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A STRATEGY FOR SLOPE HAZARD ASSESSMENT IN ROAD PLANNING AND MAINTENANCE

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1 Introduction

Development agencies are funding the construction of an increasing number of roads in mountainous regions as access to outlying districts moves up the development agenda. Infrastructure is important as a first step towards sustainable development and these regions, despite their inhospitable terrain, are often home to large populations of subsistence farming communities. The regions are therefore very important socially and economically, while requiring sympathetic development because of the fragile nature of their environment.

A substantial number of developing countries and emerging nations occupy regions with difficult mountainous or steep hilly terrain, where geotechnical hazards tend to be severe and road construction costs are high. The most severe geotechnical hazards encountered on road networks in these terrains are those associated with landsliding of natural slopes. Governments face a major problem in balancing reasonable construction and maintenance costs with how best to allocate scarce resources within such areas..

The problem of coping with slope hazards resolves into two questions:

- *On intended new road alignments*, how to minimise the incidence of potential damage from landslides, floods etc. In this case, corridors or alignments need to be compared so that the route involving the lowest overall hazard can be selected. The emphasis is on planning, at a stage where there is an opportunity to choose the most favourable location for the alignment,

- *For an existing network*, how to manage a slope maintenance programme, i.e. maintain the slopes at minimal economic cost. Here, the focus is on identifying slopes most at risk, and measuring or monitoring an existing geotechnical asset.

In Nepal, TRL and others working under DFID programmes have established a methodology for road design to suit the Nepal environment, by involvement in a number of research and road construction projects. The projects include an appraisal of geotechnical conditions on the Dharan-Dhankuta Road, design of the Maleku-Mugling Road and a seven-year monitoring study of slope movements in the Arun River basin in eastern Nepal. The monitoring study culminated in the publication of Overseas Road Note 16 (TRL, 1997a). In Indonesia DFID has supported the formation an Indonesian Slope Information System (ISIS) with a view to providing a guide to the sustainable mitigation of slope hazard within that country's infrastructure development.

The paper outlines the general principles of slope hazard definition in mountainous areas in tropical and sub-tropical regions. It presents a summary of the main approaches to slope hazard assessment. Strategies are outlined for hazard assessment on new road alignments and on existing networks. Finally, examples are given of the use of environmental monitoring in eastern Nepal, and on the use of the Indonesian Slope Information System.

2 Road Networks in Unstable Terrain

2.1 Unstable Environments in Low Latitudes

The combination of mountainous terrain and a wet climate leads to marginally stable slopes with high potential for natural landsliding. Slopes tend to approach a critical state of stability over varying intervals of time, and then fail following an event, or combination of events, that impact upon them to such an extent that they perform the function of "triggering" slope failures. These factors include: rain; vegetation changes; road construction, ageing effects and seismic events.

Intense or prolonged rain-storms have been identified as being the single greatest factor in inducing slope failure in tropical regions (Lumb 1975). Rain-induced slope failure is associated with changes in pore pressures resulting in a reduction in the effective soil strength available to resist failure.

Changes in vegetation that may occur either on or above earthworks can have a disastrous effect on their stability. The removal of deep-rooted natural up-slope vegetation and its replacement by irrigated cultivation, for example, would be likely to have a significant adverse effect on the groundwater regime and porewater conditions within that slope.

Road construction and improvement schemes frequently include some elements, particularly earthworks, that can impinge upon existing marginal slopes and trigger them to failure if inadequate measures are incorporated into their design to deal with both short and long term stability situations. Construction access tracks are also potential triggering factors that are frequently overlooked in road or other Civil Engineering projects. In road upgrade or improvement schemes, unless the original earthwork design assumptions are taken into consideration further excavation can act as a "trigger" for slope failure.

It has been established by geotechnical observation and research that there is a distinct tendency for slopes to deteriorate with age. This effect is likely to be the result of a combination of such factors as porewater equalisation, erosion and weathering induced geotechnical deterioration.

Slopes within a seismically active region can be destabilised by ground accelerations resulting from earthquakes or by the reactivation of geological faults. Both Nepal and Indonesia are recognised as seismically active regions and have a history of seismically activated slope instability. Although earthquakes are a significant cause of landslides their recurrence interval cannot really be predicted. The best the engineer can do is to study the distribution, strength and historical occurrence of earthquakes in the region, and to consider the cost of earthquake-resistant designs in the light of the risks by slope failure.

The geotechnical hazards associated with difficult geotechnical environments are serious and, in addition to posing a threat to the road, directly affect the livelihoods of people living in the area. An appropriate road design in steep, unstable terrain must take into account aspects of geology, hydrology and geomorphology (terrain-forming processes and history) . Furthermore, in an unstable environment, road design is not limited to the right of way, but to the whole slope from stream bank to watershed - a distance that may exceed a kilometre in vertical height.

2.2 Hazard and Risk

Within areas of interest the identification and classification of **hazard** is a key issue. In terms of slope instability, hazard may be defined as the delineation of areas where there is a finite probability of slope instability within a time period relevant to the road or site. Once hazard has been identified then it may be assessed in terms of **risk**, which may be defined as quantifying the vulnerability of the hazard in terms factors such as:

Economic consequences

Safety consequences (risk to life)

Engineering consequences

Relative project values may be assigned to hazard and consequences and risk can be viewed in a semi-quantifiable manner using the following general statement. (Cook et al 1998)

Risk = Hazard Probability X Consequence

The various components of a road carry different degrees of risk. It would not be appropriate to carry out the same level of hazard and risk analysis for all parts of an alignment. For example, the most 'valuable' route assets may be construction camps and bridges. Culverts and other structures are medium risk while the earthworks, pavement and side ditches and off-road drainage and slope protection measures are the lowest risk components.

3 Factors Influencing Slope Hazard in Mountainous Regions

3.1 Key Issues

In general terms discussion of slope hazard can be considered as being governed by the following general statements.

bedrock (geology) + weathering = material character

material character + structure + water = mass character

mass character + physical setting = geotechnical environment

geotechnical environment + road impact = slope performance

In many cases the following additional statement holds true for the actual failure condition.

potential slope hazard + triggering factor = slope failure

A number of key issues can then be identified as having a direct influence on the stability of slopes associated with road networks.

1. Definition and modelling of the geotechnical environment is an important step in the assessment of hazard. Road design must be appropriate to the geotechnical environment.

2. The road-natural slope interaction is a two-way process. As much importance should be attached to the impact of the road on the slope as the impact of the slope on the road.

3. Key triggering factors need to be identified that may active within an area in question.

4. There may significant hazards specific to the geomorphological environment, for example:
    - Nepal; Glacial lake outburst flood, originating in the High Himalaya but affecting valleys for many kilometres downstream.
    - Indonesia; Lahars in volcanic landscapes containing large, recent volcanoes.

3.2 The Geotechnical Environment

The correct definition and interpretation of a slope's geotechnical environment is fundamental to assessing slope hazard and identifying appropriate design options for its mitigation. In particular the correct assessment of soil or rock mass condition is an important issue.

Bedrock material in low latitude environments may be subjected to a tropical weathering process dominated by chemical alteration as much as physical disintegration. The influence of tropical weathering upon parent material is to alter significantly its geotechnical character and classical distinctions between soil behaviour and rock behaviour can be misleading (Geol.Soc 1997). Where these materials are subject in situ weathering the result may be a soil-rock profile that is a continuum of materials ranging from fresh bedrock to completely weathered residual soil. This contrasts significantly with most geotechnical models for temperate countries as it at odds with many assumptions inherent in multi-layered slope engineering analyses.

Weathering proceeds rapidly whenever rock is exposed or brought near to the surface. Within ten years partially weathered but intact rock can be significantly reduced in mass strength and in some cases may be considered a soil. Particular problems may arise due to differential weathering of soil-rock mass discontinuities (joints, faults, bedding planes). Structure has a major modifying influence on the geotechnical behaviour of materials in the mass. This influence is particularly evident in situ residual materials where the parent character may persist as relict structure in highly weathered materials. The combination of a soil-like material and a relict structure can result in potentially difficult slope problems.

In mountainous regions, rainfall is often very variable in time and geographical distribution. However, rainfall patterns are marked by periodic intense downpours that cause severe erosion and produce significant changes in pore pressure regimes, either through reduction in pore suctions or increase in pore pressures. The return periods of these events are difficult to predict and can only be anticipated by collecting rainfall records and river gauging records over long periods - at least ten years.

A feature of the hydrological regime of mountainous regions is that a small, steep catchment can quickly generate a very high stream flow lasting perhaps only a short time. Streams and rivers may undergo a considerable adjustment of their flow pattern as a result of a major rainfall event (causing a flood). Large amounts of sediment (bed load) are re-distributed along the river course, causing a change in the pattern of scour on the bed and banks. The net effect is to cut away the toe of the slopes meeting the stream, giving rise to slope instability

4 Hazard Assessment

4.1 General Approaches

There is a wide spectrum of approaches to hazard assessment ranging from subjective methodologies, based on mapping interpretation, through to detailed numerical modelling and analysis, based on the acquisition of representative site-based data. This spectrum may be conveniently discussed under three main groupings:

- The terrain evaluation approach
- The semi-empirical approach

- Numerical analysis

The objective of these approaches should be to produce a theoretical model, geomorphological, geological or geotechnical, of the slope, or slopes, concerned in order to fully understand the processes causing instability. These approaches, however, can have very different applications. For example, for new construction, the primary task is to locate an alignment that minimises the hazards likely to affect the road. This involves examining a large area of terrain in a broad way. This strongly indicates a terrain evaluation approach to the assessment. In contrast, for an existing alignment or network, the engineer is may require detailed design information for specific slope hazards. A numerical approach is more likely to be appropriate in this situation.

The general advantages and disadvantages of the approaches are summarised in Table 4.1 and discussed in the following sections

4.2 Terrain Evaluation

Terrain classification sometimes known also as the terrain evaluation method is described in detail in ORN 16 (TRL, 1997a). It is a distillation of geomorphological, geological and geotechnical mapping into a presentation that is easier for a road engineers to understand. Such mapping usually goes hand in hand with air photo interpretation.

Geomorphological mapping and walk-over geotechnical mapping are based on the premise that the landscape bears visible indicators of past instability, from which future activity may be predicted. Land forms such as concave slopes, fans, terraces and slopes with thin soil cover are indicators of particular kinds of land-forming process including instability, and are interpreted to form a picture of how the land has evolved into its present state and how it will evolve in future. The timescale of future activity cannot be defined, but the potential for a slope to fail, including its size and failure mode can be reasonably estimated by experienced personnel. In addition, the consequences of a slope failure can be assessed and thus give clues to risk as well as hazard determination.

Geomorphological mapping therefore provides the engineer with a valuable tool to separate areas of stable terrain from those that are unstable, and appreciate what processes may affect the road in the short and longer term.

Terrain classification is a procedure by which the landscape is divided up into components having fairly uniform characteristics. The premise is that where the terrain possesses the same physical characteristics it will also have uniform soil or rock mechanics features that affect engineering design. These characteristics are geomorphologically-based, therefore the concept of uniformity also implies that a terrain unit has uniform potential for hazards of particular types to develop.

An example of terrain classification mapping is given in Figure 4.1 and an example of interpretation of hazard within a terrain unit is given in Figure 4.2

4.3 Semi-Empirical Evaluation

4.3.1 General Approach

The semi-empirical approach is based on the explicit assumption that the stability characteristics of a soil-rock mass or system can be assessed on the basis of observations of the performance of other masses or systems with similar characteristics (Brand 1984) Knowledge of slope geometry and performance can then be extrapolated from these areas to new slope locations.

There may be up to three basic tools required for semi-empirical analysis and output.:

- Slope-height correlations

- Statistical analysis
- Stability charts

Data must be collated from within carefully defined geological, terrain and geotechnical environmental boundaries in order for slope angle-height design rules to be valid, otherwise slope angle-height scatter plots tend to show no clear pattern. Within tight restraints however it is possible to derive general slope angle-height guidelines. Figures 4.3 and 4.4 show slope- height plots for two adjacent, but contrasting, terrain units in Java, Indonesia.

Statistical discriminant analysis may be used, in conjunction with suitable slope data sets, to identify significant parameters contributing to instability within the area in question. For example, with respect to Figures 4.3 and 4,4, bedrock type is a key factor. This process may be taken further by the use of assigned numerical values and a factor overlay analysis to give relative hazard values, (Cook et al, 1995).

Slope stability charts such as those produced by Hoek and Bray (1981) or the more complex ones in Overseas Road Note 14 (TRL, 1997b) may be used either to compute slope angle options from assumed parameters or they may be used to back-analyze existing slope data to produce modified precedent slope designs.

It is readily apparent that effective acquisition of measurable slope information is fundamental to the semi-imperial approach. TRL has been associated with the development of two such assessment surveys within the tropical and sub-tropical geotechnical environment, as outlined below.

4.3.2 The ECAT Rapid assessment by oblique aerial photograph survey

A major problem in hazard assessment for roads is the need to make an assessment of slope condition over a large area, as rapidly as possible, including good views of the slopes well above and well below the road line. ECAT utilises a helicopter and oblique aerial photography enabling large scale oblique views and potentially covering at least one hundred kilometres of route per day. (Lawrance and McKinnon, 2000).

The photographs can be used for two purposes. Initially, they are used to compile an inventory of the road and its earthworks, from which a database is generated. Second, the photographs are interpreted for indications of slope failure and each slope given a priority rating, according to the evident need for repair. The inventory thus provides a tool to:

- Plot the location of the earthworks, along the length of the route or network.
- See where the slope failures are, and describe and classify them.
- Rank the earthworks in order of priority for repair.
- Calculate an order of cost for the repairs.

4.3.3 The Indonesian Slope Information System (ISIS)

A slope inventory has been developed by TRL as part of a DFID and IBRD supported programme to develop the Indonesian Slope Information System (ISIS), Cook and Woodbridge, (2000).

ISIS is a data collection and collation system concerned largely with the location, size, geometry and condition of earthwork and natural slopes. Its usefulness has been demonstrated in support of hazard assessment research and road betterment and design projects. The system use is straightforward and data surveys can be carried out without specialist knowledge. Characteristics of the slope, soil profile, water regime and vegetation cover along the routes are stored in a numerically coded format utilising standard database software. Further details of this system are given in Section 7 of this paper.

The limitation of a slope inventory is that, the data give information only on the slopes measured. There is no information on the slopes in the landscape at large; inventory is not an ideal tool for extrapolation unless combined with terrain evaluation, as was done in Indonesia. If used within the framework of a terrain classification, the two together form a powerful tool for planning, management and design.

4.3.4 Landslide Hazard Mapping

The aim of landslide hazard mapping (LHM) is to portray the geographical variation in susceptibility of the slopes to failure. LHM is based on the premise that the relative potential for slope failure can be assessed by evaluating causal factors. LHM can incorporate and be a development from the previously described slope inventory procedures. An example of landslide hazard mapping is given in Figure 4.5

Landslide hazard mapping may be produced by a 'direct' or an 'indirect' method. For direct mapping the study area is zoned according to the location and density of recorded landslides, then extrapolating to slopes of the same type that have not failed. The assumption is that future landslides are more likely to occur on slopes where conditions are the same as those in which sliding has occurred previously. The indirect mapping method relies on the evaluation of factors that are considered to be significant in the initiation of slope failure, and aggregating these.

The advantage of factor analysis is that local landslide-controlling factors and their role in causing slope failure are considered in detail. The limitations are that success in interpretation depends upon measuring the appropriate factors and applying a correct weighting to these. For practical reasons it is usually possible to measure only a small number of the factors involved.

For route location, LHM may be able to provide an early appreciation of relative slope stability over a large area without going to the expense of detailed geotechnical ground mapping. However, if a reconnaissance survey based on terrain classification can be accomplished, then LHM would be far slower and less cost-effective in comparison.

4.4 Stability Analysis Approaches to Evaluation

4.4.1 Classical Approach

The classical approach to Limit State slope analysis involves assessing forces promoting failure and comparing them analytically with forces resisting failure and arriving at a resultant Factor of safety (FoS). Significant geotechnical assumptions are generally required in order for the analysis to be undertaken using one of a number of well-established numerical procedures.

Brand (1985) listed five components essential to the relevant prediction and understanding of slope stability by classical numerical methods:

1. Mode of failure
2. Loading
3. Pore pressure distribution
4. Shear strength
5. Method of analysis

An understanding of the possible modes of failure is crucial to the successful application of a classical method of analysis. This is particularly important for tropically weathered in situ profiles where the mode of failure is often governed by geological factors. Relict discontinuities are frequently the determining cause of slope failure in these materials. Failures of residual soil-rock materials most frequently occur along the surfaces dictated by the relict macro-structure. Circular arc failures do not generally occur in tropically weathered in situ profiles; shallow non-circular failures being the most common.

Shear strength is commonly expressed by:

$$s = c' + \sigma' \tan \varphi'$$

Where σ', in terms of total strength is given by $\sigma' = \sigma - u$,

where u is the pore fluid pressure and c' and φ' are cohesion and friction angle respectively.

There is a significant problem in many tropically weathered in situ masses in obtaining the high quality undisturbed samples required for obtaining truly representative values of **C'** and **φ'**. This is largely due to a combination of fabric-sensitive materials and highly variable and anistropic masses.

Pore pressure distribution is critical to the classical analytical process and the importance of degree of saturation on soil shear strength together with the influence of pore suction is being increasing recognised. However the relationship between unsaturated shear strength and field moisture condition under heavy rainfall is less well understood. In the assessment of slope stability the controlling factor is the distribution of pore pressure (+ve or -ve) along the potential failure surface. This can only be assessed with great difficulty. Because of the high permeability of the residual soils these pore pressures are determined largely by the pattern of rainfall.

In summary great care needs to taken in employing classical and related design methods in residual soil-rock environments without due appreciation of the assumptions implicate in these procedures. They may at best be reasonable approximations and in terms of cost-effectiveness can probably only be justified for large failures or earthworks on major or strategic road links.

4.4.2 Hydrological modelling

DFID commissioned an extensive study to model the impacts of hydrology on the stability of earthworks in peninsular Malaysia, (ORN 14 TRL, 1997b). The basic parameters in the model are slope form, soil permeability and strength, and initial ground water condition and surface water condition. Imposed on this is rainfall of a given intensity and duration and the model works out a soil moisture condition for all parts of the slope and the way that this changes as water moves vertically down the profile during a rain period. A stability analysis calculates the slip circle most likely to be generated when the slope is in the weakest hydrological configuration.

The model assumes that two soil layers are uniform within themselves and not interrupted by discontinuities or large pore pathways that would distort the basic rate of hydraulic conductivity, or cause the mode of failure to depart from a circular form. These are significant assumptions that can cause problems within non-homogenous tropically weathered soil-rock profiles.

The model has been tested and found valid for some forms of residual soil slopes in Malaysia and Hong Kong, particularly those associated with granitic soils. However, it would not be applicable in Nepal, where soils are thin, isotropic in mass form and often structured. The same is true of the volcanic terrains of Indonesia, whose soils typically contain relict structure that would modify the rate and direction of water flow.

5 Strategy for Hazard Assessment

5.1 New Roads

5.1.1 Alignment Selection

The purpose of this stage of a road project is to find a safe alignment or review options for alignments. Essentially, this involves defining potential hazardous zones in the landscape, avoiding them where possible or identifying appropriate design options where avoidance is not possible.

A terrain map defining units or geomorphological groupings is an excellent tool for identifying the types and locations of potentially hazardous ground. The map also provides a framework for collating subsequent, more detailed information, including numerical data sets. Preliminary ground checking of typical hazard zones is desirable where practically feasible

5.1.2 Road Design to Mitigate Slope Hazard

In areas of complex geology a balance has often to be achieved between what is theoretically desirable in terms of frequent design variation along an alignment and the practicalities of construction and cost. A pragmatic approach is to develop a few standard, generic slope designs for costing purposes, knowing that these will be modified in the light of information recovered when the ground is opened up during construction.

There should be at least one stage of feasibility design in which an experienced geotechnical engineer or equivalent inspects the site on foot to map the ground in some detail and refine the designs in preparation for construction. The walk over survey stage will also be used to assess the geomorphology and hazard situation over the route as well as at particular sites. During the feasibility study it is unlikely that any quantitative hazard assessment would be justifiable or practicable. The purpose of the feasibility stage is to settle upon a strategy for detailed design and construction, and in the process to shortlist hazardous sites that may need more detailed investigation, measurement or monitoring. Utilisation of slope inventory information can be of great advantage at this stage.

5.1.3 Critical Sites

More intensive assessment of ground conditions is required where an alignment is forced to cross areas that are known to be unstable or marginal, to ensure that the route is adequately protected while not wasting money on over-elaborate protection in a situation where the risk of damage or loss is high.

In this situation it may be advisable to make a detailed landslide hazard map of the zone, in order to indicate the hazardous parts where slope protection measures and special design considerations for the carriageway are required. Slope monitoring may be appropriate at specific locations, to measure, for example, the rate of slope movement, landslide recession or erosion.

5.2 Existing road or network

5.2.1 Setting Priorities for Maintenance and Repair

Where there is a large number of failures on a network (even though many of them may be minor) there is difficulty in deciding which to tackle as a priority on a limited maintenance budget. An inventory can help in establishing a priority for earthworks most likely to fail, or most likely to constitute the greatest risk.

As earthworks come to be repeatedly re-assessed as part of condition surveys, the data can be used to update the information in the database. Thus, the deterioration of an earthwork can be tracked over a number of seasons, as well as the performance of remedial measures installed. The inventory can be structured in a way that allows sites that are moving towards failure or pose a high risk to be identified and given a higher priority than sites where deterioration is less serious or represents less of a risk. Once a database of relevant slope information has been established and analysed, then updating of the database can be focussed on those datasets that are both key to the slope condition and are likely to change within engineering time.

It is not always easy to see far above or below a road, especially in moderate vegetation, hence the advantage of system such as ECAT helicopter survey method, to get a better view and cover the ground quickly.

In an area where the soils and slope conditions are considered to be fairly uniform, semi-empirical modelling may be an appropriate way of identifying slopes most at risk. This would be especially appropriate where there is a large number of high risk sites. The engineer would have to be satisfied that the appropriate slope factors were being measured and that the model is validated for the region in question. All the slopes to be included would have to be carefully recorded in terms of their basic characteristics as inputs to the model. Also, other, visual, methods of observation should be kept up as a check on information coming out of the model.

5.2.2 Monitoring of Key Sites

For important slope hazard sites such as major cuttings, valley side traverses or stacks of climbing loops the cut slopes can be measured to assess the hazard, or kept under continuous observation by monitoring. It would be appropriate to make a detailed geotechnical assessment of an important slope that is felt to pose a risk. In such cases it may be appropriate to undertake a classical analytical approach allied to relevant data input into a geotechnical model The assessment would initially be by geotechnical mapping, possibly supported by instrumentation to measure, for example, variations in water table height, fluctuations in pore water pressure, or slope movement. Appropriate material sampling and geotechnical testing would form an important element of this procedure.

Where a site shows signs of being at risk but for reasons of size or complexity is felt to be too expensive to protect, monitoring can be implemented to detect any sudden change in condition. In extreme cases an early warning system can be installed to give warning of imminent failure and have the road closed before the slope gives way.

6 Environmental Monitoring for Hazard Assessment and Road Design in Eastern Nepal

6.1 Setting

The terrain of eastern Nepal is arranged in east-west trending ridges, following the alignment of the main geological groups. The ridges are deeply dissected by large river systems creating local relief of upwards of one thousand metres. The Arun River is the largest of these, arising in Tibet and flowing south, across the grain of the country, to the Ganges plain. The landscapes express markedly different levels of instability, stemming from both their geology and geomorphological processes.

A monitoring study of the Arun River basin was carried out between 1989 and 1996 as part of the planning for the Arun Access Road. The monitoring formed an extension of similar terrain studies carried out by the TRL and collaborators in connection with other major road routes in the region and elsewhere in Nepal. The work was carried out under the DFID Knowledge and Research (KaR) programme.

The terrain under investigation was largely unknown in terms of information about the natural environment. At best, existing records were not always accurate or not ideal for road design. In order to establish the safest and most cost-effective route it was considered necessary to evaluate the entire region by means of a variety of tools, providing qualitative and quantitative information at both regional and detailed level.

Very little published data was available for the planning of the Arun Access Road. There was a general geology map, some one-inch scale topographic mapping and some rainfall and river gauging data. The purpose of the monitoring was:

1. To establish rates of slope movement and erosion in order to compare corridors for route location and design.

2. To measure the amount of damage caused by road construction and develop appropriate mitigation methods.

In fact, the road was never built under its original terms of reference, but monitoring carried out over a seven years period provided an opportunity for the research team to evaluate the role of monitoring in hazard assessment. A full discussion of the monitoring project and its results is given in Hearn and Lawrance (TRL, 2000).

6.2 Methodology

6.2.1 General Approach

The following forms of mapping or monitoring were carried out on 230 sites selected for monitoring.:

1. Interpretation of aerial photography taken at two dates, in support of all the field activities.
2. Geomorphological mapping and terrain classification, as background to the road design work and the research.
3. Recording of rainfall with continuous (automatic) and 24 hour (manual) raingauges.
4. Slope monitoring.
    a) Rate of movement of slow moving slopes.
    b) Rate of recession of landslide back scarps.
5. Monitoring of watercourse cross section and profile..
6. Stream flow monitoring - flow rate, peak discharge and transported sediment load.

The two latter procedures were seen as an important input to the erosional and depositional aspect of the terrain models as a whole.

The techniques are discussed individually below, together with a verdict on the role of the techniques in hazard assessment.

6.2.2 Terrain classification, geomorphological mapping and air photo interpretation

Aerial photography taken in 1978 and 1990 was interpreted for general application, ultimately directed towards an evaluation of the alignment options. The interpretation process comprised an intensive study of the aerial photographs to identify stable and unstable zones, old landslide scars, stream characteristics and catchments, steep slopes, bridge crossing points, sources of construction material etc. From the photographs, areas of 'safe' ground were differentiated from difficult areas and 'no-go' areas, from which a series of alignment options was developed, for inspection on the ground. The photographs were also used to guide the field parties, and enlargements of the photographic prints acted as maps for navigation and annotation.

The aerial photographs were also used in support of geomorphological field mapping, carried out on the ground for evaluation of individual slopes and areas where route location was especially difficult. In a specialised application, the aerial photographs were used to measure the expansion of landslides by comparing the difference in the size and location of landslide head scarps between the two dates. It was found that some landslides had grown in size while others had reduced in terms of hazard as they stabilised and re-vegetated. Overall, the total area of landsliding remained roughly the same.

Finally, the aerial photographs were used as the interpretation tool to classify the terrain types of the region, based on the terrain units identified under the geomorphological mapping study. The classification was based on the five-unit terrain model of Fookes et al (1985). Figure 6.1

The interpretation of aerial photographs, with the associated geomorphological insights, was the single most useful tool of all those used for giving good general information about the stability condition of the slopes and streams, and for finding a safe route. For monitoring landslide development, aerial photography proved extremely valuable in identifying landslides both active and dormant, and showing fairly accurately in what respects they had changed over the period.

6.2.3 Rainfall recording

Rainfall varies over very short distances in eastern Nepal owing to the strongly directional approach of the monsoon and the rain shadow effect around high peaks and ridges. Government raingauge stations are operated at only three locations in the area, so five automatic (tipping bucket) stations and two manual stations were put in to record the rainfall as near as possible to the monitored sites.

For calculating the return period of storm events, rainfall records dating back thirty years or more are essential; the government records provided general data over this period of time. For statistical analysis of rainfall return periods, records covering less than about five years cannot provide sufficient data. Even the present monitoring study was considered not long enough to provide satisfactory data for this purpose.

The information on peak rainfall rates (which can be very high for periods of only a few minutes in tropical rainstorms, with high erosivity) yielded by automatic raingauges is very valuable in evaluating the potential for erosion and peak discharge. However, the automatic raingauges used in this study were prone to persistent electrical problems and gave unreliable data that, in the end, proved unusable.

6.2.4 Slope Monitoring

A total of 134 slopes was monitored. The slopes were selected through the geomorphological reconnaissance surveys, and therefore were recognised as sites where slow or intermittent movement was taking place. Monitoring was undertaken annually, after each monsoon season. A total-station theodolite was used to record the position of traverses set out down the line of maximum slope. The traverses consisted of wooden pegs driven into the slope or marks painted on large boulders. Landslide scarps were surveyed in a similar way, from Temporary Bench Marks.

The survey was considered to give a good indication of general rates of slope movement because, over the whole region, very few instantaneous landslides took place during the period of monitoring. Rates of movement varied from a few millimetres to metres per year. The upper slopes were found to move at an average of 0.1m/yr over 3.1% of the alignment length, and the lower slopes at 0.28m/yr over 4.2%. The total-station theodolite, although a ‘high tech’ and expensive piece of equipment, was found to be reliable and allowed the surveys to be made very efficiently.

6.2.5 Monitoring of Watercourse Shape

The cross section and bed profile of streams and gullies was measured annually, by pro-forma chain survey and by theodolite survey, to record changes in shape. Stream cross-section, flood marks, composition of bed material and bank and side slope stability were recorded.

The survey method was found to be accurate and would be very useful for estimating gross volumes of material deposited downstream. However, use of gully form to estimate flow discharge by extrapolation was found to give very variable answers. Calculated discharges could vary by as much as a factor of three in a 50m length of channel. This inaccuracy is due to the fact that flood events can either remove or cover up evidence of previous flow patterns, including the maximum scour depth; also, local farmers often modify or enlarge a channel as a means of controlling slope drainage. This makes it difficult to establish an accurate estimate of discharge during any given flood.

6.2.6 Monitoring of stream flow

Flood flow in Himalayan streams tends to be very rapid, highly variable over short periods and often builds up to become a fast-moving slurry of debris. Any apparatus installed in streams to measure the flow is extremely vulnerable to damage or loss. Having regard to safety and practicability, the monitoring methods adopted were basic and robust, and made use of cheap, disposable equipment.

The results from the measurements were, not surprisingly, very variable. However, by taking a good number of readings on every occasion and combining the data from a number of techniques, it was found possible to gain a reasonable estimate of flow rate and discharge volume. A flow hydrograph was constructed graphically from recordings of water velocity and depth taken every 15-20 minutes in order to estimate total flood discharge during each storm.

The measures of sediment concentration were likewise very variable, for these reasons:

- There is an upper and lower limit to the size of material that can be sampled due to the size of the sampling container and the mesh size of which it is made. The current may carry a mixture of material both larger than the mouth of the container and smaller than the mesh.
- For safety reasons it may not be possible to measure the flow at its height, or take samples from the centre of the stream, or take samples from a section of stream where flow is very vigorous. Thus, the maximum concentration of suspended sediment may be missed.
- It is sometimes physically too tiring to measure stream flow throughout the whole duration of a flood, which may last for many hours.
- 20% of annual rainfall occurs outside the monsoon season, and would therefore not be monitored.

It is considered that perhaps 50% of the moving sediment was missed due to these factors. Even allowing for this, the total erosion calculated was only one twentieth of the rate calculated by other, more accurate, methods.

By using a variety of methods and analysing the results in combination, it is possible to calculate reasonable stream flow characteristics. However, in turbulent, debris-laden torrents measures of suspended bed load are likely to be very inaccurate. Unless they can be verified by corroborating evidence, individual results should not be given too much weight.

6.3 Discussion

The intensive monitoring programme that was carried out confirmed what the geomorphological mapping had already indicated, that the landscape of the Arun Access Road corridor is generally fairly stable, with notable exceptions concentrated in a few now well-documented areas. Even gullies that were thought to be eroding were found not to have changed very much over the seven-year monitoring period. This was also true of landslide scars.

One large landslide did occur that was not wholly predicted. In July 1996, a large rock slide involving some 750,000m^3 of rock took place on the north bank of the Arun River. The slope had been identified as being a hazard, as open joints in the rock body had been noted and rock dilation monitoring was in place. However, the timing of the event had not been predicted, nor had its very large size. The rock slope gave no outward indication that failure was imminent. Other (soil-covered) slopes that were known to be moving did not fail during the period of monitoring. The reason for the triggering of the rock slide is not known; no seismic event had occurred and rainfall is believed not to have been exceptional, though no relevant record existed for the locality. It is assumed that weathering had reached a critical point within the rock mass and had acted as the triggering mechanism This rock slide illustrates the point that there are practical limits to what a monitoring programme can predict, no matter how intensive.

It can readily be appreciated that the statistical likelihood that any particular resultant effect will take place at any given time very difficult to predict. It can be seen that attempting to predict hazard simply by measuring the parameters that are thought to define ongoing geomorphological processes may result in very inaccurate modelling.

It is important, therefore, that measurement is carried out only provided the following conditions are met:

1. Measurements should be taken with knowledge of their achievable accuracy.
2. Measurements should be taken with a clear objective in mind.
3. Measurement is carried out within a background of general understanding of the geomorphological processes going on in the landscape.
4. Use only equipment that is within the capability of the survey team to manage or maintain.
5. Make sure that any electrical or mechanical equipment is thoroughly tested before being put into commission, especially if it is to be left to collect data unattended for any length of time.

7 Slope Assessment Guidelines in Indonesia

7.1 Background

Between 1991 and 1997 a slope research programme was undertaken in Indonesia aimed firstly at determining the extent of slope hazard and secondly at understanding possible mechanisms of slope failure, leading to appropriate design and hazard mitigation measures (Cook & Woodbridge ,2000) This research, centred on Java, was a collaborative venture between TRL and the Indonesian Institute of Road Engineering (IRE), the research body of the Department of Public Works (DPW). It was funded principally by the World Bank, but with significant contributions from DFID.

7.2 Setting

The Indonesian islands, situated in an active orogenic belt, have a very diverse geological make up. In Java there are over 100 active or dormant volcanoes and the macro-geology is characterised by a considerable thickness of volcanic extrusives overlying relatively weak Tertiary sedimentary rocks dominated by mudstones. The mudstone itself contains swelling minerals and is weak to very weak in character.

The terrain in Java is hilly to mountainous in the centre and south of the island with individual volcanic peaks rising to altitudes of over 2000m. The upland areas attract significantly more rainfall than the lowlands, exacerbating the potential instability of the former. In addition, the region is one of the most earthquake-prone in the world.

Key issues with respect the high frequency of slope hazards within many of the Java terrains were assessed to include the following:

- A wide range parent materials including: mudstone, sandstones, tuffs, pyroclastics, volcanic breccias, lavas and small igneous intrusions.

- The slope mass characteristics of the weathered volcanics and the mudstone are totally different.

- The occurrence of unlithified, but potentially weathered, tuffs, ashes and lahars as the result of recent Quaternary volcanic activity.

- Variable tropical weathering patterns that may have geotechnical characteristics significantly different from comparable temperate sedimentary soils

- The occurrence of geotechnically significant unconformities between volcanic materials and underlying sedimentary rocks. Slopes constructed near the interface between the two rock types are frequently a high hazard because of the hydraulic discontinuity between them.

- In some areas within Java a noticeable period of uplift and erosion in the Late Tertiary has allowed reworked volcanoclastics to be deposited on a relict, and potentially weathered, land surface.

- The ongoing volcanic activity within Java not only constitutes a serious potential slope hazard in itself but can contribute significantly to the re-activation of quiescent but marginally stable slope hazards in laharic terrain.

- The occurrence of weak layers within bedded pyroclastic and reworked pyroclastic materials.

- Intersecting mega-scale fault sets, which may be related to basement structure within Java, have been identified as being potential zones of high hazard. Active faults exist in Java whose movement can act as a failure triggering mechanism.

- Hydrogeological boundaries, particularly between high and low permeability materials, that define potential failure zones.

Hydrology has been identified as having a major influence on slope hazard in Java. In particular the effects of having high permeability limestone and volcanics overlying low permeability argillaceous materials are identified as being a potentially major hazard and the fundamental cause of many significant failures.

Slope hazard types in Indonesia are summarised in Table 7.1

7.3 Scope of Work

The immediate technical objective of the ISIS was the creation of a database of slope information on natural slopes, earthworks slopes and identified hazard. Data acquisition strategy was built around collecting field information in coded numeric format for inputting to a relational database, the structure of which is summarised in Table 7.2

Field data collection was achieved using straightforward, easy-to-read sheets, examples of which are illustrated in Figure 7.1. A Site, generally a specific road section, was divided into a number of Locations; at each Location, slope data were systematically measured and entered onto a number of standard forms. The Natural Slope form contained data relating to the general morphologic and geologic features of the terrain. The Earthwork Slope form contained specific details relating to the slope; if the slope showed a slope failure, then specific measurements were entered onto a Failure Slope form. Database files were related using key fields such as reference number and location.

Altogether 37 Sites, totalling 1200 km of road were surveyed. 207 Natural slope locations were assessed, 138 in volcanics, 41 in mudstones and 28 in limestone. 468 Earthwork slopes, comprising 379 in volcanic material, 74 in mudstone/siltstone and 28 in limestone were examined. The total linear distance of these slopes was approximately 60,000m, or about 5% of the roads surveyed. 90% of these were cut or natural slopes and 10% were embankment slopes. Within this number of slopes there were 188 Failure slope records of which were in 157 in volcanics, 25 in mudstone and 14 in limestone.

7.4 Analysis of Results

A key element in the application of the ISIS research was the utilisation of terrain mapping that already exited in Indonesia The Indonesian land-system mapping indicated over 100 separate land systems within Java. For ease of analysis these were combined into 5 broad groups:

A: Mountainous and steep hill slopes

B: Dissected plains and moderate hills

C: Rolling hills and plains

D: Low and degraded hill slopes

E: Low-lying alluvial, lacustrine and coastal plains.

Although a representative selection of land systems were surveyed for ISIS the bulk of the significant information came from groups A and B. Material, or geology, is recognised as having a significant impact on slope stability in Java (Wesley, 1973, Cook, 1997). In general terms slopes may be considered to be associated with one five main tropically weathered soil-rock mass types:

1. Volcanic masses
2. Clastic sedimentary masses
3. Limestone sedimentary masses
4. Combined volcanic and clastic sedimentary masses

Analysis of slope data in conjunction with major terrain groups allowed areas of major hazard to be identified, in particular the combination of geology with terrain provided a significant indication of zones of potential natural slope hazard in Java. Table 7.3 lists land systems that have the highest percentage of failures and confirms that those containing sedimentary sequences in combination with overlying volcanic profiles are the most hazardous.

On an immediately practical level the slope data allowed preliminary conclusions to be drawn with respect to outline designs for proposed road development in Java and else where in Indonesia (Cook et al 1995). Key points were:

1. Figure 4.2 shows a plot of slope height and angle for residual soils derived from the weathering of volcanic tuffs and ashes, for a single land system. From this it may surmised that slopes up to 12m maximum height can be safely cut at about 60° (3V:1H). The possibility of failure could be further reduced by regularly maintained drainage and erosion protection enabling even steeper slope angles to be designed

2. Figure 4.3 shows a similar plot for mudstone sequence. In this case the slope must be cut at flatter angles of 10° to 12° (1V:4H) to have a reasonable chance of not failing

3. Where argillaceous material underlies the volcanics, the interface is a major, unpredictable geotechnical weakness. Excavations where this interface is exposed, or is close to exposure, require special design with particular attention being paid to face drainage.

4. Most earthwork slopes in Java lack proper provision for drainage and minimal maintenance is carried out. This has a significant impact on the incidence of slope failure.

5. Rainfall patterns for most of Java involve distinct drier and wetter periods. Intense or prolonged periods of rainfall following the drier months are often likely to trigger natural and earthwork instability.

6. The establishment of a protective vegetation cover on earthwork slopes is not usually programmed. Only 17% of the slopes studied had a substantial vegetation cover. Where natural growth is slow to develop, weathered volcanic soils can develop a loose fabric that quickly deteriorates to scree, inhibiting the development of vegetation.

7. A limited range of remedial works is currently employed on earthwork slopes. Research is required to indicate more appropriate cost-effective methods suitable for Java.

8. In the road surveys where the quantity of fill materials in cut-fill situations is significant, the fill fails prematurely owing to inadequate engineering. This may be due to a combination of the interaction of the imposed road on a natural slope and uncontrolled spoil dumping from cut excavations. The latter is still common on many road projects and leads to down-slope failure, and can be a significant factor in earthwork slope deterioration.

9. There is some evidence for an age-related degradation of slopes back to natural slope angles unless arrested by timely maintenance and remedial programmes, see Figure 7.2. Erosion of earthwork slopes can be shown to have a definite impact on overall condition, although most volcanic soils are not highly erodible and gradual increase of erosion with time may be a significant factor in the age-deterioration of slopes.

10. The development of irrigated rice padi up-slope of earthworks could cause significant increase in potential slope hazard. Some control on agricultural use is necessary adjacent to large highway earthworks. Leakage from irrigation pipes and channels has been noted as a frequent triggering mechanism

8 Conclusions

The key to hazard assessment is to understand and model a geotechnical environment that may be impacted by engineering activity as well as undergoing continuous natural change. This can be done either by interpretation of 'preserved' evidence as seen in the land forms, by measuring a number of terrain parameters, or by acquiring and analysing representative geotechnical parameters Either way, the assessment is made on a sample taken from a complex scene and the more information, both qualitative and quantitative, that can be collected, the more representative the sample is likely to be.

There are no hard and fast rules guiding hazard assessment. The methodology used depends upon the circumstances of the requirement and the facilities available to provide the assessment. Frequently, the method applied depends upon the expertise of the professionals carrying out the work and the resources available for field measurement, data recording and database analsis. Also, the type and quality of available background data will determine the extent to which new data needs to be acquired.

Terrains of the type discussed here are usually complex and little-known. They are also difficult of access. The use of terrain classification to provide a summary map of the land forms and geomorphological processes provides an extremely useful background to all project planning.In the region containing the Arun Access Road corridor, high rates of slope movement are confined to specific locations that, to an extent, had been identified previously by terrain evaluation and geomorphological mapping. The study demonstrated that terrain mapping is capable of providing an excellent framework within which to locate preliminary alignments and plan more detailed field studies.

Numerical data sets are valuable as an accurate record of an individual terrain characteristic. However, it is important not to place too much reliance upon the results from any single analysis, and wherever possible to corroborate results with independent evidence obtained by other methods.

Hydrological records are among the most versatile records that can be obtained, in the sense that they can be used for erosion studies, stream flow characteristics and flood levels - some of the most common and widespread damaging agents on roads. It would be desirable if projects could measure these during their lifetime, to add to a lengthening historical record of hydrological data for the region.

Methods of slope design require careful selection to meet both the requirements of the project and the available parameters. Classical analytical methods should be adopted with caution and need careful selection in the light of anticipated hydrological conditions and failure mechanisms. Slope hazard investigations in the tropically weathered environment have to overcome significant problems of sample suitability and representability in arriving at realistic parameters for shear strength and moisture condition. A semi-empirical or terrain evaluation approach should be carefully considered before embarking on detailed numerical analysis.

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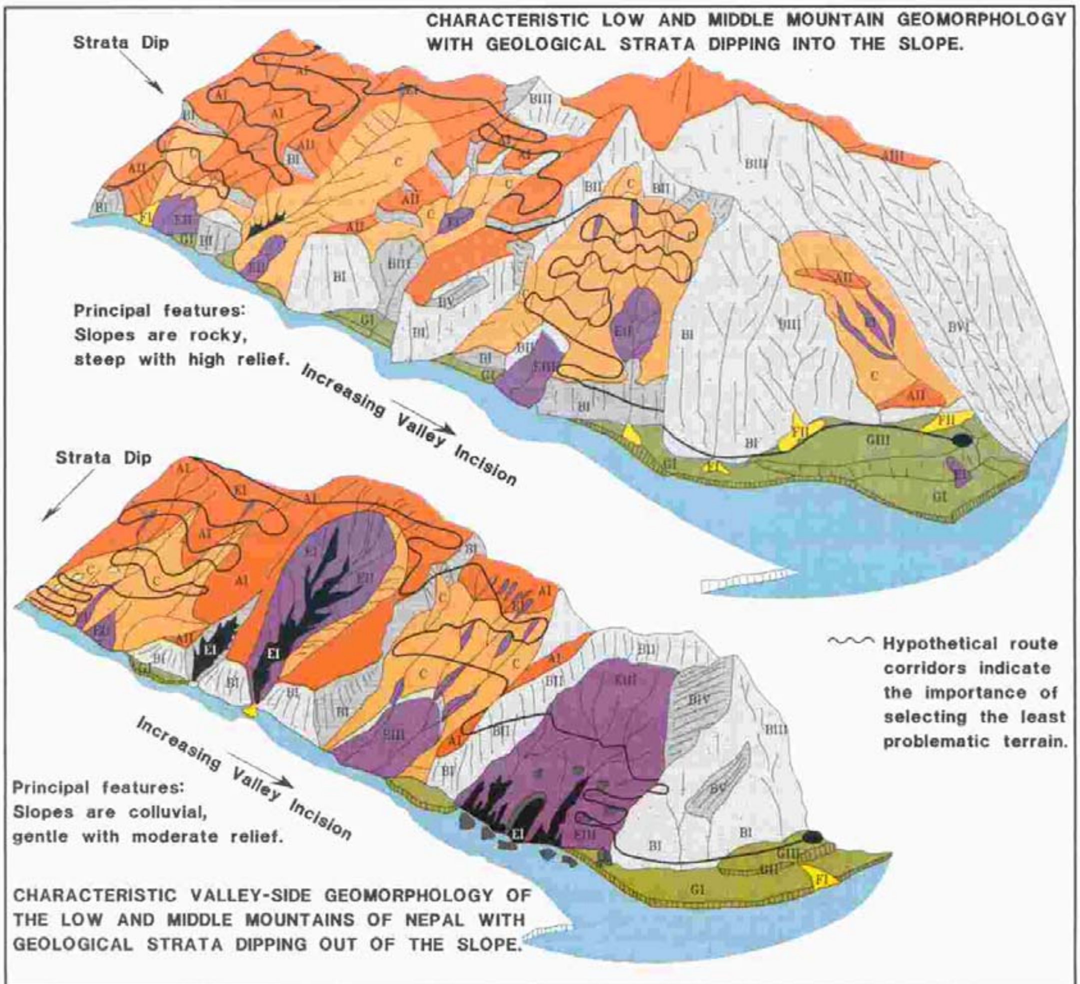
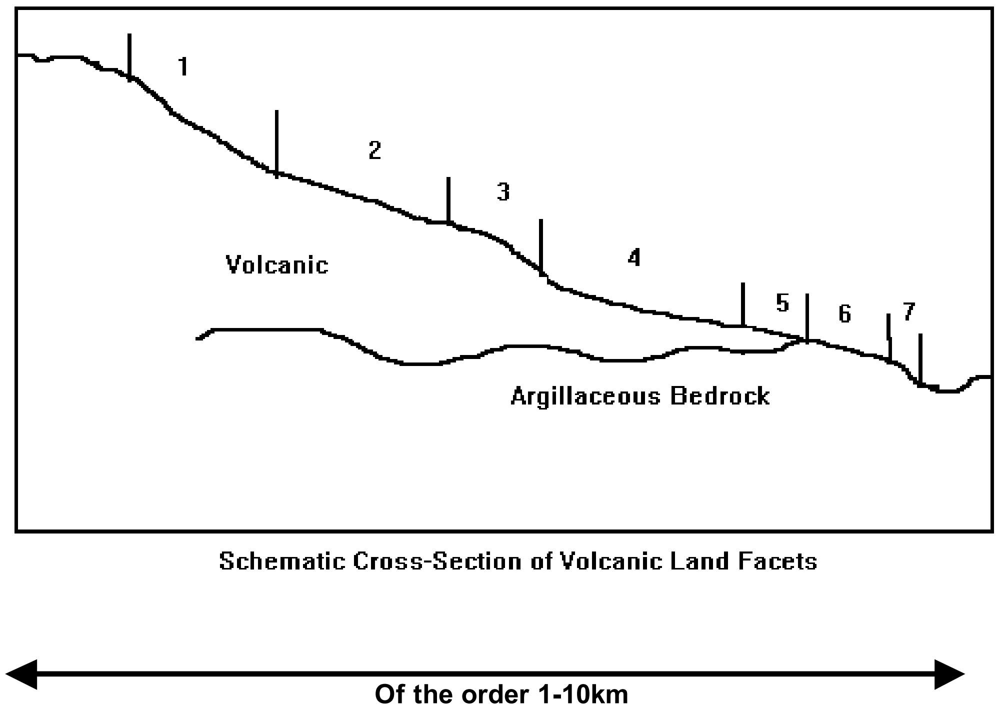


LANDFORM TYPE	LANDFORM SUB-TYPE	
A Rounded - flat, residual soil slope, either ridge or spur top or mid - slope bench. Expect erosion rather than slope failure. Soil depths will range from 1m to 10m on weathered rock.	AI	Rounded ridge and spur summits, and gently sloping ground with residual soil cover.
	AII	Mid slope benches with residual soil cover.
	AIII	Structurally controlled dip slopes with residual soil cover.
B Rock slopes	BI	Miscellaneous rock cliffs, either structurally controlled or steep lower valley sides (greater than 45 degrees).
	BII	Rock cliffs formed along margins or in scars of mass movement.
	BIII	Irregular steep slopes (up to 45 degrees).
	BIV	Bedding, foliation or joint plane surfaces usually exposed as slip surface of deep seated failure.
	BV	Structural bench.
	BVI	Structurally controlled ridge and ravine topography.
C Slopes covered by colluvium but generally stable	C	Colluvium and weathered rock fall deposits.
E Areas of unstable ground in surface soils or deep-seated ancient slope failures.	EI	Mudslides, debris slides and rockslides on steep and frequently wet lower valley slopes.
	EII	Mudslides and debris slides associated with local erosion and soil saturation.
	EIII	Large, deep-seated slope failures usually with adverse structural control.
F Fan deposits	FI	Active fan surfaces, usually on flood plains.
	FII	High level fan deposits, usually associated with high level terraces or deposited by catastrophic landslides.
G Terrace gravels	GI	Flood plain terrace (periodically inundated).
	GII	Terrace flank.
	GIII	High level terrace.

Figure 4.1 Example of Terrain Mapping from Nepal, ORN 16 (TRL, 1997a)



Schematic Cross-Section of Volcanic Land Facets

Of the order 1-10km

Facet	Facet Description	Natural Slope Hazard
1	Steep Upper Volcanic Slopes	Lava/laharic flow; Unpredictable non-geotechnical hazard
2	Older Laharic Slopes	Lahar reactivation by erosion - debris slide
3	Older Laharic Scarp	Back-sapping/erosion of slopes above
4	Volcanic/Shale Slope	"Reservoir" translational slide or creep
5	Volcanic/Shale Unconformity	Spring-line erosion influencing Facet 5
6	Shale Slope	Shallow translational failure, especially if debris covered.
7	Alluvial Terrace	Toe erosion leading to activation of slopes above .

Figure 4.2 Natural Slope Hazards within a Typical Indonesian Volcanic-Sedimentary Land System.

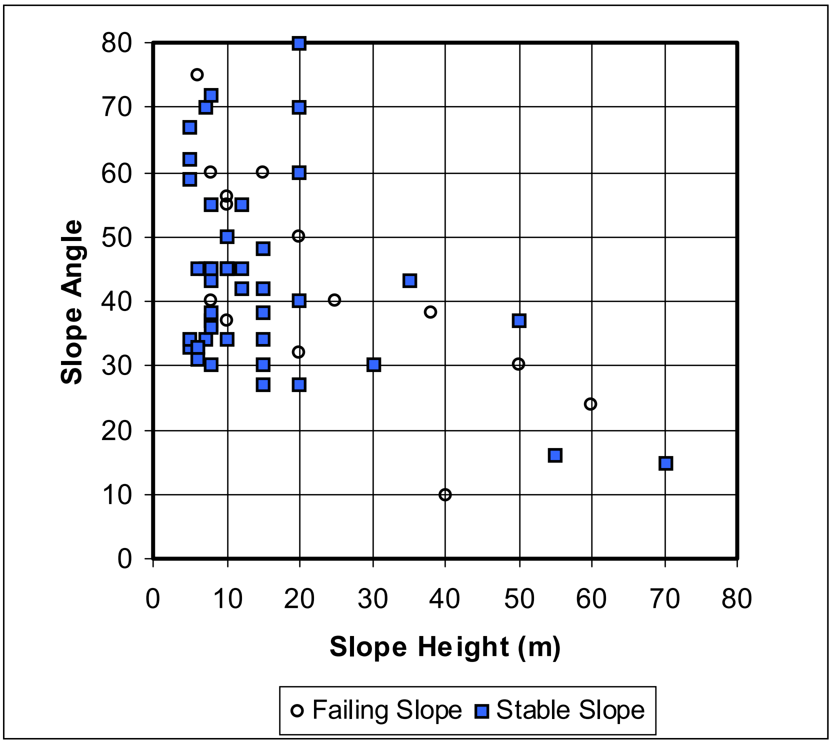


Figure 4 3 Slope Height-Angle Relationships for Volcanic Slopes in a Single Land System

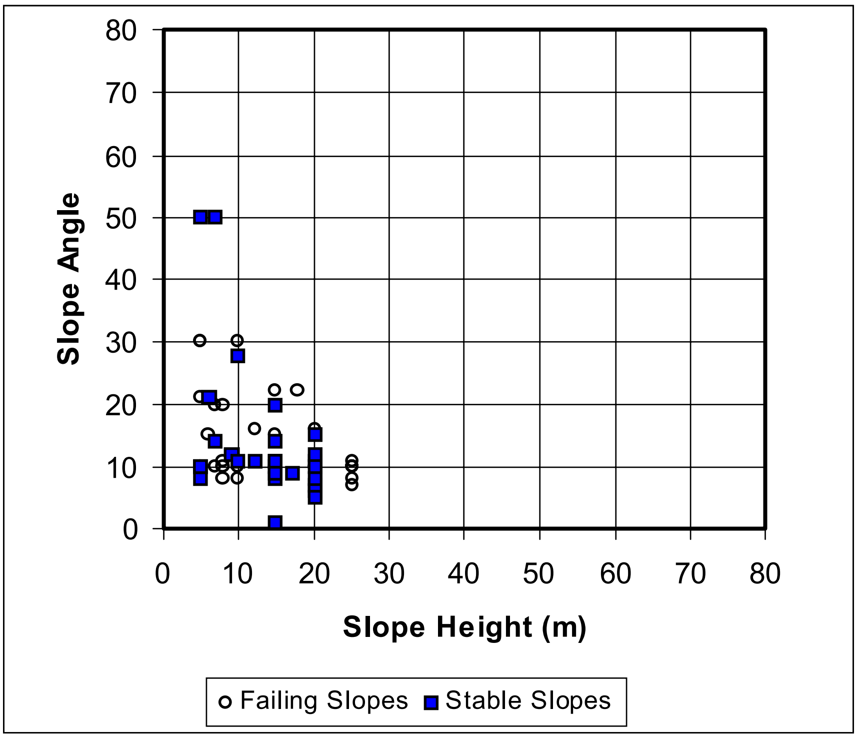
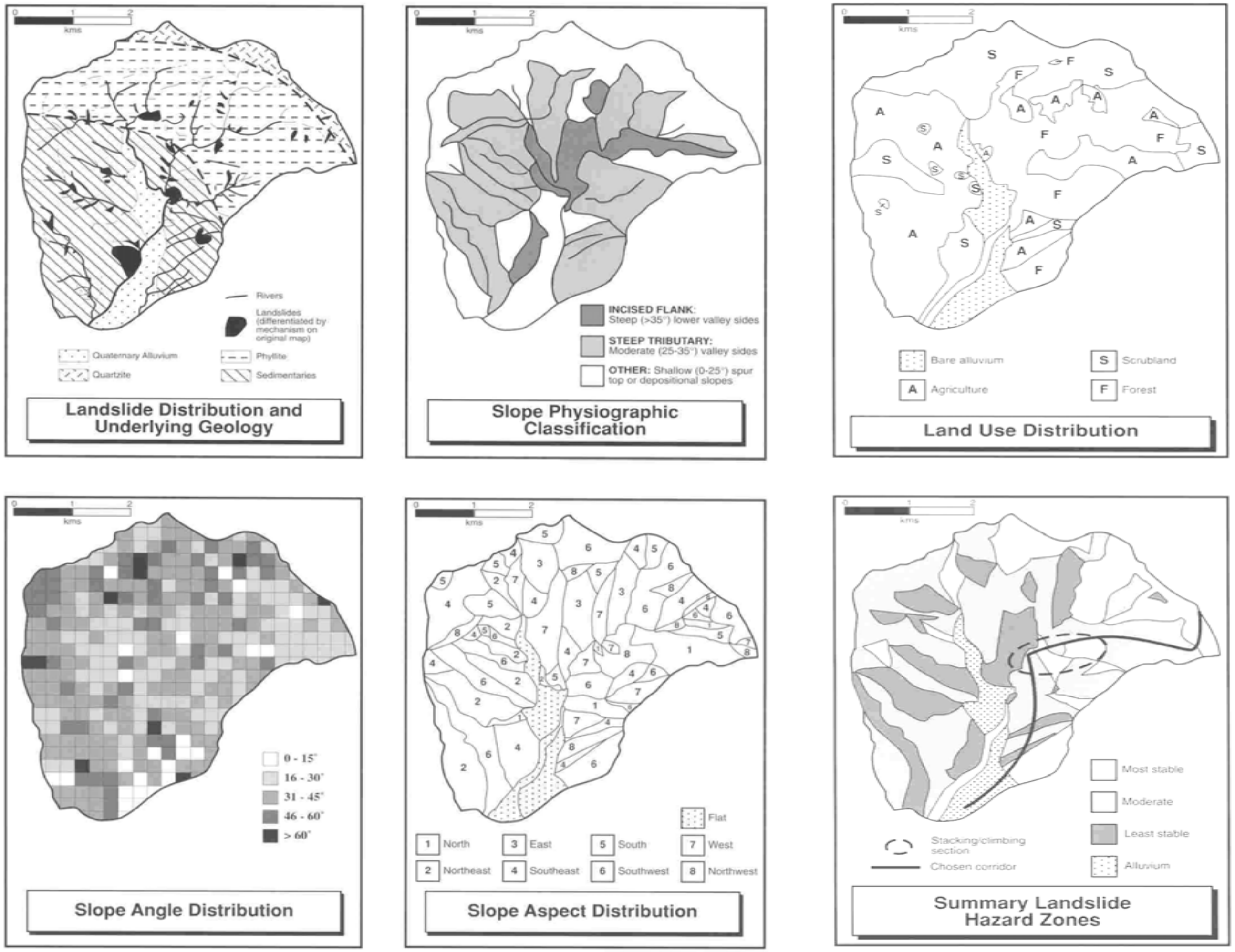


Figure 4 4 Slope Height-Angle Relationships for Mudstone-Slopes in a Single Land System



FACTOR	CATEGORY	O / E	HAZARD RANK
ROCK TYPE	Sedimentaries	1.2	3
	Phyllite	0.8	2
	Quartzite	0.3	1
SLOPE ASPECT	North	0.7	1
	South	2.0	2.5
	East	2.2	3
	West	0.7	1
	Northwest	0.6	0
	Northeast	0.9	2
	Southeast	0.9	2
	Southwest	0.5	0
PHYSIO-GRAPHY	Incised flank	2.9	3
	Steep tributary	1.1	2
	Other	0.3	1
LAND USE	Scrub	1.0	NOT SIGNIFICANT
	Agriculture	1.1	
	Forest	0.9	
SLOPE ANGLE	0 - 15°	0.7	
	16 - 30°	1.0	
	31 - 45°	1.3	
	46 - 60°	0.8	
	> 60°	0.4	
CHANNEL PROXIMITY	Stream rank:		
	First Order	0.9	
	Second Order	1.1	
	Third Order	1.5	
	Fourth Order	0.9	
	Fifth Order	1.0	

Build up of hazard rank for the illustrated catchment. Hazard ranks for each factor category are summed for every terrain unit and assigned to one of three hazard classes. 3 is the most unstable condition.

N.B. The expected number of landslides (E) is calculated on the basis of the percentage study area coverage of each factor category multiplied by the total number of observed landslides (O) in the study area. Thus, higher O/E ratios indicate a greater occurrence of instability than would be expected from a random distribution.

Figure 4.5 Example of Landslide Hazard Mapping, ORN 16 (TRL, 1997a)

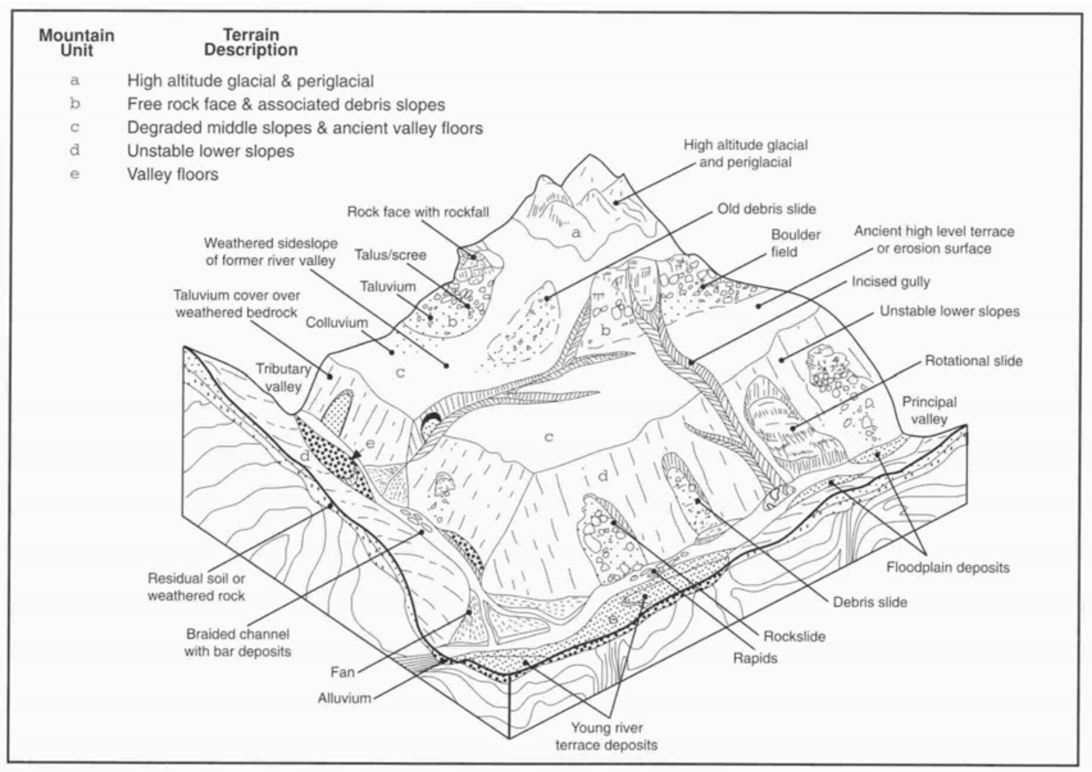


Figure 6.1 Generalised Five-Fold Terrain Definition for Young Mountain Belts

(Fookes et al ,1985)

SHEET 3: EARTHWORK SLOPE

1. Province		2. Site No.	
3. Location No.		4. Slope type	
5. Chainage			
6. Geology		7 .Land system	
8. Overall angle		9. Overall height	
10. Slope profile		11. Slope plan	
12. Slope shape		13. Slope length	
14. Road section		15. Road profile	
16. Berm Nos.		17. Berm widths	
18. Bench heights		19. Bench angles	
20. Material			
21. Structure		22. Favourability	
23. Upslope H		24. Upslope angle	
25. D/slope H		26. D/slope angle	
27. U/slope erosion		28. U/slope stblty	
29. D/slope erosion		30. D/slope stblty	
31. Drainage		32. Engineering	
33. Vegetat'n type		34. Vegetation %	
35. Hydrology		36. Weather	
37. Slope erosion		38. Slope stblty	
39. Slope sheets		40. Failure sheets	
41. Photos		42. Sketches	
43. Inspectors		44. Date	
45. Comments			

SHEET 4: FAILURE DETAILS

1. Province		2. Site No.	
3. Location No.		4. Failure No.	
5. Chainage			
6. Fail type		7. Fail size	
8. Fail location		9. Fail profile	
10. B/scar H		11. B/scar angle	
12. Fail angle		13. Fail condition	
14. Fail causes			
15. Fail materials			
16. Damage caused		17. Potential	
18. Remedials		19. Effectiveness	
20. Fail date			
21. Photos		22. Sketches	
23. Inspectors		24. Date	
25. Comments			

Figure 7.1 Typical ISIS Field Data Collection Sheets

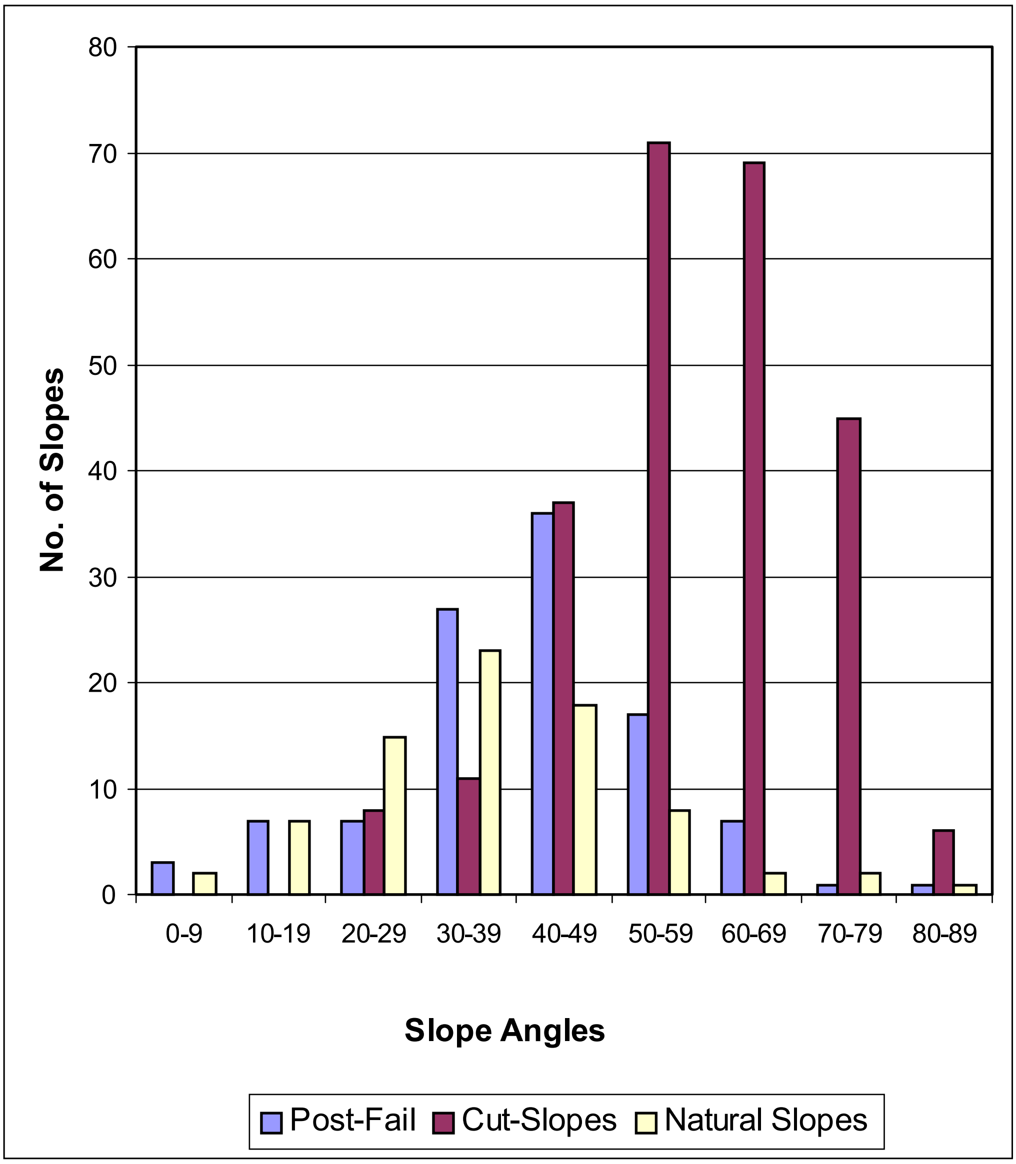


Figure 7.2 Relationships between Cut-Slopes and Stable Natural Slopes for Java Volcanic Terrains

Table 4.1 Advantages and Disadvantages of General Hazard Assessment Approaches

Methodology	Advantages	Limitations
Terrain analysis	Rapid and relatively inexpensive, therefore most appropriate for large areas and comparing planning options. Gives an integrated picture of terrain conditions, showing the relationship between the land forms and various types of instability Historical events can be interpreted from preserved land forms (e.g. terraces or scoured slopes as evidence of past flood levels).	Ground mapping is difficult to carry out in heavily vegetated terrain. Information cannot be used directly for design, only as a design guide. Based primarily on surface morphology and colour (or tone), therefore limited by information contained in these visible factors. Where conditions are hidden subsurface or beneath vegetation a, factors contributing to instability may be missed or inadequately taken into account
Semi-Empirical Analysis	Information relates to actual stability situations. Basic data collection can be rapid. Is related to soil-mass behaviour patterns rather than individual materials Can lead to relative hazard ratings and outline designs Can be utilised in engineering design procedures for complex tropical terrain models	Requires knowledge of slope behaviour in relevant terrains. Requires experienced interpretation and some cases statistical knowledge Cannot give detailed numerical analyses eg engineering Factors of Safety Cannot give numerically based justification for design
Classical Numerical Analysis	Provides numerically verifiable solutions to stability models leading to detailed designs for slopes and stabilisation remedial measures. Relevant existing failures may be back–analysed to obtain analytical parameters Analytical solutions may be performed repeatedly and rapidly using computer software	Requires input of design parameters that may difficult and costly to obtain in a representative manner. Theoretical assumptions may not always be applicable to complex tropically weathered soil-rock masses. Not readily applicable to multi-mode slope failures Not normally economically appropriate to analyse large numbers of variable slopes along a single alignment

Slope Hazard Type	Description
Volcanic Hazards	Landslide hazards primarily associated with contemporary volcanic activity, these may be lava and pyroclastic flows; caldera-collapse, avalanches; and hot or cold laharic flows.
Natural Landslides	Failures on natural slopes, usually associated with young developing terrain. this may involve the re-activation of marginally stable laharic slopes.
Cut-slope Failure	Failure of man-made excavation faces
Embankment Failure.	Failures of man-made embankments. These may be sub-divided in to those associated with failure of the fill material and those associated with the failure of the foundation material.
Combined Cut-Embankment Failure	This form of failure is associated with the reasonably common road-section situation in hilly terrain where material has been excavated up-slope and placed down-slope to form a carriageway partly in cut and partly on fill.
Combined Earthwork and Landslide Failure	These failures occur where either natural instability has caused earthwork failure or where the impact of excavation or fill placement has resulted in the failure of natural slopes.

Table 7.1 General Slope Hazard Types in Indonesia

General Site	Natural Slope Location	Earthwork Slope Location	Slope Failure Location
Province	Site reference no.	Site reference no.	Site reference no.
Site Reference no.	Location reference no.	Location reference no.	Location reference no.
Site type	Slope type	Slope type	Failure reference no.
Location by road link	Location by chainage	Location by chainage	Location by chainage
Location by map reference	General geology	General geology	Failure type
Topographic maps	Land system	Land system	Failure size
Geology maps	Slope height & angle	Overall slope height & angle	Failure location on slope
Land system maps	Slope profile	Slope geometry (profile/plan/shape)	Failure profile
General terrain	Terrain setting	Slope length	Back-scar height & angle
Rainfall conditions	Slope material	Road section & profile	Failure angle
	Land use	Berm numbers & width	Failure condition
	Vegetation cover	Bench heights & angles	Failure causes
	Hydrological conditions	Slope material	Failure material
	Recent weather	Geological structure	Actual & potential damage
	Slope condition	Slope condition	Remedial works & effectiveness
	Photograph	Drainage	Failure date
		Remedial/stability works	Photograph references
		Vegetation cover	Sketches
		Hydrological conditions	
		Recent weather	
		Upslope height, angle & condition	
		Downslope height, angle and condition	
		Natural slope sheets ?	
		Failure sheets ?	

Table 7.2. ISIS Data Files and Data Sets

Land System Units	
Geomorphology	Bedreock Geology
Strongly dissected tilted plateaus on tuff sediments	Tuff; lahar;sandstone;mudstone
Very steep ridges on tuff sediments	Lahar; mudstone
Hillocky plains on mixed sediments	Sandstone; mudstone; conglomerate
Hillocky plains on directed crystalline tuff sheets	Lahar; mudstone
Irregular mt. ridges on intermediate andesitic volcanoes	Andesite, basalt; breccia
Irregular mt. ridges on intermediate andesitic volcanoes	Marl; andesite; basalt; breccia
Asymmetric broadly dissected ridges on sst and mdst	Sandstone; mudstone
Young intermediate strata volcanoes	Andesite/basalt;lahar
Parallel ridges on volcanic tuffs in dry areas	Lahar; ash
Flat to undulating volcanic plains	Alluvium; recent volcanics;lahar
Undulating to rolling sedimentary plains	Tuff; conglomerate; mudstone
Moderately dissected lava flows	Andesite; breccia; lahar
Moderately steep and dissected lahar slopes	Alluvium - recent volcanics
Hillocky plains on lava flows in dry areas	Andesite; breccia;lahar
Steep hills on marls with rock outcrop	Limestone; sandstone; mark

Notes: Decreasing hazard from top to bottom
Listing based on ISIS data for cut-slopes and natural slopes

Table 7.3 Java Land Systems with Highest Slope Hazard