 or larger. Available maps and aerial photos may suffice for rapid assessment of the extent of hazards, otherwise new engineering geological and geomorphologic maps need to be prepared from field walk-over surveys. It is crucial to understand the effect of the type and magnitude of the hazard on the type and size of the structure proposed in order to assess the risks from the hazards. The frequency and magnitude of the hazards and their relationship to the risk can be determined from subjective assessments.

### ***Detailed design stage***

The map scale has to be much larger at the detailed design stage. Feasibility stage assessments may be adequate in low hazard and no hazard areas; in high hazard areas, a 1:2,000 to 1:10,000 survey is necessary to indicate engineering geological and geotechnical details. These allow slope stability analysis and the determination of the factors of safety with or without any proposed countermeasures. Hazards can often be modified by countermeasures.

## **Hazard and Risk Assessment Methods**

A number of methods have been developed to assess hazards for project feasibility studies. These methods are not normally justified in pre-feasibility studies because of the amount of work involved.

### ***Slope mass rating method (Romana 1988)***

(For a detailed description of this method see also Anbalagan and Singh, this volume). The Slope Mass Rating (SMR) index for measuring the stability of rock slopes was developed by Romana (1998). It is based on Bieniawski's (1979) rock mass rating index, which uses adjustment factors for dip direction, dip amount, and method of blasting. It is expressed numerically as:

$$\text{SMR} = \text{RMR} - (\text{F1} \times \text{F2} \times \text{F3}) + \text{F4} \text{ or}$$

$$\text{SMR} = \text{RMR} + (\text{F1} \times \text{F2} \times \text{F3}) + \text{F4}, \text{ if the factor F3 is itself expressed as negative}$$

where RMR is the rock mass rating. The RMR is indicated by values within a range of 0 to 100 (the higher ratings indicate lower hazard) and is computed by adding together rating values for the five parameters:

- strength of intact rock;
- RQD or rock quality designation (measured or estimated);

- spacing of discontinuities;
- condition of discontinuities; and
- water flow through discontinuities.

F1, F2, and F3 are adjustments for joints and F4 is an adjustment factor for the method of excavation. The likely extent of different types of failure can be predicted from the limits of SMR values (Table 12.1). A rock slope hazard map can be prepared to show the relative values assigned to the type and extent of failures.

### ***Soil slope movement hazard rating method (Deoja and Thapa 1989)***

The soil slope movement hazard rating developed by Deoja and Thapa (1989) is expressed numerically as:

$$H = D[(R + H_w)(S + C) + (I + L)]$$

where, H = hazard value, D, R,  $H_w$ , S, C, I, L are weightages for depth of soil, rainfall, depth of water table, soil characteristics, complexity, slope, and land use respectively. The level of hazard is low where H lies between 0 and 30, medium for an H of 31 to 50, and high for an H of more than 50. The weightages for the different factors are given in Table 12. 2.

The extent of damage depends upon the hazard level and the type of instability. Instabilities such as debris flows, deep-seated slides, GLOFs, landslide dams, major undercutting by rivers, and high seismicity are regarded as high hazards. Soil hazard maps can be prepared based upon the relative hazard values calculated by this method.

**Table 12.1: Prediction of types and extent of failure from Slope Mass Rating (SMR) values**

Plane failure		Wedge failure		Toppling failure		Soil-like failure	
SMR values	Failure	SMR values	Failure	SMR values	Failure	SMR values	Failure
>60	None	>75	None	>65	None	>30	None
40-55	Big	60-75	Some	50-65	Minor	10-30	Possible
15-40	Major	40-55	Many	20-35	Major		
		15-40	None				

**Table 12.2: Weightages for different factors**

Depth of soil (m)		Annual Rainfall (m)		Depth of water table		Soil characteristics <sup>1</sup>		Complexity		Slope angle (degrees)	
Range	Weightage, D	Range	Weightage, R	Range	Weightage, $H_w$	Range	Weightage, S	Range	Weightage, C	Range	Weightage, I
0-0.9	0	0-0.4	0.5	0-5	0.5	GW, GP, SW, SP	0.5	Strong dissection moderate dissection simple dissection	1.5	0-14	1
1-5	1.5	0.5-2	1	6-10	2	GM, SM	1		0.75	15-24	3
6-10	2	2-3.5	1.2	11-20	1.5	GL, SL	2		0.25	25-34	5
11-15	3	>3.5	1.5	>20	0	ML, CL, OL	2.5			35-54	7
15-20	2.5									45-54	7
>20	2									55-60	8
										60	8

<sup>1</sup>soils classified according to the Unified Classification System.

Basic symbols G – gravel; S – sand; C – clay, M – silt, O – organic; modifying symbols W – well-graded, P – poorly-graded, M – with silt fines, L – low liquid limit

### **Map overlay method (Gupta and Anbalagan 1997)**

(For a detailed description of this method see also Anbalagan and Singh, this volume). The area to be mapped is divided into facets; then structural, land use and land cover, relative relief, lithological, slope morphometry, and hydrogeologic condition maps are prepared from existing maps and field surveys. Ratings are then assigned for each facet of these various maps based upon a predetermined rating scheme. The total estimated hazard is the sum total of these ratings for each facet. The hazard map is then prepared using five categories of hazard on a scale of 0 to 10: very low hazard (rating <3.5); low hazard (3.5-5); moderate hazard (5.1-6); high hazard (6.1-7.5); and very high hazard (>7.5).

### **Landslide hazard mapping method (TRL Overseas Road Note 16 1997)**

The relative hazards of different sites can be assessed by landslide hazard mapping (LHM). Maps are prepared based upon a series of factor maps that are derived from 1:25,000 scale aerial photos, 1:50,000 scale topographical maps, and 1:200,000 scale geological maps. The factor maps are landslide distribution and underlying geology maps, slope physiographic classification maps, slope angle distribution maps, slope aspect distribution maps, land use distribution maps, and summary of landslide hazard zones map. These records are then set against the actual density of landslides and compared with those expected had there been no control of the distribution of slope failure.

### **Landslide risk assessment procedure (Einstein 1988)**

The Landslide Risk Assessment Procedure as developed by Einstein is a formal procedure for hazard and risk assessment. It involves the preparation of separate state-of-nature, danger, hazard, and risk maps. The first-level state-of-nature map, is prepared by combining information from topographic, geological, vegetation, hydrological, and geotechnical maps, with test results, displacement measurements, water level observations, and visual observations. The second-level danger map, is prepared by making an inventory of existing and potential slope instabilities. The third-level hazard map maps the dangers and the probability of 'dangerous events' occurring. The fourth-level risk map shows the hazards and their potential consequences. The fifth step in this method is to calculate the hazard by working through probability calculations from the data shown on the state of nature and danger maps.

### **Hazard and risk assessment by pre-assigned ratings (Deoja et al. 1991)**

The mountain risk engineering (MRE) handbook prepared by ICIMOD in 1991 (Deoja et al. 1991) suggests quantification of hazards and risks. It describes the assessment of hazard by preparing maps showing various attributes of a slope such as slope angle, soil and rock type, sub-surface and surface drainage conditions, rock discontinuities, faults, and land use, and rating these attributes on a scale of 0-1 using a rating table suggested on the basis of experienced judgement. The total rating, called the state-of-nature, is an indication of the probability of slope failure assuming that the ratings are valid for the threshold rainfall that is considered to be the main trigger of slope failure. Rainfall factors are also suggested so that this probability can be modified for other threshold rainfall values. At present these are indicative values based on judgement rather than research and detailed analysis. The MRE handbook suggests a simplified method of hazard assessment using charts and tables rather than detailed mapping for the pre-feasibility stage of a project. For the feasibility stage, detailed mapping and detailed ratings are suggested.

Risks are quantified by multiplying the hazard with the value of the potential loss expressed in monetary or physical terms. For example, assume that a deep-seated rock slide in the influence area of a road section could wash out the entire 1 km of road costing Rs 10 million per km. Let the hazard

be 0.70 for the particular influence area of the road. This means that the probability of a deep-seated rock slide occurring once during the design period (the analysis period) is 70%. The risk is therefore 0.7 km (i.e.,  $0.7 \times 1$  km) of road washout or 7 million rupees (i.e.,  $0.7 \times 10$  million rupees) worth of loss during the analysis period (taking into account the loss of the structure only).

### ***Examples of hazard and risk assessment in road projects in Nepal***

Alexis Wagner carried out hazard mapping for the feasibility studies for the Rapti integrated roads in 1986 and the rehabilitation of the Lamosangu-Jiri road in 1988-1990. The hazard maps (called risk maps by Wagner) were prepared on the basis of slope maps, geological engineering maps, and morphostructural maps by assigning tentative weights on a scale of 0 to 100 for structures (number of wedges, orientation of slope, bedding, and dip), lithology, hydrogeological condition, and tectonic condition. Risks and levels of risk of plane failure and wedge failure in rock structures were predicted on the basis of the structure and the total weight. The calculated 'risks' were in fact what are more commonly called 'hazards' because the extent of damage to and from the road in terms of loss of life or property was not calculated. The information was therefore of little value for comparison of alternatives or economic appraisals.

ITECO, Nepal carried out a feasibility study for the Baitadi-Darchula road for the Department of Roads of HMG Nepal in 1990 using a combination of Wagner's rock slope hazard rating and Deoja's soil slope hazard rating techniques to assess the hazards and the risks in terms of the expected loss of road length, and thus facilitate comparison of the alternatives.

### ***A simplified approach to risk management for linear infrastructures in mountainous regions***

Engineers prefer to assess hazards and risks quantitatively by using tables and charts rather than by preparing rigorous maps at various levels and overlaying the maps to calculate the total hazard. Risk management for linear infrastructures like roads or canals normally means the development of designs that ensure both the safety of the proposed structures and non-alteration of the natural hazards during the design life of the structure. A rather simplified approach can be taken in such a case. The approach suggested here uses a clear distinction between hazards and risks. It employs ratings or weights similar to the probabilities assigned subjectively. The approach is described briefly.

#### **Step 1 Evaluation of the 'state-of-nature'**

The area which could influence the proposed road or canal or any structure is divided into slope facets (or watershed areas) with distinct characteristics in terms of slope, land use, soil and rock types, and geological structures. Various attributes of the facet are assigned ratings as shown in Table 12.3, the description of the attributes, and their ratings recorded in a table similar to the example shown in Table 12.4. The total value of the state-of-nature (SN) is an indication of the degree of instability of the slope, that is the probability of slope failure. The ratings suggested in Table 3 may be changed if the evaluator's experience so dictates (e.g., to suit local conditions).

#### **Step 2: Assessment of danger**

This stage involves making an inventory of existing, potential, and imminent dangers such as erosion, gullying, debris and mudflows, undercutting, and landslides. The geometry and impact area of each feature is noted on the facet or watershed area. Table 12.5 shows a suggested format for collecting the data. A danger map showing all of these features should be prepared on the same



Table 12.3: Rating for the parameters used to determine the state of nature (SN)

Topography				Drainage			
Slope Deg.	Rating	Relative Relief (m)	Rating	Surface drainage type	Rating	Ground water depth (m)	Rating
Soil Slope		0-50	0	Simple	0	Dry	0
0-5	0	51-100	0.03	Active	0.04	Wet	0.04
15-25	0.05	101-150	0.06	Very		Flowing	0.09
16-25	0.1	150-200	0.09	Active	0.08		
26-35	0.14	>200	0.12				
36-45	0.12						
>45	0.1						
Rock Slope							
<45	0						
46-60	0.03						
>60	0.14						
Landuse		Fault		Soil			
Type	Rating	Distance from Road (m)	Rating	Soil Type	Rating	Soil depth (m)	Rating
Thick vegetation	0	>50	0.16	Compact alluvium	0-0.04	<1	0
Mod Vgtn	0.03	51-100	0.08	Loose alluvium	0.07-0.12	1-3	0.04
Sparse	0.06	>100	0.04	Colluvium	0.06-0.08	4-6	0.06
Barren	0.09			Eluvium	0.04-0.06	7-10	0.10
Cultivated	0.09			Talus	0.08-0.12	11-15	0.12
				Till	0.06-0.12	16-20	0.08
				Debris	0.06-0.12	>20	0.05
Lithology/Structure							
Rock	Rating	Weathering Grade	Rating	Joint spacing	Rating	Orientation of discontinuity	Rating
Massive, Resistant Limestone quartzite	0	Fresh	0	Wide, >1m	0	Slope oblique to joint/bedding > 30°	0
Highly cemented, conglomerate	0.01	Moderate	0.02	Medium 51-100cm	0.03	Dip slope of joint +15°	0.04
Soft rock	0.02	High	0.04	Close, 50-10 cm	0.04	Dip slope of bedding +15°	0.08
*Alternative phyllite quartzite	0.04	Complete	0.06	Tight, <10cm	0.06		
Weak rock crushed	0.06						

scale as the state-of-nature map. Imminent danger can be predicted by looking at site conditions but predictions are not made at this stage. This map will assist in predicting future dangers.

Where a shallow soil slide exists in a particular facet or unit in the watershed and influences the proposed structure then the probability of occurrence of a shallow slide is rated as '1'. Since the area of the potential landslide may only be a fraction of the total area of the facet, the probability that a shallow soil slide will cover the entire area of the facet is less than one. This allows for adjustments to be made for the possible non-homogeneity of the state of nature on the facet.

### Step 3: Assessments of hazards

A hazard assessment is a determination of the probability of a certain danger occurring in a certain area within a certain period of time. The hazard can be assessed by comparing the value of the state-of-nature with the existing and imminent dangers and their types, sizes, and geometry. Table 12.6 shows a suggested format for such records and assessments. The conventional low cost and

**Table 12.4: Format for recording the state-of-nature (SN) and type of instabilities**

Chainage	Facet				State of Nature, SN												Total SN	Type of Probable Instability
	No	Length of Facet/ road L	Size of facet sqm LxBxH	Area of Facet sqm A	Slope Degree	Relative Relief	Drain- age	Ground Water	Land Use.	Fault	Rock/ Soil Type	Soil Depth	Weath- ering Grade	Joint Spacing	Orienta- tion of Discon- tinuity			
1	2	3	4	5	6	7	9	10	11	12	13	14	15	16	17	18	19	

Note: Record the description or actual value on top and assign the rating value from the chart for the particular case on bottom

**Table 12.5: Format for an inventory of existing dangers within a facet or block**

Chainage	Facet			Existing Danger					Describe Imminent Danger and likely Impacts	Remarks				
	No	Length of facet/road L	Size of facet sqm LxBxH	Area of facet sq m A	Type	Size LXBxH	History	Area			Length along Proposed road			
								area (a) sqm			% 100xa/A	L m	% 100xL/L	
1	2	3	4	6	7	8			9	10	11	12	13	14

SSSS = shallow soil slide; DSS(R/T) = Deep seated soil slide (rotational/translational); DF = Debris flow; MF = Mud flow; MRS(P/W) = Minor rock slide (planar/wedge); MRS(p/w) = Major rock slide (planar/wedge)

least-disturbance method of road construction does not normally involve modification of the natural hazard by the road construction.

#### Step 4: Risk assessments

In road building, the risk is expressed in terms of the potential type and extent of damage to the road and the area of the facet. There may be triggers such as heavy rainfall and improper road cuts or landslide removals more than once during the 15 to 20 year analysis period, but for simplification only one failure is usually considered. It is up to the experience of the evaluator to estimate the values of minor and major failures. Minor soil slides or rockslides above the road cut may only cause minor damage to side drains and pavement layers. Major slides above the road cut or slides with a failure surface encompassing the entire road may cause full damage to the road section. For example, a minor failure over one metre of the road may only incur costs of 10% of the total cost of completely replacing one metre length of the road, whereas major danger may entail a 100% replacement cost. There may also be other risks such as the loss of land, damage to houses, and injury to people and animals. Obviously there will be very serious risks in highly populated areas. Table 12.7 shows the format suggested for assessing the risks.

#### Step 5: Risk Mitigation

Once the level of risk has been determined in terms of the monetary value of the damage to the structure, life, and property, there are several ways to proceed. Risk can be managed by

- living with the risk;
- avoiding the risk, for example by moving the alignment away from hazardous sections;
- reducing the risk by only building a minimum of standard stretches of road in hazardous sections;
- removing the hazards, for example by removing unstable material; and
- reducing the hazard or modifying the state-of-nature by providing active countermeasures, for example by building retaining walls or buttresses, adding vegetation and/or plantations, and by other soil and rock reinforcement measures.

### **Conclusions**

In mountainous regions, assessment of the hazards and risks to new infrastructures from erosion, gully, and landslides, and in turn the effect of new infrastructures on the environment and the infrastructure itself, is crucial during the feasibility stage and project appraisal and feasibility studies. It is necessary so that the best use can be made of resources and the environment protected from irreversible impacts. Due to the dynamic nature of mountain environments and the complex of variables involved, it is difficult to determine and quantify these uncertainties and convert them into potential economic impacts. Nevertheless, experience and judgement can be applied to make a reasonable assessment.

There is a strong tendency among engineers to avoid hazard and risk assessments because of the need to collect a considerable amount of geological data and the difficulties in the assessments of probabilities. No matter whether a probability is assessed or not, the assessments of geological, geomorphic, topographical, lithological, and land use attributes will definitely contribute to an engineer's understanding of a site and will make clear to him the innumerable uncertainties already hidden in assumptions about the material strengths and external forces that act upon a structure over a period of time. Uncertainties exist, but it is better to know their extent and try to design the

Table 12.6: Format for prediction of instabilities

Chainage	Facet			State of nature		Existing danger		Predicted danger			without influence of road			Remarks
	No	Length of road along facet, L	Size of facet sqm LxBxH	Area of facet sqm A	SN	Imminent danger type	Type	% area covered	% Length of road affected	Danger type	Probability of occurrence	Prob. of full area under danger	Combined prob. (hazards) P 12x13	
1	2	3	4	5	6	7	8	9	10	11	12 <sup>1</sup>	13	14	15

<sup>1</sup>This is to be based on judgement on the basis of the values in Columnne 6, 9, and 10 and other site conditions use values within zero to one. Assume one time occurrence during the design life

Table 12.7: Format for Reading Hazards and Risks

Chainage	Facet			Hazard			Risks				Other Risks			Total Risks	Remarks			
	No	Length of Facet /road L	Size of facet sqm LxBxH	Area of Facet sqm	Type of Danger	Size	Proba- bility p	Type of Danger	Probabil- ity of full damage to road	Road length fully damaged 8x10x3	% of facet length 11x100/3	Value of road dmgd	Land Area 8x5			Others Value		
1	2	3	4	5	6	7	8	9	10 <sup>1</sup>	11	12	13	14	15	16	17	13+15+16	

<sup>1</sup>This is to be estimated on a zero to one scale on the basis of judgment/degree of belief. A shallow slide may damage 10 to 20 per cent of structure whole a deep seated slide or major under cutting or debris flow may washable the complete structure.



project and its structures around them than to have false confidence through overlooking them. The frequent failure of high cost roads; the alarming environmental damage from inappropriate techniques used in road construction; the scarcity of funds for maintenance; and the insufficient impact that roads have had on Nepal's mountain economies are sufficient reason to justify the need for hazard and risk assessments in the early stages of a project cycle.

Risk management using the simplified approach discussed in this paper will also be helpful in generating data for research and analysis, and thus contribute to the development and refining of probability ratings and formal approaches to the risk management of linear infrastructures in mountainous terrain.

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