Chapter 14*

HAZARDS AND RISKS

14.1 INTRODUCTION

Road engineering on hill slopes involves analysis and design within the context of uncertain knowledge of slope stability. In particular, uncertainty regarding slope stability arises from three inter-related sources.

14.1.1 *Natural Variability*

The geologically active Himalayan slopes are constantly under the influence of uplift, weathering, and erosion. The variations in the tectonic movements, parent material, altitude, and climate result in variations in the extent of slope instability in time and space.

14.1.2a *Measurement Errors*

Spatial and temporal averages of various physical parameters, relating to soil and rock behaviour, result in measurement errors of true values. Such errors result in the uncertainty of true values.

14.1.2b *Simplification Errors*

Analytical models often involve a simplification of the physical world. Simplification is responsible for a certain degree of variation in properties defined by such models. Examples of such properties include the effective stress in soil, soil classifications, and rock joint strength parameters.

This chapter is addressed to the conceptual structures and techniques for dealing with the uncertainty of slope stability for road engineering in hilly areas.

14.2 HAZARDS

Hazard is a source of risk that may cause damage to, or loss of, life and property. Hazard can also be defined as the probability of occurrence of a particularly damaging phenomenon, within a specified period of time and within a given area, because of a set of existing or predicted conditions in the given time and space. The damaging phenomenon becomes a matter of concern only when it entails a certain degree of damage or loss to the population or the resources within its influence.**

Hazards may be classified as relative hazard, absolute hazard, and monitored hazard (Harten and Viberg 1988). Relative hazard is assessed by assigning ratings to different factors contributing to hazard. Absolute hazard is expressed deterministically, e.g., factor of safety, or probabilistically. Monitored hazard is assessed by actual measurements of the effects, e.g. deformations.

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* Tables without credit lines in this Chapter are compiled by the author.

** Einstein (1988) has also defined hazard as: Hazard = probability that a particular danger will occur within a given period of time.

14.3 RISKS

Risk is a potential loss of life and property and may be defined as *"the combined effect of the probability of occurrence of an undesirable event and the magnitude of the event"*. Thus, there is always an element of uncertainty associated with risk. Varnes (1984) proposed the following definitions of risk in a UNESCO study:

"Natural hazard (H) means the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon.

Vulnerability (V) means the degree of loss to a given element or set of elements at risk (see below) resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).

Specific risk (R_s) means the expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H times V.

Element at risk (E) means the population, properties, economic activities, including public services, etc., at risk in a given area.

Total risk (Rt) means the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon, and is therefore the product of specific risk (R_s) and elements at risk (E). thus:

$$R_t = (E)\,(R_s) = (E)\,(H \times V)."$$

Varnes points out that the French word *risque* should be regarded as equivalent to the English word hazard. Einstein (1988) has defined risk as *"probability of an event times the consequences if the event occurs"*. It may be expressed as:

RISK = hazard x potential worth of loss.

14.4 USE OF HAZARDS AND RISKS IN DECISION-MAKING ON HILL ROADS

14.4.1 *Prefeasibility and Feasibility Assessments*

The prefeasibility and feasibility stages of the decision-making process, relating to linear structures such as roads, involve the choice of a route from several alternative routes and the choice of alternative technologies for a given route.

The comparison of technological alternatives will become necessary only for major investments, that is major roads and major structures, such as tunnels, high-tech retaining walls, stabilisation of major landslides, and major river training works.

Risk analysis involves analysis of physical risks, i.e., risks of failure of structure and analysis of economic risks, i.e., certainty of the return on investments. Economic risk analysis involves identification of all variables that account for costs and benefits, assessment of probability, distribution of each variable, and the use of simulation technologies to obtain a distribution of probability and rate of return. Pouliquen (1975) gives a detailed account of these procedures.

For most purposes relating to linear hill infrastructure, physical risk analysis is adequate. The information from physical risks alone could be used for a choice of route. The value of physical risks may be incorporated into the traditional cash flow analysis for a choice of route based on economic feasibility.

The steps involved in prefeasibility and feasibility risk assessments based on physical risks are:

- assessment of hazard by subjective probability distributions based on engineering-geologic information,
- assessment of loss caused by the hazard based on subjective judgements from past experience,
- assessment of expressed value of risk by multiplying the hazard by the loss, and
- selection of the route based on either the total risk (total length of route likely to be lost) or the economic return given this loss as additional costs.

It should be noted that the assessment of probability of damage at a particular time or a series of damages at various points in time in the design life is a question of rigor, depending upon the scale of work. Direct use of binomial or other mathematical distributions are less likely to represent the distribution of probability that would actually happen with landslide occurrences in real life. Distributions obtained by step rectangular distributions through subjective assessments of likelihood, based on the experiences of relevant experts, would probably lead to the most representative curve fit. The simplest approach, that of using a single probability for a time immediately after the completion of the structure, is believed to serve the purpose for most cases of feasibility decisions.

The subjective assessment of the extent of damage, should the hazard occur, is again dependent upon the technological level, i.e., the extent of mitigation at the design perceived during feasibility assessment. It is thus suggested that, for simplicity, the design and mitigation selected during the assessment should be such that no significant modification of hazard is occurring as a result of the selected standards. The use of hazard-based standards and mitigation suggested in the Application Guide of this handbook is believed to ensure that such an assumption is reasonable and applicable to most situations of hill roads in a primarily rural economy.

14.4.2 *Detailed Design Stage Assessments*

Decisions on alternative designs, involving major investments and sophisticated technology for risk mitigatory actions, require more rigorous analysis of risks and decision-making techniques.

Decision-making concerning choice of standards for road cut designs, design of retaining walls and breast walls, design of drainage and erosion controls, and design of stabilizations for minor slides for most of the road sections can be based on the hazard levels, or rapid assessments of water table conditions and geotechnical properties of the soil and risk without rigorous investigations and analysis, but with experienced judgements and empirical designs. However, major structures and major stabilzations require detailed geotechnical investigations and rigorous analysis of slope stability. Decision-making on the design type, under the uncertainties of variation in the material properties and site conditions over time, requires charaterisation of uncertainty, rigorous assessment of probabilities, and use of a decision tree. A brief discussion on these is therefore presented in the following sectors.

a) *Uncertainty Characterization*

The characterization of uncertainty involves methods to estimate such probabilities. This section will outline approaches to the characterization of uncertainties.

Two approaches are possible for estimating probabilities or, more generally, probability distribution functions. The first is the classical frequentist approach that is based on a definition of the probability of realizing an event A, P(A) = PB, as being the per cent of times event A would be observed in an experiment that can be repeated an infinite number of times under constant conditions. The second approach is based on probability as a subjective degree of belief of the likelihood of realizing the event of concern. Standard books, such as the one by Guttman et al. (1982), provide statistical estimation methods to follow the first approach and the same book discusses the second approach using Bayesian Updating.

The choice of approach regarding estimation of probabilities is largely determined by the resource constraints of the investigation. While the subjective approach is more readily done, the frequentist approach has the advantage of scientific rigor, i.e., it will be more reliable. In terms of road projects, the subjective approach is suited to preliminary investigations and the frequentist approach will serve the needs of detailed phases best.

In addition to estimation, probability models and forecasting methods are useful in risk assessment. Readers are referred to Ross (1985) for probability modelling and to Guttmann et al. (1982) for forecasting.

b) *Examples of Risk Mitigation Calculations*

Let us take the case of a 0.65 probability that wedge failure will occur on a given section of a hill road in the year of rock-bolting and it is proposed to rock-bolt to minimise the possibility of wedge failure. To calculate the effectiveness of rock-bolting as an active countermeasure against wedge failure, reductions in the probability of realizing the danger, given rock-bolting,*** as well as reductions in possible damage, given rock-bolting, must be estimated. The probability of wedge failure p(wf), given rock-bolting (rb), can be calculated, using Bayesian updating as:

$$P(wf/rb) = \frac{p(rb/wf)\ p(wf)}{p(rb/wf)\ p(wf) + p(rb/\overline{wf}) + p(\overline{wf})} \qquad (1)$$

*** The notation to indicate a probability of realizing an event A given the occurrence of another event B is p (A/B).

where,

$p(rb/wf)$ = a likelihood function (posterior probability) that indicated the probability of rock-bolting failure against wedge failure or the true negative rate,

$p(wf)$ = the prior probability of a wedge failure, i.e, the hazard is 0.65,

$p(rb/\overline{wf})$ = another likelihood function that indicates the probability of rock-bolting success against wedge failure or the false positive rate, and

$p(\overline{wf})$ = the prior probability of no wedge failure, i.e., the complement of p(wf):0.35.

The values of $p(rb/wf)$ and $p(rb/\overline{wf})$ may be estimated subjectively or objectively as follows: to estimate $p(rb/\overline{wf})$ ask the following question: "In what percentage of wedge failure cases is rock-bolting a success?" The question implies that the success of rock-bolting means that there was no failure and that rock-bolting was used. The estimation of $p(rb/wf)$ may be calculated as the complement of $p(rb/\overline{wf})$.

In our case, $p(wf) = 0.65$ and $p(\overline{wf}) = 1\text{-}0.65 = 0.35$. Suppose past experience is used to estimate $p(rb/\overline{wf}) = 0.90$ and so $p(rb/wf) = 1 - p(rb/\overline{wf}) = 0.10$. Using equation (1), $p(wf/rb) = 0.17$. This means that the application of rock-bolting as an active countermeasure will reduce the probability of a wedge failure from the original value of 0.65 to 0.17.

If one kilometre of road is completely damaged, in the event of wedge failure occurring, then the expected loss in the year immediately after rock-bolting will be:

$$E_L = 0.17 \text{ X } 1 = 0.17 \text{ Km.}$$

This probability of 0.17 can be treated as a probability for the successive year and then the re-rock-bolting, if done, will result in a probability of:

$$P_2(wf/rb) = \frac{0.17 \times 0.10}{0.17 \times 0.10 + 0.9 \times 0.83}$$

$$= 0.02$$

The expected loss in year 2:

$$E_2 = 0.02 \text{ x } 1 = 0.02 \text{ Km.}$$

This process can be continued until $P_n(wf/rb) = \leq 0.01$. The total loss is then the sum of all the expected values.

c) *Review of Decision Trees*

A decision tree is a network of modes connected by arcs that represent decisions, possible outcomes, or consequences (Fig. 14.1). The nodes can either be event nodes (Nodes 2,3, and 4 in Fig. 14.1) or decision nodes (Node 1 in Fig. 14.1), depending upon whether the arcs originating from the node represent possible events or decision alternatives respectively. The arcs originating from an event node are assigned probabilities, based on the relative likelihood or the occurrence of the event realization that the arc represents. A decision problem involving uncertainty can be represented on a decision tree by configuring arcs and nodes to model the decision problem and the uncertainties.

Each possible path through the tree, that originates at the source node, can be assigned a numerical value whose magnitude is an expression of the relative merit (or dismerit) of the sequence of decisions and outcomes that the path represents. The mumerical value is frequently expressed in monetary terms in engineering applications of decision trees. Numerical values of losses are shown in Figure 14.1.

Expected values (which represent the most probable values) of utility functions, u, are used to choose between alternative decisions. The expected value criterion is a practical method of choosing between alternative actions if a function, u ($path_i$), is such that u ($path_i$) represents the relative preference for path i. In the case of individuals, who are usually risk averse, the utility function might be non-linear in the measure of relative merit (rupees, for example) so that each path's relative merit measure would have to be transformed into a utility based on a non-linear utility function. On the other hand, large firms and political bodies usually have utility functions that are linear in the measure of relative merit, since the amount of money involved in any one decision is small compared to the volume of monetary activity these organisations are involved in. When utility is linear with relative merit, the relative merit itself is a valid criterion for choosing among alternative decisions, since a linear transformation will not affect the preference ranking. Road projects may be assumed to have a utility function that is linear in monetary measure.

Once a tree has been configured to model a decision problem facing uncertainty, and the end utilities have been assigned, the backward roll procedure can be used to determine the best path, i.e., the path that maximizes utility. The procedure begins at the end of the tree, with the utilities for sets of arcs leading back to the same event node. The expected value of each set of arcs is assigned to the predecessor nodes of those sets of arcs. Next, the procedure examines the sets of event nodes leading back to the same decision nodes. The procedure assigns the greatest utility, from among the event nodes, to the predecessor decision node, for all sets of event nodes leading back to the same node. In doing so, it selects the best decision arc for that particular decision node. This procedure of taking expected values at event nodes and maximizing utility at decision nodes is repeated until the associated expected value for the best strategy will have been identified. An example of the application of this procedure is given below.

Suppose a cut slope is made as a marginal equilibrium slope. The options available are 1) to leave the slope as is in the hope that it will not fail, 2) to construct breast walls to ensure that no failure ocurs, and 3) to apply cheap vegetative stabilizations that will improve the slope's stability but not ensure it. Figure 14.1 illustrates a decision tree model of the situation. Assume that the probabilities of failure in the three cases are 0.60, 0.05, and 0.30, respectively, and that failure results in a loss of pavement worth Rs. 250,000 plus any cost incurred in implementing the decision (let the cost of the breast wall be Rs. 100,000 and the cost of vegetative stabilizations be Rs. 50,000).

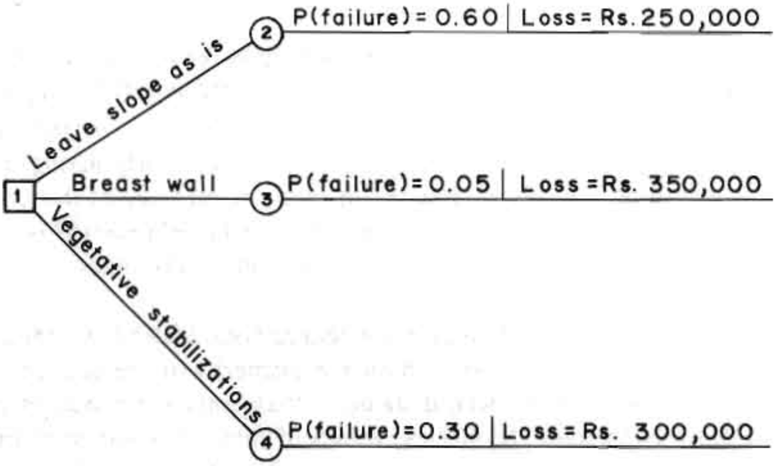

Fig. 14.1 Decision tree for cut slope

Using the backward roll procedure discussed earlier, Nodes 2,3, and 4 are assigned the expected values of the utility, their events have:

$$\text{Utility}_{\text{node 2}} = 0.60\ (250{,}000) = \text{Rs. } 150{,}000$$
$$\text{Utility}_{\text{node 3}} = 0.05\ (350{,}000) = \text{Rs. } 17{,}500$$
$$\text{Utility}_{\text{node 4}} = 0.30\ (300{,}000) = \text{Rs. } 90{,}000$$

14.5 ASSESSMENT OF HAZARDS AND RISKS

The Mountain Risk Engineering (MRE) approach is concerned with hazards and risks relating to decision-making on the choice of alignment or design type for linear infrastructures such as roads or canals in mountainous areas. The concept of hazards and risks and the techniques of their assessment in this chapter are based on the mapping framework by Einstein (1988). The formal risk assessment procedure described by Einstein involves 5 levels, and these are given below.

1. State of Nature Mapping
2. Danger Mapping
3. Hazard Mapping
4. Risk Determination
5. Actions

For linear infrastructures, e.g., hill roads in developing countries, it is not always possible to adopt rigorous investigation, data collection, procedures, or mapping techniques. Table 14.1 is therefore suggested for the extent of rigor in hazard and risk assessments for various types of road at various stages of the project cycle. Table 14.2 presents a simplified chart for hazard and risk assessment. Please read the footnotes to Table 14.2 carefully.

Table 14.1 Approach to Hazard and Risk Assessment and Utilization

Project Cycle	* Minor Roads	* Medium Roads	* Major Roads and High Volume Roads
Prefeasibility Stage	Record of dangers by walk-over survey. No further work.	No detailed mapping of state of nature and danger. Assess hazards and risks as per 22.2.3 in Chapter 22. Summarize hazards and risks as per Table 14.2. Comparison of alignments based on risk.	Same as for medium roads. Helicopter should be used for overview of the terrain along proposed routes.
Feasibility Stage	No extra work.	Detailed mapping of state of nature, danger and hazards. Assess hazards (Section 23.2). Design to be based on hazard levels. Assess risks using Tables 22.4 to 22.11 in Chapter 22. Incorporate risk in economic analysis.	Detailed mapping state of nature, danger, and hazard Risks to be assessed to compare alternative alignments and alternative technologies. Tables 22.4 to 22.11 can be used for risk assessment.
Detailed Survey and Design Stage	Avoidance, and mitigation by direct observation in the field.	Detailed mapping only in areas that are changed/ different from the feasibility assessments. Further detailed mapping in critical areas, employing geophysical investigations. Geotechnical parameters also to be investigated and tested for critical areas Optimize design on the basis of information from hazard parameters and geotechnical information and analysis. Choice of design to be based upon risk analysis using decision tree for major structures.	Rigorous investigation of geotechnical parameters in the critical areas identified from hazard maps, and design optimization employing rigorous analysis of slope stability, uncertainty, characterization, and decision trees for critical structures.

See Chapter 22 for definitions

Table 14.2 Hazards and Risk

Chainage	Length L	Hazard (probability of occurrence)								Per cent of road likely to be damaged*								Risk to (only the high cost value of p.x) p.x.l/100
		MSS p	MRS p2	MDF p3	MUC p4	M,SS p5	M,RS p6	M,DS p7	M,UC p8	MSS x1	MRS x2	MDS x3	MUC x4	M,SS x5	M,RS x6	M,DF x7	M,UC x8	

* x_1, x_2, x_3, x_4 - Based upon past experience, may be 20 to 30 per cent.
x_5, x_6, x_7, x_8 - Based upon past experience, may be 80 to 100 per cent.

<u>Notes</u>

1) L = length of road section with uniform characteristics, e.g soil/rock type, slope, water table/seepage conditions, dip slope of rock, influence of faults, rainfall, and existing instabilities such as landslides, under cutting and land use.

MSS = Minor Soil Slide;
MRS = Minor rockslide;
NDF = Minor debris flow; and
MUC = Minor under cutting
M,SS = Major soil slide;
M,RS = Major rockslide;
M,DF = Major debris flow; and
M,UC = Major undercutting

2) Probability of occurrence is suggested for only one time occurrence immediately after the completion of the road. Even though there could be several occurrences during the design life of the road, the probabilities differ for each depending upon the state of nature, counter measures, and danger events at the time of other failures. The prediction of these probabilities, although possible, is quite complicated and is not recommended for decision making at the feasibility stage and for normal design of road elements. However, rigorous treatment and prediction is justifiable for decisions relating to large-scale structures on major roads.

3) Risks at the later periods of the design life of the road do not significantly affect the feasibility decisions based on economic analysis because of the discounting to present value.

4) The hazard prediction without the road could be different from that with the road depending upon the design type, standard, and mitigatory measures for the proposed road. A low cost and double-lane road in the mountains may significantly increase the hazards. However, it is found that roads planned, designed, and constructed based on MRE approaches are the ones which do not significantly alter the hazard level ascertained for "without the road" cases.

5) Hazard levels can be subjectively ascertained either by using information from rigorous field data collection and the subsequent state-of-nature maps, and danger maps or by direct inspection and observations in the field, depending upon the level of likely investment, size, and importance of the proposed infrastructure.

6) Prediction of the extent of road failure at 100 per cent probability because of the various events is again a subjective judgement based on prior experience. Statistical data, if available, may be used depending on the importance of the road and the structures under consideration.

7) Damage to the environment because of road failure is also not considered, since MRE-based roads are not expected to significantly alter the hazard that already exists without the road.

8) See Chapters 22 and 23 for further details on hazard and risk assessment techniques suggested for roads.