Landslide Risk Assessment in the Rural Sector

Guidelines on best practice




Remote Sensing
Landslide Hazard and Risk Mapping
Land Use Planning and Management
Route Corridor Engineering

DFID Department for International Development

Landslide Risk Assessment in the Rural Access Sector

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PREFACE

This document is an output of a project funded by the Department for International Development (DFID), UK entitled 'Landslide Risk Assessment in the Rural Access Sector'. The Project was instigated as part of DFID's Knowledge and Research Programme for the benefit of developing countries. The project was carried out by Scott Wilson Kirkpatrick & Co. Ltd, in association with the University of Durham.

The principal aim of the project was to investigate, develop and test desk study and mapping techniques that enable rapid and reliable methods of landslide assessment to be carried out over large areas for the benefit of road corridor planning and management. Many developing countries are located in mountainous regions, and suffer from poor road access and lack of data concerning topography, geology and environmental hazards. Landslides are among the most frequent and damaging environmental hazards in these areas, causing loss of life, loss of livelihood and disruption to road traffic and economic activity. Many authorities lack the required information and know-how to overcome these problems, and the purpose of this project was to develop guidelines that enabled improved and affordable methods of landslide assessment and management.

The project commenced in September 2000 and concluded with the finalisation of this document in October 2003. Project activities focused on the Himalayan kingdoms of Nepal and Bhutan and were carried out in association with the Department of Local Infrastructure Development and Agricultural Roads (DoLIDAR) in Nepal and by the Department of Roads (DoR) in Bhutan. It was the enthusiasm shown in the project by these two government departments that enabled the objectives of the project to be realised, through secondment of staff, training, fieldwork and the preparation of project outputs. The Department of Roads of Nepal also provided assistance in the Nepal training workshops through secondment of staff for training.

Project outputs have included reports and training materials on the use of remote sensing in landslide assessment and route corridor planning, landslide mapping, landslide frequency analysis, landslide susceptibility, hazard and risk mapping, road condition survey with respect to landslides, and social parameters in risk assessment and risk management.

Scott Wilson and the University of Durham would like to thank all government, employed staff, advisors and other personnel in Nepal and Bhutan who worked hard to make this project a success. In particular, sincere gratitude is paid to:

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CHAPTER 1

INTRODUCTION

1.1 Landslides and Related Phenomena

1.1.1 Landslides represent a serious problem in most mountainous areas, causing damage to roads, buildings and other structures, and disrupting the activities of the local people. They also threaten the lives of the people themselves – for example, on average over 300 people are killed by landslides each year in Nepal alone, and large earthquakes in mountainous areas may trigger landslides that kill many thousands of people. In addition, there is some evidence that the numbers of people being killed by landslides is increasing each year. Clearly therefore it is necessary for planners and engineers to do all that is possible to minimise the impact of landslides on infrastructure and the community.

1.1.2 Road construction probably represents the most dynamic of developments currently taking place in rural areas and the minimisation of landslide effects should be high on the list of project implementation priorities. This can be achieved through the correct selection of alignments, the use of appropriate engineering measures, and the implementation of good land management practices. If these objectives are achieved, roads will suffer less damage and closure, and the risk to road users and the nearby population will be reduced.

What is a landslide?

1.1.3 A landslide is a downslope gravitational movement of a mass of earth or rock as a unit owing to failure of the material. A catastrophic or fast-moving landslide is obvious when it occurs because often a large mass of soil and rock will move rapidly downslope leaving a fresh scar, usually devoid of vegetation, that is visible for several kilometres distance. By contrast, slow moving landslides can be difficult to detect and old landslides often become revegetated within years, and may be imperceptible without close slope inspection. They too can pose considerable risk to engineering structures, land use and public safety if their movement is reactivated, but they are often overlooked. Furthermore, over geological time, widespread deposits of transported debris (colluvium) can accumulate on slopes, often to several metres in thickness. Reactivation of movements within this colluvium is common on many hill slopes, and it is often difficult to identify this movement unless there are obvious effects, such as progressive cracking to buildings. Appendix 1 contains guidance on the recognition of landslides on the ground.

1.1.4 Unfortunately, there is usually very little information available concerning the locations of, and risks posed by, landslides in mountainous regions, especially in developing countries where information on ground conditions is often extremely limited. This has implications for the planning and management of rural infrastructure and the protection of rural communities. The purpose of these guidelines is to provide useful advice to enable planners and engineers to minimise and manage landslide hazards and to protect investments and the community at large from their effects.

What is a rural access corridor?

1.1.5 A rural access corridor is a road, its associated earthworks and structures, and the surrounding land and communities that are affected by it. In hilly and mountainous areas, in particular, a road cannot be thought of as a simple line on a map; it has both engineering and social influences that can extend well outside the limit of earthworks and drainage. Significantly, roads are built, wherever possible, in the more gentle parts of hilly or mountainous regions, and these areas are often intensely cultivated. Furthermore, roads are usually designed to provide access to as many communities as possible, and consequently there is an important interface between the engineering, community and land use needs of the road corridor.

1.2 The R7815 Landslide Risk Assessment in the Rural Access Sector Project

1.2.1 The Landslide Risk Assessment in the Rural Access Sector Project (LRA project) was funded by the UK Department for International Development (DFID) between September 2000 and July 2003 as part of its Knowledge and Research Programme for the benefit of developing countries. The principal aim of the project was to develop and test rapid and essentially desk study-based methods of landslide mapping to assist in the identification of the most stable corridors for rural road planning. The identification and selection of route corridors requires information on where existing landslides are located and the potential risk they pose to a road and its structures. Furthermore, planners and engineers need to be aware of those areas that might become unstable in the future, i.e. those slopes that are most susceptible to landslides.

1.2.2 In order to address these needs, the LRA project has reviewed the information that can be obtained from remote sensing sources, given that in many countries only small-scale geological and topographical maps may be available. Satellite imagery in particular is able to provide ever-increasing resolution in ground interpretation, and therefore has the potential to usefully supplement whatever desk study mapping data already exists. Landslide susceptibility and hazard mapping are techniques used to identify those areas most prone to landslides and the effects of landslides, and are compiled from desk study data supplemented with field-derived information. Landslide susceptibility, hazard and risk mapping, if carried out correctly, can be extremely useful in the identification and selection of road corridors, and the LRA project has developed and tested a number of schemes.

1.2.3 Once a preferred route corridor is identified, then the planning and detailed design of the alignment and engineering structures need to be undertaken. This must proceed with full consideration of landslide and slope instability problems. Furthermore, the design, construction and maintenance of a road must be planned and managed in conjunction with neighbouring rural populations, land use and other infrastructure. This interface takes place over a much wider area than just the road reserve or right of way. For instance, the excavation of slopes can trigger landslides that extend considerable distances upslope, affecting neighbouring land and buildings. Road drainage frequently leads to erosion, slope instability and loss of agricultural land downstream. On the other hand, certain land use practices can adversely affect the stability of slopes and earthworks adjacent to the road. One of the objectives of the LRA project was, therefore, to examine the increase in landslide hazard and risk within road corridors as a result of this interface, and to recommend measures to combat it. This requires consideration of land planning and management over a wider area, termed here the ‘rural access corridor’.

1.2.4 The LRA project was undertaken in Nepal and Bhutan. Mountainous terrain predominates in both of these countries. Monsoon rainfall frequently triggers landslides that pose significant risk to rural roads and adjacent communities. Road construction forms a major component of the development programmes of both countries, and yet information on landslides and ground conditions is lacking. While these two countries were the focus of the LRA project and are the most immediate beneficiaries of its outputs, other countries with infrastructure development programmes in populated mountain regions are likely to benefit also. Furthermore, many of the conclusions drawn from this project and embodied in these guidelines will be of potential interest and value to geo-scientists and engineers worldwide.

1.2.5 While the focus of these guidelines is on landslide studies for road planning and engineering, the techniques and recommendations are potentially applicable to a range of district planning and infrastructure projects, as illustrated especially in Chapter 4.

1.3 Best Practice Guidelines

1.3.1 This document summarises the findings of the LRA project under the subject headings listed in Table 1.1. This table also indicates the intended audience of each chapter.

Chapter	Subject Heading	Intended Audience
2	Remote sensing	Private & Public Sector Specialists
3	Landslide hazard and risk mapping	Private & Public Sector Specialists
4	Land use planning and management in route corridors	District Planning Authority/ Roads Authority
5	Route corridor engineering	Roads Authority/ Consulting Engineers

Table 1.1 Subjects and intended audiences of this document

1.3.2 These guidelines are intended specifically for road projects in developing countries. Remote sensing offers potential application across a wide range of sectors, but this document focuses on its application to landslide mapping and terrain evaluation for route corridor planning. The mapping techniques proposed in these guidelines are intended to provide route corridor planning assistance in those areas where existing information is limited. Additionally, rural road construction in developing countries tends to occur on a low-cost, low-technology and labour-intensive basis. Methods of geotechnical investigation, design and construction recommended in these guidelines are aimed predominantly at this application.

1.3.3 The guidelines are aimed specifically at landslide problems. The other engineering, economic, environmental and social factors that come into play in the planning of road corridors are not dealt with in these guidelines, except where they interface with slope stability and landslide hazard. The guidelines, therefore, do not cover any of the non-geotechnical issues that govern the management of infrastructure and land use in road corridors.

1.4 Reading the Guidelines

1.4.1 These guidelines are intended to be most useful to planners and engineers in developing countries educated to degree level. The chapter covering remote sensing requires that the reader is familiar with the basic concepts of satellite image technology, while the chapter on landslide hazard and risk mapping assumes that the reader has a basic grasp of Geographical Information Systems (GIS) and the manner in which GIS is used to analyse spatial data. The chapters on route corridor planning and route corridor engineering assume that the reader is familiar with basic geological and geotechnical concepts with respect to slope stability.

1.4.2 Most road authorities in developing countries are responsible for route corridor planning, design, construction, maintenance and upgrading. Chapters 2 (remote sensing) and 3 (hazard and risk mapping) are mostly applicable to the identification of route corridors while Chapters 4 (land management within the route corridor) and 5 (route corridor engineering) are mostly relevant to the management of landslide hazards encountered during project implementation and in the context of protecting vulnerable land uses and communities within the rural access corridor.

1.5 Geographical Application of the Guidelines

1.5.1 As mentioned earlier, practitioners in Nepal and Bhutan, as well as those in India and Pakistan will be most familiar with the subject content of these guidelines as they have been developed within the Himalayan setting. Nevertheless, many of the recommendations made are relevant to hilly or mountain terrains in most of southern and south-east Asia, and some are global in their application. However, it is important to note that the landslide susceptibility mapping described in these guidelines has been developed for slopes underlain by the predominantly metamorphic rocks found in the Himalayas. Therefore, while the methods of analysis may remain approximately the same in other geological regions, the actual data presented in Chapter 3 of these guidelines will be inapplicable outside the Himalayas.

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CHAPTER 2

REMOTE SENSING FOR LANDSLIDE STUDIES IN THE RURAL ACCESS CORRIDORS

2.1 Introduction

2.1.1 Some of the problems associated with the identification of landslides on the ground are described in Paragraph 1.1.3. Problems of identification can be compounded by dense vegetation, processes of erosion, and the effects of human occupation and modification of the landscape. In addition, access on the ground may be made difficult by dense vegetation, very steep slopes, gullies and water-courses, especially if no roads have yet been built. It is sensible, therefore, to maximise ways by which landslides can be identified and mapped without actually needing to undertake intensive fieldwork.

2.1.2 The techniques known collectively as remote sensing, in which the ground is interpreted using images or data collected from a distance (usually from air or from space) offer considerable potential for landslide mapping. Furthermore, remote sensing can allow the mapping of factors that cause landslides if, for example, areas of wet ground can be identified on the image or the photograph. Finally, it can also allow the mapping of towns, villages and infrastructure that might be affected by landslides, such as roads and buildings.

2.1.3 However, whilst remote sensing appears to offer the solution to many problems, in reality it is not that simple. The technology is expensive, there are limitations in terms of when the image or photograph can be taken, and there can be limitations in terms of the size of objects that can be identified in the image. The user must therefore be aware of these potential limitations, but increasingly the development of new technologies and methods is meaning that they can be circumvented.

2.2 Uses of Remote Sensing

2.2.1 Allowing for these limitations (discussed in more detail later), how can remote sensing be used in landslide hazard and risk mapping? Basically, there are five main ways in which the techniques can be applied:

a) *Landslide detection*: Remote sensing can be used to detect landslides in the landscape and, sometimes at least, to decide what type of landslide they are. Of course, the landslide must be detectable on the image or photograph, which means that it must be large enough to appear (often a major limitation of satellite images, and even a problem in aerial photographs at times);
b) *Factor mapping*: If the factors significant in causing increased landslide susceptibility (see Chapter 3 for discussion) are known, such as certain types of rock and topography, it might be possible to use remote sensing to map them;
c) *Land use interpretation and classification:* Remote sensing can be used to identify land use type, which might be important in terms of increasing

susceptibility to landslides, or of making the impacts of landslides more significant;

d) *Vulnerability assessment*: Remote sensing can be used to map objects or infrastructure that might be affected by a landslide, such as a road or a community;

e) *Landslide monitoring*: If multiple sets of imagery are available for previous years or even decades, it might be possible to determine when landslides have occurred and the time periods over which they remain active.

2.3 Why Use Remote Sensing?

2.3.1 Basically remote sensing offers five key advantages:

a) it can provide a perspective or view of the landscape that cannot normally be achieved. This might be vertical – i.e. looking onto the ground from directly above, as if from an aeroplane – or from an oblique angle. In the case of aerial photographs and some types of satellite imagery, it also allows stereoscopic viewing of the terrain (i.e. the terrain can be viewed in three dimensions), which means that it is easy to interpret relief;

b) some types of remote sensing use parts of the electromagnetic spectrum that cannot be seen by the human eye, such as infrared (i.e. heat) and even microwave radiation. Landslides that might not be visible with the naked eye in remote sensing imagery might be visible using these parts of the spectrum;

c) the perspective view allows the interpretation of the manner in which different terrain features are positioned relative to each other. This can help in the determination of whether a particular feature has been created as a result of landslides or some other process such as erosion, river deposition or man made effects;

d) in some cases a computer can be programmed to identify the characteristics of a landslide as they appear on the image. This way, mapping of landslides can be done automatically, which is quick and efficient;

e) remote sensing can provide images from different time periods and under different conditions that can help determine when landslides occurred and how active they are.

2.4 User Needs for Remote Sensing in Landslide Studies

2.4.1 Remote sensing is usually thought of as a highly complex and expensive way to collect information about the ground. In many ways this is correct – the collection of satellite images uses technology that is at the forefront of science, and it is possible to perform very complex analyses using computer software. However, the use of remote sensing does not necessarily require this level of technology. In its simplest form, remote sensing can involve just the examination of an aerial photograph or a print-out of a satellite image. At this level, interpretation is not complex or difficult, although clearly a little practice is needed to perfect the skill. In most rural access projects, the end-user requirements probably don’t justify the more complex approaches, and so it is the simple techniques upon which these guidelines concentrate.

2.4.2 While the basics of remote sensing are described in this chapter, a little detail is also given on the more complex applications. In certain circumstances good results can be obtained using complex methods, although usually the end-user requirements do not require this level of analysis.

2.5 Types of Imagery and their Uses

2.5.1 Introduction

2.5.1.1 Two main types of remote sensing images are described in these guidelines: aerial photographs and satellite imagery. Although the principles for the interpretation of these two image types are quite similar, there are some fundamental differences between them that must be considered. Most importantly, an aerial photograph is a physical print taken with an optical camera, whereas a satellite image is a digital dataset taken with an electronic sensor. Of course, aerial photographs are collected from much closer to the ground surface (typically less than 1000 m) than is a satellite image (typically 800 km or more). Aerial photographs have many advantages in terms of available resolution, lack of atmospheric distortion, etc., but there are disadvantages too, most notably the amount of distortion of the image that occurs away from the centre of the picture, which is much greater in a photograph than it is in a satellite image (see Figure 2.1). The main types of aerial photographs and satellite images, their advantages and disadvantages, and their main applications are described in more detail below.

2.5.2 Aerial photographs

2.5.2.1 Aerial photographs are typically taken using specially designed cameras mounted on an adapted light aircraft that is flown along a carefully chosen path above the ground surface during good weather (so that the site is free of cloud). The quality of the film in the camera and the flying height of the aircraft determine the resolution of the photographs. Typically, the aircraft flies at a height of 500 – 2000 m, providing a photographic scale of 1:12 500 – 1: 50 000. Even a 1:50 000 photo can allow objects of less than a metre on the ground surface to be seen through a magnifying stereoscope, although the small size of the photograph can make mapping difficult unless the photo is enlarged.

2.5.2.2 Aerial photographs have many strengths over other types of imagery. Advantages of aerial photographs include:

a) usual availability in archive form. Many areas have several sets over a reasonable period of time;
b) relatively easy to commission the collection of new sets where required;
c) good resolution of ground detail;
d) availability of stereo coverage;
e) interpretation skills are usually available and quite easy to learn, though land form and landslide interpretation requires more experience;
f) imagery is intuitive to analyse i.e. interpretation is based on visual recognition;
g) the imagery does not require complex analytical techniques.

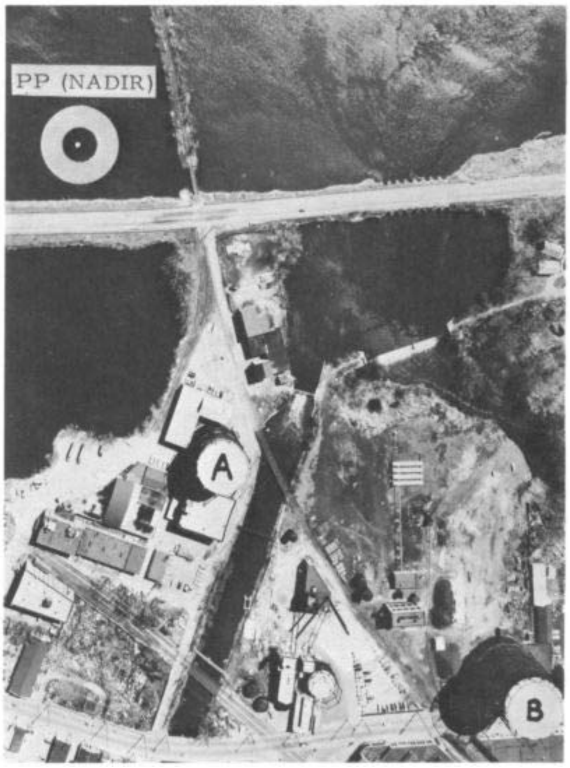


Figure 2.1 Vertical aerial photograph and vertical satellite image illustrating radial distortion

Aerial photograph on the left: *the camera was centred over the point marked PP. Note how radial distortion means that it is possible to see some of the side of the tower marked A and even more of the tower marked B.*
Satellite image on the right: *these radial distortions are much less pronounced for satellite images due to the much higher elevation of the instrument.*

2.5.2.3 However, disadvantages with aerial photography can include:

a) high cost should commissioning of a new set be required;
b) interpretation is only provided in the visual part of the electromagnetic spectrum;
c) limited spatial coverage for any particular set of photographs;
d) sensitivity to low cloud and to the effects of sun angle;
e) high levels of distortion away from the centre of the image, especially in mountainous terrain;
f) interpretation can be subjective and non-standard.

2.5.2.4 In landslide studies, aerial photographs are ideal for:

a) identifying and mapping landslides;
b) undertaking rapid terrain assessments;
c) identifying the factors that control landsliding, as a basis for landslide susceptibility mapping.

2.5.3 Satellite imagery

2.5.3.1 Satellite images are available from a wide range of instruments operated by both governmental and commercial organisations. The cost of the purchase of a satellite image can be very high, and this has put off many potential users. However, these costs are reducing as more imagery becomes available. Furthermore, the costs are probably comparable to the cost of commissioning new aerial photography (see below).

2.5.3.2 The main types of satellite imagery that are available are described in Table 2.1 and a brief review of the main sensors is given in Appendix 2. The main advantages of the use of satellite imagery include:

a) a single image covers a wide area (for example a Landsat image covers an area of 185 x 185 km);
b) the availability of information beyond the visible part of the electromagnetic spectrum (this enhances interpretation – see below);
c) the potential for digital image analysis;
d) low levels of distortion away from the centre of the image;
e) availability of archive images for all land areas of the world;
f) frequent repeat collection of images – many satellites have the capability to collect an image for any given area at least once a month.

2.5.3.3 However, disadvantages include:

a) in some cases low spatial resolution, meaning that only large objects can be seen and identified;
b) high cost of large scale imagery;
c) in some cases there is no ability to view the images in stereo;
d) the images can be difficult to interpret and sometimes require high levels of technology for processing.

2.5.3.4 Because of this, satellite imagery can be useful for the following aspects of landslide studies:

a) identifying and mapping large landslides and those whose features are indistinct;
b) undertaking rapid terrain assessments at a small scale;
c) in some cases, identifying the factors involved in determining landslide susceptibility.

Sensor type	Typical image size	Spatial resolution	Minimum feature size (m)	Spectral resolution	Temporal resolution	Stereo coverage	Acquisition	Typical cost *
Black and White Photographs 1:50,000	11km x 11km per photograph	0.5m	2.5	Visible	As required	Yes	Archive and programming	$10/km²
Black and White Photographs 1:25,000	5.5km x 5.5km per photograph	0.25m	2.5	Visible	As required	Yes	Archive and programming	$15/km²
Black and White Photographs 1:10,000	2.2km x 2.2km per photograph	0.1m	1.0	Visible	As required	Yes	Archive and programming	$35/km²
Colour aerial photographs 1:50,000	11km x 11km per photograph	0.5 m	2.5	Visible	As required	Yes	Archive and programming	$10/km²
Colour aerial photographs 1:25,000	5.5km x 5.5km per photograph	0.25 m	2.5	Visible	As required	Yes	Archive and programming	$15/km²
Colour aerial photographs 1:10,000	2.2km x 2.2km per photograph	0.1 m	1.0	Visible	As required	Yes	Archive and programming	$38/km²
Landsat 7ETM+	185 x 185 km	30 m m/s (15 pan)	45	Pan + 8 bands: 4 visible, 4 IR	16 days	No	Archive only	$0.01/km²
SPOT IV	60 x 60 km	20 m m/s (10 m pan)	30	Pan + 4 bands: 2 visible, 2 IR	26 days	Yes	Archive and programming	$0.1/km²
IKONOS	11 x 11 km	4 m m/s (1 m pan)	12 3	Pan + 4 bands: 3 visible, 1 IR	11 days	Yes	Archive and programming	$18-63/km^2
IRS-1D	142 km^2	23 m m/s (6 m pan)	72 18	Pan + 4 bands: 2 visible, 2 IR	24 days	No	Archive and programming	$10/km²

Sensor type	**Typical image size**	**Spatial resolution**	**Minimum feature size (m)**	**Spectral resolution**	**Temporal resolution**	**Stereo coverage**	**Acquisition**	**Typical cost ***
Radarsat	45 km^2	8 m	variable	Microwave	24 days	No	Archive and programming	$66/$km^2$
ERS-1	108 x 108 km	25 m	variable	Microwave	35 days	No	Archive and programming	$0.1/$km^2$
Quickbird	25 km^2	2.4 m m/s (0.6 m pan)	1.8	Pan + 4 bands 3 visible, 1 IR	variable	Yes	Archive and programming	$30 per km^2
ENVISAT (forthcoming)	108 x 108 km	30 m	variable	Microwave	35 days	No	Archive and programming	$0.1 per km^2
Orbview 3 (forthcoming)	8 km x user defined	4 m (1 m pan)	3	Pan + 4 bands: 3 visible, 1 IR	3 days	No	Archive and programming	Unknown

M/S: Multispectral
PAN: Panchromatic (Black & White)

* The cost of aerial photography per km^2 varies significantly according to the size of the area to be photographed. The rates provided are based on a total area of between 50,000 and 100,000km^2.
** Data on aerial photography costs provided by Hansa Luftbild. German Air surveys.

Table 2.1 Characteristics of the main sensors

2.6 Using Remote Sensing in Landslide Studies in the Rural Access Sector

2.6.1 Flow path of analysis

2.6.1.1 Figure 2.2 summarises the use of remote sensing for landslide studies in the rural access sector. The steps shown are described in detail below.

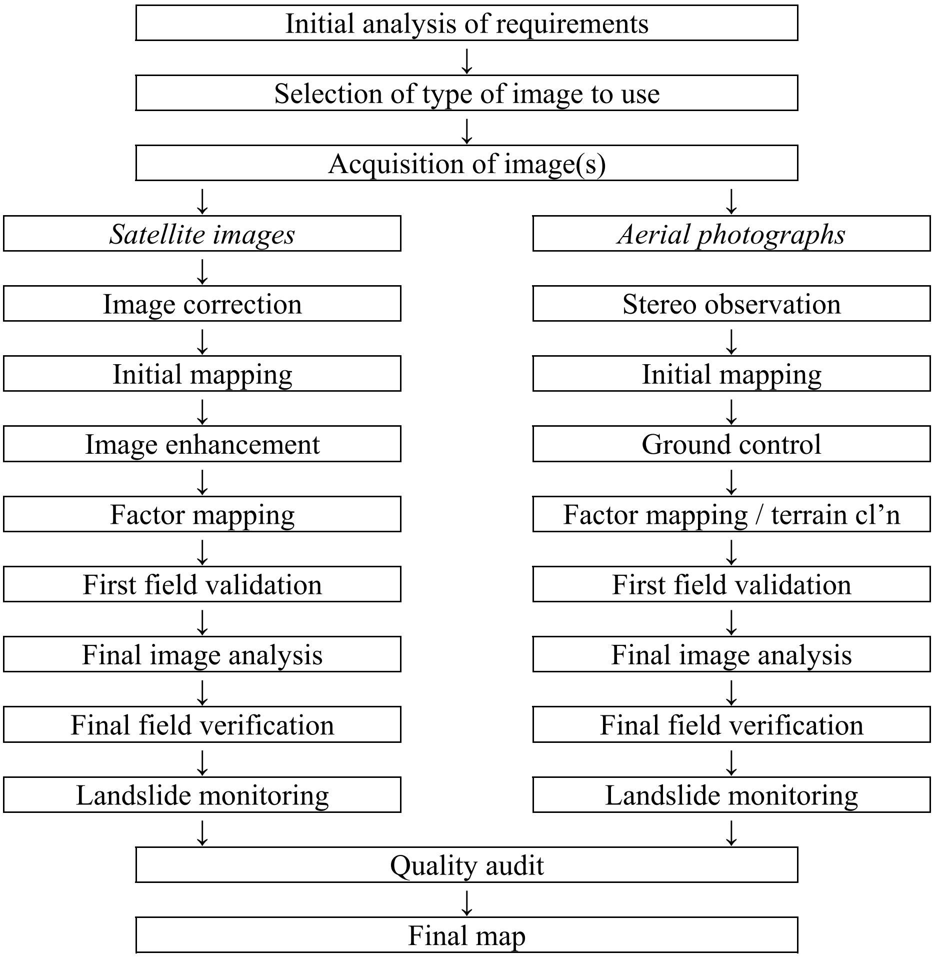


Figure 2.2 A generic scheme for the application of remote sensing in landslide studies

2.6.2 Initial analysis of requirements

2.6.2.1 As a first step, it is important to decide what are the requirements of the study. The ways in which remote sensing imagery can be used have been described in preceding sections. Figure 2.3 provides a summary of the main applications of the different types of imagery and should be used to determine what is needed from the imagery, and whether remote sensing can actually provide that information.

2.6.3 Using satellite imagery

2.6.3.1 If satellite images are to be used then the following steps should be taken:

Step 1: Which images should be used?

2.6.3.2 There is no doubt that many people are put off using satellite images because of the difficulties in deciding which images to buy. This is critical as images can be expensive. The large range of image types available makes this decision quite difficult. Figure 2.4 is a flow diagram to help in this decision-making, based on combinations of study area size and available budget. First, it is necessary to review the best type of imagery to use. Generally one of Landsat ETM+, SPOT or IKONOS should be considered, although the other sensors outlined in Table 2.1 and Appendix 2 may also be of some use. In most cases, Landsat ETM+ will prove to be the optimum imagery to use due to its excellent spectral resolution and low cost. SPOT IV will usually only be useful if stereo capability is required (rare at small scales) or if imagery needs to be specially acquired. IKONOS provides excellent spatial resolution (i.e. ground detail), but the cost will almost always preclude its use in low cost applications. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument that is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). The instrument has a very promising capability as it is able to collect data in 14 distinct bands with a maximum resolution of 15m. To date relatively little research has been conducted on the use of ASTER in natural hazards research, but it is potentially a very capable tool. It has not been examined as part of the LRA project.

Step 2: Buying the image

2.6.3.3 Once the imagery type has been selected, but before actually purchasing the imagery, it is advisable to check that other local or national organisations do not own the imagery already. This can significantly reduce costs. Assuming that the image is not available in this way, the image should be acquired from a data reseller. Care should be taken to ensure that the reseller is providing an image that is clear, has no cloud cover over the area of interest, does not have large distortions associated with it, and has been taken at the correct time (i.e. within the last few years and when the sun is high in the sky). Usually data resellers will be willing to provide a low resolution 'taster' image to ensure that it is suitable.

2.6.3.4 Finally, it is worth thinking about the format of the image that is needed. If the imagery is going to be used purely for a visual investigation of the terrain, in a similar manner to that used for an aerial photograph (see section 2.6.4), then a 'hard-copy' (i.e. print) may be all that is required. Data resellers are often willing to produce such an image for the area of interest, either as a black and white image (a so-called panchromatic image) or as a colour image (termed a colour composite image). If the latter is required then it is usually best to opt for a 'true colour composite', which has the appearance of an aerial photograph. Using this hard copy print landslide identification can be undertaken in much the same way as with an aerial photograph.

2.6.3.5 If the data is being acquired for more detailed analysis then it is best purchased in digital format – i.e. as a computer file that can be loaded into the analysis software. This is usually delivered in a standard format on a CD.

Step 3: Examining the image

2.6.3.6 Once the image has been provided it is well worth taking a look at the raw imagery before processing. If the image is in hard copy format then this is a relatively easy task. If it is in digital format then it will need to be uploaded into the software to be used for analysis. Available software packages include ERMapper® and ERDAS Imagine®, both of which are commercial software products, and the open source (i.e. free) software GRASS®, which can be obtained over the internet. Once the data has been uploaded into the software it should be examined on the screen or printed as a true colour composite.

2.6.3.7 At this stage it is worth verifying that:

a) the imagery covers the area being studied;
b) the imagery is of a good quality;
c) there is little or no cloud cover over the study area;
d) in the case of digital imagery, all the required bands are present and free of errors.

2.6.3.8 Assuming that the imagery meets the required standard, the initial examination should start with the identification of all the key features in the study area, such as the main towns, roads, mountains and rivers. Once this has been achieved key terrain features should be identified, such as rock outcrops, areas of colluvium and terraced land, perhaps using some of the techniques described in section 2.6.4. Finally, any obvious landslides in the image should be identified. It is worth compiling a rough map of the main features for future reference.

2.6.3.9 If a hard copy image is being used then subsequent analysis should be undertaken using the techniques described in the aerial photo section (2.6.4). The steps below only apply to imagery in digital form.

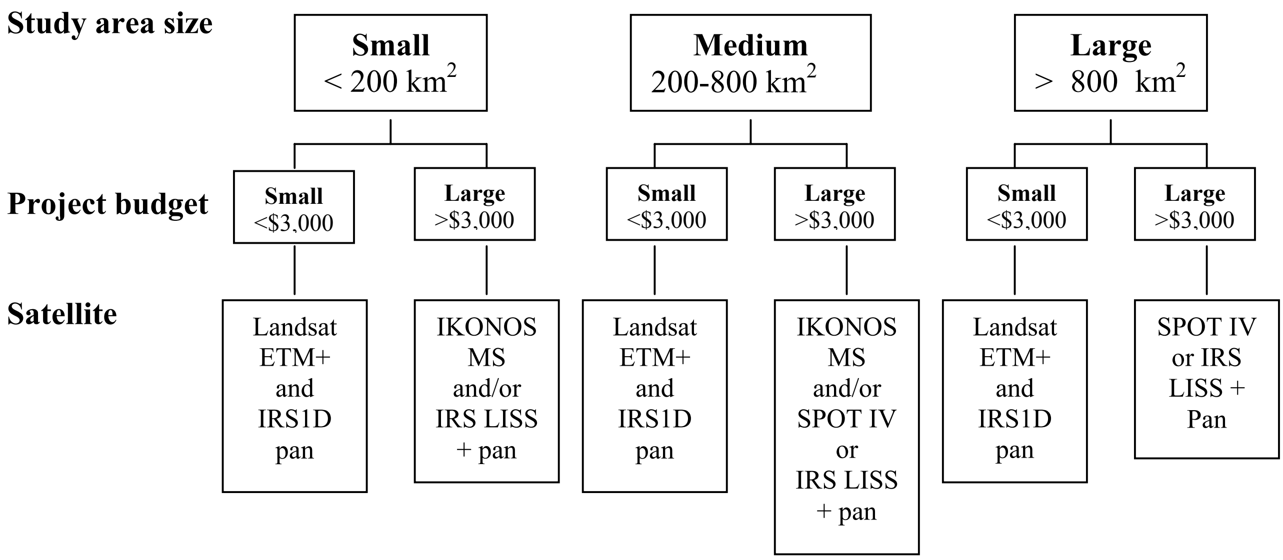


Figure 2.4 Recommended image types for different budget and study area combinations

NB Other image types may equally apply. Those shown in Figure 2.4 are those analysed as part of the LRA Project

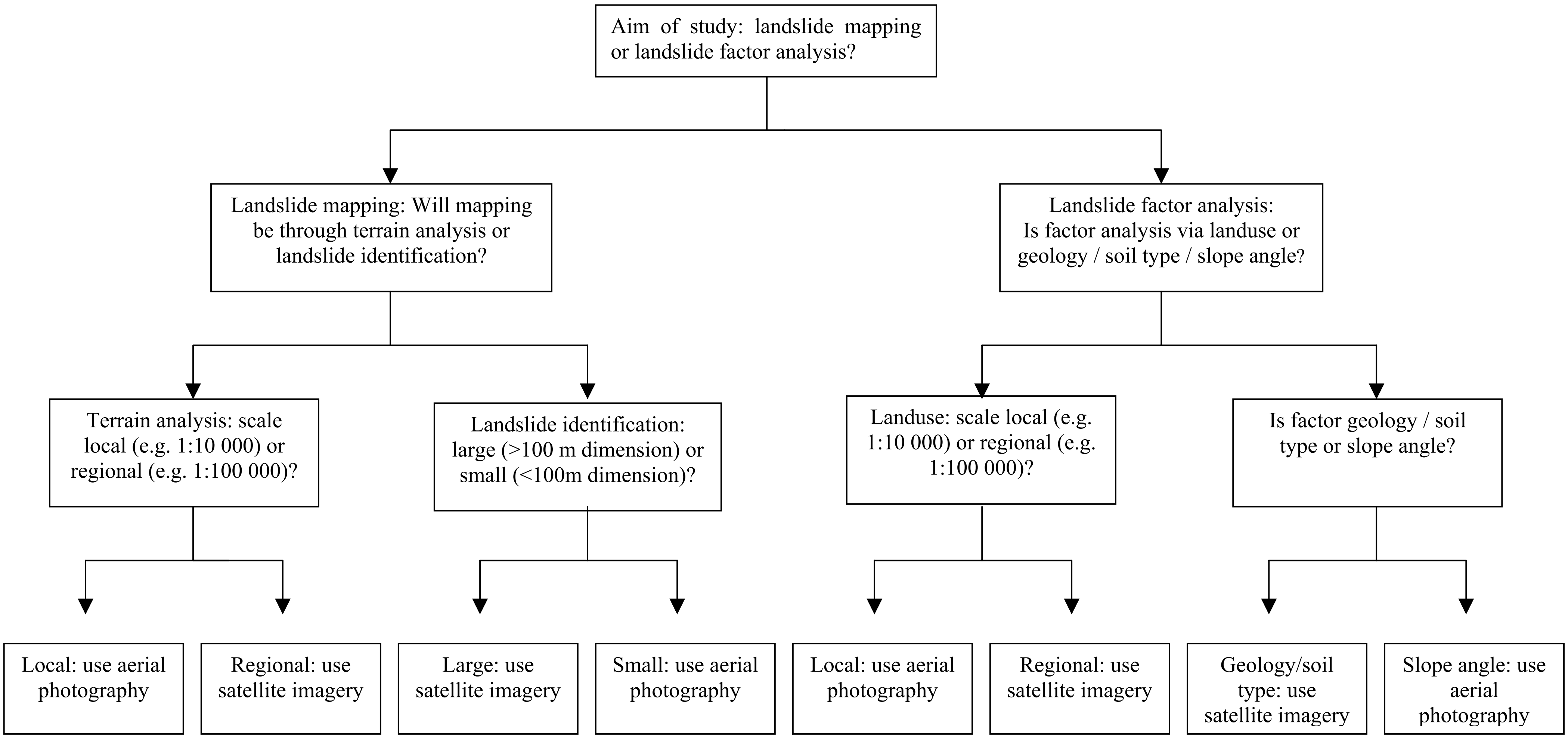


Figure 2.3 The selection of the best type of remotely sensed image to use in landslide studies in the rural access sector

Step 4: Image correction

2.6.3.10 In many cases, the image will be provided in digital form having not been rectified. When originally collected, all imagery contains distortions. These are primarily related to the increasing distance from the sensor and the terrain away from the centre of the image, but may also occur as a result of imperfections in the sensor itself (for example, distortions in the camera lens in the case of aerial photographs) and atmospheric effects. These are corrected during the process of rectification and geo-correction.

2.6.3.11 The digital form of satellite imagery means that rectification and correction in appropriate software is a comparatively simple task. The user identifies key points on the imagery for which the location is known very precisely (for example survey base points). The computer uses the coordinates of these points to warp the image so that it exactly fits the grid that is being used. Clearly the accuracy of this process is dependent upon the precision with which the ground control points are located both on the ground and on the imagery, the number of points used (a minimum of five is required), and their geographical distribution across the image. In general, greater numbers of points lead to increased accuracy.

Step 5: Initial mapping

2.6.3.12 The image can now be used to produce an initial assessment of the features to be mapped, whether these are landslides themselves, landslide controlling factors (for susceptibility mapping), or a terrain classification. This is best achieved using a true colour composite image, upon which features can be identified using the same techniques as for aerial photographs (see section 2.6.4 below). A flow diagram that can be followed to assist in this initial mapping is provided in Figure 2.5. It provides the main diagnostic features by which active and relict landslides can be mapped.

2.6.3.13 In some cases, this may provide sufficiently good results that further manipulation of the imagery is not needed. If so, the next stage should be the first field validation.

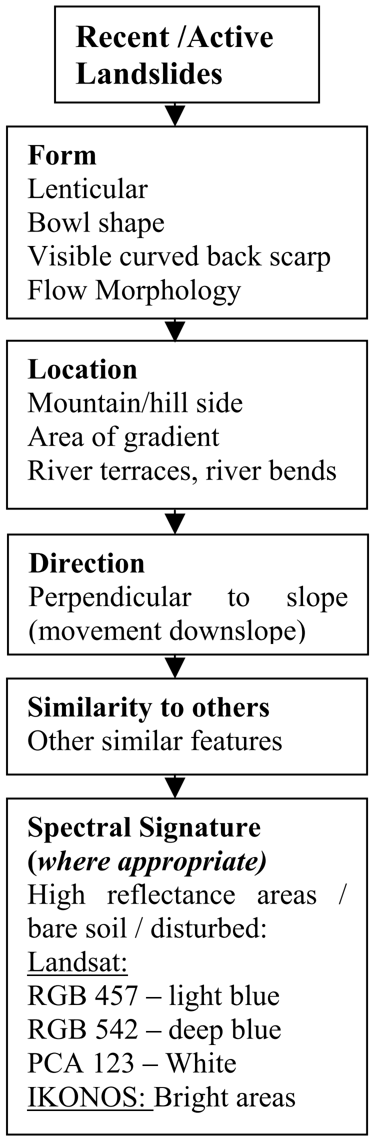


Figure 2.5 Recommended procedures for the mapping of landslides from satellite imagery.

Step 6: Image enhancement and factor mapping

2.6.3.14 Image enhancement is used to highlight features in the landscape, whether these are landslides themselves, factors involved in triggering landslides, variations in land use, or terrain types. Basically, image enhancement is used to change the appearance of an image to make the feature that is being mapped more distinct. This is much the same as changing the brightness or contrast of a television in order to make the picture more comfortable to view. The various types of enhancement that can be accomplished are as follows:

2.6.3.15 *Contrast Stretching:* This is the most common method by which the contrast (i.e. the difference in tone between the dark colours and the light colours) of an image can be maximised. Satellites collect information about the ground as a numerical value, known as a Digital Number (DN). So, for example, if the band being used was the black and white (panchromatic) band, then the instrument might assign a value of 0 if the ground in that pixel was completely black and 255 if it was completely white. If the colour was someway between these an intervening number would be ascribed. In many images, because spectral variation is limited, only a small proportion of these values are used, perhaps because the image was taken in the early morning when light was poor. As a result, even the brightest surface might only have a value of say 150. In contrast stretching, the DN values are redistributed by the programme to encompass all 256 values. This gives maximum discrimination between surface materials and, for example, emphasises the differences between vegetated areas and those with bare rock and soil. As many landslides have unvegetated back scars and some have exposed shear surfaces, this can sometimes allow the discrimination of areas affected by landslides.

2.6.3.16 Contrast stretching can be applied both to the differentiation of landslides themselves and to the mapping of related factors. So, for example, contrast stretching can be used to highlight changes in land use as it may emphasise the different spectral responses of various vegetation types.

2.6.3.17 *Filtering:* A development of the contrast stretching technique is to use the software to reclassify the DN values so as to emphasise the contrast between different land features. This is usually undertaken with an edge enhancement filter or a local enhancement filter, which emphasises high spectral differences but does not affect the useful low frequency brightness. The software does this by changing the DN value of each pixel in turn by considering the values of adjacent pixels. This has been proven to emphasise landslide features and can aid in the mapping of other features of interest.

2.6.3.18 *False colour composites:* The combination of the three visible bands to produce a photo-realistic true colour composite image is discussed above. In the other bands, such as the IR band, information is held in the same way. So, a value of zero indicates that no radiation of that wavelength was detected, whilst a value of 255 indicates that the maximum amount was received. Colour can be used to represent this visually. Thus, the information obtained from the ground can be represented in an artificially constructed (false colour) image. The information from another band could be taken and represented with various hues of one of the other primary colours (green or blue), and the same for a third band. These three images could then be combined together, much as a television combines images in red, green and blue to provide a 'false colour composite' image, which represents a composite of the information in any three of the bands. The advantage of this is that the eye is very good at interpreting these images (assuming that the user is not colour blind).

2.6.3.19 This technique is very commonly used in remote sensing studies. A number of composites have proven to be very useful, and these are given in Table 2.2. If required, these can be further enhanced by performing filtering on the images, or by enhancing Hue, Saturation and Intensity (HSI).

2.6.3.20 *Band ratios:* Sometimes it has been found that the information in different bands if used together can yield useful information about the ground. Take for example an area of wet soil. If the ground is wet then it might be expected to cool down less quickly on a sunny day, and so may appear warm in the IR bands if the image is taken early in the morning. At the same time it might also appear to be dark in colour. So, it might be possible to detect and area of wet soil by looking for areas of ground that are dark in colour (low DN value in the visual bands) and warm (high value in the thermal bands). The computer can then be programmed to find areas with these characteristics by taking the ratio of the value in the visible bands to that in the IR bands – areas with a high ratio might be wet soil. The software can calculate this ratio for every pixel. As a result a new 'band' of information is created, which can be displayed using the techniques described above for false colour composites.

2.6.3.21 Various types of ratios can be produced – one technique is to take the ratio of the values from three bands against a different set of three bands, and then to display the result as a false colour composite. Consequently, the data from six bands can be represented in a single image. Further, knowledge of the spectral properties of specific surfaces can allow this technique to highlight specific features. A useful example is the Normalised Difference Vegetation Index (NDVI), which is commonly applied to Landsat 7ETM+ data. The NDVI highlights variations in vegetation type and density and is commonly used for the classification of forested areas. As such it is useful in landslide studies, both to highlight areas of active instability (unstable ground often causes vegetation stress that can be detected through this method and, in extreme cases, active landsliding leads to vegetation clearance that is easily detected). In addition, this technique can also be used in the mapping of other related factors, such as land use. Some success is also met with the use of other ratios in Landsat data, notably ratios designed to detect the characteristics of clay soils (the clay ratio) and iron oxide (the iron oxide ratio). The clay ratio is the ratio between Landsat bands 5 and 7, and can be used to identify clay-rich landslide debris and can also highlight variations in rock and soil mineralogy, which might be a factor in landslide occurrence. The iron oxide ratio, which is the ratio between bands 3 and 1, highlights areas in which water percolation is occurring. As water percolation is a factor in landslide initiation, this may aid in the identification of instability. However, while these techniques provide great potential, they must be backed-up by field verification given the degree of speculation involved.

2.6.3.22 *Unsupervised classification:* Image processing software can automatically divide the pixels in an image into a series of classes according to their spectral characteristics. The software allows the user to either select the number of classes into which the imagery should be divided, or it can do so automatically. Whilst research into these techniques in landslide studies remains limited, potentially it offers a powerful technique for the delineation of either landslides themselves (assuming that they have some unique set of spectral characteristics) or landslide factors such as vegetation types for factor analysis. A number of methods for unsupervised classification are available, including *minimum distance to mean*, *parallel piped* and *maximum likelihood*. Of these, only the maximum likelihood technique has to date shown good results for landslide studies, having been successfully applied to both Landsat and SPOT imagery. In both cases the technique clearly highlighted areas of bare soil associated with recent failures.

2.6.3.23 *Supervised classification:* In supervised classification, the user selects one or more areas within the image of interest. So, for example, the user might select a known landslide. The computer will determine the spectral characteristics of the area and will then undertake a classification of the image based upon these characteristics, using one of the techniques described above. This can be a very cost effective way of finding areas of specific interest. For example, the technique can aid in the identification of areas underlain by colluvium once one or more areas have been identified. As before, the maximum likelihood technique would appear to be the most useful for undertaking supervised classifications.

2.6.3.24 At the end of this stage a map should be produced showing the results of the analysis. This may well cover only about 25% of the total area at this stage, but should represent the best possible attempt to identify and locate the items of interest. If more than one type of data is being collected, a number of maps will probably be required.

Table 2.2 Potentially useful false colour composite images for Landsat ETM+ and SPOT imagery

Band numbers (R, G, B respectively)	Application	Notes
Landsat ETM+		
4,5,7	Lithological units	Useful for differentiating landslides. Band 4 highlights bare soil; 5 and 7 highlight soil and rock mineral composition. Bare rock appears as dark blue. areas of mixed rock, soil and vegetation appear as light blue.
5,4,2	Soil, vegetation and water	Useful for highlighting areas of wet, bare soil, which may be a symptom of erosion and landslides. Also highlights wet areas and variations in vegetation
SPOT		
3,2,1	Vegetation	Highlights vegetation variations, water, bare rock and soil. Has some limited use in highlighting landslides
4,2,1	Vegetation and land use	Highlights vegetation variations, water, bare rock and soil. Has some limited use in highlighting landslides, but due to less tonal variation is less effective than 3,2,1 or 4,3,1.
4,3,1	Land use	Most effective SPOT image for highlighting landslides and landslide factors. Less affected by shadows than most images.
4,3,2	Land use	Similar to 4,3,1 but with less contrast.

Step 7: First field validation

2.6.3.25 At this stage it is strongly advised that a field check of the image interpretation is undertaken. This is best done by visiting the field site, preferably in good weather. A minimum of 20% of the area analysed to this point should be examined in the field. This field validation should check:

a) the quality of the imagery in relation to the features on the ground surface itself;
b) the accuracy of the interpretation made to date, including any misinterpretations or features that have been missed. In both cases notes should be made so that further analysis can be undertaken on the imagery;
c) the occurrence of systematic errors, for example the misidentification of ground features on the imagery.

2.6.3.26 This ground verification is best undertaken through geomorphological mapping in the field. It is greatly assisted if a hard copy, true colour composite is available so that features identified on the ground can be compared with the imagery, and vice-versa.

Step 8: Final image analysis

2.6.3.27 Based upon the results of the initial image analysis and the field validation, a final analysis should be conducted. This will probably involve refining the interpretation and analysis methods to more closely correlate with the features on the ground, and an attempt to manipulate the imagery to highlight features that were not previously identifiable. As a result, a final map can be produced, together with a summary commentary.

Step 9: Second field validation

2.6.3.28 Once the final map has been produced, a brief field validation visit should be undertaken to ensure that the interpretation is appropriate. This should be brief, covering perhaps only 5% of the total area in detail.

Note on landslide monitoring

2.6.3.29 To monitor landslides over time, a series of images can be obtained covering a number of years. Such analyses are relatively time-consuming, so should only be attempted where really necessary. A series of landslide maps should be compiled, each independently of the other in the first instance. These can then be compared to determine change through time, although correlation between images should be used to ensure that apparent changes have not occurred simply because of misinterpretations or errors.

2.6.4 Using aerial photography

2.6.4.1 If a decision is made to use aerial photography, then the steps outlined in Figure 2.2 should be followed.

2.6.4.2 The techniques used for undertaking aerial photograph interpretation (API) on both black and white and colour aerial photography are essentially the same, regardless of scale. The strength of this technique includes its widespread acceptance, high levels of spatial resolution, stereo coverage, and relatively low cost. However, disadvantages include the potential for masking by cloud, forest or shade, inherent subjectivity due to the need for interpretation, and the time-consuming nature of the process.

2.6.4.3 API should always be undertaken by an experienced practitioner who is familiar with the landforms, processes and materials in the study area. As with all remote sensing methods, the practitioner will become increasingly knowledgeable about the area and the features being mapped as the exercise continues, requiring that an iterative approach is adopted, with frequent revisiting of areas already mapped. Care is needed when using stereo pairs of photographs since the vertical exaggeration renders slopes apparently steeper than they actually are. In some cases this vertical exaggeration can make the interpretation of ground features difficult.

Stereo observation

2.6.4.4 The images should be set up under a stereoscope and examined in a systematic manner. Table 2.3 lists the main landslide features that can be mapped from aerial photographs.

2.6.4.5 Mapping is normally undertaken onto acetate sheets using a pre-determined set of symbols. The information from these sheets can then be transferred onto topographic maps or can be digitised an entered into a GIS, in which case rectification and geo-correction of the data will be needed.

Table 2.3 Landslide features identifiable on aerial photographs

Feature	Appearance in aerial photographs
Landslides by activity level	
Active	Fresh, arcuate failure scar with high reflectance and low vegetation levels Slipped mass with immature / disturbed vegetation and areas of bare ground Landform disturbed and uncharacteristic of surrounding area Possible rock spalls on margins Springs, ponds and wet ground in slipped mass Areas of slope in tension (cracks) and in compression (hummocks) Disruption of drainage pattern
Suspended or intermittent	As above, but vegetation more mature. Scarps and cracks beginning to revegetate. Some evidence of 'pioneer' species
Relict	As for active, but more subdued topography. Vegetation now well–established
Landslides by mechanism	
Progressive soil creep	Immature / uncharacteristic vegetation Disturbed / hummocky ground surface Small ridges / terracettes perpendicular to movement direction Discontinuous / uneven irrigation and cultivation
Mudslides	Long, narrow, planar track Clear lateral boundaries Disturbed vegetation Weathered rock or fresh soils in back scar Lobate toe Usually located on lower slopes with moderate to low slope angles
Debris slide	Weathered rock or fresh soils in well-defined back scar Clearly defined, unvegetated track containing boulders Usually have moderate slope angles
Debris flow	Weathered rock or fresh soils in well-defined back scar Clearly defined, unvegetated track containing poorly-sorted (jumbled) debris Depositional fan at toe Flow lines composed of debris forming margins of flow track
Progressive rock creep	Difficult to identify through API, but often found in fractured rock masses occupying high, steep slopes. Ridges and trenches running across the slope may be visible Possible rock spalls on margins
Rockfall	Rock fall scar, sometimes with arcuate form Progressive rock fall may lead to formation of concave talus slope with gradient of 33-38°. Larger particles accumulate towards toe.
Rapid, catastrophic rock slide	Failed mass of chaotic boulders and rafts of rock Slope angle of failed material lower than adjacent slopes Large scar
Slow rock slide	Hummocky and furrowed slopes in head of failure Large scar Slope rupture and small vertical displacements along margins
Rotational landslide in soil	Arcuate back scar in plan Concavo-convex slope profile in section from back scar to toe Well defined lateral shears Back-tilted block with reverse slope below back scar Ponds at junction of back scar and back-tilted block Areas of water seepage In some cases, multiple slipped blocks are seen forming a 'staircase'

Feature	Appearance in aerial photographs
Rotational landslide in rock	As for soils failures but: surface of failed mass is often covered in boulders, giving irregular surface Secondary failures are unlikely
Rock avalanche	Rockfall scar, although sometimes removed by weathering Failed mass forms thin tongue of boulders with pressure ridges & flow lines Often sorting of boulders along track Very large volumes of debris may be seen
Other features important in landslide studies	
Shallow soil	High percentage of rock outcrop Marked structural control in morphology Patchy vegetation
Deep soil	Concavo-convex slope profile with lobate and gently rounded lower slopes Dendritic drainage pattern
Residual soil	Red / red-brown appearance in colour aerial photographs Often occupies rounded ridge and spur summits and/or flat/gently sloping benches Often intensely cultivated Prone to erosion and landsliding
Rockfall/ rockslide colluvium	Deposits of boulders below rock cliffs with scar Unsorted with chaotic arrangement Low levels of vegetation, often of shrub-type
Undifferentiated colluvium	Long, gentle slopes with marginal stability – shallow landslide scars often visible Boulders at toe Immature drainage systems with water seepage on lower slopes
Rock outcrop	Steep slopes High light reflectance Repeated pattern of structural surface Low levels of vegetation
Strong rock	Steep and rugged topography V-shaped gullies and valleys, knife-edge ridges Rockfalls and rockslides
Weak rock	Gentle slopes with rounded spurs and ridges No visible outcrop Concave slopes Shallow slope failures
Springs	Wet ground with dense vegetation in many cases Often located at breaks of slope or geological boundaries
Eroding gullies	Irregular channel in plan High reflectance from bare surfaces Fallen trees in channel bed sediment deposition downstream

Ground control

2.6.4.6 Ground control is required to enable geo-rectification of aerial photographs for photogrammetric purposes. A number of ground control points should be identified, usually a minimum of two in each stereo overlap. These should be surveyed points on the ground that can be easily identified on the photographs.

Factor mapping or terrain classification

2.6.4.7 If the aim of the study is landslide factor mapping or terrain classification (for the purposes of landslide susceptibility mapping – see Chapter 3), then these exercises should be undertaken at this stage. In both cases the ground is evaluated in terms of the range of topographic features, and areas of similar features are identified and delineated.

First field validation

2.6.4.8 At this stage it is strongly advised that a field check of the API is undertaken. This should involve a visit to the field site, preferably in good weather. A minimum of 20% of the area analysed to this point should be examined. This field validation should check:

a) the quality of the photographs in relation to the features on the ground surface itself;
b) the accuracy of interpretation made to date, including any misinterpretations or features that have been missed. In both cases notes should be made so that further analysis can be undertaken on the photographs;
c) the occurrence of systematic errors.

2.6.4.9 This ground verification is best undertaken through geomorphological mapping in the field. It is greatly assisted if the aerial photographs are available in the field as well so that features identified on the ground can be compared with the photographs, and vice-versa.

Final API

2.6.4.10 Based upon the results of the initial API and the field validation, a final analysis of the photographs should be completed. This will probably involve refining the interpretation and analytical methods to more closely correlate with the features on the ground. As a result, a final map can be produced, together with a summary commentary.

Second field validation

2.6.4.11 Once the final map has been produced, a brief field validation visit should be undertaken to ensure that the interpretation is appropriate. This should cover perhaps only 5% of the total area in detail.

Landslide monitoring

2.6.4.12 To monitor landslides over time, a series of photographs should be obtained covering a number of years. The techniques used are essentially the same as those for monitoring using satellite imagery. Of course, the scope for undertaking this exercise is controlled by the record of aerial photography available.

2.7 Quality assurance (QA)

2.7.1 In landslide studies, QA is an essential process. It is recommend that the following QA procedures are undertaken:

a) a review of any interpretations made using direct observation from the imagery, such as API or the analysis of true colour composite images, is undertaken by an experienced landslide mapper. This is best conducted through an independent mapping exercise on 10% of the imagery. The two analyses should then be compared and an analysis made of the differences between the two interpretations. Any systematic differences should be determined and corrections made to the whole interpretation where appropriate;
b) where multispectral analyses have been used, a review of the methods used in that analysis and the interpretations that have resulted should be undertaken. Where possible, this should include a field visit.

2.8 Problems, Errors, and Solutions

2.8.1 In many cases the major problems associated with the use of remote sensing in landslide studies in the rural access sector arise due to limitations in spatial resolution, which mean that smaller landslides cannot be detected. These can only be overcome by using imagery with a higher spatial resolution or through the use of other techniques, such as ground mapping. A further major cause of problems is a lack of spectral resolution, which means that landslides cannot be detected. Unfortunately landslides do not have a unique spectral signature in either the visible range or in other parts of the electromagnetic spectrum, so their detection will always be to an extent subjective. In many cases, the most important aspect of the study is the experience of the practitioner – so whichever remote sensing technique is employed it is essential to return to areas that have been analysed as the practitioner's knowledge of the area improves, and to ensure that every effort is made to use knowledge gained from the ground truthing to strengthen the image analysis process. Nonetheless, the skills needed to analyse aerial photographs can be acquired through training and field validation to a level sufficient to enable basic interpretation to be carried out. Therefore, this is a technique that can be applied widely. Satellite image interpretation is more difficult, but if a true colour composite can be acquired the same techniques as for aerial photography can be applied relatively easily, although usually not in stereo.

2.9 Conclusions and Future Developments

2.9.1 Remote sensing techniques represent a powerful method for the delineation and mapping of landslides, for generating datasets for factor analysis, and for providing information for landslide risk assessment. API remains the most commonly-used technique, and it continues to have many strengths and advantages. One of the most important of these is its widespread acceptance, but the availability of data, stereo coverage and high spatial resolution are also real advantages. The great advances in the spatial resolution of satellite imagery, and the reductions in cost both in terms of the images themselves and the software required to interpret them, have rendered these techniques increasingly valuable. Real advantages in terms of the large spatial coverage of the data, the multispectral nature of the data, and the potential for automatic or semi-automatic classification are being realised at present. However, the remaining high cost of imagery with photo-quality resolutions and the lack of stereo capability in most systems continue to be real drawbacks.

2.9.2 Future developments in remote sensing technology will lead to real advances in the use of these techniques. In the near–future, the following advances can be anticipated:

a) the availability of the SRTM (Shuttle Radar Topography Mission) digital elevation datasets with global coverage to a height precision of 30 m;
b) the availability of 0.5 m resolution satellite imagery;

c) the availability of highly capable ‘shareware’ image processing software, such as GRASS®;
d) the development of low cost digital aerial photographic acquisition systems that can be mounted on non-specialist platforms such as light aircraft, remotely controlled aircraft, balloons, or kites.

2.9.3 In the slightly longer term it is likely that developments will lead to:

a) the availability of hyperspectral satellite instruments that provide much greater spectral resolution;
b) enhanced algorithms for landslide detection;
c) the development of INSAR technologies for landslide displacement monitoring.

CHAPTER 3

LANDSLIDE HAZARD AND RISK MAPPING

3.1 Introduction

3.1.1 In the planning phase of many road projects there is a need for simple and reliable techniques to detect existing landslides and to identify terrain that might be susceptible to landslides in the future. Chapter 2 discusses ways in which remote sensing can be used to identify existing landslides, but the susceptibility of any given area to future landslides also requires consideration. Furthermore, planners and engineers would benefit from an indication of how large future landslides might be, how likely they are to move, and their probable effects should movement occur. Landslide hazard and risk mapping are techniques devised to assess these issues.

3.1.2 The aim of this chapter is to provide an introduction to these mapping techniques, including the techniques that can be used for assessing landslide susceptibility, hazard and risk. The techniques described here are meant to be easy to understand and apply, and do not require high levels of specialised knowledge and data. More detailed techniques are available, but these are usually too data-intensive and too complex to apply in the planning of rural access. They are also, often, of unproven reliability.

3.2 Definition of Terms

Landslide susceptibility, hazard and risk

3.2.1 To allow a proper understanding of the terms used in these guidelines, a few basic definitions are needed (Figure 3.1):

a) landslide – defined in 1.1.3 and comprising slide, flow, spread and fall categories;
b) susceptibility – those slopes most likely to be the locations of existing and future landslides. One slope may be more susceptible to landslides than another as a result of topographical and geological factors. Susceptibility is usually expressed in non-specific terms (high, medium or low) and therefore has no absolute meaning;
c) hazard – the likelihood of any given area being affected by landslides over a given period of time. Hazard is dependent on landslide location, size and travel distance (see below), and frequency or probability of occurrence. Hazard therefore describes the potential to cause damage;
d) vulnerability – the extent of damage likely to be suffered (none, partial, complete) by infrastructure, land use and people as a result of a landslide occurring;
e) risk – the total potential losses, in economic and social terms caused by landslides over a given period.

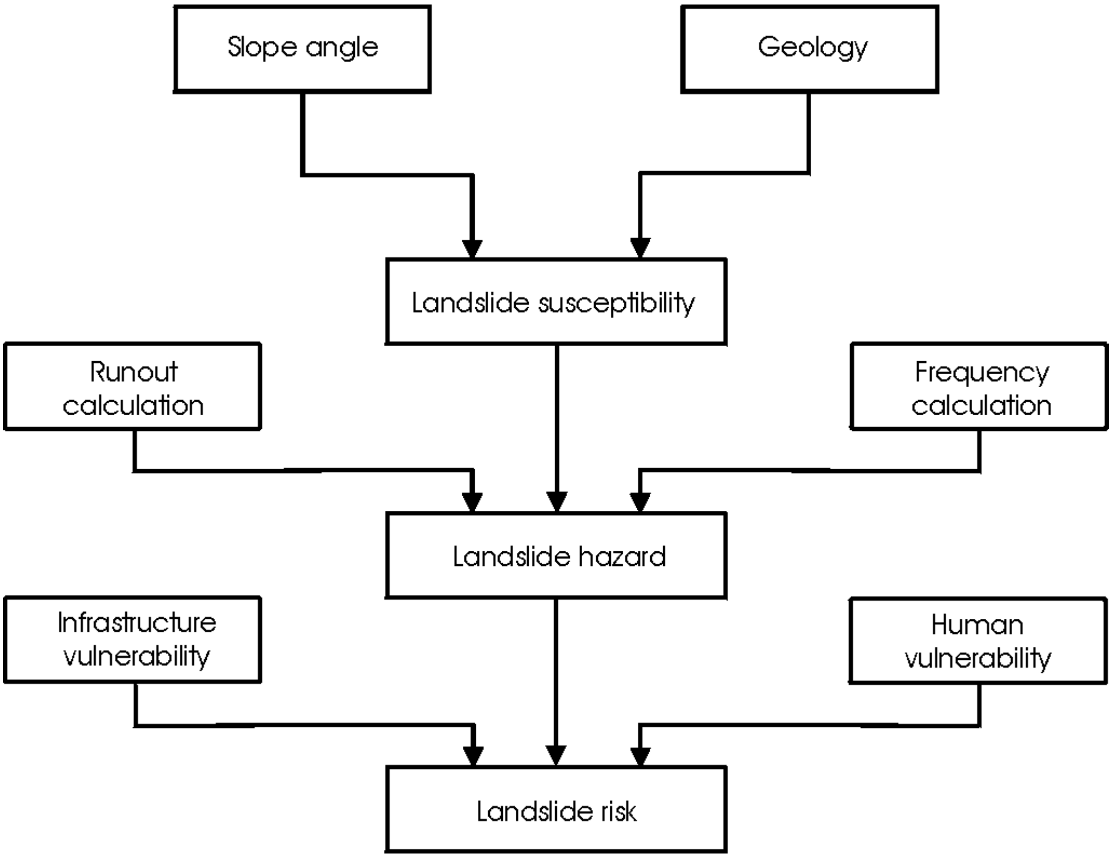


Figure 3.1 Flow diagram illustrating the steps in the assessment of landslide susceptibility, hazard and risk, in this case using slope angle and geology as the principal factors in determining landslide susceptibility.

3.2.2 Traditionally, a) to c) above have been evaluated by engineering geological personnel engaged in infrastructure projects, while d) and e) are rarely evaluated in any formal way.

Geomorphological mapping

3.2.3 In standard engineering geological practice, geomorphological mapping is used to record existing and potential future landslide locations. The mapper examines and interprets the landscape, interpreting on the basis of the shape and distribution of landforms, the processes that have and continue to fashion their development, and the materials in which they are formed. In some ways the approach used is similar to that of a doctor identifying an illness in a patient – a set of symptoms are used to diagnose the cause. As in medicine this is a skilled task – generally it is best undertaken by someone with a good knowledge of geomorphology in general and of the environment being examined. It is also highly labour-intensive and subjective.

Susceptibility mapping

3.2.4 Some of these problems can be reduced through the application of landslide susceptibility mapping, in which a simple assessment is undertaken of the factors that are involved in the occurrence of landslides, such as the slope angle and the material type, in order to identify the areas that are prone to the effects of landslides. So, for example, a particular combination of geology and slope angle might render a slope susceptible to landslides.

Hazard assessment

3.2.5 Hazard assessment requires more than just a knowledge of landslide location. To be useful, it is necessary to know how likely it is that a landslide will occur and, when it does, how large it is likely to be, and how much land it might affect. Hence, landslide hazard describes the probability of any given area or location being affected by landsliding during a given period. In mountain regions the geographical effects of landslides often extend well outside their area of origin due to the lengthy travel distances of landslide debris. Landslide runout is, therefore, an important consideration in any landslide hazard assessment.

Risk assessment

3.2.6 Should a landslide occur it might destroy a road and demolish some houses. Alternatively, it might occur in a remote forested area and have no effect on people at all. Landslide risk describes the potential outcome of a landslide, which takes into consideration landslide hazard, the vulnerability of people and their structures, and the potential economic and social loss or impact. The potential economic loss should be calculated in terms of the costs of any damage and loss of earnings and trade. Furthermore, lives are often at risk and this must also be taken into consideration. As the discussion in this chapter shows, it is usually very difficult to assess these risk elements with any reliability. Risk is usually expressed in probability terms – e.g. there is a 10% chance of US$ 1 million of economic loss in the next 20 years.

Practical applications

3.2.7 In virtually all cases there is insufficient data available to carry out a full assessment of landslide risk, and consequently the procedures defined above are academic to most planners and engineers. Maps that claim to portray landslide risk are usually either incorrectly defined or are likely to be based on assumptions that may not be tenable. However, in many cases a full landslide risk assessment might not be needed. For example, in planning an initial alignment for a road, a landslide susceptibility assessment might be perfectly adequate. For the engineering design of the road itself a landslide hazard assessment might be needed. Landslide risk might not need to be determined in this case. However, if a sum of money is provided specifically to reduce vulnerability to landslides, then a full landslide risk assessment would be required.

3.3 Landslide Susceptibility

3.3.1 Introduction

3.3.1.1 There are two main elements in determining landslide susceptibility. First, existing landslides should be identified and mapped. In steep terrain, existing landslides usually move on a regular basis, posing an obvious threat to land use and infrastructure. Second, a comparison of mapped landslides with key factors, such as topography and geology, helps determine future landslide locations.

3.3.2 Landslide identification and mapping

3.3.2.1 Chapter 2 describes ways in which landslides can be identified from remote sensing. While remote sensing, and especially aerial photography, can help identify the majority of landslides in a given area, it will be necessary to supplement this with field mapping using the recognition criteria described in Appendix 1. Ideally, landslide mapping should differentiate between the source area of the landslide and the landslide mass itself, and its runout. The scale of mapping is an important consideration. The limit for mapping individual landslides, except where the features are very large, is about 1:25,000, but even at this scale a landslide that is 50 m in length will only be 2 mm on the map. Ideally, a scale of 1:10,000 or larger should be used, but topographic maps at this scale are rarely available in developing countries. The largest available scale map should be used.

3.3.3 Factor analysis

3.3.3.1 Usually a range of factors will be responsible for the initiation and continued movement of landslides in a given area. These factors include the strength of soils and rock masses, geological structure and the orientation of joints, slope angle and slope aspect, groundwater levels, soil moisture, and the influence of external factors including seismic acceleration, toe undercutting by rivers and land use effects.

3.3.3.2 These factors are often difficult to reliably investigate and analyse even on a slope-by-slope basis, and therefore the prospect of incorporating them effectively into desk study-based landslide susceptibility mapping is extremely limited. Landslide susceptibility mapping for rural access planning needs to be rapid and easy to apply, and largely reliant on existing data without recourse to detailed field mapping and investigation.

3.3.3.3 Some published susceptibility mapping schemes have attempted to resolve this problem of limited data availability by introducing surrogate or indirect factors that can be determined from available data sources. These factors often include land use, slope aspect, relative relief, drainage pattern and rainfall distribution. Their relationship with landslide initiation and landslide susceptibility is usually speculative and therefore extreme caution must be exercised in developing and applying these techniques.

3.3.4 Landslide susceptibility mapping in the LRA project

3.3.4.1 The primary objective of landslide susceptibility mapping is to yield a reasonably accurate map, using the minimum number of factors or input parameters and deriving the necessary data primarily from desk study. The studies carried out by the LRA project in six areas of Nepal and Bhutan covering a total area of over 2000 km² have analysed the mapped distribution of landslides against a total of 13 different factors derived from desk study (Figure 3.2). Only two factors (rock type and slope angle) were found to be consistently correlated with the distribution of landslides but this two-fold scheme proved satisfactory in explaining the majority (over 70%) of landslide locations across the six study areas as a whole. The susceptibility rating derived from the LRA project are based on landslide density and are shown in Table 3.1.

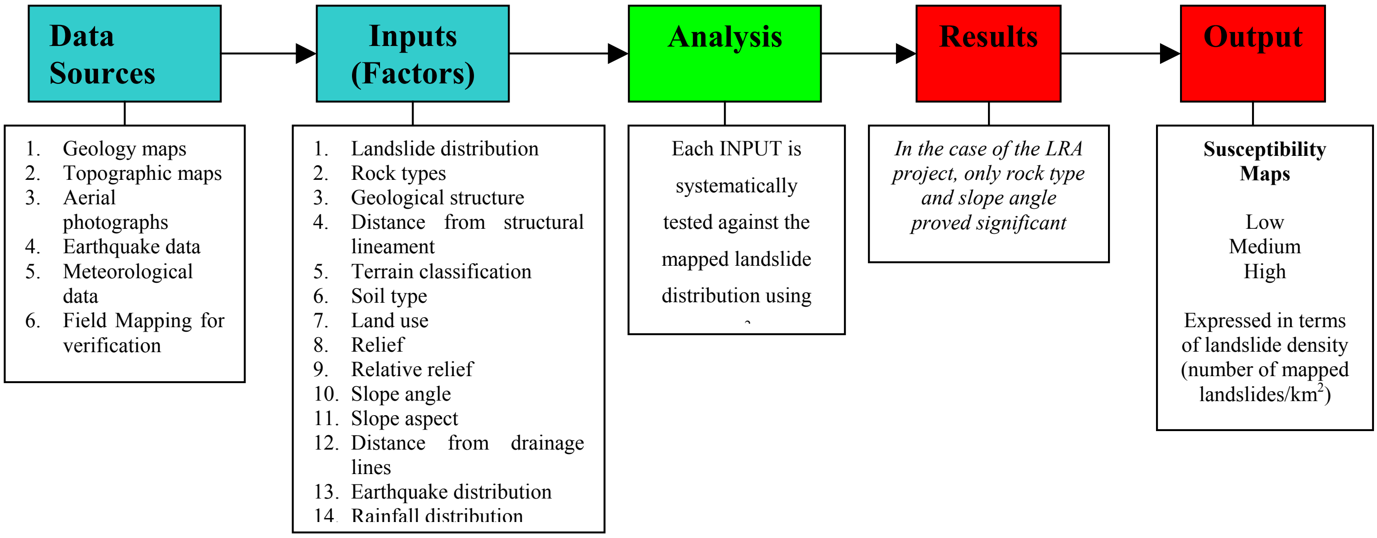


Figure 3.2 Guide to factor analysis for landslide susceptibility mapping

3.3.4.2 The mapping of landslides for the two-fold scheme (rock type and slope angle) was heavily reliant on the interpretation of aerial photographs at a scale of 1:50,000. If good quality aerial photographs exist then geological interpretation can be used to derive two additional factors: structural orientations and terrain classification. This four-fold scheme was developed and applied in one of the Bhutan study areas and was able to increase the ground resolution in the differentiation between landslide density and hence susceptibility.

3.3.4.3 The two-fold and four-fold schemes described above have proved successful in accounting for mapped landslide distributions. The two-fold scheme can be applied early on in rural access corridor planning, while the four-fold scheme is intended for more detailed analysis, perhaps once a corridor is chosen or when comparisons need to be made between corridor alternatives. Thus the two-fold scheme is more applicable to regional or district planning, while the four-fold scheme has a greater engineering application. Both schemes are described in Appendix 3. The procedures are briefly summarised below.

3.3.5 Applying the two-fold scheme

3.3.5.1 The steps below summarise the procedure.

Step 1: Compile maps of rock type and slope angle for the area of interested and carry out field validation. Potential sources of information for this are detailed in section 3.3.7.

Step 2: For the study area, divide the slope / rock type combinations into three classes based upon the landslide density values indicated in Table 3.1. This can be done either by having three equally sized classes in terms of the densities themselves, or by dividing the study area up so that approximately a third of the area lies in each density class (preferred option). If the area being studied straddles a major geological structure, such as the Main Boundary Thrust in Nepal, it may be better to divide the area into two along this boundary and to consider the areas either side of the structure separately.

Step 3: Plot a map of relative susceptibility based upon the division in Step 2.

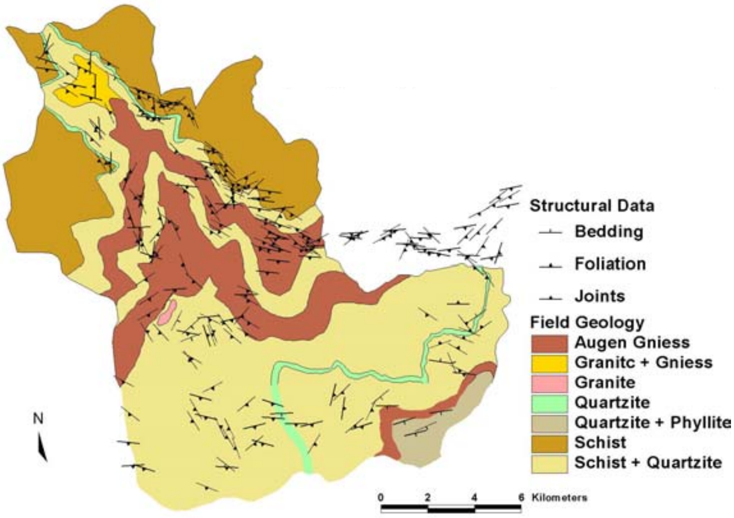
Step 4: Check this final map against observed landslide locations, derived from aerial photograph interpretation or field mapping to confirm its validity.

Table 3.1 Landslide susceptibility ratings and corresponding density values.

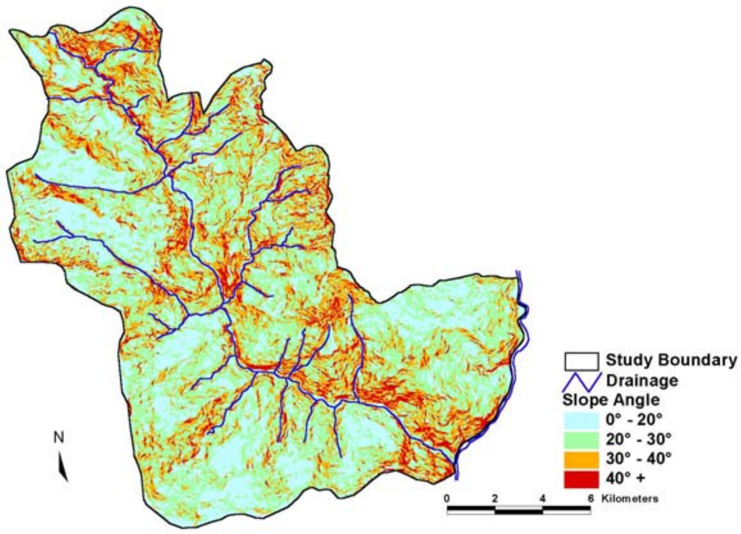
Susceptibility Class	Rock Type	Slope Angle	Indicative landslide density (landslides/Sq km)
Low Landslide Susceptibility (Rating of 1)	Granite	0° - 20°	0.00
	Granite	20° - 30°	0.00
	Granite	30° - 40°	0.00
	Granite	> 40°	0.00
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	0° - 20°	0.00
	Slate/shale with Limestone &/or Quartzite	0° - 20°	0.00
	Quartzite & Phyllite	0° - 20°	0.16
	Mica Schist & Gneiss	0° - 20°	0.20
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	20° - 30°	0.20
	Mica Schist and other minor rock types	0° - 20°	0.22
	Gneiss & Mica Schist	0° - 20°	0.25
	Mica Schist & Phyllite	20° - 30°	0.26
	Mica Schist & Quartzite	0° - 20°	0.27
	Gneiss	0° - 20°	0.30
	Phyllite (with Quartzite &/or Limestone)	0° - 20°	0.30
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	30° - 40°	0.36
	Quartzite & Phyllite	20° - 30°	0.36
Moderate Landslide Susceptibility (Rating of 2)	Limestone/Dolomite with Quartzite, Phyllite &/or shale	> 40°	0.40
	Mica Schist & Phyllite	0° - 20°	0.43
	Phyllite (with Quartzite &/or Limestone)	20° - 30°	0.46
	Mica Schist and other minor rock types	20° - 30°	0.48
	Mica Schist & Gneiss	20° - 30°	0.53
	Quartzite & Phyllite	30° - 40°	0.54
	Gneiss	20° - 30°	0.55
	Mica Schist	0° - 20°	0.56
	Slate/shale with Limestone &/or Quartzite	30° - 40°	0.59
	Mica Schist & Quartzite	20° - 30°	0.60
	Slate/shale with Limestone &/or Quartzite	20° - 30°	0.60
	Quartzite & shale &/or Sandstone	20° - 30°	0.62
	Quartzite & shale &/or Sandstone	0° - 20°	0.65
	Gneiss & Mica Schist	20° - 30°	0.66
	Slate/shale with Limestone &/or Quartzite	> 40°	0.67
High Landslide Susceptibility (Rating of 3)	Quartzite & Phyllite	> 40°	0.72
	Mica Schist	30° - 40°	0.75
	Mica Schist	20° - 30°	0.77
	Fine grained Sandstone (siltstone/mudstone)	0° - 20°	0.78
	Mica Schist	> 40°	0.80
	Mica Schist & Gneiss	> 40°	0.81
	Gneiss	30° - 40°	0.82
	Mica Schist & Phyllite	30° - 40°	0.83
	Phyllite (with Quartzite &/or Limestone)	30° - 40°	0.88
	Mica Schist and other minor rock types	30° - 40°	1.00
	Gneiss & Mica Schist	30° - 40°	1.00
	Mica Schist & Gneiss	30° - 40°	1.02
	Gneiss	> 40°	1.02
	Medium to coarse grained Sandstone	0° - 20°	1.03
	Quartzite & shale &/or Sandstone	30° - 40°	1.15
	Mica Schist & Quartzite	30° - 40°	1.19
	Quartzite & shale &/or Sandstone	> 40°	1.45
	Phyllite (with Quartzite &/or Limestone)	> 40°	1.55
	Mica Schist & Quartzite	> 40°	1.58
	Mica Schist and other minor rock types	> 40°	1.58
	Medium to coarse grained Sandstone	20° - 30°	1.64
	Gneiss & Mica Schist	> 40°	1.89
	Medium to coarse grained Sandstone	> 40°	2.15
	Medium to coarse grained Sandstone	30° - 40°	2.48
	Mica Schist & Phyllite	> 40°	2.62
	Fine grained Sandstone (siltstone/mudstone)	20° - 30°	2.91
	Fine grained Sandstone (siltstone/mudstone)	30° - 40°	3.33
	Fine grained Sandstone (siltstone/mudstone)	> 40°	6.85

Figure 3.3 Development of the landslide susceptibility map using the two-fold scheme.

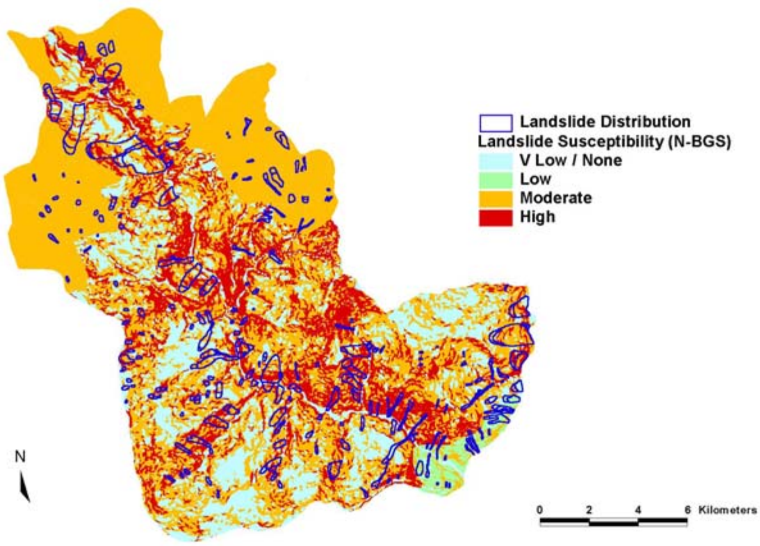
Geology Map – Sunkosh Daga Bhutan, derived from desk study, detailed API with field verification



Slope Angle Map – Sunkosh Daga Bhutan, derived from a 3-D model (digital elevation model) of the ground surface taken from the topographic maps



Susceptibility Map – Sunkosh Daga Bhutan, Combining the geology map with the slope angle distribution

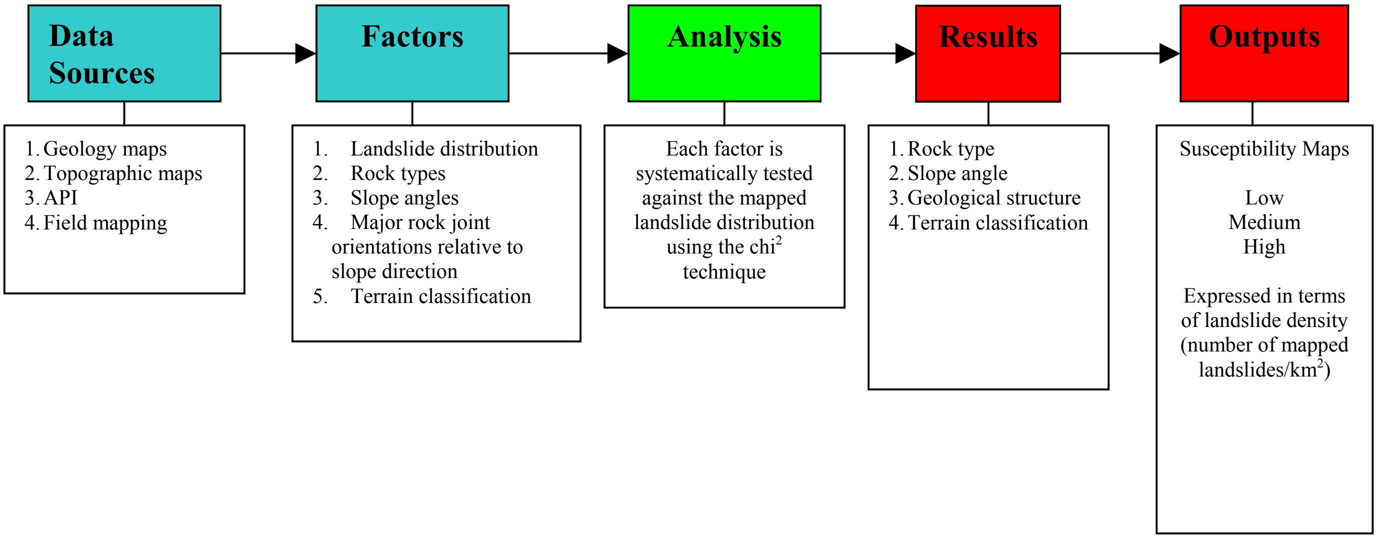


3.3.6 Applying the four-fold scheme

3.3.6.1 The technique (Figure 3.4) is based on the combined use of terrain evaluation, primarily to map the location of slope materials, the analysis of geological structure and the analysis of rock type and slope angle relationships.

3.3.6.2

Figure 3.4 Guide to the applications of the four-fold scheme



3.3.6.3 The steps below summarise the procedure:

Step 1: The project area is subdivided into its constituent rock types and these are shown on a topographic map (preferable scale 1:25 000). This must be verified through field observation.

Step 2: A slope angle map is derived from contour data. A four-fold scheme (0-20°, 21-30°, 31-40°, greater than 40°) is suggested.

Step 3: Aerial photographs are used to determine the dominant rock structural orientations. These are combined with any published geological mapping data to derive groupings of dominant joint set orientations.

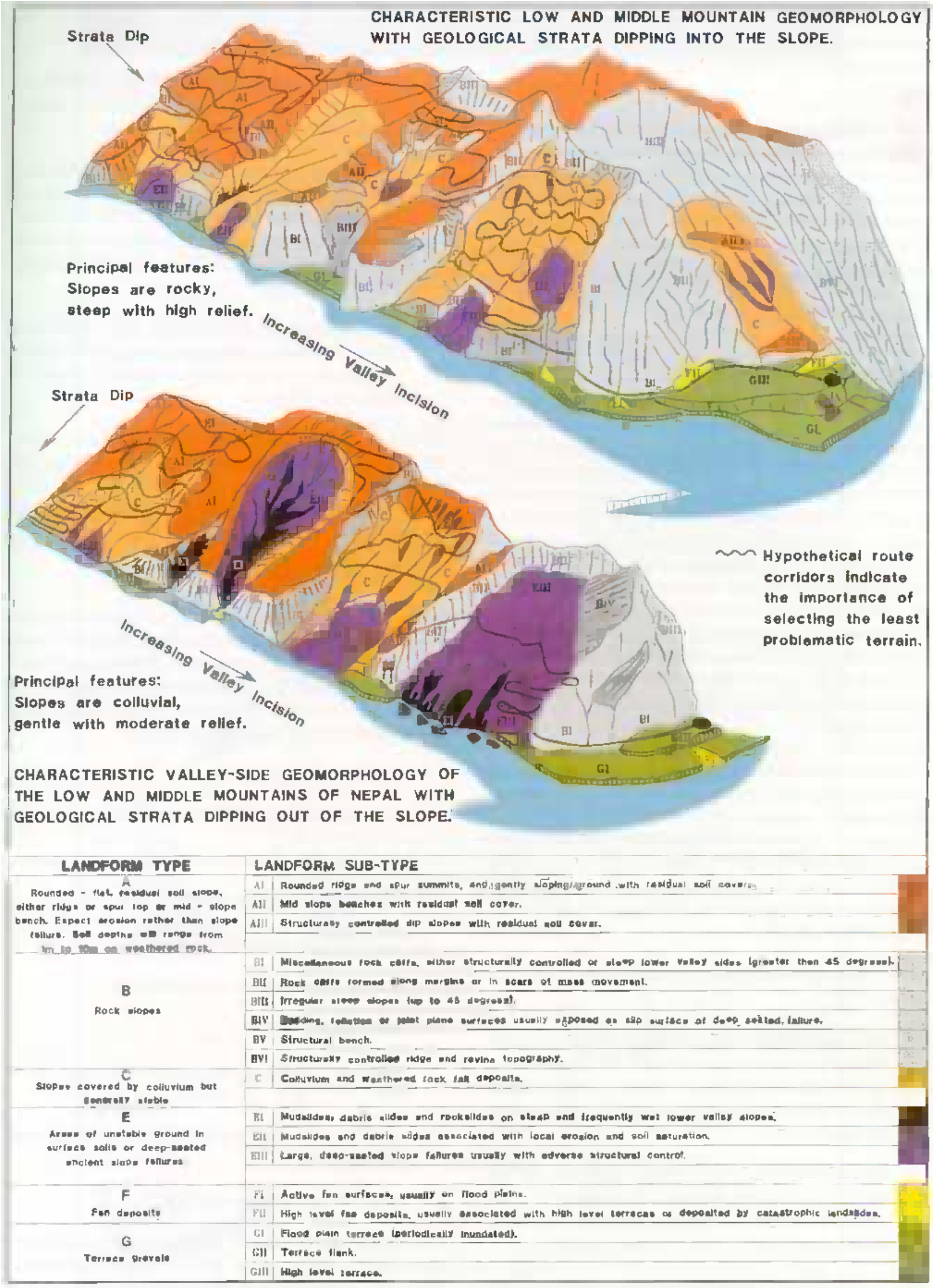
Step 4: The direction that each individual slope faces is determined from the digital contour data. The aspect of each slope is compared against the dominant joint set orientations to identify the slopes that might be prone to movement along these joint sets.

Step 5: Aerial photographs are used to subdivide the project area on the basis of terrain type. Figure 3.5 illustrates the range of terrain types that might be considered. However, the LRA project has shown that such a classification is too complex for landslide susceptibility mapping purposes, and consequently a three-fold scheme, based simply on i) colluvium ii) in situ soil and iii) rock-dominated terrain, is suggested.

Step 6: The rock-dominated terrain areas are then further subdivided according to their underlying rock type.

Step 7: The project area is subdivided into units based on rock type, slope angle, structural orientation – slope aspect and terrain type. The densities of mapped landslides derived from aerial photograph interpretation are then correlated against this subdivision to confirm the degree of confidence with which the resultant map can explain the distribution of landslides. This four-fold procedure has been proven to work satisfactorily using LRA project data and has performed well in an independent test case

Figure 3.5 Illustration of terrain classification from east Nepal



Taken from Overseas Road Note 16 (1997)

3.3.6.4 The steps described above are best undertaken using GIS-based data manipulation and analysis. The procedure can be applied manually, though it would prove considerably more time-consuming.

3.3.7 Sources of information

Geological mapping

3.3.7.1 Information on the geology of an area can be obtained in two ways. First, and most simply, it can be taken from geological maps, many of which are available from government mapping agencies. In most countries these are available at a scale of 1:500,000 or 1:1 million, although increasingly coverage at a larger scale is available. If only small scale maps are available, their accuracy and level of detail may be too small to provide anything other than a general overview of geological formations (age-classified groups of rock types) and the main geological structures (faults, anticlines and synclines). If this is all that is available then landslide susceptibility mapping based on either the two-fold or four-fold schemes may not be feasible. In this case there will be no choice but to resort to fieldwork to collect the primary data. Larger scale maps (preferably 1:50,000 in scale) can provide direct information about the rock types within an area, although sometimes these too only show geological formations, in which case an interpretation will be needed of the main rock types within each formation.

3.3.7.2 It is recommended that field verification is always carried out as it is frequent to find errors and inconsistencies across map boundaries.

Topographical and slope mapping

3.3.7.3 Slope angle data can be difficult to obtain, but the best source of information is topographical maps, which may be obtainable from the local or national survey department. Increasingly, topographical maps are available in digital form. If not then contours will have to be digitised if a GIS analysis is to be used. Care must be taken with the accuracy of such maps, both in terms of the location of features and especially with respect to contour data. Ideally, topographical mapping at 1:25,000 scale with a maximum contour interval of 20m should be used. Smaller scale and greater contour interval mapping can be used but the accuracy and reliability of any landslide susceptibility mapping derived from it will need to be considered. If contour mapping cannot be used then recourse may have to be made to aerial photography and photogrammetry.

3.3.8 Determining the accuracy of the analysis

3.3.8.1 At the end of the analysis, a map is produced indicating the susceptibility to landsliding across the study area. The techniques described above are simple but have been shown in the LRA study at least, to be about 70% accurate based on the existing landslide distribution. In any area it is sensible to check the accuracy of the assessment by comparing it with the map of exiting landslides. How good has the susceptibility determination been at predicting where these landslides are? If there are significant areas in which the predictions appear to be inaccurate, what is the reason? Sometimes this may be due to factors that haven’t been considered (such as detailed geological structure and groundwater levels) or it may be the result of a problem with the input data. If this is the case, it might sometimes be possible to put the problems right. If so, then the scheme should be modified. It will be necessary to combine the susceptibility analysis with the landslide map, by considering all areas underlain by existing landslides to have a high susceptibility.

3.3.9 Uses of susceptibility maps

3.3.9.1 The production of a landslide susceptibility map alone might be sufficient to satisfy the requirements of the project. For example, in the initial planning of the best route for a rural access road, it may not be necessary to know the frequency of landslides, but just where they are most (or least) likely to occur. This is certainly supported by the feedback received during the course of the LRA project, and the uncertainties involved in the calculation of hazard and risk (see below) may not justify taking the analysis further anyway. So, once landslide susceptibility has been determined, the end-user should decide whether the data that they now have is good enough for their purposes. If it is not, then a landslide hazard assessment should be undertaken.

3.4 Landslide Hazard Assessment

3.4.1 Landslide frequency and probability

3.4.1.1 The landslide susceptibility assessment technique described above yields a density of landsliding that is likely to occur in a given area. This density can be used to provide an indication of the frequency of occurrence of landslides. The LRA project examined how long landslides remain visible in the landscape through the analysis of sequences of aerial photographs, from which landslides were mapped in terms of when they occurred and when they became invisible again because of erosion and revegetation. It was calculated that, on average, landslides remain visible for about 50 years. So, the landslide densities calculated from the susceptibility analysis equate approximately to the densities of landslides that would be expected to occur in each area over a 50 year period. This data can then be used to assess the probability of landslides occurring. Taking, for example, a density of 0.030 (i.e. 3% of the area is landslides for a particular rock type / slope angle combination), landslides might be expected to occur in 3%/50 of the area per year – i.e. 0.06% of the area. Thus, the probability of a landslide occurring at any particular point is 0.06% per year. This may appear surprisingly high, but if this rock type / slope angle combination covers 1 km^2, for example, a total of only 600 m^2 would be expected to become newly unstable each year, equivalent to one landslide with dimensions of 25m x 25m. From past experience, a frequency of this order would appear to be reasonable.

3.4.1.2 The use of the 50 year period is based on limited data and therefore it is recommended to refine the assessment for any given study area in the ways outlined below. In addition, this ‘landslide life’ value will vary greatly according to the environment (see below).

Refining the density classes

3.4.1.3 Based upon the landslides that have been identified from aerial photograph interpretation and field mapping, the true landslide density for each rock type / slope class combination in the study area can be determined. This can then be used to produce a better estimate of probability of occurrence based upon the return period of 50 years, or the equivalent value, described above.

Improving the occurrence statistics

3.4.1.4 A further improvement can be achieved by determining the average residence time for landslides in each study area. This is best done by examining several sets of differently dated aerial photographs. The landslides in each epoch of photographs should be mapped independently. This can then be used to identify when landslides occurred and how long it has taken for landslides to become invisible again. The average residence time can thus be estimated. This can then be used to improve the frequency calculation for the area concerned, as described above.

Combining local knowledge

3.4.1.5 Local people often have some knowledge of when landslides have occurred. The occurrence statistics can be further improved if local people, village records and district archives are consulted to determine more accurately when landslides have occurred, and also where landslides that have now stabilised are located. However, studies conducted during the LRA period revealed that the ability of local people to remember the year or even the decade during which particular landslides occurred reduces significantly with the passage of time. Historical dating in this way is perhaps only accurate within approximately ten years of occurrence unless written records exist.

3.4.2 Considering landslide triggers

3.4.2.1 In addition to the analysis of the historical occurrence of landslides, an investigation of the frequency of landslide trigger mechanisms can provide further information. In most cases three potential triggers can be identified. These are rainfall (which causes changes in ground water level and hence the stability of slopes), earthquake shaking (which can literally shake a slope to failure) and human activity (usually either through slope excavation and filling, irrigation or changing land use).

3.4.2.2 If rainfall is a major trigger of slope failure, then rainfall records should be a useful source of information about when landslides might occur. Usually, a threshold rainfall value is taken as a trigger in landslide initiation. This threshold may be expressed in terms of rainfall intensity (if intensity data is available) or in terms of 24 hour rainfall data. 24-hour rainfall data is usually the only information available in remote areas, and even then, records are often short or intermittent, and the density of rain gauges is often too low to be able to reflect the immense local variations in rainfall that usually characterises mountain areas. The LRA project has found that 200-250mm/day of rain is a common threshold for widespread landslide initiation, but this figure will vary from region to region and is itself inexact given the complexity of landslide initiation. Several attempts have been made to analyse rainfall/landslide relationships using data derived from Nepal and Bhutan but no consistent conclusions have been drawn beyond the generalised threshold given above.

3.4.2.3 An alternative approach is to examine the rainfall records in the context of known landslides in the area. If dates can be placed on the landslides observed during field mapping, then the rainfall records can be examined to try to determine what the rainfall conditions were at that time. The full dataset can then be used to find out how frequently those conditions recur or are exceeded. Dates for the landslides might be obtained from some or all of the following:

a) local knowledge, both at administrative level and from local people;
b) local and national newspapers;
c) government statistics (for example, in Nepal the Ministry of Home Affairs compiles records of flood and landslide-related disasters);
d) academic papers and research reports.

3.4.2.4 These data sources might help to determine the triggering events that lead to landslides, but care should be taken in the interpretation of the data. Data analysis undertaken during the LRA project proved inconclusive in most cases.

3.4.2.5 Earthquakes might also be a significant factor. Earthquake data is available with a global coverage for no cost via the United States Geological Survey at the following web site: http://neic.usgs.gov/neis/epic/epic.html. This database lists every detected earthquake since 1973 worldwide. The database has also been extended to include all known earthquakes since 2150 BC. The user can download data in spreadsheet or map format for any given area of the earth's surface. If possible this data should be supplemented by local seismic records, which will provide a better resolution of local, small events. Finally, to allow a good interpretation of the data, reference should be made to the Global Seismic Hazard Assessment Programme (GSHAP) at http://seismo.ethz.ch/gshap/homepage.html. Probabilities of the occurrence of seismic intensities are given for the entire world.

3.4.2.6 A large earthquake would probably have a devastating effect on any road alignment, and consequently any risk assessment that did not account for earthquake hazard would be less than representative. In reality, it is very difficult to take seismic triggering of landslides into consideration because the earthquake database is too short and our understanding of the ways in which earthquakes trigger landslides is too poor. Where there is limited information it is virtually impossible to work out the frequency of occurrence of these events, and this represents a significant limitation in the risk analysis. Consequently, it is normal to accept that seismic hazard cannot be realistically allowed for in landslide susceptibility and hazard mapping. It must be remembered though that, in so-doing, the earthquake hazard in any study area is being ignored.

3.4.2.7 Having looked at the occurrence of the triggers, the estimate of return period for landslides can often be improved. If it can be shown, for example, that landslides occur when the precipitation exceeds 200 mm in a one, two or three day period, then rainfall record can be used to determine how often this occurs and so estimate the return period of landslide activity. This can then be factored into the frequency calculation. In reality, however, it is difficult to find such simple relationships in most cases.

3.4.3 Landslide area

3.4.3.1 The second issue that must be addressed in the compilation of a hazard map is that of the area affected. First, the surface area that will become unstable in the initiation of a landslide should be considered. Second, the area that is likely to be engulfed by that landslide – i.e. the runout area – needs to be determined. Unfortunately neither are easy to assess with any certainty without detailed field investigation.

3.4.3.2 It is likely that once failure has been triggered the landslide mass itself will include an area upslope, an area downslope and an area to each side as well. Thus, although an area upslope might have a lower susceptibility rating, a failure triggered from downslope might still cause movement at this point as a result of unloading and progressive failure. The landslide will also move down the slope, covering an area, part of which may have a lower susceptibility rating. If this area is likely to be affected by a landslide from upslope then the hazard rating should reflect this.

3.4.3.3 The following sections provide detail of how to deal with these problems to provide an estimate of the area to be affected by a landslide.

3.4.4 Landslide runout

3.4.4.1 From an analysis of the landslides mapped as part of the LRA study, it was apparent that several factors influence the mobility (travel distance) of a landslide, by controlling the processes that operate during the landslide.

3.4.4.2 The following three factors appeared to have the most influence on the mobility of landslide debris:

1. the failure mechanism of the landslide;

2. the source volume (the initial failure volume) of the landslide;
3. the topography or the flow path of the landslide.

3.4.4.3 Figure 3.6 illustrates the relationship between landslide runout distance and failure volume. This graph is derived from one of the LRA study areas in Nepal and shows the general trend between increasing failure volume and horizontal travel distance of the debris. Debris slides, rock falls and rock slides show similar relationships between failure volume and travel distance, while landslides that become channelised into concentrated debris flows show a much greater scatter in this relationship. As would be expected, however, channelised debris flows travel a greater distances than other landslide mechanisms with the same volume.

3.4.4.4 Other graphical relationships derived by combining data from more than one study area reveal even more scatter than is shown in Figure 3.6. When trying to use graphs to estimate landlslide runout, two major limitations must be borne in mind:

a) there is considerable scatter in the data, reducing the confidence and accuracy of estimates;
b) it is usually the case that the mechanism and volume of failure cannot be predicted, especially when recourse to field investigation is not possible.

3.4.4.5 Therefore, the production of hazard maps for district planning and for the identification of route corridors at the feasibility stage of a road project, requires a more simple and pragmatic approach. The approach adopted by the LRA project has comprised the following steps:

Step 1: The downslope boundary of each high and moderate landslide susceptibility area is assumed to be the source of a potential landslide.

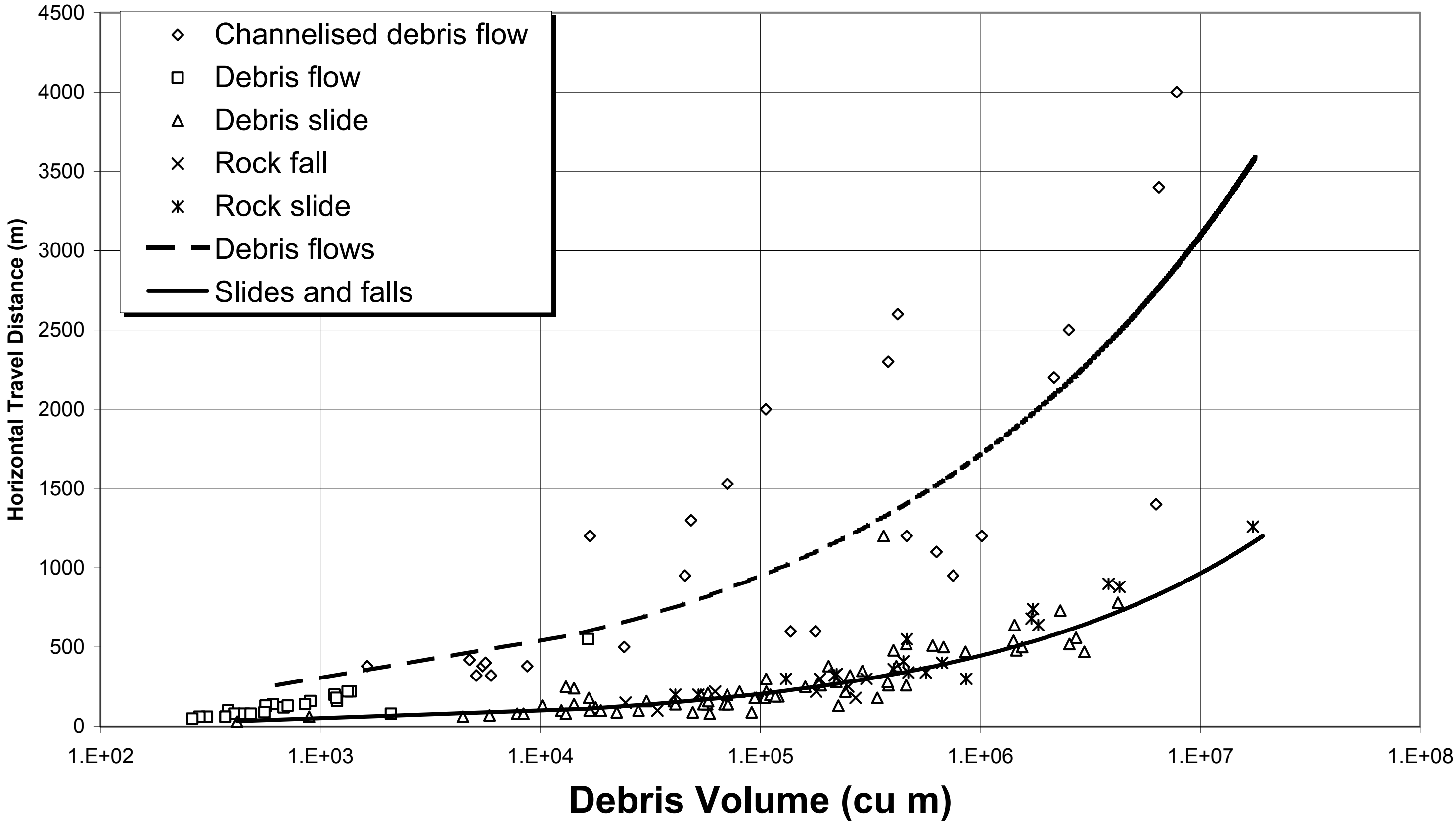
Step 2: A runout path is plotted downslope from this boundary to the point where the underlying slope decreases to 20° or less.

Step 3: A potential landslide is assumed to come to rest 50m beyond the 20°slope as its momentum dissipates. If the slope steepens to more than 20° again before the 50m is reached, then runout is assumed to continue.

Step 4: If the landslide runout path intercepts a drainage line, it is assumed that it will travel down that drainage line to the confluence with a main channel.

3.4.4.6 This method is based entirely on assumption and is likely to significantly overestimate runout distance in the majority of cases. It also requires very time consuming manual plotting of runout paths on topographical maps.

Figure 3.6 Landslide Travel Distance



3.4.5 Final hazard map

3.4.5.1 Figure 3.7 illustrates the susceptibility hazard and risk maps produced for part of one of the LRA project study areas. The effect of landslide runout means that much larger areas of the map are shown as high hazard than are shown as high susceptibility on the susceptibility map. Existing infrastructure is also shown on these maps. It is interesting to note that, while much of this infrastructure is sensibly located with respect to high landslide susceptibility areas, larger portions of it are potentially at risk from landslide runout; a fact that is probably frequently overlooked by planners and engineers.

3.4.5.2 The accuracy of the final hazard map will depend upon the quality of the information used as an input, in particular in relation to the geology and the slope angles. Clearly, improved information will lead to a better hazard assessment. The other main source of potential error is in the assessment of landslide frequency or probability. For the sake of practicality, and given the lack of data to adopt an alternative approach, the LRA project has assumed the following:

- 1.0 probability of slope failure in all high susceptibility areas during a 25 year period
- 0.5 probability of slope failure in all moderate susceptibility areas during a 25 year period
- 0.25 probability of slope failure in all low susceptibility areas during a 25 year period

Twenty five years is equivalent to the nominal design life of a low cost rural road.

3.5 Landslide Risk Assessment

3.5.1 Having established that a landslide will affect a given area or structure in a given time with a given probability, then the economic and social losses that will take place are a function of the probability of the landslide occurring, the value of the resources or investment at risk and their vulnerability to complete destruction (loss) by the landslide.

3.5.1 Vulnerability

3.5.1.1 The vulnerability of a road, structure, land use or person to landslide damage will vary according to the landslide mechanism, speed of landslide movement, depth of movement and the degree of early warning. Also the type of element (e.g. house, road, field etc) at risk will determine the potential for complete economic loss. A cultivated field might quickly be restored following landslide movement, while a road may have to be completely reconstructed along the length affected. The risk map produced in Figure 3.7 has assumed 100% vulnerability (total loss). This may seem overly pessimistic but there is no data to hand to suggest otherwise. Vulnerability is usually discussed in terms of human vulnerability and the fact that certain groups of society are more vulnerable to the effects of landslides than others. This is because they are forced to live in high hazard areas and have little means of escape or protection when landslides occur. Vulnerability is discussed further in Chapter 4 with respect to community vulnerability to landslides.

3.5.2 Risk mapping

3.5.2.1 Figure 3.7 shows the final risk map produced for the illustrated study area. The vulnerability has been assumed to be 100%, i.e. total loss will occur and therefore the map shows the economic loss calculated to occur per km² per year. This is based on landslide runout from high and moderate susceptibility areas, the assumed probabilities described in paragraph 3.4.5.2 and the calculated and summed economic values of land use and infrastructure affected. It is clear that, due to lack of data, there are many assumptions made in the derivation of this map and it is therefore recommended that such maps are not produced until the data is available to justify them. Furthermore, these maps have little practical value over and above susceptibility maps in the planning of rural access corridors.

3.6 Conclusions and Future Developments

3.6.1 A wide range of landslide susceptibility mapping techniques has been developed in various parts of the world. Many techniques are based on the summation of as much as ten different factors. However, few analyse relationships between each factor and the actual distribution of landslides, and fewer still test the output maps against this distribution. The reliability of many of these schemes that are based on supposition and arbitrarily applied weighting systems must, therefore, be open to question.

3.6.2 On the other hand, those schemes that are based on field data collection and intensive analysis of actual slope conditions, including geology and geological structure, groundwater, soil types and soil profiles, are likely to be much more successful. However, the fact that they are based primarily on field-derived data means that their potential application to rapid landslide assessment over large areas is low.

3.6.3 The LRA project has systematically tested relationships between mapped landslide distributions and a range of geological, terrain and land use factors in order to derive a technique that is reasonably robust and reliable and applicable at desk study stage over large areas. The combination of rock type and slope angle correlated against landslide density provides a reliable indication of landslide susceptibility in all six of the Nepal/Bhutan study areas. None of the other factors mapped and analysed provided any consistent relationships with mapped landslide distributions. The two-fold scheme (rock type and slope angle) also worked well when applied to two other test areas in Nepal and also correlated well with the locations of new landslides that were triggered during the course of the study.

3.6.4 Aerial photograph interpretation allows two further factors to be included in the analysis: dominant rock joint orientations and terrain classification. This four-fold scheme requires specialist interpretation but the skills can be learnt reasonably quickly.

3.6.5 The four-fold scheme provides greater resolution in the differentiation of landslide density and therefore provides a more accurate technique for assessing individual route corridors. It is therefore recommended that road departments and planning authorities apply the two-fold scheme for landslide susceptibility mapping over large areas, as would be the case for route corridor identification and comparison, and the four fold scheme for the assessment of selected route corridors to assist in alignment design. Both schemes should be supported by field validation, with standard engineering geological and geotechnical assessment techniques used to develop the design as the project progresses (see Chapter 5).

3.6.6 Both the two-fold and four-fold schemes would be significantly improved if groundwater conditions could be included in the analysis. While remote sensing can provide some indications (see Chapter 2), without detailed field mapping the assessment of groundwater conditions is a matter of conjecture if undertaken from desk study. This is an important area where future research could be directed, given that non-seismically triggered landslides are essentially controlled by three factors: material strength, slope angle and water condition.

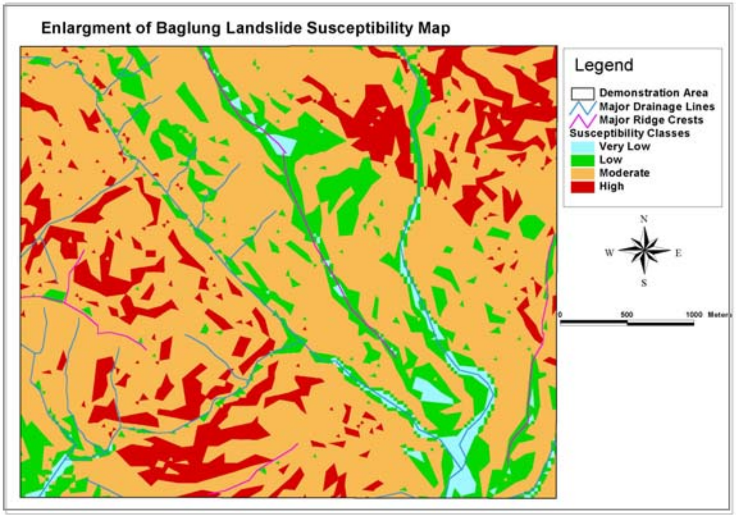
3.6.7 The LRA project has developed a prototype landslide risk map for part of one of the study areas. This map depicts the economic loss likely to occur as a result of landslides per km^2 per year. The map is based on the valuation of existing land uses and structures and is of some potential benefit to district planners. However, an engineer planning a road already knows the value of his or her structure and is only really interested in the location of existing landslides, the susceptibility of slopes to future landslides and the magnitude, frequency and depth of slope movements when they do occur. Therefore, from an engineering perspective, there seems little point in going through the process of producing a landslide risk map, especially considering the major assumptions that have to be made in its production. It is recommended therefore that government agencies make efforts to collect landslide event data in order to provide a database against which future landslide frequency can be better evaluated. In the meantime, and in any case, planners and road engineers can use the techniques described in Chapters 4 and 5 to evaluate and manage landslide risk in their planning and project areas.

Figure 3.7 Example of the Development of Susceptibility Hazard and Risk Maps for the Baglung Area Nepal

Susceptibility Map

A landslide susceptibility map provides an indication of the areas that are most prone to landslides.

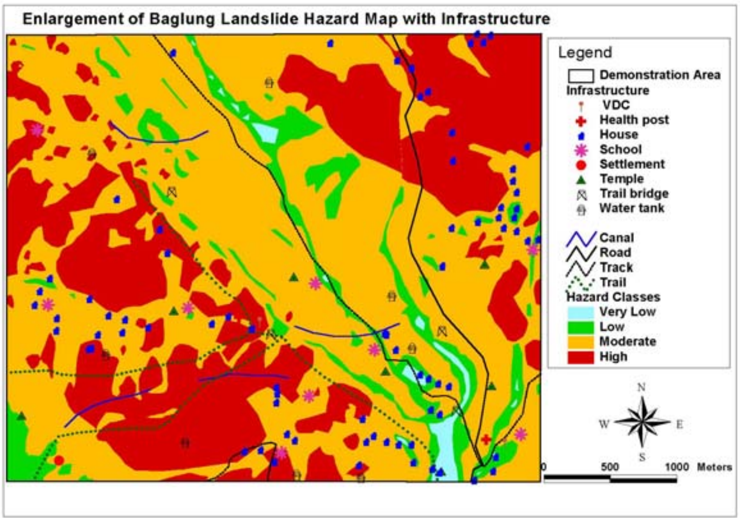
The one shown here is based on the two-fold analysis method, incorporating slope angle and rock type.



Hazard Map

Landslide hazard maps combine the susceptibility analysis with an assessment of landslide frequency (probability of landslide occurrence) and the area affected by any potential landslide (landslide runout)

The adjacent hazard map has been combined with an infrastructure map (location of settlements, schools etc)

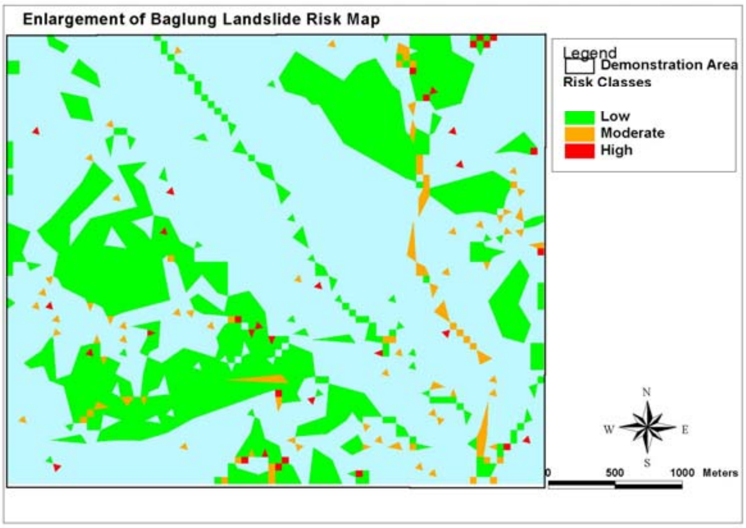


Risk Map

A landslide risk map provides indication of the level of economic risk that is posed by potential landslides. It is based upon the overlay of the landslide hazard map and the economic value asset map combined with an assessment of vulnerability. Risk is expressed in terms of potential economic loss per km²/yr.

The adjacent map is also of the Baglung area of Nepal. The risk classes are based on economic values established from the LRA study.

Low = < US$ 229 loss / km² / yr
Moderate = US$ 229 to 687 loss/ km² / yr
High > US$687 loss / km² / yr



Landslide Risk Assessment in the Rural Access Sector

Guidelines on Best Practice

CHAPTER 4

LAND USE PLANNING AND MANAGEMENT IN RURAL ACCESS CORRIDORS

4.1 Introduction

4.1.1 This chapter examines the planning and land management issues associated with landslide hazards in rural access corridors.

4.1.2 If the risk posed by landslides to rural livelihoods and investment in infrastructure is to be reduced, planners must embark on a programme of risk assessment and risk management from an early stage. In many cases the only assessment of landslide susceptibility, hazard and risk that takes place in rural areas occurs during the design of high-investment projects that pass through them, such as highways, water supply pipelines and electricity transmission systems. Even then, the hazard assessments are often incomplete and large proportions of rural areas tend not to be assessed at all in terms of landslide potential, unless as a reactive measure after landslide losses have occurred, i.e. when it is too late.

4.1.3 Section 4.2 of this chapter examines the interaction between landslides and land use. The ways in which landslides can be recognised by the non-specialist are described, and approaches for the management of landslides in order to minimise their impact on the community within the rural access corridor are discussed. Sections 4.3 and 4.4 examine the interaction between land use, engineering and slope instability within and alongside rural roads.

4.2 Landslides in the Rural Access Corridor

4.2.1 Landslide types and their recognition on the ground

4.2.1.1 For the purposes of land use planning and land management, it is convenient to subdivide landslides into the following categories:

a) existing landslides that are stable under present slope conditions;
b) existing landslides that undergo intermittent or constant movement;
c) potential landslides that will occur as ‘first time’ failures, ie on slopes in virgin ground that will undergo landsliding at some time in the future.

4.2.1.2 Appendix 1 lists and illustrates some of the more common indicators of landslide movement. Differentiation is made between indicators of active and relict movements, colluvium vulnerable to movement, potential first-time failures and debris flows (see below).

a) Stable landslide masses

4.2.1.3 In many areas, landslides that have moved in the past have now become stable. This might be because debris has moved onto a slope with sufficiently low gradient that movement cannot occur (Figure 4.1). Such landslides are usually identified using the following:

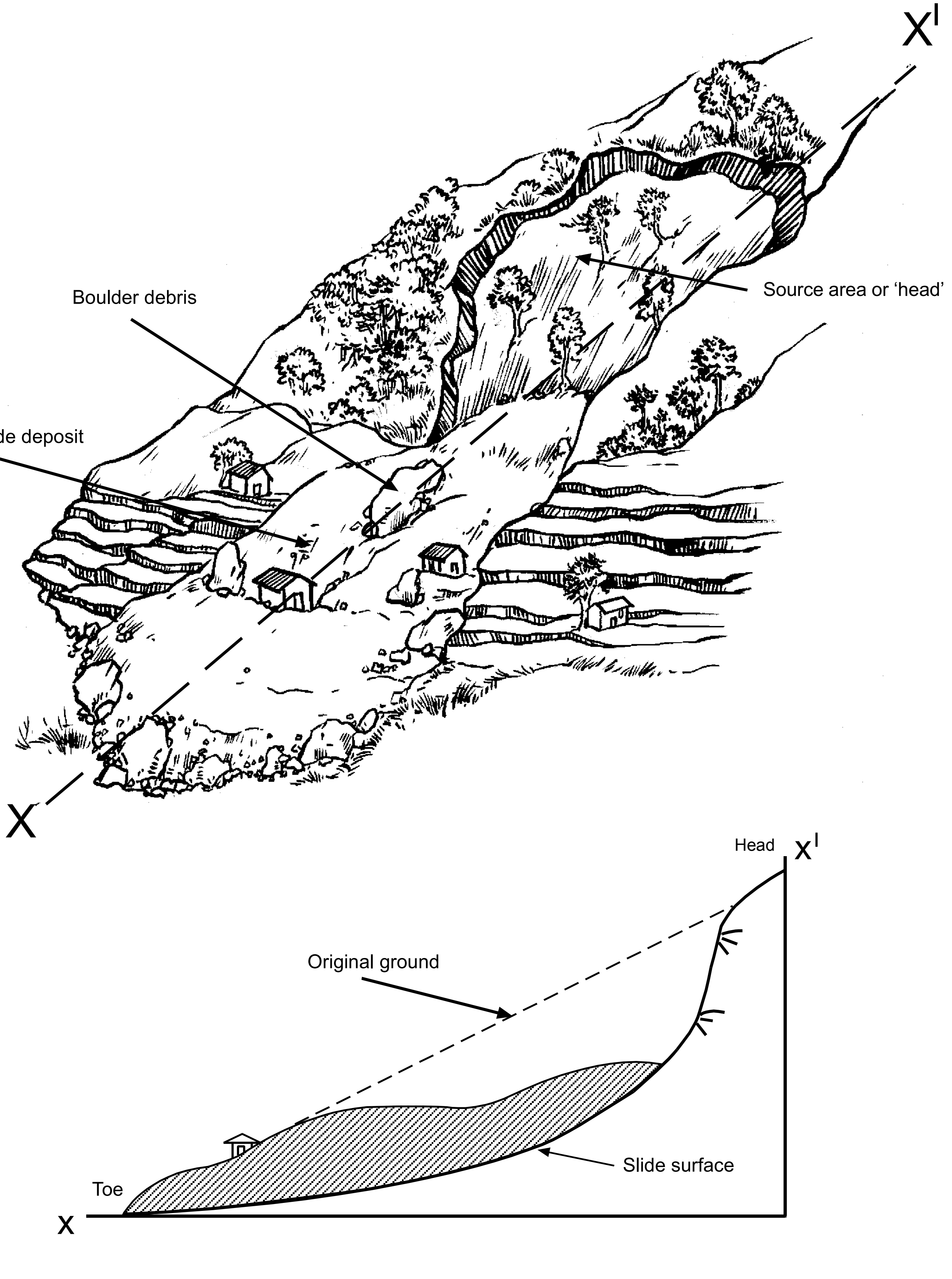
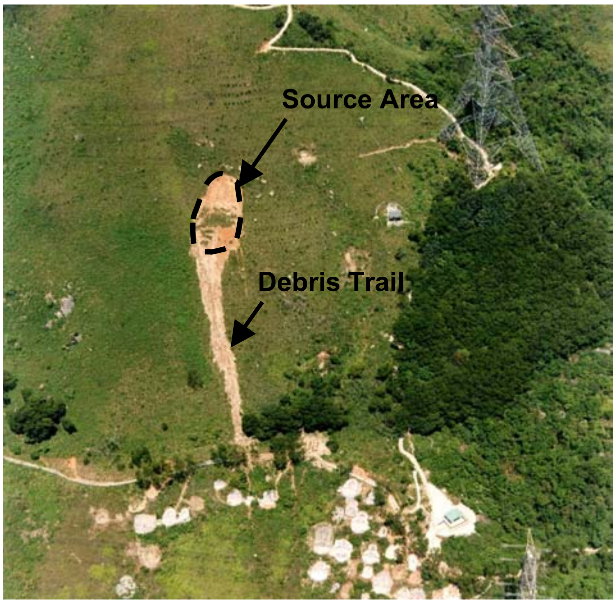


Figure 4.1 Sketch of old landslide mass now stable due to significant reduction in slope angle upon initial failure

a) their morphology or shape;
b) their materials;
c) historical record of past movement.

Morphology

4.2.1.4 Landslide masses often form spoon-shaped landforms with steep upper slopes, representing the source area of the failure, and gentle lower slopes that form the depositional area. Slopes are often irregular and drainage is disturbed. A lack of established streams can also indicate the presence of a landslide.



A landslide scar typically comprises a source area (the location of the initial failure) and a debris trail (the area of ground covered by the failed material)

The length of a landslide debris trail is often referred to as the runout distance

NB: Electricity pylon top right hand corner for scale.

Materials

4.2.1.5 Landslide materials are usually characterised by unsorted or chaotic deposits of granular materials, often containing boulders and blocks of rock.

4.2.1.6 If it is suspected from the above that a slope could have been formed or affected by previous landsliding, and either rural communities or infrastructure (existing or planned) are potentially at risk from it, then the following actions should be taken (Figure 4.2):

a) consult with local people to determine if they are aware of any ground movements;
b) examine the suspect slope to determine if there are any signs of distress, such as ground cracking;
c) identify any seepages or areas of water-logged ground that could become unstable;
d) evacuate, monitor or investigate, as required.

4.2.1.7 If these enquiries indicate that slope failure is imminent then the slope must be evacuated and specialist geological or geotechnical advice sought. Even if there are no signs of reactivated movements in ancient landslide deposits it must be remembered that movements can be reactivated by:

a) gully erosion at the toe;

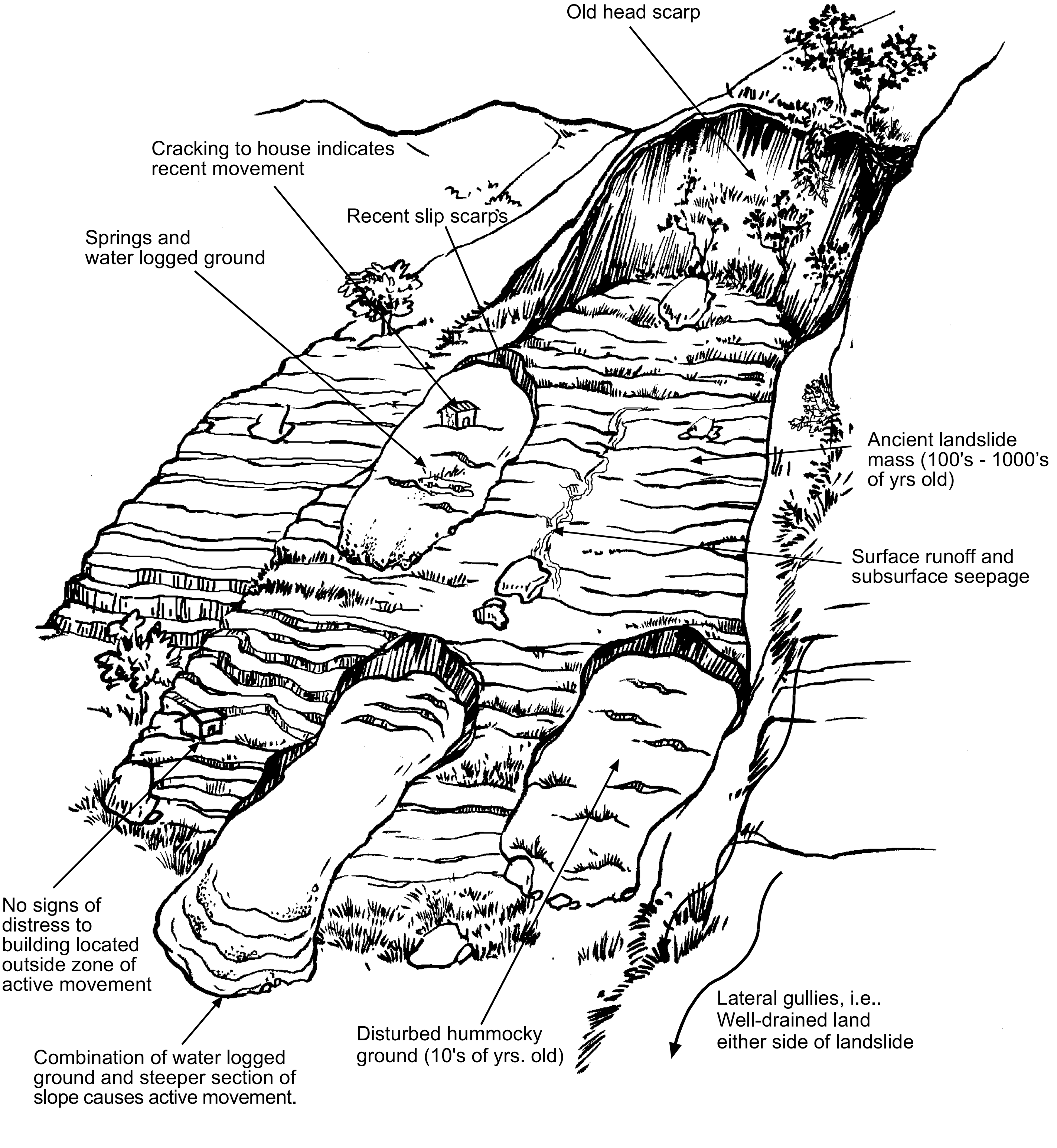
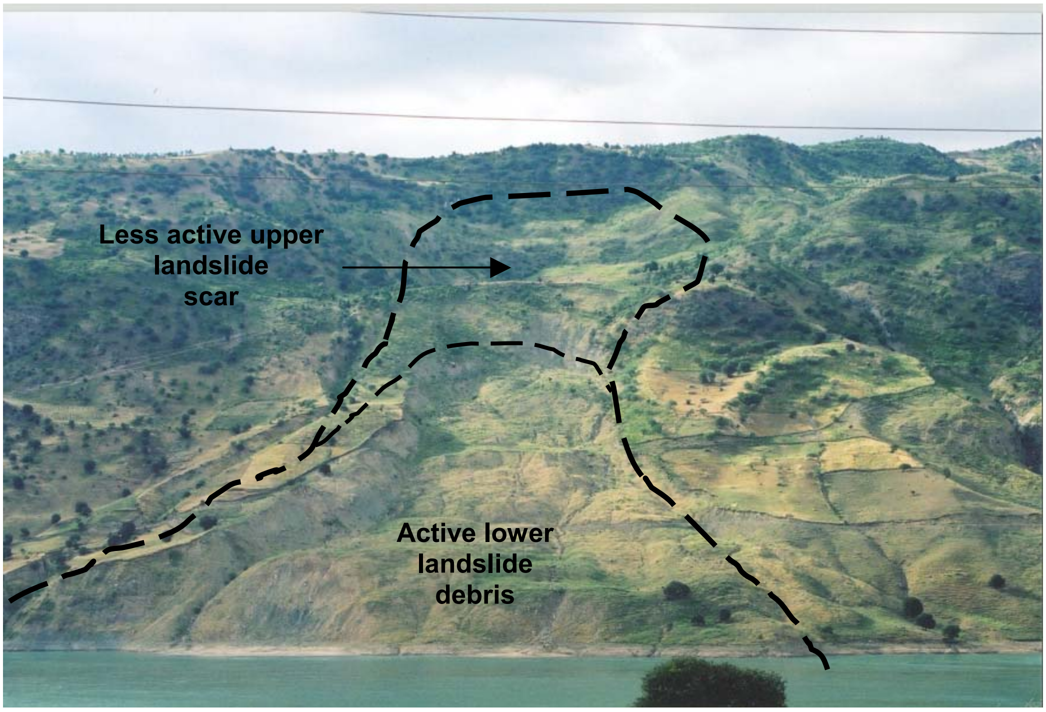


Figure 4.3 Indicators of landslide activity

b) import of water to a slope by irrigation;
c) excavations for roads and other infrastructure;
d) extreme rainfall and earthquakes.

b) Slow moving landslide masses

4.2.1.8 Figure 4.3 illustrates some of the evidence for slow and intermittent landslide movement. These movements often take place in pre-existing landslide material. They frequently have a history of slope movement spanning several generations. Often farmers and village communities continue to occupy land that is undergoing gradual movement. The recommendation would always be to evacuate such areas so that permanent accommodation can be sought in more stable locations. However, many communities prefer to remain where they are because their family tradition has been established there. Furthermore, there may be little alternative land available to move to. It can often be extremely difficult to move people at risk from landslide areas unless movements are so rapid (nominally greater than 1m per year) that continued occupation is impracticable. Figure 4.4 shows a flow chart of decision-making and action that might be adopted in these situations, though it is important to bear in mind that each case will be different, and the decision to evacuate a particular slope should be based upon a thorough risk assessment.



Large deep-seated slow moving landslide. The dashed outline shows the extent of the landslide scar. Most of the lower portion of the landslide is still active and human occupation and cultivation are impractical. Most of the upper scar is older and less active and cultivation is on-going.

4.2.1.9 Assessing the level of risk posed by a slow moving landslide can sometimes be difficult. Extreme rainfall or an earthquake could eventually trigger rapid movement leading to potential loss of life. Indicators to look out for in assessing the level of risk posed by such slopes include the following:

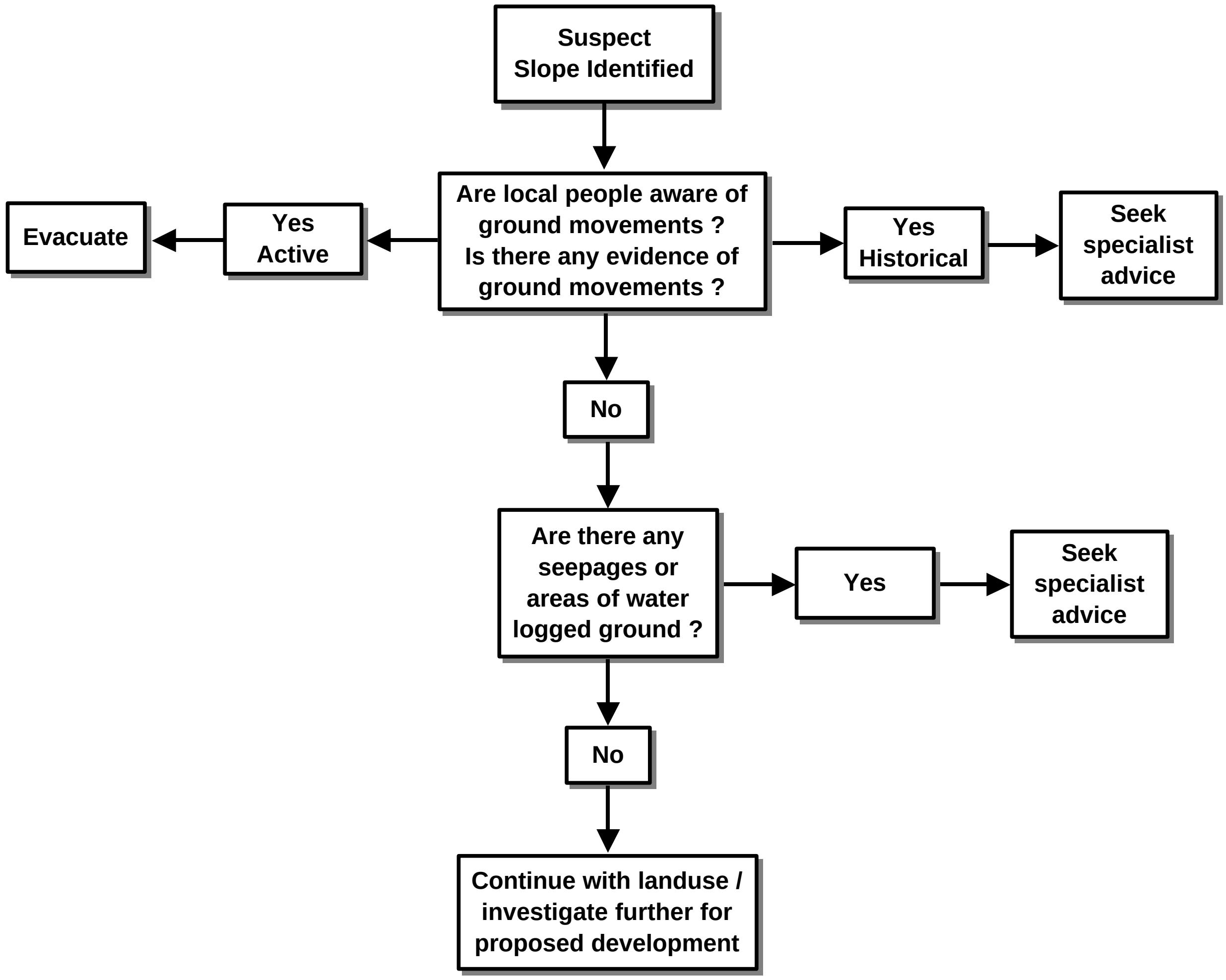


Figure 4.2 Investigative flow chart for old landslides

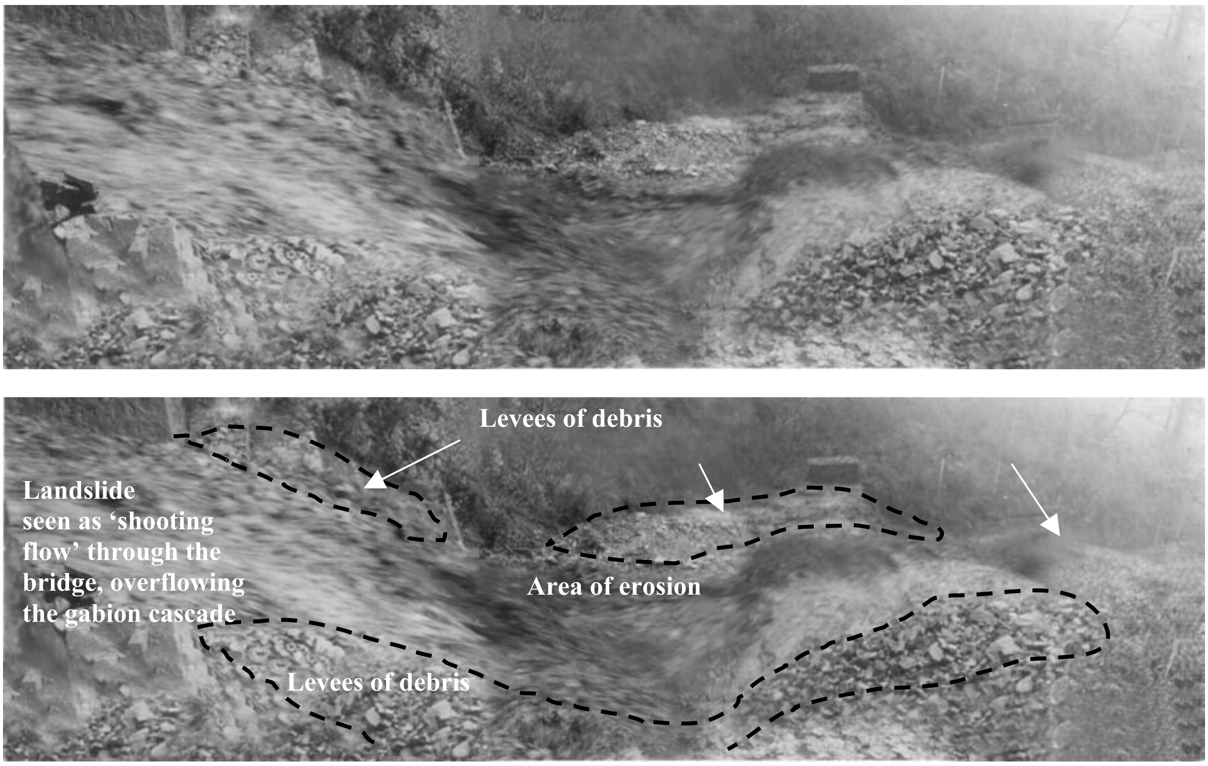
a) the outline of a landslide in plan has a head, a toe and side margins. If the extent of active cracking is continuous around this outline then rapid movement might be imminent;
b) if there is no topographic or geological barrier to movement, i.e. if the slope is free to fail downslope, then rapid movement might be expected. In some cases, ground movements can be seen to be 'ramping up' against a resistant rock outcrop or a high point in the topography of the slope, thus restricting the rate of movement;
c) the shape of the slope can sometimes give an indication of the potential for rapid movement. If the slope steepens towards the toe then it may be more prone to rapid movement than a slope that becomes more gentle in the downslope direction;
d) if the topography of the ground upslope of the landslide is such that it tends to concentrate drainage into the landslide area itself, then this may lead to rapid movements;
e) if the slope is located adjacent to a sizeable drainage line, erosion of the toe during flooding could lead to sudden loss of support and rapid failure.

c) First-time failures

4.2.1.10 First-time failures are landslides that have failed for the first time, i.e. they are not reactivations of older movements. First-time failures usually occur in rock or residual soil for the following reasons:

a) toe erosion by streams or rivers removes support to the slope above;
b) prolonged heavy rain leads to a rise in groundwater that triggers deep failure;
c) intense rainstorms lead to saturation of surface soils triggering shallow failure;
d) an earthquake places increased stresses on a slope;
e) progressive weathering of rock and soil reduces strength and induces failure;
f) land use and engineering practices can induce failure either through cutting, filling or drainage disturbance.

Typical debris flow in Nepal



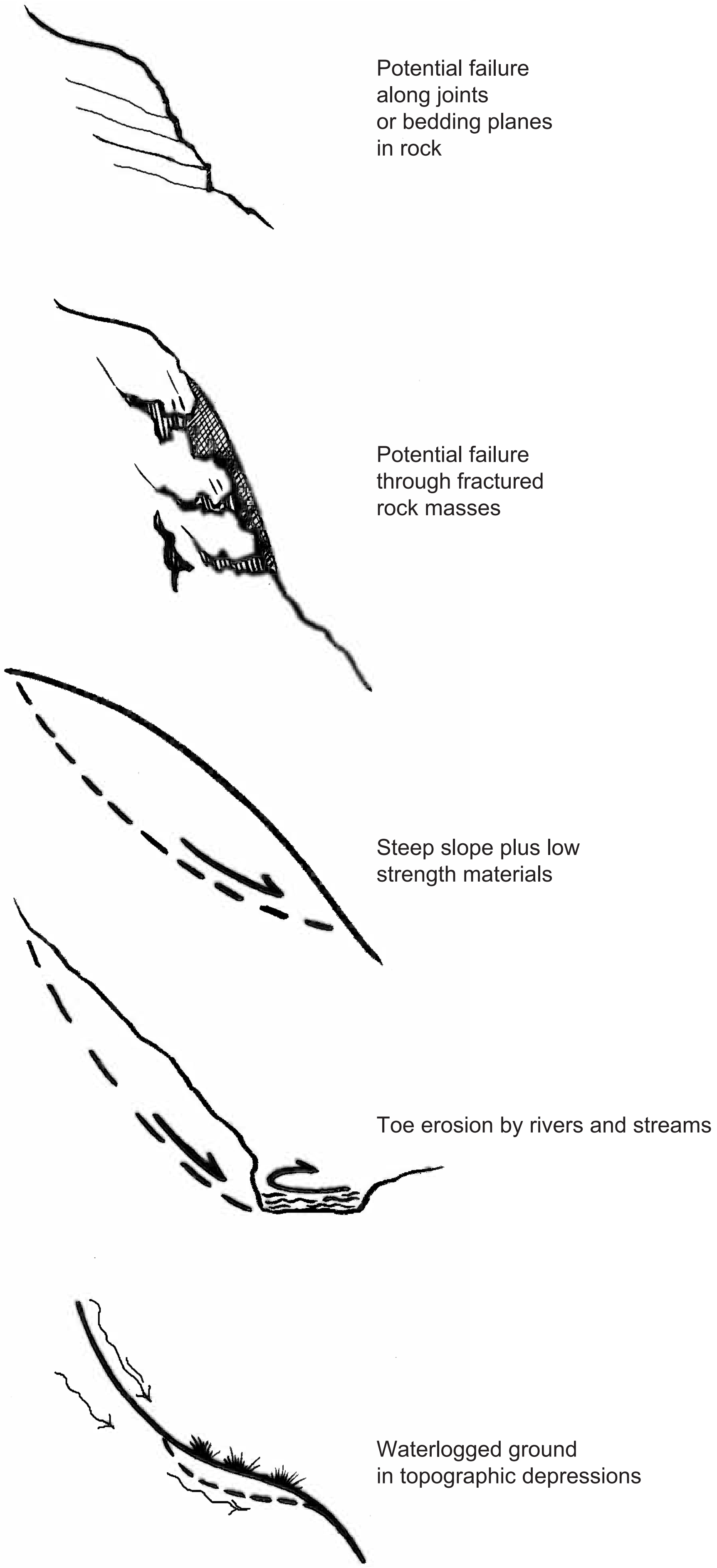
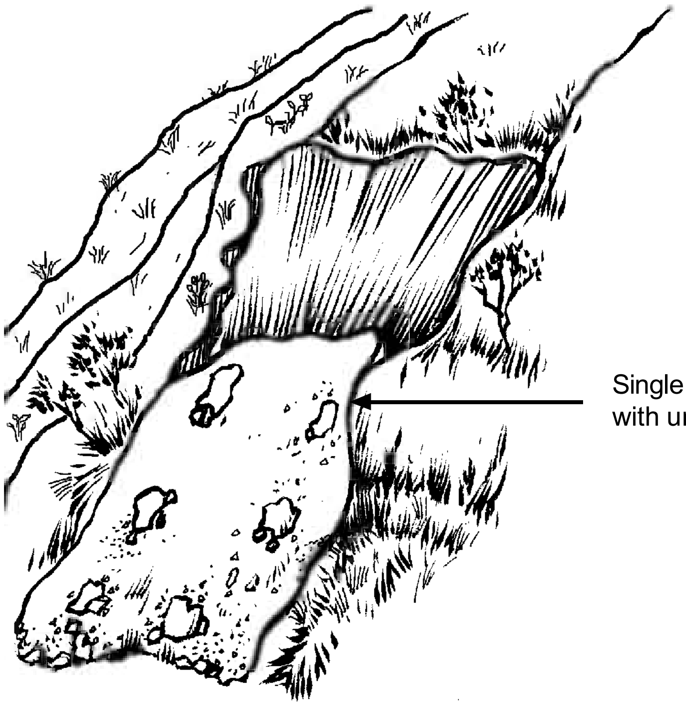


Figure 4.5 Typical ground conditions that encourage first-time failure.

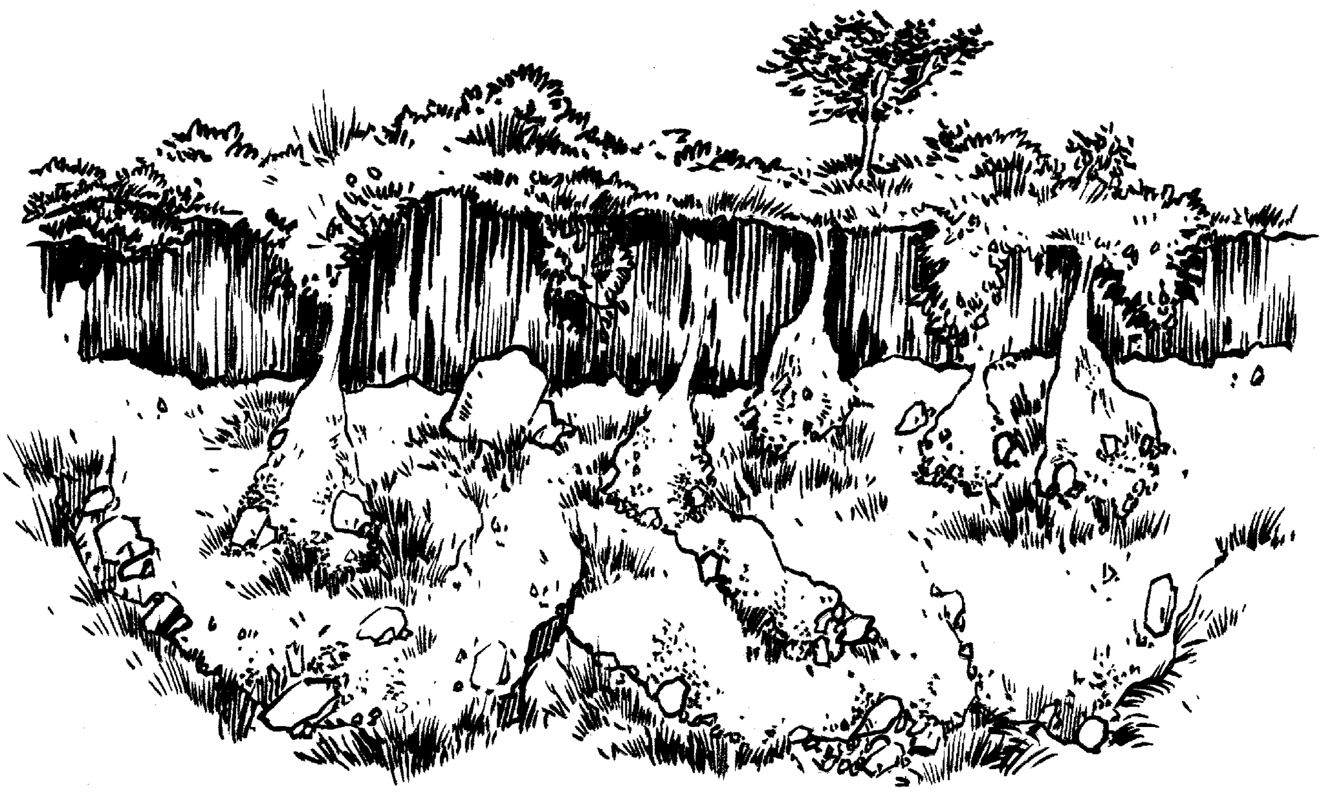
Figure 4.6 Landslide and undifferentiated colluvium

Landslide colluvium



Single - sourced landslide colluvium with underlying failure surface

Undifferentiated colluvium



Multi-sourced and undifferentiated colluvium derived from multiple landslides and rockfalls with no underlying failure surface

4.2.1.11 First-time failures probably pose the greatest potential risk to communities and infrastructure as they usually occur totally unexpectedly and without warning. They also tend to move much more quickly and over greater distances than reactivated failures. In the extreme (and not infrequent) case, first-time failures can become debris flows downslope, especially when they enter drainage channels. Debris flows move at a rate of metres per second and usually cause the highest fatalities among unsuspecting communities in mountain regions.

4.2.1.12 Identifying locations where first-time failures might occur is a difficult task. However the following indicators may prove relevant (Figure 4.5):

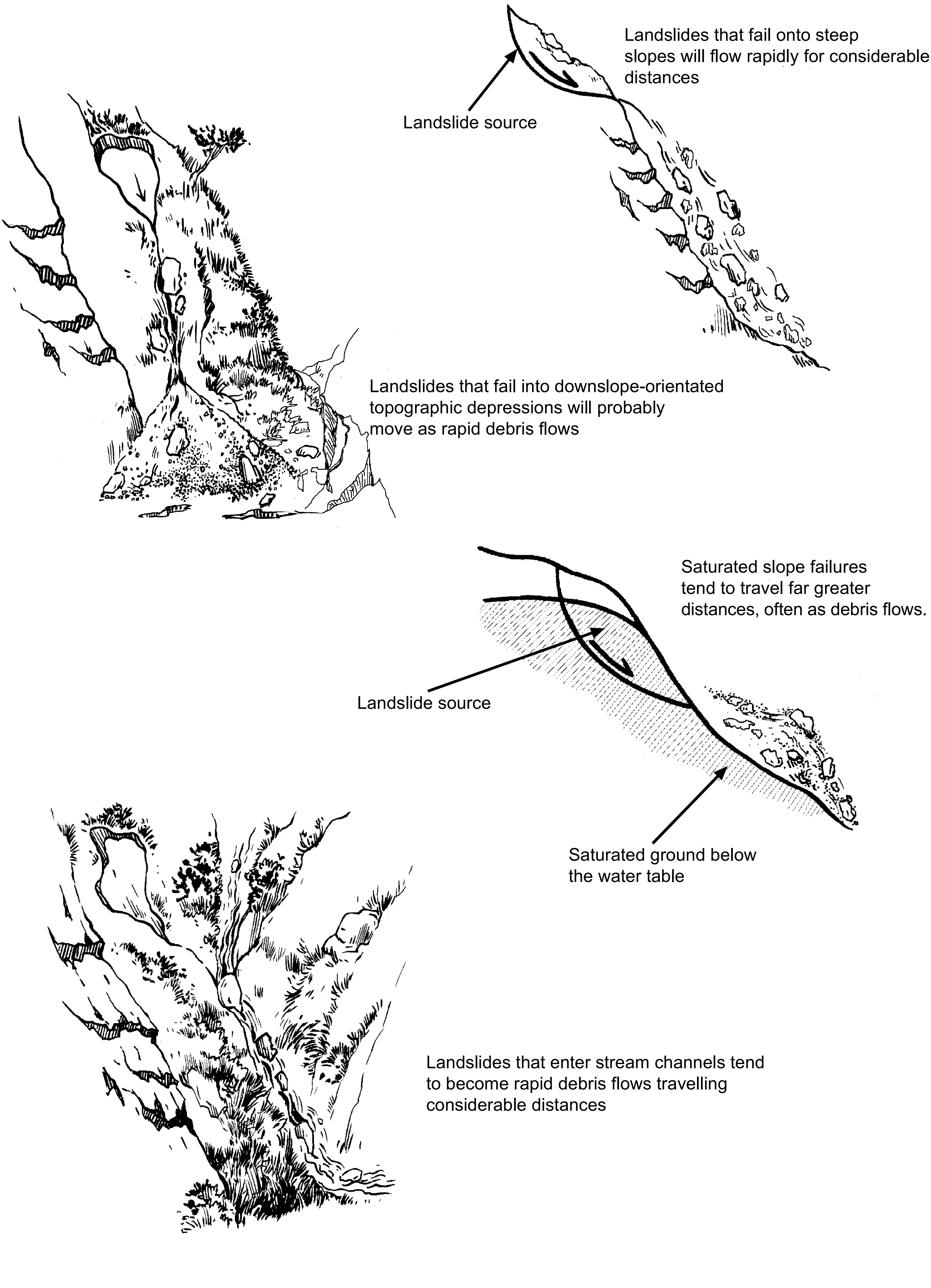
a) adverse geological structure (joints dip out of the slope);
b) fractured rock masses occupying steep ground;
c) weak rock occupying steep slopes;
d) slopes with active stream or river erosion at their toe;
e) steep topographic bowls containing residual soil or colluvium where surface water/groundwater accumulates.

4.2.1.13 Colluvium is a term used to describe transported material, often derived from past landslides or rock fall. Colluvium can occur over large areas from multiple sources. It is usually chaotic or jumbled in its structure and is of low strength. Failures within undifferentiated colluvium can be classified as first-time failures if there is no pre-existing failure surface (Figure 4.6).

4.2.1.14 The potential for landslides to move rapidly downslope as debris flows is governed by the following factors (Figure 4.7):

a) steep slopes below the source area or landslide origin will almost certainly guarantee that rapid movement will take place with sufficient momentum to carry material downslope as far as river terraces and into river channels themselves;
b) the topography may concentrate landslide material so that it travels downslope as a linear mass rather than as a dispersed mass;
c) if the landslide debris is saturated when it fails then it will have a greater potential to become a debris flow downslope;
d) if the landslide mass enters a stream channel it is likely that it will behave as a debris flow, either because it becomes linearly concentrated or because it is able to mix with stream water, or both.

Figure 4.7 Common conditions that give rise to debris flow



The most rapid landslides are channelised debris flows

These are landslides where the failed material has entered a drainage line (becoming channelised). These types of landslide tend to be rapid because the debris mixes with water in the drainage line.

Due to the relatively high velocity of these types of landslide, further material may be eroded from along the drainage line, adding to the total volume of the landslide. The consequences of these types of landslide can often be severe because their travel distances are usually far greater than anticipated. In neither of the illustrated case was the landslide hazard predicted.

4.2.2 Assessing landslide risk

4.2.2.1 The risk that existing or potential future landslides pose to rural communities and infrastructure is made up of the following factors (Figure 4.8):

a) the location of existing landslides;
b) the location of potentially unstable slopes (potential first-time failure areas);
c) the rate and frequency of movement;
d) the vulnerability of the community or infrastructure to landslides.

The location of existing landslides and potentially unstable slopes

4.2.2.2 Section 4.2.1 above outlines how landslides can be identified in the field. From a planning point of view it is not feasible to commission a field-based study to examine every slope in a given district. Chapter 2 describes how landslides can be mapped rapidly and reliably by remote sensing. The conclusion drawn is that aerial photographs provide the most cost-effective way of mapping existing landslides. Aerial photographs are usually available for most areas and can be interpreted relatively quickly. Landslide source areas and deposits are drawn onto acetate and then digitised or drawn directly onto a topographic map.

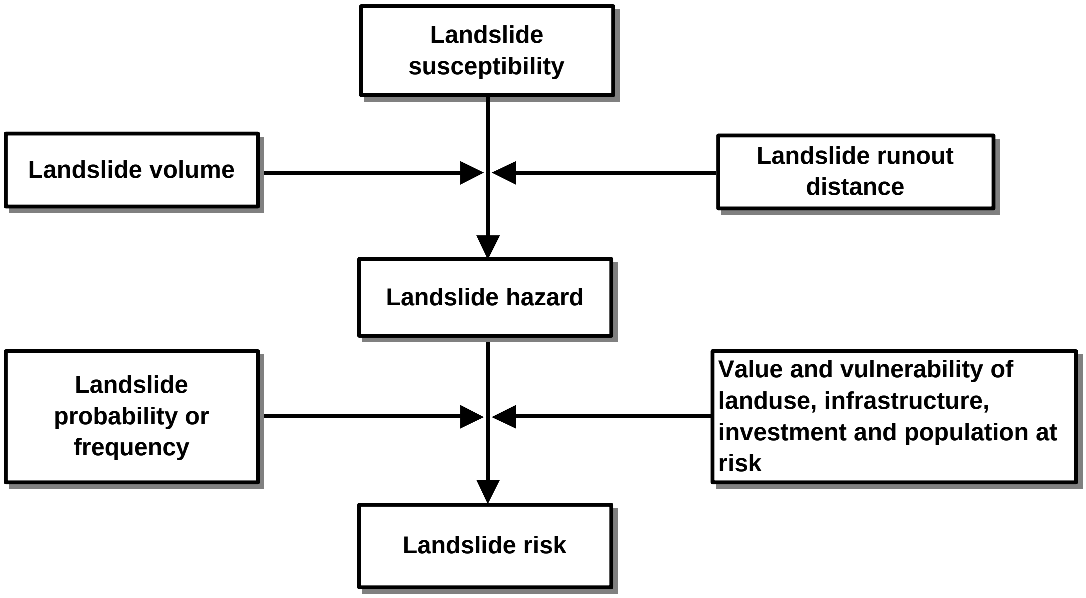
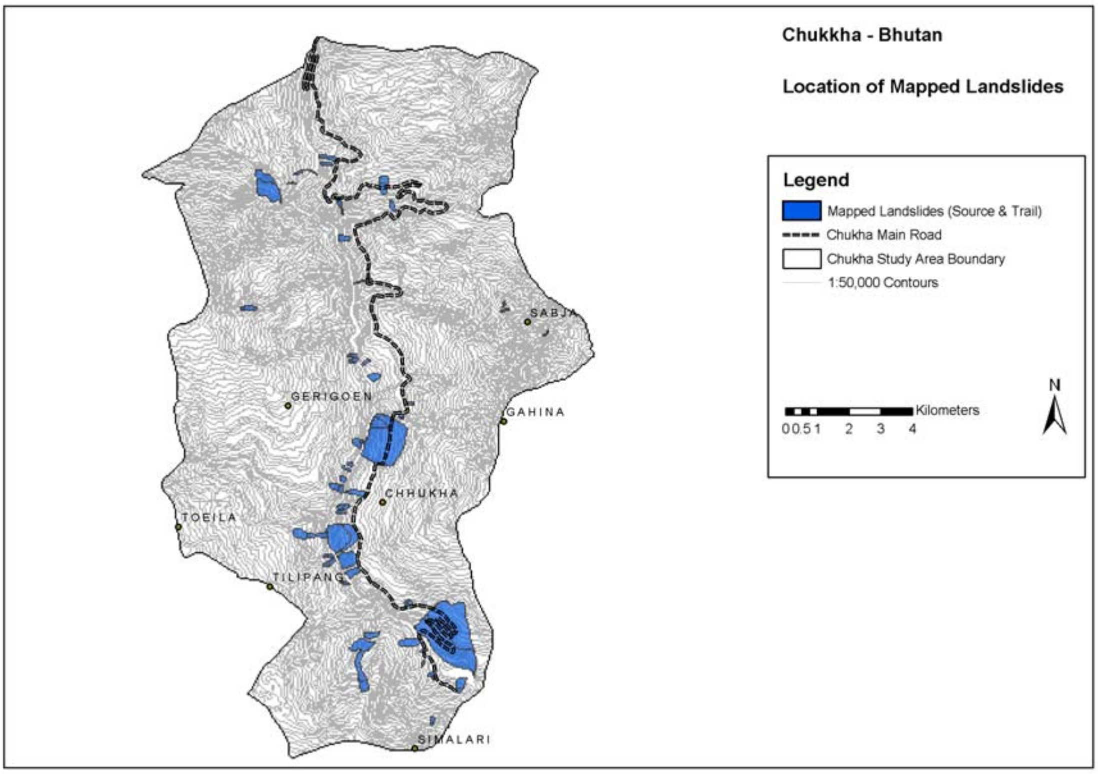


Figure 4.8 Definition of landslide risk for district planning purposes



Example of a landslide distribution map, with the landslides identified from aerial photograph interpretation and plotted onto a 1:50,000 scale topographic map

4.2.2.3 Despite the advantages of rapid landslide mapping offered by aerial photography, the following factors should be borne in mind:

a) aerial photographs larger than 1:10,000 in scale can be difficult to interpret when examining large areas for planning purposes (there may be too many photographs to deal with and individual landforms extend onto two or more sets of stereo pairs, making interpretation difficult);
b) aerial photographs smaller than 1:50,000 scale are only effective in mapping the larger landslides (most landslides are less than 100m in dimension – this has a size of 2mm on a 1:50,000 scale aerial photography). High-powered magnification through a mirror stereoscope can aid the identification of the smaller landslides, but 1:25,000 is the preferred scale for interpretation;
c) cloud and shade can inhibit interpretation, making recourse to fieldwork a necessity;
d) distortion in mountain areas can lead to errors in terrain interpretation;
e) first-time failures that have occurred after the aerial photographs were taken will not be shown;
f) aerial photograph interpretation for landslide mapping and terrain evaluation requires specialist skills. This is only acquired with experience.

4.2.2.4 It is recommended that each district authority carries out the following tasks in order to make best use of aerial photography (assuming it exists):

a) acquire the most recent aerial photography of the district;
b) purchase a mirror stereoscope;

c) have an officer trained in the interpretation of aerial photography (this would ideally be the district soil conservation officer if one exists);
d) plot the landslides (preferably digitally using GIS) onto existing topographic maps.

4.2.2.5 As described in Section 4.2.1 the prediction of future first-time failures requires a knowledge of the factors that initiate failure. Landslide susceptibility mapping can provide a preliminary guide to the identification of those slopes most likely to be the locations of future landslides. One of the conclusions drawn from Chapter 3 is that a knowledge of rock type and slope angle can provide a reasonable preliminary assessment of landslide susceptibility. These two factors can normally be derived from published sources and therefore a district authority can develop a map that shows those areas that are most susceptible to landslides. By combining this with the mapping of existing landslides from aerial photography a very useful planning document can be developed. It allows the identification of existing communities, land uses and infrastructure at risk and assists in the planning of future investments.

4.2.2.6 Figure 4.9 illustrates the various stages in the procedure outlined above. The landslide susceptibility analysis can be improved still further by the inclusion of terrain classification and geological structural data derived from aerial photographs using the techniques described in Chapter 3.

Rate and frequency of landslide movement

4.2.2.7 Rate and frequency of movement are key elements in assessing the potential danger posed to communities and infrastructure. Unfortunately there is usually insufficient data available to assess either of these factors. Individual landslides can be monitored, but it takes several years to build up a representative dataset for any given slope. Furthermore, ground movements may be minor or non-existent until catastrophic failure takes place, once a certain geological threshold has been exceeded. Regarding the frequency of movement, there is usually insufficient historical data available and lack of aerial photograph record, to allow any meaningful assessment to be made (see Chapter 3 for discussion). Therefore, for initial assessment purposes, it is recommended to assume that each identified landside or high susceptibility area will fail completely within a human lifetime or, in the case of road corridor planning, within the design life of a low cost road, nominally 25 years. While this may be overly conservative, there is no proven alternative approach to be adopted in situations where there is insufficient geotechnical or frequency data.

4.2.2.8 When fieldwork is carried out in specific areas and in specific road corridors, then it becomes both possible and necessary to carry out geotechnical assessments on a slope by slope basis. The guidelines outlined in Figures 4.2 and 4.4 and the discussion given in Section 4.2.1 will generally apply. A suitably experienced engineering geologist or geotechnical engineer should be able to provide a more realistic assessment of likely ground movement rates and the likelihood of catastrophic movement.

Assessing vulnerability to landslides

4.2.2.9 The vulnerability of a road or a structure to landslides is governed by two sets of factors. First, the location of the landslide and its length and direction of runout will determine whether it has potential to do damage. Second, and assuming the landslide does encroach on the infrastructure in question, the vulnerability of that infrastructure to damage caused by the landslide will depend on the volume and speed (momentum), frequency (regularity), depth and aerial extent of movement. These factors are difficult to define without intensive investigation and modelling, and even then significant uncertainties usually remain. It is recommended, therefore, that

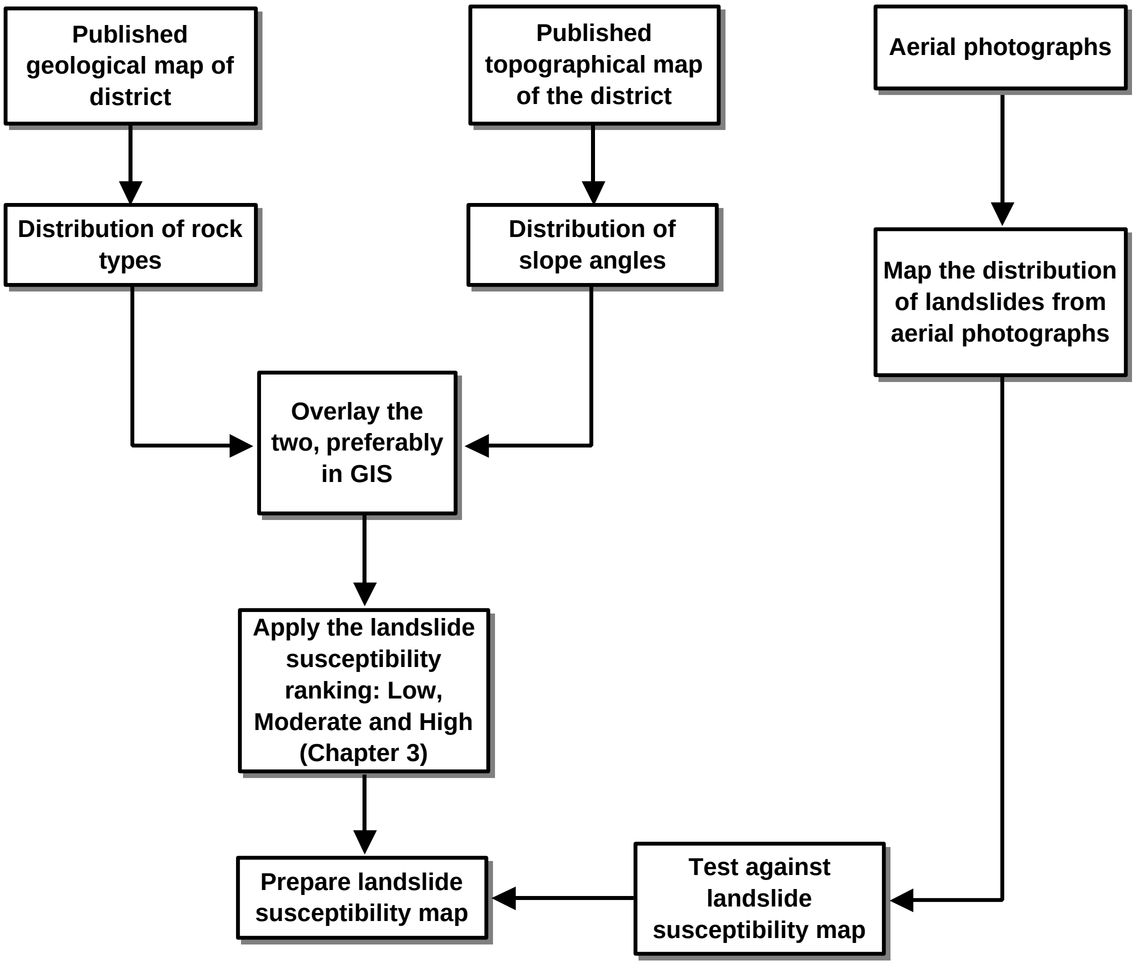


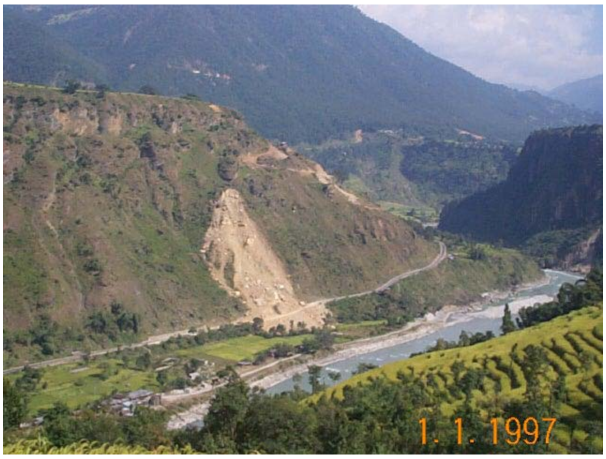
Figure 4.9 Derivation of landslide location and landslide susceptibility maps for district planning purposes.

vulnerability is assumed to be 100% in areas affected by existing and potential future landslides (high susceptibility areas) and their anticipated runout paths. This approach may, again, appear overly conservative but it is recommended that vulnerability only be downgraded from 100% if engineering geological site assessment indicates that such a course of action is justified.

4.2.3 Reducing landslide risk in rural access corridors

4.2.3.1 Measures to reduce landslide risk can be grouped into the following categories:

a) avoidance;
b) relocation;
c) stabilisation;
d) protection;
e) operational change



An example of two landslides (of similar size) but with very different consequences.
L*andslide risk is dependent upon the probability of a landslide occurring and an assessment of the consequence of the landslide if it were to occur.*

4.2.3.2 The obvious means of reducing vulnerability is avoidance or relocation. In this regard, a knowledge of the following potentially problematic zones would be of benefit to the planning authority:

a) relict landslides that have not moved in the historical past but could do so in the future;
b) areas of colluvium that are vulnerable to reactivated movement;
c) areas most likely to be the sites of future first-time failures.

Photograph showing two types of landslide

Landslide Number 1: *deep-seated, slow moving mudslide, with ongoing reactivation due to removal of toe support by river erosion.*

Landslide Number 2: *shallow flow-type landslide with retrogressing head scarp.*

Landslide Number 1 poses the greatest risk to the road as the failure surface passes beneath the road foundation.

a) *Avoidance*

4.2.3.3 Avoidance relates mostly to the construction of roads, buildings and other infrastructure in the more stable areas. However, this practice frequently puts pressure on existing cultivated land, sometimes forcing farmers to search for land elsewhere, and often in areas that are less stable. Avoidance requires information to be available at the planning stage and sufficient planning control measures to be in place to prevent development in areas vulnerable to landslides. As described above, aerial photograph interpretation and landslide susceptibility mapping can greatly assist in the derivation of the required data. However, it is lack of planning control that is usually the critical issue. This problem should be addressed in the following way:

a) the district planning authority should develop a formal landslide zoning based on the procedure shown in Figure 4.9;
b) any proposed changes to land use and infrastructure, especially roads, should be governed by regulations set down according to these landslide zones. These regulations should comprise the following:

    a. prevention of development and land use change in all high susceptibility areas (including existing landslide areas) unless the developer/contractor can demonstrate that an acceptable geotechnical solution can be found. A Geotechnical Clearance Certificate would be issued by a suitably qualified person within the district authority or by their consultant, but the risk would remain with the developer
    b. permission for development in moderate susceptibility areas subject to certain geotechnical investigations and safeguards on the part of the developer/contractor (engineering geological mapping, ground investigation and designed mitigation)

c. permission for development in low susceptibility areas, subject to the application of sound engineering practice (Chapter 5).

4.2.3.4 Formalised planning control such as this should be the objective of all district authorities in landslide-prone areas. However, until such a system is in place it will be necessary to require that all proposed developments and significant changes to land use be preceded by a thorough landslide assessment comprising the following:

a) aerial photograph interpretation to identify existing landslides and other areas of potentially difficult ground;
b) landslide susceptibility mapping, preferably at 1:25,000 scale using the approach described in Chapter 3 and applied in Figure 4.9;
c) field investigation of landslides and high/moderate susceptibility areas;
d) development of an outline design that demonstrates acceptable landslide avoidance or mitigation.

c) Relocation

4.2.3.5 Whereas avoidance is the result of good planning, relocation is usually the outcome of poor or unplanned land use control. In the event of a landslide or ground movement taking place in a high risk area, relocation must be immediate. However, as described above, farmers and others who permanently occupy slow moving landslides are often reluctant or unable to abandon their land as they have no alternative. There are also cases where people continue to occupy dwellings located within metres of active landslide back scarps. In these circumstances the district authority should commission a study by a suitably qualified specialist (geologist or soil conservation officer) to determine whether:

a) occupation of the slope can continue, subject to certain safeguards;
b) the slope cannot be permanently occupied, though it can be farmed, with farmers living outside the affected area;
c) the slope must be abandoned altogether.

4.2.3.6 Figure 4.10 indicates a course of action that might be taken in forming a decision to abandon unstable slopes. The people affected must be shown evidence of the possible outcomes of occupying landslides or potentially unstable slopes. This could include a simple handout such as that shown in Figure 4.11 containing photographs of landslide effects in other areas. Total abandonment will require the district authority to identify or create alternative land for occupation and farming. This might include:

a) conversion of government lands for use by resettled families;
b) conversion of certain forest areas to cultivation if the underlying ground is suitable;
c) assistance with earthworks, drainage and turfing of alternative areas to make them suitable for agriculture.

4.2.3.7 Whatever the solution, immediate evacuation and relocation must be compulsory on slopes considered to be high risk.

c) Stabilisation

4.2.3.8 Slope stabilisation is an option in some cases. However, stabilisation requires sufficient confidence in a design and sufficient funds available to construct and maintain that design. In some cases the construction of a toe wall or the introduction of drainage may succeed in achieving an immediate improvement in stability, especially in the case of smaller slope failures. In most cases, however, there will remain an element of uncertainty in the performance of any landslide stabilisation

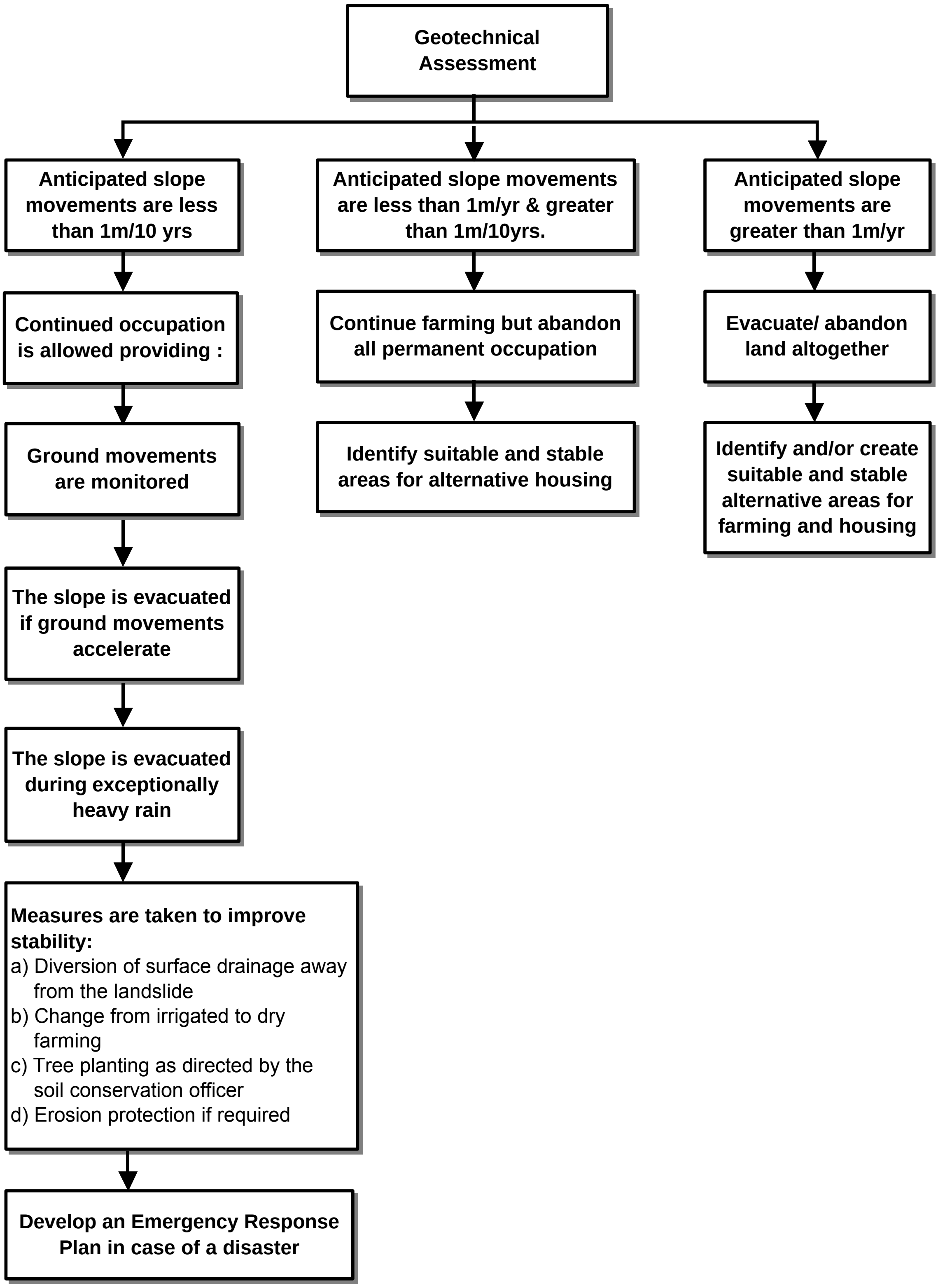


Figure 4.10 Risk management flow chart for unstable slopes

DANGER FROM LANDSLIDES

Landslides kill !

People who live in mountains are at risk from landslides. Landslides can occur:

- ➔ **During and following heavy rain**
- ➔ **During long periods of torrential rain**
- ➔ **During earthquakes**
- ➔ **Unexpectedly**

- ✳ **Be alert. Report any ground movements and cracking to the district authority.**
- ✳ **Monitor any observed movement or ground cracking**
- ✳ **Move your house to stable land**
- ✳ **Ask your district authority how you should manage your land**
- ✳ **Be prepared for immediate evacuation to safety**

Figure 4.11 Public Awareness Leaflet

measures unless a full geotechnical investigation and analysis is carried out. Even then, the designer may not be able to develop a design with complete confidence, due perhaps to complex soil and groundwater conditions or the lack of adequate foundation for retaining structures.

4.2.3.9 Nevertheless, low cost technology measures can be adopted by farmers to improve stability. They commonly include the following:

a) diversion ditches and bunding to keep surface water off unstable slopes;
b) drainage ditches on unstable slopes;
c) use of certain shrubs and plants to increase water uptake and evapo-transpiration;
d) use of bamboo as mini-piles for slope support;
e) construction of dry-stone walling as local support to slopes;
f) use of deep rooting shrubs and trees to provide greater resistance to ground movement;
g) replacement of cohesive soils with free-drainage gravels and rock fill.

4.2.3.10 Landslide stabilisation measures are discussed in Chapter 5 in relation to road corridor engineering.

d) Protection

4.2.3.11 Protection of structures from landslides is rarely an option except in the case of diversion bunds in stream and river channels to deflect debris flows and floods away from habitation and high value structures.

e) *Operational change*

4.2.3.12 Certain land use practices have a negative effect on slope stability and therefore improvements can sometimes be achieved if operational changes are made in the way land is managed. Some examples are described below.

Irrigation

4.2.3.13 Irrigation can have an adverse effect on slope stability in essentially two ways. First, irrigation canals are often constructed across long lengths of slope at a more or less constant gradient and consequently are unable to avoid areas of soft soil or unstable ground. Cracking, leakage and blockage to irrigation canals can lead to soil saturation, erosion and slope failure, to the point that in many localities irrigation canals are among the most frequent causes of slope failures. Second, the introduction of large quantities of water to a slope through irrigation can cause ground movements, especially in colluvial soils. A common occurrence is the failure of colluvium over rock head surfaces due to the influx of water from irrigation. In residual soils, however, soil saturation brought about by irrigation tends to be confined to the surface layers due to the lower permeability of the underlying weathering profile, and resultant ground movements are shallower and less frequent.

4.2.3.14 The control on irrigation is difficult to implement. Irrigated cultivation, for instance, is reliant on large quantities of water. It is very difficult to persuade farmers to reduce quantities of irrigation water, even when ground movements take place. If these are slow enough, farmers are still able to maintain their cultivation. Furthermore, it is often found that farming communities operate in isolation of one-another, i.e. there may be little attempt to integrate water needs and water conservation in order to reduce erosion and slope instability over wider areas. The same is also true where roads intercept farming areas: a lack of co-operation between the road authority and the farming community often means that surface runoff is not properly controlled, especially during heavy rainfall.

4.2.3.15 Positive drainage measures can be implemented by farmers to improve stability. However, the limited technology and resources usually available means that the local community can realistically only attempt to implement surface drainage measures. Nevertheless, the majority of landslides are probably only a few metres deep and therefore surface drainage measures can often be effective. Furthermore, control of the surface drainage over large areas can have a significant effect on groundwater levels and also the stability of deeper landslides.

4.2.3.16 The following drainage measures might be considered:

a) alterations to the irrigation system if irrigation water is the source of soil saturation and slope failure;
b) unlined ditches above landslide areas to divert surface water onto adjacent slopes or into nearby streams;
c) opening up of spring areas with spring water led away from the area via drainage ditches;
d) bamboo inserted horizontally into a saturated soil mass to discharge water, though this will have only a local effect.

Land use change

4.2.3.17 A change in land use, for instance from forest to agriculture, or from non-irrigated farmland to irrigated farmland, can result in slope problems. The removal of forest areas from steep slopes usually results in erosion rather than landslides, though this erosion can develop into landslide problems through gullying if it is allowed to go unchecked.

4.2.3.18 Reforestation on its own is unlikely to have any significant influence on slope stability, unless movements are shallow and very slow. Reforestation should only be contemplated once at least marginal stability has been achieved through other means, such as drainage and engineering structures. In some cases, however, landslides may be instantaneous, ie a slope fails immediately from a steep to a more stable shallow angle, and ground movements then cease. In these circumstances tree planting can be successful and have positive effects.

4.2.3.19 A change in land use from an irrigation-based system to a dry farming system can have a positive effect on stability if soil saturation is considered to be the principal cause of ground movements.

4.3 Land Management in the Road Corridor

4.3.1 Defining the road corridor

4.3.1.1 The road corridor includes the nominal right of way plus the slope and drainage lines affected by the road, either directly or indirectly. The right of way defines land set aside by the road authority for construction and maintenance. Some road authorities procure land as the right of way based on a nominal distance (usually less than 5m) either side of the designed extent of earthworks and drainage works. In unstable terrain this practice can be restrictive, and it is usually better to allow a wider margin. For instance, for a low cost road on flat ground the total width of the right of way might be 20m, ie 10m either side of the designed centre-line. On moderately sloping ground (15^o to 40^o) the right of way might sensibly be 60m and in mountainous terrain (side slopes greater than 40^o) it might be 120m wide. These widths are normally applied to sections of alignment no less than 2km in length based on average topographic cross-section. All landowners and other stakeholders legitimately occupying the right of way are usually compensated through land acquisition and, theoretically at least, further development or change in land use within the right of way is prohibited from then on without the written consent from the road authority.

4.3.1.2 In reality, the following outcomes are common:

a) landowners are compensated through land acquisition but they continue to occupy land, farm and build houses and commercial premises within the right of way;
b) speculative development takes place close to the roadside to benefit from passing traffic;
c) the physical effects of road construction, most notably spoil disposal, erosion and slope instability, can extend outside the right of way;
d) changing land use on the slopes outside the right of way can have a significantly adverse effect on the stability of slopes within the right of way.

4.3.1.3 Consequently, in addition to imposing land use controls within the right of way, a wider planning footprint needs to be defined that covers areas of landslides and potential slope instability adjacent to the right of way. Ideally, planning permission would be required for any changed land use or building development within this footprint. Furthermore, there may be instances where existing land use might need to be modified (for instance from irrigated to rain-fed farming) in order to improve stability within the planning footprint. This planning footprint essentially defines the road corridor and it requires close co-operation between the road authority, the local planning authority and the stakeholders occupying the road corridor.

4.3.2 Landslides in the road corridor

4.3.2.1 It is a widely held view that road construction leads to a higher incidence of landslides and ground movements and therefore a higher level of risk to those living and working in the road corridor. From surveys undertaken in Nepal and Bhutan, it is apparent that, on average, the density of landslides is between 2 and 4 times greater within road corridors than it is outside them. Surveys revealed that up to 20% of any given road alignment is unstable. A considerable proportion of this instability must be road construction-induced because precisely the same surveys carried out on neighbouring ‘natural’ hillsides with the same geology, land use and slope angle revealed that levels of background slope instability were much lower. Much depends upon the extent of slope and drainage disturbance that is allowed to take place. This can be minimised, though usually not eliminated, through appropriate design and construction practices.

4.3.2.2 Excavating slopes for the road formation width is the principal cause of road-induced landslides. These landslides usually comprise shallow failures in cut slopes that frequently extend into adjacent ‘natural’ hillsides. They mostly occur during and immediately after construction, although failures are not infrequent in road cuttings and adjacent slopes several decades after construction as a result of heavy rain. Road drainage can also have serious consequences for stability.

4.3.2.3 Investigations carried out by this project show that, on average, colluvium is almost three times more susceptible to failure in cut slopes than is either rock, residual soil or alluvium. Furthermore, it is common, if not usual, to find cut slope and road failures taking place in previous landslide locations, often a result of excavation during construction. Quarrying and spoil disposal are also responsible for frequent slope instability problems, especially when they are undertaken in a speculative or uncontrolled manner.

4.3.2.4 The engineering selection and management of the road corridor with respect to landslide hazards is discussed in Chapter 5. The remainder of this chapter is concerned with the management of land use and its interface with engineering in the road corridor.

4.3.2.5 Figure 4.12 illustrates the conflict for stable land that is common in many rural road corridors. As pressures for land within the road corridor increase during construction and operation of the road, cultivation and development are increasingly forced into more marginal areas. These areas commonly comprise flood plains, steep slopes, landslides and colluvium. Also, the value of land is usually increased considerably within road corridors and, without close control, there is a tendency for speculators and landowners to take advantage of the opportunity to make short-term financial gain by developing or leasing land for development. Often this development is not major, and therefore is not seen as detrimental. However, in terms of its frequency and its tendency to extend right up to the road edge it can have an extremely detrimental effect, often increasing levels of landslide hazard and landslide risk dramatically. Thus, the public are at heightened risk from landslide hazard. Figure 4.13 shows some of the factors that lead to heightened risk.

4.3.2.6 Houses and commercial premises are constructed close to the road edge, either in widened cuttings or on extended fill slopes, and there is often a rapid process of land use change within the road corridor. This may include the progressive abandonment of agricultural land for other uses as land values increase, a change in cultivation pattern from staple to cash crops and an increase in the logging of forest areas for house construction and commercial purposes. Within a relatively short period of time the topography, land use and drainage character of the road corridor will have been altered significantly. With the increased population density of the road corridor, the potential risk posed by landslides, erosion and flooding is that much greater.

4.3.2.7 This extreme scenario is mostly found in densely populated areas and alongside trunk roads with high traffic volumes. Nevertheless, such situations will become increasingly common along all classes of road as development takes place and, while the road authority that originally selected the alignment may have taken landslide hazard into consideration, it is usual to find that all other developments take place in ignorance of it.

What can the road authority do?

4.3.2.8 The road authority is responsible for the design and maintenance of earthworks and structures, and has a duty to warn and protect the public from landslides within the right of way. The following steps could be taken (Figure 4.14):

a) align the road in the most stable location possible;
b) design cutting angles taking geotechnical advice;
c) identify areas where there is a perceived high risk from landslides and earthworks instability, and make them known to the local authorities;
d) identify those areas in the right of way where development can take place without endangering the road or the public (travelling or resident);
e) design the spoil disposal plan and road drainage schemes so that unstable and potentially unstable areas are avoided as much as possible, and areas that are currently stable are not rendered unstable;
f) use drainage structures and slope protection techniques that are in harmony with the local land use;
g) take an active role in the management of land inside and outside the right of way through discussions with farmers, landowners and the local authorities;

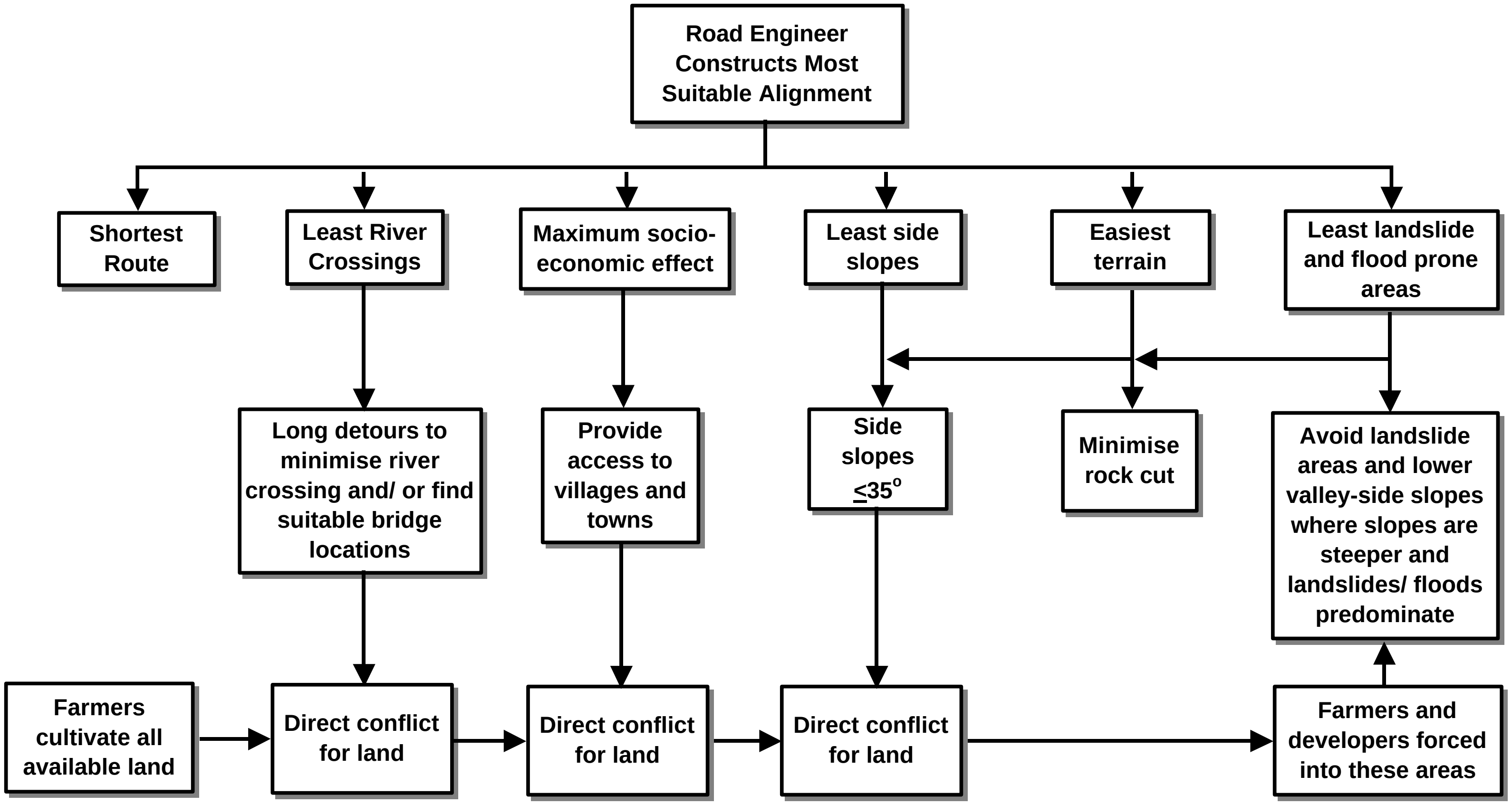


Figure 4.12 Conflict for land in rural road corridors

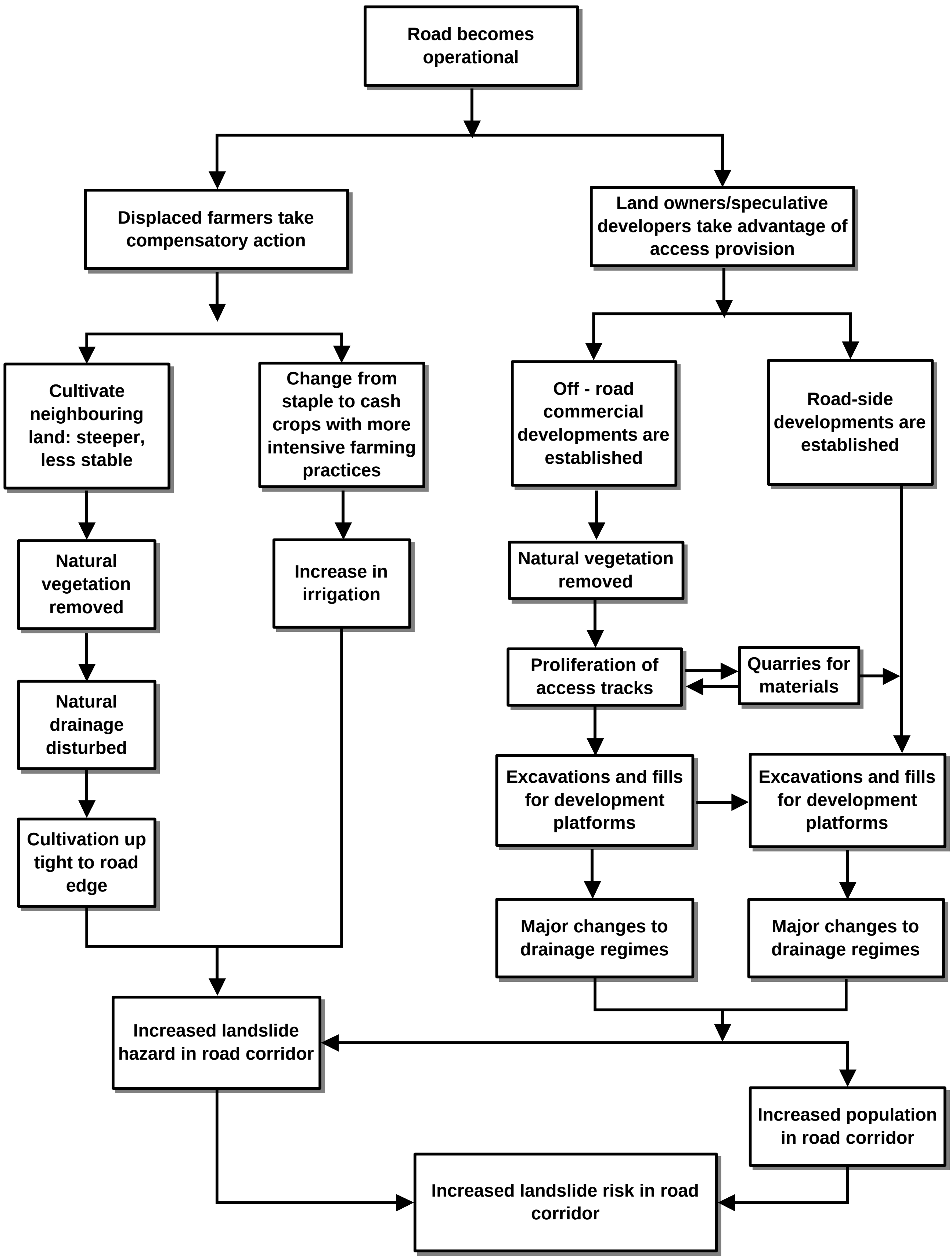


Figure 4.13 Factors contributing to increased landslide risk in road corridors

Stakeholder	Landslide hazards from natural terrain	Earthworks stability	Drainage	Landuse
Engineer/Road Authority	1. Identify landslides and potentially unstable slopes. 2. Design alignment accordingly. 3. Alert local authority/ public to high risk situations. 4. Investigation and monitoring of unstable slopes.	1. Design cut slopes and fill slopes according to geotechnical properties. 2. Liaise with farmers over bio-engineering methods and planting schemes above cuttings. 3. Careful location and control of quarries and spoil areas.	1. Keep road drainage out of landslide areas. 2. Maximize the number of culverts and side drain turnouts. 3. Liaise with landowners/ farmers over drainage.	1. Maintain a close control of quarry operations within the right of way.
Landowners/ farmers	1. Be aware of the location and extent of unstable ground. 2. Notify the local authorities of cracks or accelerated ground movements. 3. Avoid locating permanent dwellings in or close to stream channels.	1. Use dry farming practices above cut slopes. 2. Liaise with road authority over maintenance of vegetation on earthworks slopes.	1. Agree cross-road drainage requirements with roads authority. 2. Keep stream channels clear. 3. Maintain effective drainage of slopes.	1. Take advice before extending cultivation onto previously uncultivated slopes. 2. Liaise with soil conservation officers over crops, planting schemes and land management.
Developer	1. Be aware of existing landslides and take geotechnical advice when developing new sites. 2. Avoid drainage lines. 3. Liaise with road authority and local authority.	1. Liaise with road authority over all proposed earthworks.	1. Liaise with road authority over all proposed drainage works.	1. Minimise disturbance to natural vegetation cover and drainage.

Figure 4.14 Stakeholder responsibility in landslide management within road corridors

h) have in place an emergency response plan in the event of a major landslide and co-ordinate this with the local authorities.

4.3.2.9 Some of these actions are discussed in more detail in Chapter 5.

What can the landowner/farmer do?

4.3.2.10 Landowners and farmers are responsible for the management of their land and they should be aware that failure to do this properly could have detrimental effects on nearby slopes and road structures. They can take the following actions (Figure 4.14):

a) provide a margin of at least 3m between the top of cut slopes and the downslope limit of any cultivation, ie avoid cultivating tight to the top of the cut, and thus avoid surface runoff directly onto road-side slopes;
b) employ dry/rain-fed farming practices on slopes above cuttings;
c) plant crops that are deep rooting adjacent to the top of the cut slope;
d) maintain control of all drainage on their land, maximise drainage efficiency and maintain all drainage structures;
e) locate permanent dwellings away from drainage lines and from the top of cut slopes;
f) liaise with the road authority over the management of vegetation on and around cut slopes;
g) report any signs of ground movement to the road authority or the local authority;
h) ensure the land is not used for unauthorised/illegal development.

What can the developer do?

4.3.2.11 The developer is referred to here as either a landowner wishing to change the land use on or adjacent to a given slope, or a speculator (either through leasehold or illegally) wishing to develop a given slope or a site adjacent to the road for commercial purposes. The developer needs to take the following actions (Figure 4.14):

a) always liaise with the local authority and road authority over development proposals (although this is unlikely to happen when the developer is operating illegally);
b) be aware of the potential hazard from landslides, arising either from potential earthworks failures or from the surrounding natural terrain;
c) be aware that debris flow hazards frequently originate well outside, i.e. often hundreds of metres, and occasionally kilometres, outside the right of way;
d) avoid obstructing natural drainage lines and avoid building permanent structures in or over drainage lines;
e) minimise disturbance to natural vegetation;
f) site any development on stable ground;
g) minimise disruption to drainage systems;
h) obtain specialist geotechnical advice when in doubt.

What can the planner/local authority do?

4.3.2.12 The planner or local authority must assume responsibility for the management of the road corridor outside the right of way with regard to a number of issues, including land management and slope stability. This responsibility must commence during project planning and continue throughout project operation (Figure 4.15). Initially, the local authority should define the extent of the planning footprint that defines the road corridor and ensure that all stakeholders (road authority, farmers, landowners and developers) are aware of this and in agreement through consultation. The footprint document (showing the mapped location of the footprint with respect to recognisable features on the ground) should then be signed as agreed by all stakeholders as part of the road design approval process.

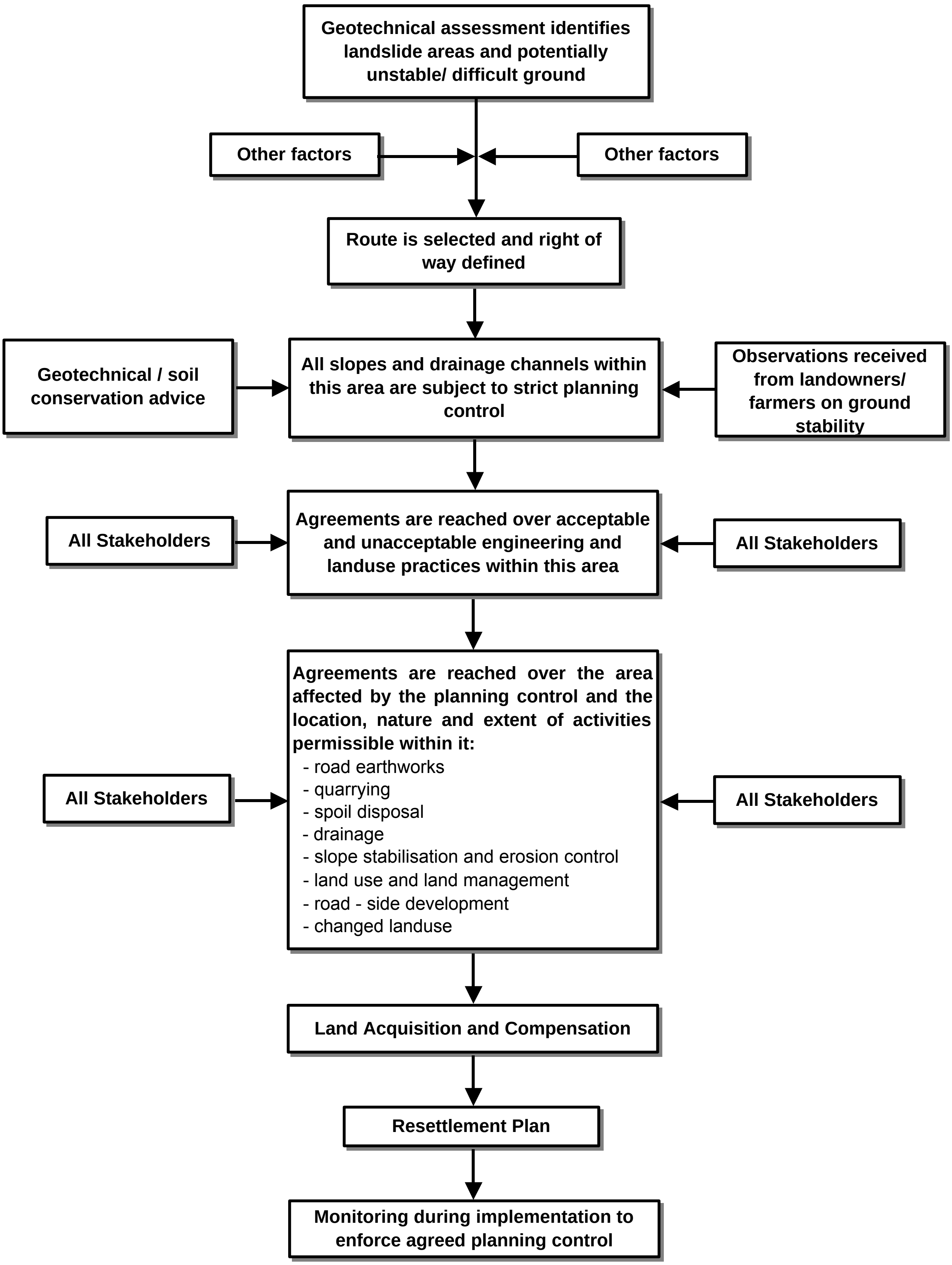


Figure 4.15 Action Plan for effective planning control against landslide in the road corridor

4.3.2.13 While there may be adequate systems in place to pay compensation to displaced landowners and farmers, the resettlement plan is often hindered by a lack of suitable alternative land to move to. The option of creating land through earthworks and purpose-designed and constructed spoil disposal areas has been mentioned earlier in this chapter with respect to landslide evacuation. However, this is unlikely to create significantly large areas of land in mountain terrain and may, in fact, prove suitable for only a few land uses. The local authority may therefore need to provide further assistance to displaced farmers, landowners and householders to enable them to successfully convert otherwise marginal land to stable and productive land.

4.3.2.14 During construction and operation of the road, the local authority, the road authority and community representatives should work together to ensure that the controls on land use and development are enforced. Ideally, the local authority should permanently employ a soil conservation engineer or similar specialist who can provide advice and carry out site checks when planning permissions are sought.

Emergency Response Planning

4.3.2.15 Each district authority should have in place an Emergency Response Plan in order to evacuate disaster areas and minimise risk to the community. This plan should be drawn up in consultation with the road authority and community representatives, and disseminated to all stakeholders and sectors of the community. The plan should comprise:

a) appointment of an officer responsible for disaster response management in each district and at sub-district level;
b) appointment of a geotechnical engineer/soil conservation officer on constant standby;
c) liaison/agreement between the local authority, road authority and local contractors regarding the availability of earth moving plant for emergency works;
d) agreed procedures for informing the public in the event of an emergency;
e) agreed procedures for evacuating the public from disaster areas;
f) specific arrangements for evacuation and safe muster stations in areas of known high hazard;
g) procedures in place for immediate notification and management of emergency services: medical, army, air force (for airborne evacuation) and police.

4.4 Conclusions and Future Developments

4.4.1 This chapter has made recommendations for improved recognition and management of landslides within rural access corridors. It is recognised that many of the recommendations are both idealised and generalised and there will be valid reasons in specific cases where they cannot be applied. Furthermore, the implementation of some of the recommendations will require a significant degree of institutional effort and institutional change, and it will be necessary to convince the authorities involved that the benefits outweigh the costs and logistical difficulties.

4.4.2 Nevertheless, it is clear that a great deal can be achieved without necessarily incurring large costs. Information dissemination and public awareness campaigns can achieve significant improvements and the development of simple landslide susceptibility mapping for district planning purposes is a relatively inexpensive task as long as basic topographical and geological mapping exist. The skills are usually available in-country to do this, including the use of GIS technology in the preparation of data and outputs.

4.4.3 This chapter discusses the need to carry out geological and geotechnical assessment whenever suspect slopes are identified and communities and investments are at risk. The LRA project has found that usually there are skills available in-country to undertake these tasks. What is lacking is the incentive and resources to apply them.

4.4.4 It would seem appropriate, therefore, to suggest that district authorities consider expanding manpower resources to deal with the identification, delineation and management of zones considered to be of highest landslide potential in their district. This would include the provision of advice to landowners and farmers and the identification of situations where urgent mitigation measures are required.

4.4.5 The management of land within the road corridor itself is complicated by land ownership issues, confused, poorly defined or even conflicting land management responsibilities and the frequent lack of control on landuse change and development. It is recommended, therefore, that consideration is given to the development of planning policy that establishes a road corridor planning footprint in which clear lines of responsibilities and land management control are agreed by all stakeholders.

Landslide Risk Assessment in the Rural Access Sector

Guidelines on Best Practice

CHAPTER 5

ROUTE CORRIDOR ENGINEERING

5.1 Introduction

5.1.1 There are many issues that affect the selection, design and implementation of road schemes in populated mountainous or hilly terrain, and slope stability is among the most significant. It is important to bear in mind during the discussions that follow that the emphasis here is on landslide and slope stability-related issues and not the full breadth of engineering and socio-economic considerations that come into play during feasibility and design studies. In the case of new road construction it is usually necessary to examine a number of potential road corridors in order to decide which is the most suitable. Those with the least landslides and difficult ground conditions will pose less problems for the construction and maintenance of the road in the longer term. By contrast, the upgrading of an existing track or road may allow only very limited opportunity for avoiding landslide locations, and in the case of particularly problematic alignments, a difficult choice may need to be made between realignment on the one hand and stabilisation on the other, both of which can be very costly. Consequently there is a need at the earliest possible stage for geological and geotechnical considerations to be fully incorporated into project planning, feasibility study, design, construction and maintenance/operation.

5.2 Requirements of Route Corridor Engineering

5.2.1 The engineering of a rural road corridor must satisfy the socio-economic factors that govern the decision to provide that access in the first place. There must be a proven demand for a road to be constructed, and the benefits of satisfying this demand must outweigh the costs and potential disbenefits of constructing the road, namely the cost of its construction and maintenance, the cost and impact of any slope and drainage hazards that will be encountered, and any environmental consequences of the construction. The requirements of route corridor engineering, therefore, must be to construct a road to the required operational standard that satisfies the socio-economic justification for the access provision, with the minimum exposure to slope and drainage hazard, and with the maximum integration into the rural environment. There are very few roads that satisfy all of these criteria, primarily through lack of data, lack of foresight or lack of concern at the planning stage.

5.2.2 Rural road construction in many populated mountainous regions is taking place at a rapid rate and it would seem that a significant proportion of this construction is occurring with insufficient or non-existent geological or geotechnical consideration. The underlying justification for building a road lies not in its construction but in its operation and this requires adequate levels of funding for earthworks, drainage and quality control during construction and maintenance during operation. This requirement is well known to road engineers, but planners responsible for funding these projects must be made aware of the fact that road building in the mountains requires greater financial and technical investment than on the plains, and if the minimum of funds are not available and the commitment to proper planning, design and quality control is lacking, then it is advisable not to contemplate the investment in the first place.

5.3 Engineering Programme for Road Construction

5.3.1 Project phasing

5.3.1.1 A road construction or rehabilitation project is normally subdivided into the following stages:

a) feasibility study (including remote sensing, determining route alignment and field survey)
b) preliminary design (preliminary design of an outline scheme with outline solutions to critical issues identified from the feasibility study)
c) detailed design
d) construction
e) operation

5.3.1.2 Depending on the length of road, its cost and funding mechanism, a), b), and c) above may form distinct and separate stages or be integrated within a single continuous project management process. Whatever the process, it is important that the considered options and design parameters are clearly stated at each stage of the process and that there is maximum consultation with stakeholders. The role of landslide and slope stability assessment during each of the project phases is briefly described below.

Feasibility study

5.3.1.3 The feasibility study will define the route corridor options, considering the terms of reference for the road project, making use of remote sensing information and identification of general areas of instability and high risk/major landslides using techniques described in Chapters 2 and 3. In unstable mountainous regions, topography and stability often become the critical factors and must be assessed in a progressive manner from the general to the specific as route corridor options are first identified and then assessed. The quality of the feasibility study is usually of critical importance to the success of the project when important decisions are made regarding the selection of alignments, design standards and methods of construction. Time spent at the feasibility stage is therefore a worthwhile investment but it is so often the case that feasibility studies are incomplete or do not take due consideration of landslide susceptibility. Table 5.1 compares the approximate costs of carrying out various feasibility study exercises to assess landslide susceptibility with the average construction cost of a 50km long rural road with a gravel surface. Although the feasibility stage costs are quoted in US$ they are based on local personnel carrying out the work on local (in this case, Nepalese) fee rates for independent consultants (i.e. excluding any overhead and profit levied by consulting firms). The table illustrates the extremely low cost of feasibility studies when compared to the overall construction costs. Given the benefits of the outputs (described in Chapters 2 to 4) there is clear argument for maximising geological and geotechnical inputs to feasibility studies for new road construction.

Table 5.1 Comparison between the cost of the feasibility study and the construction of a 50km long rural road

Project Stage	**Cost**	**% of overall construction costs**
Construction	50 km of road at US$ US$ 60,000 per km = **US$ 3 million**	**100%**
Desk study	US$ 1,000	0.03%
Remote sensing (Landsat and API)	US$ 3,000	0.1%
Landslide susceptibility mapping	US$ 5,000	0.15%
Field reconnaissance mapping	US$ 5,000	0.15%
Total Geotechnical Feasibility Study	**US$ 14,000**	**0.5%**

Preliminary and detailed design

5.3.1.4 While the avoidance of landslides and other potentially unstable areas is the preferred solution, it is usual to find that there is no alignment option that is free of landslide problems. The risk posed by each of the main problem areas therefore needs to be identified before decisions are made on alignment selection. Often the size and complexity of the larger landslides, especially on low cost mountain roads, is such that the affordable engineering solutions are capable of only short-term and superficial effect, and do not prevent longer-term movements and road damage from taking place. It is not uncommon to find road alignments where road deformations and temporary loss of access are the inevitable outcomes of crossing large, deep-seated landslides. This situation is frustrating to many road authorities who do not have the funds or technical capabilities to deal with these large landslide problems. Affordable maintenance is often barely enough to cope with only the minor slope failures in and above cut slopes that block the road from time to time. This outcome has very significant risk, investment and operational implications that must be considered and designed for throughout the project phasing.

Construction

5.3.1.5 During construction, the designed measures to stabilise or mitigate against landslides and slope instability are put into place. Some adjustments may need to be made to take account of unforeseen ground conditions or any slope stability, topographical or land use changes that may have taken place during the intervening period. It is usual to undertake all detailing work during construction itself in order to cater most effectively for the ground conditions revealed.

Operation

5.3.1.6 During operation and maintenance, continued slope problems will require attention for the following reasons:

a) pre-existing slope failures are too large to be stabilised and a degree of continued movement has been allowed for;
b) the constructed design has failed to create an immediately stable condition;
c) new first-time failures occur as a result of cloud bursts or land use changes within the road corridor (see Chapter 4 for discussion).

5.3.2 Engineering design elements

Alignment corridor identification and selection

5.3.2.1 The selection of the alignment corridor is the most critical element in any road construction project. In some cases the selection of an alignment corridor may be obvious, as would be the case in ridge top or valley floor alignments between two villages or towns in the same topography. Also, in areas where road links already exist, the existing network will usually dictate the selection of an alignment for a new road.

5.3.2.2 Land use will also be an important factor in the selection of an alignment. Roads that cross irrigated farmland are likely to suffer drainage and instability problems while at the same time consuming valuable farmland. Slopes occupied by jungle or forest are often the locations of steep and/or unstable ground. Forests are also protected in many areas, and road construction may be prohibited.

5.3.2.3 A road constructed along an unstable or partially unstable alignment will prove problematic during construction and operation. Periodic or catastrophic ground movements may give rise to cut slope failures, road blockages, progressive road failures or sudden breaches in the road formation. The cost of keeping the road open will become excessive and in fact may not be practicable in the long term. Logic dictates that if road maintenance cannot be afforded then there is little point in embarking upon construction. Too often road projects are regarded as a one-off construction cost, with little or no recognition of the fact that many of the slopes crossed by an alignment may be terminally unstable (meaning that failure is inevitable in time).

5.3.2.4 This serves to emphasise the need to ensure correct road alignment, as a means of minimising future hazard. Inevitably, slope failures will occur from time to time, as a result of local cloud bursts, and these should be dealt with as an ongoing maintenance commitment. What should be avoided, wherever possible, are the larger failures that will continue to cause problems for access during the design life of the road and its structures.

Table 5.2 Typical terrain features and their implications for alignment stability

Alignment type	Feature or Facet	Typical Problems Encountered	Existing landslide feature?	Potential landslide location?
Ridge top	Rounded relief	Deeply weathered soils likely. Some erosion potential.	No	Possibly
	Sharp relief	Rock at surface. Costly and difficult rock excavation possible.	Unlikely	No
	Irregular relief	Difficult alignment along ridge top between high points and low points.	Possibly	Possibly
	Asymmetric relief	Joint-controlled slopes will influence stability of alignments and cut slopes.	Possibly - check for debris mass at toe	Possibly
	Ridge lines generally	May be subject to greater rainfall.	Possibly	Possibly
	Ridge lines generally	May be more affected by seismicity.	Possibly	Possibly
Valley side	Slopes are steeper than 40^o	Probably underlain by rock and therefore likely to be more costly to construct but less costly to maintain.	No	Unlikely
	Slopes are 25^o - 35^o	Potential to be colluvial or landslide material	Likely	Likely
	Continuous rock slopes with constant dip	Likely to be formed in dominant joint set controlling long-term stability of the slope. Depending on strength of rock this joint set could be problematic in excavations and foundations.	Possibly - check for debris mass at toe	Possibly
	Large embayments	Either erosional in origin or formed by landslide(s).	Probably	Secondary landsliding possible in primary landslide debris
	Large areas of paddy field	Drainage problems likely. Soils probably colluvial in origin and potentially unstable	In a mountainous area, possibly the debris mass of a large landslide	Possibly
	Rounded spurs	Probably formed in residual soils and stable	No	No
	Elongated mid-slope benches	Either ancient river terraces or rock benches. Both stable and 'easy' for road construction	No	No
	Local mid-slope benches	Could be as above, or part of deep seated landslide	Possibly	Possibly
	Forest/jungle areas	Possibly areas of wet ground, steep slopes, instability	If approximately 25-35^o slope, possible landslide material	Possibly
Valley floor	Steep forested slopes forming margins of river (ie no river terrace)	Possibly actively unstable. Very difficult for road alignment.	Less than 35^o slope, possible landslide material	Probably
	Steep forested slopes behind river terrace	Possibly old, periodically active instability.	Less than 35^o slope, possible landslide material	Possibly

5.3.2.5 A great deal of judgement is required in assessing the level of survey, risk and hazard assessment, engineering design and costing required to adequately assess route corridor options. In the more straightforward case, one option will be clearly superior and often this will follow the corridor of an existing walking track or mule track which has developed over a period of centuries as the most sustainable and effective route. In this case design options will centre on local realignments to avoid identified problem areas or areas of difficult alignment geometry. In the less straightforward case, two or more options may appear feasible. The detail of the assessment must be sufficient to allow engineering to be developed for all viable options to a level that permits adequate identification and assessment of problem areas. While feasibility studies should maximise the use of desk study data, there will be a need for some confirmatory, topographical, engineering and geological / geotechnical field survey to be carried out. However, care should be taken to avoid collection of an unnecessary degree of detail.

Design of the alignment

5.3.2.6 Once the corridor is chosen, the task is then to select the most appropriate alignment from an engineering, stability, land use and socio-economic point of view. The relative importance of these issues will vary according to the conditions of the route corridor itself:

a) satisfying the engineering design standard for the horizontal and vertical alignment is essential throughout an alignment, but becomes critical and of over-riding concern in steep and complex ground;
b) stability considerations dictate the detailed location of the alignment and its cross-section when areas of slope instability or potential instability have to be crossed, i.e. where they cannot be avoided in the selection of the alignment;
c) land use and socio-economic considerations are most prevalent when an alignment corridor crosses farmland.

5.3.2.7 The resources required to develop the alignment design will depend upon the level of detail applied to the route corridor selection at feasibility study stage. The use of computerised geometric alignment design is considered desirable to enable more accurate cost estimation and to facilitate later development of the detailed design. However, in practice, these resources are usually not available for rural road construction.

Design of cross-section

5.3.2.8 It may be preferable to cross certain slopes in cut or fill, or a combination of the two. Simply from the point of view of reducing cost and minimising spoil it may be preferable to balance cut with compacted fill in the same cross-section. However, this is rarely achieved in practice. For example, the construction of unreinforced fill slopes is only normally feasible on side slopes of 30^o or less and, for geotechnical reasons, balanced cut and fill in the cross-section may not be the preferred solution. Table 5.3 and Figures 5.1 and 5.2 list and illustrate some of the factors that might be considered in selecting the preferred cross-section when crossing unstable or potentially unstable ground, though it must be emphasised that the geometric constraints on the vertical and horizontal alignment in steep and complex ground may dictate that a choice does not exist. It should be stressed that each case will be different and will require its own field assessment.

5.3.2.9 Selection of the road carriageway width is of critical importance on mountain roads, where even small increases in width on sloping ground can have major impacts on the volume of earthworks and the need for walling structures. In mountainous areas, the selection of inappropriately wide formations will tend to result in either high construction costs or the creation of extra width through the construction of spoil shoulders, which later tend to slump and fail leading to high maintenance and rectification costs. It is recommended that the minimum width to ensure safe and effective passage of traffic is selected. Each country usually has its own guidelines.

Table 5.3 Preferred cross-sections when encountering slope instability problems

	Slope Condition	Choice of Cross-section	Explanation	Mitigation Options	Limitations
5.3.a	Alignment across top of landslide	Full cut	Removes active load driving failure	Maximise opportunity for constructing road formation in insitu (unfailed) ground by widening its cut. Do not spoil into landslide area.	Maximum cut angle 35˚ to 40˚. Should not undercut any landslide debris above.
5.3.b	Alignment across toe of landslide	Full fill	Adds weight to resisting force	Bench and compact fill/slope interface. Ensure drainage of slope is not compromised. Retained fill may be an option where foundation stability permits.	Profile of landslide failure surface needs to be checked for potential to cause heave of inner portion of road
5.3.c	Alignment located on steep colluvial slope	Mostly full cut	Slope too steep for fill slope, foundation for retaining walls uncertain	Back-analysis of slope stability, and incorporation of small dry stone and grouted masonry structures to limit erosion may be appropriate. Approved spoil location outside landslide area required	Maximum cut angle should be 35˚ to 40˚. Cut slope geometry may need to be steeper, hence need for slope structures.
5.3.d	Alignment located across joint-controlled slope	Cut/retaining wall	Depending upon condition of the rock, some cutting may be possible. If foundation is stable then mostly retaining wall is preferable	Dowelling or rock bolting of key blocks may be appropriate. Limited sidecasting of spoil may not be a problem.	Persistence of adverse joints needs to be inspected. Adverse sheet joints can result in dangerous instabilities.
5.3.e	Alignment located across rock cliffs	Cut/retaining wall	Cutting is usually the only feasible option with retaining walls across gullies and rock clefts. Assumption: existing cliffs unlikely to be at limiting angles	Dowelling or rock bolting of key blocks may be appropriate. Limited sidecasting of spoil may not be a problem.	Very careful fitting of the horizontal and vertical alignment is needed to fit and optimise the design
5.3.f	Alignment located across lower valley side slope	Cut/mostly retaining wall	Depends on founding stability for walls and strength of materials exposed in cuttings	Positive drainage to wall backfills likely to be essential	Large size rock debris is often difficult to clear. Clearance is often essential to provide stable foundations
5.3.g	Alignment located on or adjacent to ridge top	Full cut/minor walling	Full cut due to limited slope length above the road	Consider land use implications on any platforms at ridge top. Approved spoil location required	Consider rounding cut slope to cater for lower strength soils at ridge top

Illustrations are shown schematically on Figure 5.1.

Figure 5.1 Sketches showing slope conditions listed in Table 5.3

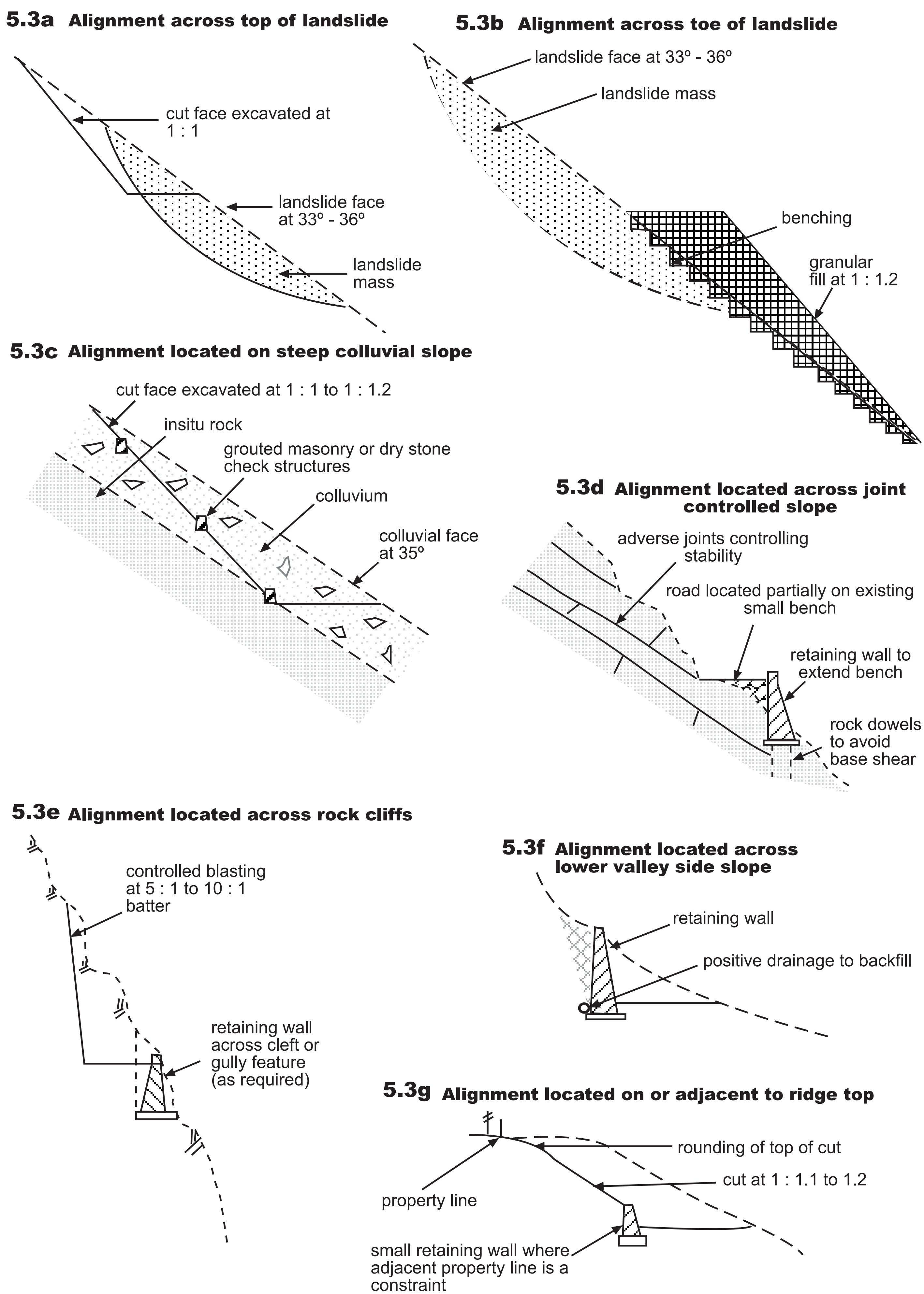
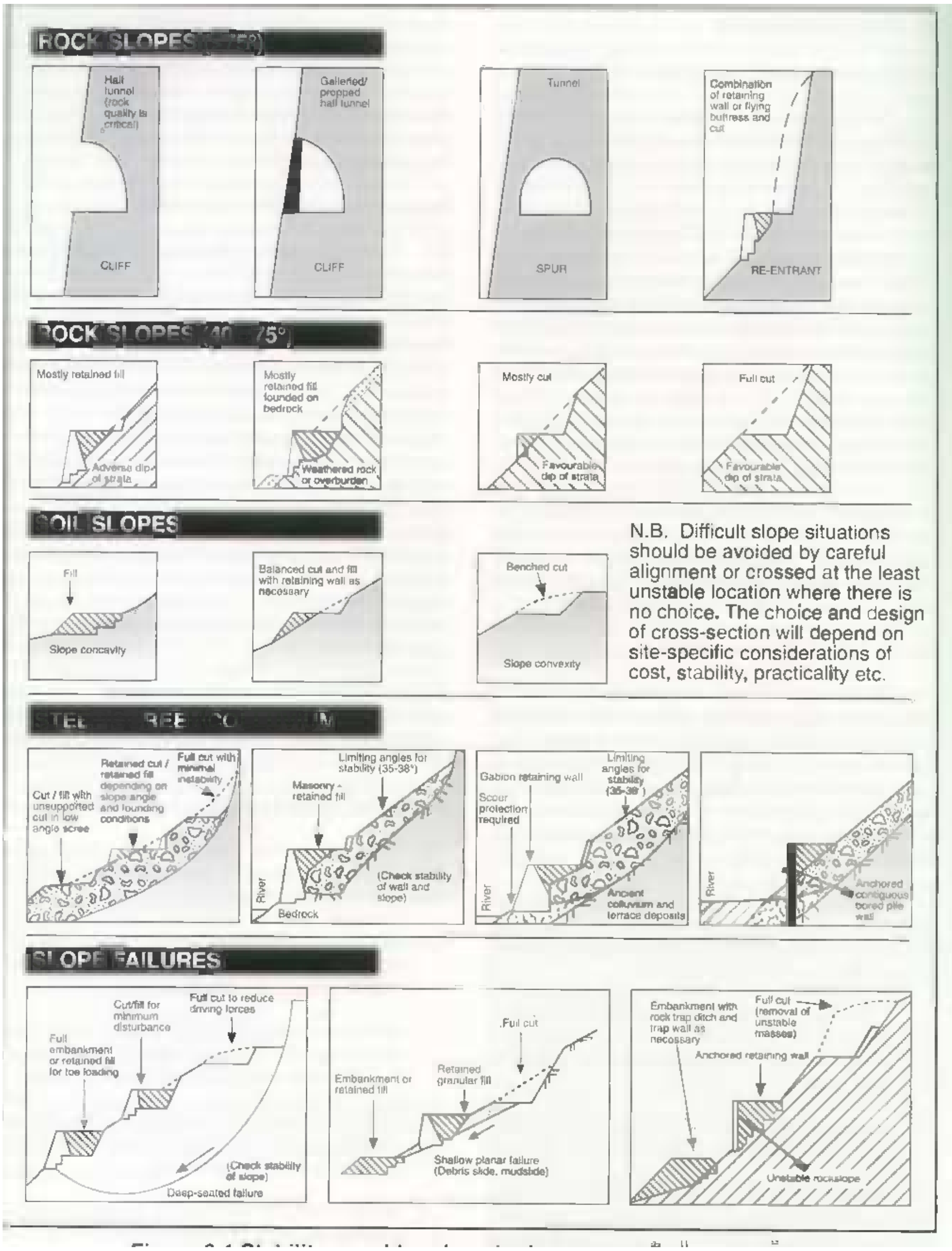
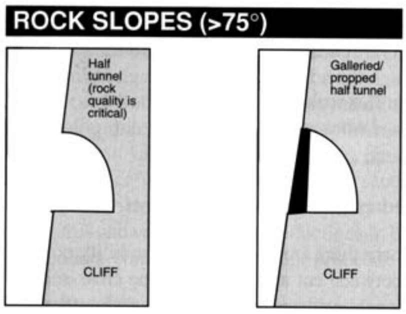


Figure 5.2 Stability considerations in the choice of cross- section



Taken from Overseas Road Note 16 (1997)



Half tunnel constructed in a near vertical rock slope

Slope design, protection and stabilisation

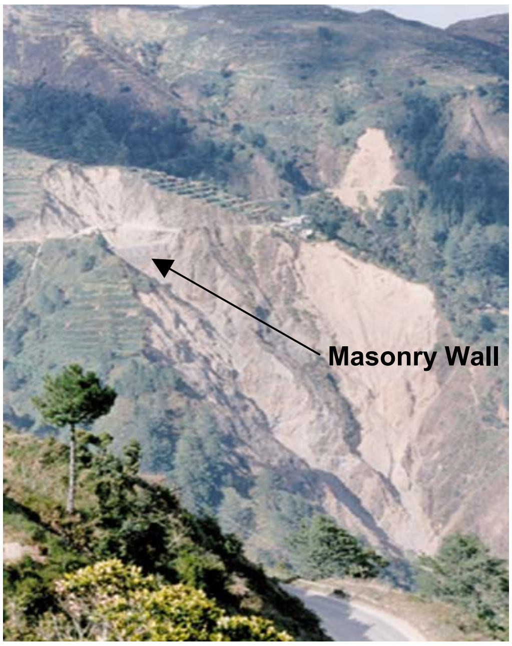
5.3.2.10 Usually slopes are classified into their assumed constituent materials and a cutting slope applied according to material type and cut height, based on observation and stability charts for purposes of quantity estimation. Nominal cutting angles are applied right through to the construction stage unless an alternative design proves necessary, either through investigations during design or through unforeseen ground conditions during construction. It is important to recognise, however, that ground conditions (material type, material strength and drainage condition) can be very difficult to predict prior to construction unless trial pitting and drilling are undertaken comprehensively as part of the design. Even then, the maximum depth of a hand-dug trial pit is usually 2m at best. The most experienced geologists can be proved wrong when construction excavations expose materials and depths to rock that are very different to those anticipated from the surface during design.

Bio-engineered slope protection (erosion control mat with hydroseed)

Masonry retaining wall with shotcrete surface protection

5.3.2.11 When there is no alternative but to cross landslides and unstable slopes it is necessary to have an outline design prepared even at the feasibility study stage, based on investigated or anticipated ground conditions in relation to the final configuration of the alignment on the slope in question. It is common to find that a range of 'off the shelf' stabilisation options will have been identified during feasibility study, and even design stage, without any real consideration as to how they will be implemented in relation to the detailed vertical alignment and the materials encountered. It is important, therefore, to have at least an outline or concept design for each landslide or potentially problematic slope encountered before a decision is made to proceed with a particular alignment. This requires an early review of the following:

a) where are the major slope failures?
b) what is causing slope failure?
c) what are the likely depths and rates of ground movement?
d) what measures are likely to prove most effective in making the road safe?

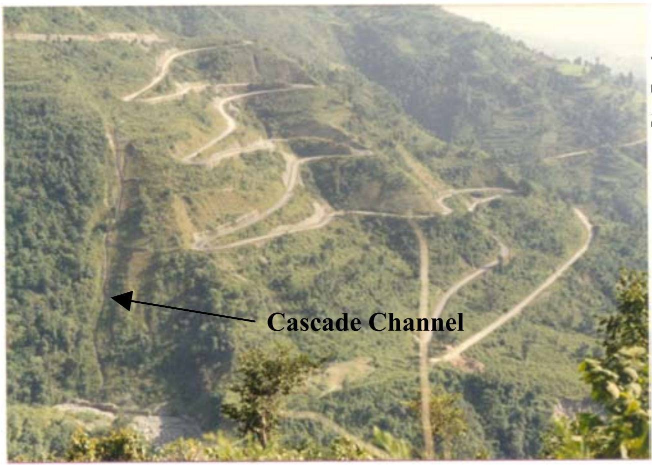


Road alignment passing through a recent and still active landslide scar, but the road formation has been made safe by the construction of a well-founded masonry wall.

5.3.2.12 These questions require desk study, remote sensing and fieldwork to yield the required answers (see Chapters 2-4 and sections 5.4 and 5.5 of this chapter). In addition, there needs to be a clear distinction between surface layer instability, or erosion susceptibility, and deeper slope instability. The former can be treated by provision of bio-engineering techniques; measures that are only applicable to surface protection to a depth of 0.5m to 1m depth. The latter, involving any instability below this level, requires engineering solutions such as earthworks, drainage, structures and reinforcement. Often, stabilisation options are referred to incorrectly as 'bio-engineering' techniques on the assumption that any slope problems that materialise during construction will be dealt with through the application of bio-engineering measures. It is important that engineers realise that the major slope problems that affect roads in a significant way cannot be dealt with by the use of bio-engineering when they occur. Geotechnical investigation of slope hazards should therefore be a critical element in any road construction and improvement project.

Drainage

5.3.2.13 Drainage of the road pavement and the subgrade is critical to the performance of the road, and the maintenance of cross-drainage is an essential element in this. Nevertheless, in most cases the detailing of drainage structures can be left until design and construction. The stability of the drainage system is an important consideration for the long-term stability of the alignment, particularly as drainage instability (channel bed incision and bank erosion) can have adverse effects on slope stability. Adequate provision must be made in the cost estimates for significant off-road slope protection at cross-drain inlets and outlets. The latter may need to extend regularly to 10m downstream or in excess of 100m in extreme cases.



Masonry cascade channel conveys side drain turn out runoff.

Spoil disposal

5.3.2.14 While spoil disposal cannot be planned and costed until mass-haul calculations are carried out during design, consideration must also be given to spoil arisings and spoil disposal during feasibility study. Initial identification of potential spoil areas should be made and this will enable typical haul distances to be assessed and quantities estimated for outline costing purposes.

5.4 Landslide Investigation

5.4.1 Landslide investigation for feasibility study

5.4.1.1 Landslide investigations for feasibility studies usually comprise the following elements:

a) desk studies;
b) field surveys;
c) landslide hazard and risk assessments;
d) analysis.

Desk studies

5.4.1.2 Desk studies ordinarily form the major part of a terrain and landslide mapping exercise during feasibility study. The following data sets are usually referred to:

a) topographical maps in hard copy and digital form if the latter are available;
b) geological maps and related data (publications, reports);
c) aerial photographs and satellite imagery;
d) land use mapping if available;

e) published records of landslides in the area (newspaper articles), rainfall and seismicity.

5.4.1.3 Usually most countries possess topographical mapping, geological mapping and aerial photographs, though scales may be small (especially in the case of geological mapping). The mapping itself may be old and out of date or unavailable in the border regions of some countries. In some cases there is little option but to supplement inadequate desk study with field survey.

Topographical maps

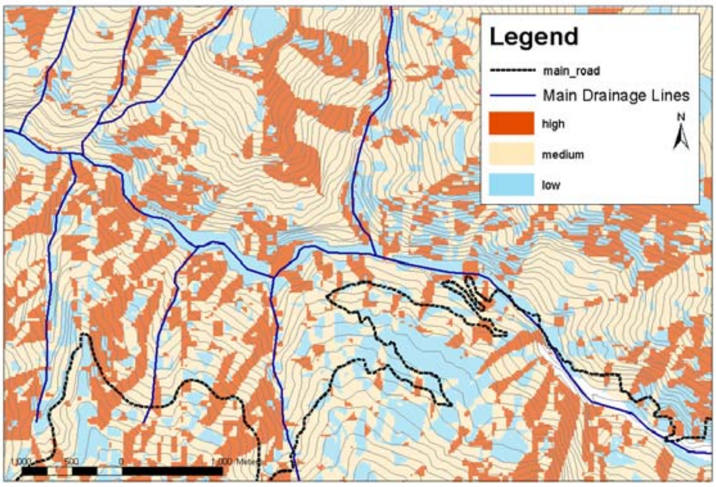
5.4.1.4 Topographical maps usually provide a reasonable indication of the difficulty of one alignment compared to another in terms of the steepness and complexity of the terrain. Although 1:25,000 is the preferred scale, accurate and detailed 1:50,000 scale contour maps can provide adequate representation of general terrain conditions for feasibility study purposes. A contour interval of 20m is the maximum recommended for reasonable terrain evaluation, although a 50m interval provides an approximation.

Geological maps

5.4.1.5 Geological maps vary considerably in their detail and accuracy. The mapped geology may have to be modified to varying degrees and there are occasionally significant inconsistencies across map sheet boundaries. However, most geological maps will show the broad distribution of the different rock types and lithologies, the main geological structures present, such as folds and faults, and the principal orientation of bedding planes or foliation. A prior knowledge of the strength or stability of the different lithologies present can provide an approximate indication of the relative stability of different alignment options, especially when rock types and slope angles are compared by overlaying the geological map with contour information portrayed on topographical maps.

Susceptibility maps

5.4.1.6 The relationships between geology and topography can be taken a stage further at feasibility study stage in the preparation of landslide susceptibility maps for the study area. The preparation of these maps is described in Chapter 3. They can provide a rapid overview of the relative stability of large areas and are best applied to the comparison of route corridors and the preliminary selection of the preferred route. They can be particularly useful when combined with landslide mapping from aerial photograph interpretation.

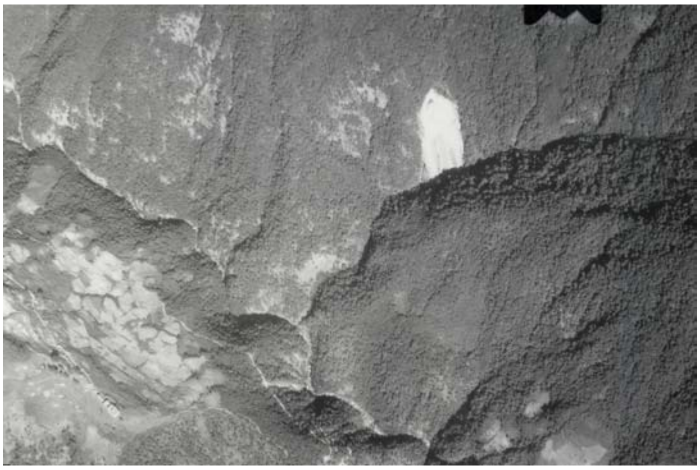


Landslide susceptibility map derived from a combination of geology and topography

Aerial photographs

5.4.1.7 Aerial photograph interpretation is an extremely useful multi-purpose technique for identifying and evaluating route corridor options. In particular it can provide information on the following factors:

a) topography (cliffs, river terraces, steep slopes, gullies and streams);
b) landslide mapping (source and runout areas, interpretation of mechanisms and causes by comparison with other terrain factors);
c) erosion mapping (slope and river bank erosion);
d) broad distinction between rock outcrop, residual soil, colluvium and alluvium (though differentiation between residual soil and colluvium can be difficult and sometimes unreliable);
e) structural orientations (faults and joint/foliation orientations through their control on topography);
f) land use;
g) interpretation of successive photography (if this is already available) can provide an indication of the rate of change in drainage patterns, erosion and landsliding.



Aerial photograph (taken in 1984) showing a recent landslide

Field photograph (taken in 2002) of the same landslide

5.4.1.8 The methods and recommended best practice approaches to aerial photograph interpretation are discussed in Chapter 2.

Field surveys

5.4.1.9 The purpose of field surveys is to confirm the desk study interpretation and gather whatever supplementary data is required to assist in the:

a) identification and selection of route corridor options;
b) assessment of slope, drainage and land use conditions within individual corridors;
c) determination of requirements for bridging and other high investment engineering structures along different alignment alternatives;
d) inspection of high risk locations to assess conditions and define potential engineering solutions;
e) assessment of potential material sources for road construction;
f) preliminary environmental assessment;
g) determination and assessment of any socio-economic and other non-technical considerations that might influence the selection of the alignment and the design.

5.4.1.10 While 1:50,000 scale topographical mapping can be used for broad alignment comparison, 1:25,000 scale mapping is preferable for recording specific data on topography, geology and landslides in the field. This is usually assisted by GPS (Geographical Positioning Systems) for accurate positioning. The following information can be recorded onto topographical maps directly in the field for confirmation of alignment and preliminary assessment of ground conditions for feasibility review and cost estimation:

a) locations of cliffs, steep slopes, ridges, gullies, streams, and rivers to draw attention to those features that are most relevant from an engineering point of view;
b) confirmation of geology and the broad distribution of colluvial and residual soils;
c) mapping of landslide locations and assessments of landslide size, depth, activity and risk implications;
d) site-specific observations, such as at bridge sites and high risk landslides;
e) land use types and land use practices, especially with regard to irrigation and slope drainage;
f) materials sources for construction.

Landslide hazard and risk assessment

5.4.1.11 Once a route corridor has been selected, it is then necessary to define the approximate location of the alignment and confirm its feasibility from an economic, engineering and environmental point of view. Landslide mapping and slope stability assessments should form an integral component of this exercise. Field-based assessments of landslides for feasibility study purposes should be based on the following indicators:

a) the distribution of colluvium (colluvium, being at residual strength, is usually susceptible to landslides and ground movements on steep slopes and/or where groundwater is high or where surface soils saturate);
b) the distribution of clayey residual soil on steep slopes and/or where groundwater is high or where surface soils saturate;
c) the location of landslide features, usually identifiable by head scarps and landslide deposits or flow deposits below;
d) the location of more subtle landslide features (usually identifiable through changes in slope morphology, the presence of an unusually large number of

boulders on a slope, disturbance to drainage patterns, ground cracking, springs and vegetation pattern);
e) damage to agricultural terraces, walls and buildings;
f) old landslide back scarp and side scarp features incorporated into agricultural terracing patterns.

5.4.1.12 The above are some of the features indicative of landslide locations. An indication as to whether an identified landslide or area of ground is still moving, either actively or intermittently, can sometimes be determined from the following indicators:

a) freshness of the scarp. How defined is it? Is it vegetated or bare? If it is vegetated, how recent is the vegetation?
b) freshness of the failure mass topography. Does it remain distinctly different from the surrounding slope morphology? Does it retain a different vegetation cover from the surrounding ground?
c) evidence for active ground stress. Are there active tension cracks above the slide area, within it or at its margins? Active tension cracks usually expose bare soils and can be traced across the ground surface into neighbouring 'undisturbed' soils where the ground is seen to 'boil up' rather than crack. This is indicative of incipient crack development or propagation;
d) evidence of oversliding or flow in the toe area. Can the toe of the landslide mass be seen to be overriding unfailed ground and other features, such as walls, paths etc?
e) active cracking and disturbance to neighbouring structures such as walls, houses and outbuildings;
f) evidence of disturbed vegetation. Are trees offset from vertical or otherwise disturbed?
g) is the slope continuing to be destabilised by high groundwater levels, an inflow of surface water (such as irrigation) or the removal of toe support, such as by stream or river erosion?
h) does the local farming community report active movements?

5.4.1.13 The majority of slope problems encountered during the longer term within road corridors are due to the reactivation of pre-existing landslides or areas of low strength colluvium. These landslides usually pose the greatest risk to road operation and maintenance. However, the assessment of landslide risk is not only reliant on the identification of existing landslides. Slope excavation for road construction can trigger first time failures and, as described in Chapter 4, recorded landslides are usually more numerous within road corridors than they are outside them, suggesting that many of the landslide problems encountered by roads are, in fact, self-generated.

5.4.1.14 The questions usually asked when an alignment is located across or close to an identified landslide are:

a) what will happen to the road?
b) when and how frequently will it happen?
c) what can be done to prevent it happening?

5.4.1.15 These questions are central to risk assessment and risk management. To answer these questions the following information is required:

Factual
a) the areal extent of the landslide;
b) the depth of the landslide;

c) the mechanism of failure;
d) the current rate of failure;
e) the location of the proposed alignment, both vertically and horizontally in relation to the geometry of the landslide;
f) the profile of the groundwater regime and how this varies with rainfall.

Analytical

a) the existing factor of safety of the landslide;
b) the effects of road earthworks (cuts and fills) on the factor of safety of the landslide;
c) the predicted effects of remedial measures (earthworks, drainage and retaining walls) on the final factor of safety;
d) the stability of individual engineering facets, such as cut slopes, fills and retaining walls when located on or close to the landslide in terms of temporary and permanent excavation stability, bearing capacities and foundation stability.

5.4.1.16 In some cases, a combination of engineering geological mapping and observational experience will allow this information to be derived sufficient for feasibility study and outline design. An experienced engineering geologist may therefore be able to answer the risk assessment questions with a degree of confidence. In other cases, and especially where the landslide is large and active, the level of risk dictates that there is no other option but to properly investigate and analyse the mechanics of movement before answers can be given with any degree of confidence. Landslide investigations and analyses may, therefore, be required even at feasibility study stage where the interpretation of landslide risk is critical to deciding between different alignment alternatives, or the feasibility of constructing and maintaining a particular alignment.

In the case of the Halsema Highway, located in the Central Cordillera of the Philippines, the assessment of the engineering feasibility and cost estimation for reconstructing the road after major earthquake and typhoon damage was dependent largely on geotechnical considerations. Ground investigations therefore formed a significant component of the feasibility study. Usually, however, geotechnical investigations and analyses are confined to the design stage of a road construction programme (see below).

Feasibility analysis

5.4.1.17 The analysis carried out at feasibility study usually comprises of engineering and environmental/social components and gives rise to the data required for a cost-benefit analysis. The engineering analysis requires the development of the engineering concept to an extent that allows a construction cost estimate to be derived within acceptable confidence limits. The length of the alignment will dictate the total cost of pavement works, side drainage and cross drainage works, while an assessment of materials will allow conceptual cutting angles to be derived for earthworks calculations when combined with broad topographic data. Point sources of high construction expenditure are almost exclusively considered to be bridging structures, major walling structures, and major scour protection works (when alignments are located close to valley floors). Slope stabilisation and, to a lesser extent, erosion control can also be significant, especially when the constructed design fails to control landslide problems that would otherwise have a continued adverse effect on the operation of the road. Furthermore, the environmental mitigation that should be mandatory on all roads, regardless of their status, usually requires the selective disposal of spoil material in stable and non-erosive locations, and this can represent a significant cost in steep terrain. At this stage, for cost comparison purposes, it is reasonable to apply average haul distances per cubic metre of spoil material based on an assumed spoil disposal area spacing. For individual large excavations it would be prudent to apply more specific haul distances.

5.4.1.18 Geotechnical analysis employed during feasibility study is usually concerned with the confirmation of bridge foundation feasibility and back analysis of landslides and failed slopes for outline review and costing of stabilisation.

5.4.2 Landslide investigation for design

Detailed survey

5.4.2.1 Detailed survey usually relates to the derivation of a ground model suitable for applying highway design software to the optimisation of the alignment, generation of cross-sections and the calculation of earthworks quantities. In the case of low cost rural roads, this is seldom carried out and the process of fixing the alignment is undertaken by a highway engineer/surveyor in the field once the corridor is identified. In this case quantities have to be calculated manually, and there is considerable room for error, especially in steep terrain. With the availability of desktop computer aided geometric design programs, and the capability of modern total station survey instruments to record and download large quantities of ground survey data, it is now cost-effective to use highway design software and produce designs which can be accurately measured and which provide cross-sections at critical locations for analysis. As these designs can be amended and fine-tuned as the project proceeds, the design can be optimised and, most importantly, impracticable or high volume earthworks, which may be overlooked in a less sophisticated design, can be identified and avoided.

5.4.2.2 Should an approach be adopted which does not permit the generation of a design based on surveyed cross-sections, then individual survey will need to be carried out in specific problem areas. In the case of difficult landslide slopes at least one cross-section will be required to allow analysis and general arrangement of remedial measures to be configured.

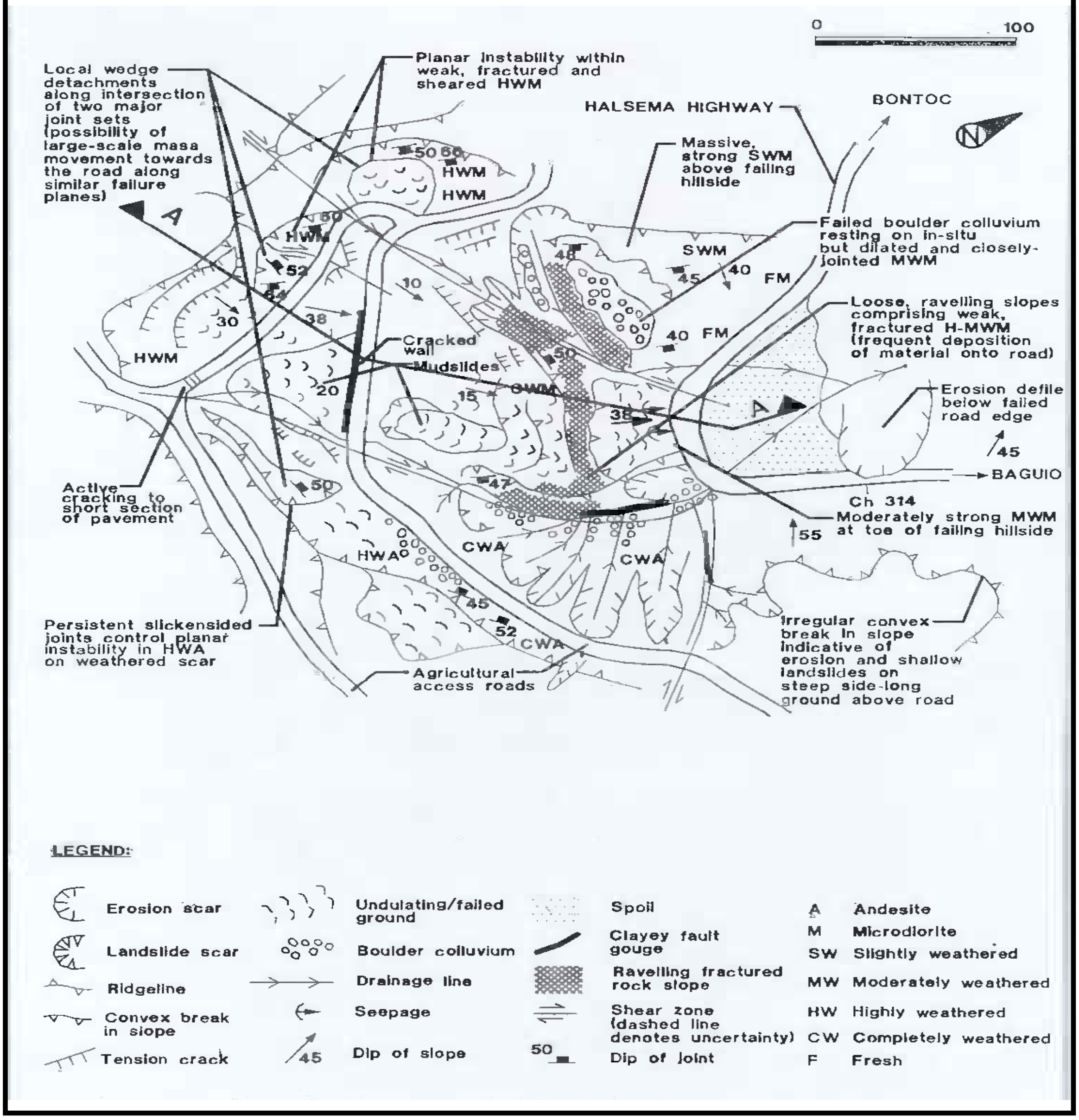
Engineering geological mapping

5.4.2.3 As part of the survey, engineering geological mapping will be required within the chosen route corridor for the following reasons:

a) routine geotechnical data needs to be collected for the detailed assessment of landslide hazard for design purposes;
b) sites and slopes requiring special geotechnical investigation and analysis need to be identified;
c) geological, soils and drainage data need to be derived to assist in the scheduling of cutting angles and the assessment of founding conditions for walls;
d) material sources need to be identified and evaluated for construction purposes.

5.4.2.4 There are standard procedures for carrying out engineering geological/geomorphological mapping, and these are described in various engineering standards. An illustration of an engineering geological map carried out for route alignment and design purposes through unstable ground is shown below.

Typical engineering geological map for road improvement purposes



5.4.2.5 The levels of investment available for the construction of low cost access roads serving low density rural communities are usually insufficient to support intensive geotechnical investigations, and it is therefore rare to find ground investigations undertaken other than at bridge sites. Whilst financial resources often pose a real constraint in this regard, failure to take due regard to landslide and slope hazards can result in major losses during construction and operation. In many of the less developed countries there is a growing availability of skilled engineering geologists capable of carrying out this work. The cost of employing a local engineering geologist for a month would be negligible compared to the construction cost of any mountain road, even those with the lowest of construction budgets, and often negligible in comparison to the cost of remediating the damage caused by a single landslide for which the engineering solution was not optimised.

5.4.2.6 At the design stage the detailed horizontal and vertical alignments and the choice of cross-section (cut, fill or retaining wall, where there is a choice) need to be fixed, and any stabilisation, drainage and slope erosion/river scour protection measures need to be designed. All of these design elements require slope-specific, drainage-specific and site-specific information that can only be derived from field survey and mapping, ground investigation and analysis. There is no choice but to derive these data and carry out conventional analysis for engineering design purposes. Once the alignment corridor is selected through desk study, susceptibility mapping and field reconnaissance, there can be no replacement for engineering geological mapping and geotechnical analysis.

Does landslide hazard mapping have a role during detailed design?

5.4.2.7 Ordinarily, landslide susceptibility and hazard mapping is confined to the selection of route corridors at the planning and feasibility study stage. During the design stage the route corridor is more or less selected and geotechnical attention needs to be focused on the assessment of individual landslides, slopes and sources of geotechnical hazard within the corridor. The use of a susceptibility or hazard-based approach to design is relevant when the corridor is wider and there are several options of detailed alignment location within that corridor. Also, there may be some advantage in lumping together several factors to gain a statistical overview of where high susceptibility or high hazard areas might occur. This could be based, for instance, on a combination of measured slope angle, soil type and soil depth, rock discontinuity data and weathering grade, drainage and seepage patterns and the locations of existing landslides and signs of slope distress. This information is usually portrayed on a detailed engineering geological map and can only be collected through intensive fieldwork over relatively small areas. It is therefore most relevant to the design of alignments within chosen corridors rather than the selection of corridors from large areas.

5.4.2.8 To conclude, there are certain circumstances when it might prove advantageous to produce a landslide susceptibility or hazard map for design:

a) when there is sufficient range in the selection of alignment within a given road corridor;
b) when there is a requirement to categorise slopes along an existing constructed alignment for slope management purposes;
c) when investment in road rehabilitation or upgrading works are being planned, again along an existing alignment.

Ground investigation

5.4.2.9 The parameters usually required to be determined from a landslide ground investigation include the following:

a) depth to in situ rock;
b) geotechnical characteristics of the overlying materials (strength parameters and density);
c) presence of any soil layers that may influence the location of existing/potential failure surfaces;
d) groundwater profile and soil moisture condition;
e) the depth and configuration of slip or shear surfaces.

5.4.2.10 Ground investigation conventionally comprises trial pits and drill / boreholes. Hand dug trial pits in landslide materials are cost-ineffective and potentially dangerous due to collapsing pit walls. Machine-dug trial pits are the preferred method of shallow excavation as long as access can be provided safely. It is rare to find failure surfaces exposed in trial pits, especially in granular soils. It is more common to find zones of disturbance, either in rock or colluvium, that represent the zones of sliding or shear. Trial pits, once excavated need to be logged according to recognised procedures but the safety of site personnel must be paramount.

5.4.2.11 Drilling is notoriously difficult in landslide deposits. The complexity of the ground usually makes interpretation difficult, and the presence of boulders slows drilling progress and can lead to spurious interpretations of depth to rock when large boulders are encountered. Core recoverability is usually very low and consequently the value of drilling operations, unless they are undertaken to prove the depth to rock head alone, needs to be taken into consideration before they are scheduled.

During the ground investigations carried out for the flood damage rehabilitation of the Prithvi Highway in Nepal a number of boreholes were put down to determine depth to rock head and to identify ground conditions for analysis and design. The results of the investigation were disappointing. In most cases bedrock was not encountered within economic drilling depths and the core recovery was so low that an assessment of in situ geotechnical properties was not possible. At one site, however, the failure surface had taken place through vertically inclined rock bedding and the discordant bedding recovered in the drill core enabled the failure plain to be pin-pointed accurately. It must be concluded, however, that this outcome is relatively rare, especially as most landslides that are likely to be investigated will probably comprise chaotic boulder colluvium and landslide debris.

5.4.2.12 There are occasions when a knowledge of the depth to rock is sufficient. These occasions include investigations undertaken to:

a) determine founding depths in rock for retaining walls;
b) determine the maximum likely depth of failure assuming that failure has occurred in overburden, or along the rock head/overburden surface.

5.4.2.13 Consequently, drilling can provide useful information concerning the practicality and cost of one design option over another, and can enable abortive excavations to be avoided during construction. It is recommended therefore that drilling investigations are only undertaken at locations where a knowledge of the rock profile is important in the analysis of stability or failure at a high risk landslide site. In most other cases a design can be developed through surface observation and trial pitting. Furthermore access for drilling rigs and excavators in remote areas may prove difficult and impracticable.

5.4.2.14 Non-intrusive seismic refraction surveys are being increasingly used in landslide investigations. While they offer some potential, they are reliant on there being a distinct variation in the seismic velocity of the soil/rock layers present in a slope. Failure surfaces that occur within colluvium for instance are unlikely to be identified from these surveys. Seismic surveys do not provide any details on the geotechnical characteristics of the soil, other than perhaps its inferred density.

Slope analysis

5.4.2.15 A slope analysis requires the following parameters to be defined:

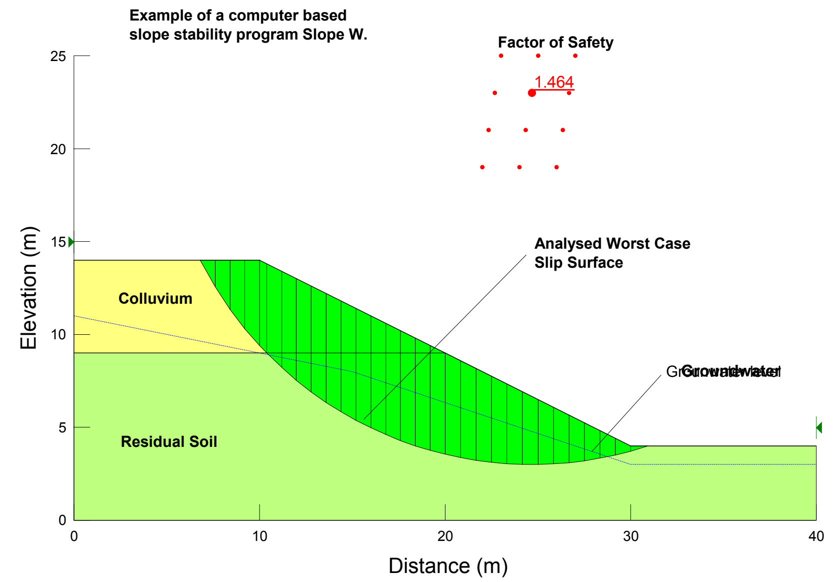
a) depth and configuration of the failure surface in the slope section;
b) strength and density of soil/rock materials and the configuration of any soil/rock layers;
c) groundwater table and/or soil moisture condition;
d) accurate cross-section for analysis.

5.4.2.16 Ground investigations and laboratory analyses can provide some of this data, but usually there are many uncertainties, unless intensive and costly investigation is being undertaken. Most methods involve the analysis of a failed slope that requires risk assessment and/or stabilisation. In this case, back analysis is undertaken of the slope to determine the condition of the slope at the time when failure took place. A factor of safety of 1.0 is assumed and, if the pre-failure topography can be reasonably surveyed, then the unknown parameters are reduced to:

a) failure surface location;
b) strength parameters;
c) water condition (assuming seismic acceleration is not a factor).

5.4.1.17 Field investigations combined with sensitivity analyses usually allow the slope failure conditions to be approximated. Laboratory test results can help, but they should be viewed cautiously as laboratory conditions usually fail to reproduce insitu slope conditions with the required reliability. Particle size distributions and classification tests, together with any insitu density probing (SPT or DCP) can provide useful assistance in deriving/confirming soil strength parameters. It must be borne in mind, however, that if a reactivated failure is being analysed, the strength of materials on the failure surface may be considerably less than the soil layer as a whole. Generally, it is common practice in most slope analyses carried out for low cost roads to rely more on assumed soil parameters and sensitivity analysis than it is to rely on laboratory test results, especially in heterogeneous mixed soils.

5.4.2.18 Once a plausible slope model has been constructed in the computer analysis, then remedial works can be incorporated into the model to test their influence on the factor of safety, using the same 'design' soil parameters, failure surface and groundwater condition. These normally include toe support by filling or retaining wall, drainage and flattening of the slope wherever this is possible. For high risk landslide locations the design should aim to achieve a factor of safety of 1.2-1.3. However, in the case of large landslides it may be difficult to achieve a factor of safety much above 1.0 and a risk management decision needs to be made as to whether the small increment in stability justifies the investment. If retaining walls form part of the stabilisation scheme, their stability against bearing capacity failure and overturning should also be analysed.



Computer based soil slope stability analysis

5.4.2.19 The analysis of potential first-time failures is difficult to carry out due to the usual lack of confidence in determining any of the slope parameters without intensive ground investigations and testing. The assessment of these slopes is therefore usually undertaken by engineering geological inspection and empirical methods.

5.4.2.20 It is not within the scope of these guidelines to review the analytical methods of slope stability analysis of soil and rock slopes. Nevertheless, in view of the obvious importance of this to landslide risk assessment, a selection of relevant suggestions for further reading is given at the back of this document.

Scheduling of slope works

5.4.2.21 This is done following engineering geological inspection and analysis. Usually, it is best to have a series of prescriptive measures to deal with readily identifiable slope problems. The sizing, design and arrangement of these measures of course will depend on each site condition. Table 5.4 provides some guidance, but the procedure to be adopted should follow the outline given below:

a) assess the scale of the failure, i.e. it's areal extent and likely depth;
b) assess the mechanism of failure and current rate of movement;
c) determine the likely cause of the failure;
d) assess the materials involved and the probable groundwater condition;
e) prescribe the combination of measures likely to be appropriate in yielding a solution (normally this is most likely to comprise a combination of toe support, trimming and drainage);
f) carry out whatever surveys are required to determine design and arrangement details;
g) apply standard details and site specific designs as appropriate.

Table 5.4 Proposed prescriptive measures for slope stabilisation/protection using the decision tree approach

Material	Site Conditions	Failure Mechanism	Site Description	Prescriptive measures
Rock Slopes	**Blocky rock mass** (Well spaced persistent discontinuities)	**Planar/wedge/ toppling failure**	Minor (small) rock block failures	1. Provision of rock catch ditch at slope toe (low cost) 2. Anchored wire mesh (medium cost) 3. Rock catch fence (low cost)
			Major (large) rock block failures	1. Removal of blocks by crow bar or by blasting (low to medium cost) 2. Rock bolts (medium to high cost) 3. Buttress and/or dentition (medium cost) 4. Dowel bars (medium to high cost)
	Disintegrated rock mass (Closely spaced intermittent discontinuities, or highly to completely weathered rock)	**Rotational/planar failure**	Large deep-seated slope movements with exposed slide scars in rock and significant ground disturbance, usually over large areas. Toe erosion by river at base of slope	1. Toe support through gravity retaining walls or anchored systems (high cost) 2. Cutting back of slope where feasible (medium to high cost) 3. Rock anchoring systems to the rock mass itself (high cost) 4. Scour protection at toe (high cost)
			No toe erosion	As for rotational/planar without scour protection
		Ravelling	Ravelling of small individual rock blocks	1. Provision of rock catch ditch at slope toe (low cost) 2. Anchored wire mesh (medium cost) 3. Rock catch fence (low cost) 4. Shot crete (medium cost)

Table 5.4 (continued) Proposed prescriptive measures for slope stabilisation/protection using the decision tree approach

Material	Site Conditions	Failure Mechanism	Site Description	Prescriptive measures
Soil Slopes	**Granular or fine grained**	**Shallow failure**	High groundwater level (active seepage)	1. Gabion or masonry toe wall with weep holes (low-medium cost) 2. Cut off drain at slope crest with slope drainage and erosion protection (low-medium cost) 3. Counterfort drains and erosion protection (medium cost) – soil nails (medium cost) 4. Soil
			Dry conditions	1. Remove failed mass (low cost) 2. Gabion toe wall (low-medium cost)
		Deep seated failure	High groundwater level (active seepage)	1. Remove failed mass where possible (low-medium cost) 2. Cutting back of slope where possible with surface protection and drainage (medium cost) 3. Horizontal drains with surface protection and drainage (medium cost) 4. Gabion toe wall founded on rock/stable soil with drainage (medium cost) 5. Soil nails with horizontal drains and surface protection (high cost) 6. Mini piles with horizontal drains and surface protection (high cost)
			Dry Conditions	As above but without the deeper drainage option, surface drainage should be used to prevent ingress of water.
			Removal of toe support by river scouring	1. Scour protection: gabion/masonry revetment, gabion mattress and groynes, rock armouring (high cost

5.5 Design of Earthworks

5.5.1 Introduction

5.5.1.1 On mountain roads this usually comprises the formation of cut slopes, though fill slopes are common on less steep ground. The following precautions and measures should be observed when designing and forming cut slopes:

a) the cut slope batter should be to the required design, determined by reference to the exposed materials;
b) the cut slope batter should be uniform (unless a benched cut slope is contemplated) with all overhanging materials removed. A batter board or similar control is required on larger cut slopes to prevent overcutting/undercutting;
c) any large boulders exposed in the cut slope during excavation can be left protruding from the cut slope if they are judged to be stable and their removal would destabilise surrounding materials, thus unnecessarily enlarging the cut;
d) rounding at the top of the cut slope to match surrounding slope profiles or erosion/gully features should be applied as necessary;
e) account should be taken of the variability in strength of materials exposed in the excavation. It is usual to find that weathered materials predominate towards the top of the cutting and consideration should be given to cutting these back to a shallower batter to compensate for their lower strength;
f) verification inspections should be carried out during excavation to identify low strength horizons or seepage lines which may require special attention, such as benching, drainage or surface protection.

5.5.1.2 Fill slopes suffer instability from the following causes:

a) inadequate compaction leading to settlement and erosion of the exposed soil;
b) settlement of underlying soft materials not removed prior to forming the embankment;
c) failure of embankment side slopes if they are constructed too steep or with sub-specification materials, including uncompacted spoil to make up road widths;
d) failure of the slope that supports the embankment either through pre-existing instability or through embankment loading.

5.5.1.3 The design and specification, and particularly the supervision of construction, must be applied to reduce the potential for these problems occurring. In particular, control of layer thickness, control of moisture content of fill material, control of variations in fill material and timing of compaction relative to wet or dry weather.

5.5.2 Designing cut slope angles

5.5.2.1 Slope stability analysis is traditionally divided between soil slope stability and rock slope stability. In soil slopes, failure either develops along a circular or, more usually, a non-circular slip surface, and is a function of the slope geometry, applied loads, water table and soil shear strength parameters. In the case of rock slopes, unless very highly weathered, the shear strength of the rock mass is many orders of magnitude higher than the shear strength along rock joints or discontinuities. Failure surfaces are therefore dictated by the orientation and dip of these joints and discontinuities relative to the slope face. It is usually the case along low cost rural roads for cut slope design angles to be prescribed according to anticipated rather than investigated ground conditions. An assessment is made of the likely composition of each section of road cutting and a design slope angle is applied, either on the basis of stability charts contained in publications referenced at the end of this document or on the basis of precedent (Table 5.5). Slope stability analysis and site-specific design are only undertaken in very deep cuttings, at high-risk sites or at locations of existing landslides.

Designing cut slope angles in soil

5.5.2.2 For soil slopes associated with low cost roads it is important to make an assessment of the different materials present on site. A basic stability assessment should be carried out so that a broad factor of safety can be determined for different slope angles within each of the materials classes identified along the road alignment. High risk cuttings may require ground investigation with more detailed stability assessments.

5.5.2.3 For low cost roads it is common to adopt a nominal factor of safety for cut slopes of 1.1 against slope failure. The cost of ensuring that all cut slopes during design have a factor of safety of not less than 1.1 under all conceivable geological and drainage conditions would be prohibitive. Variable ground conditions exposed during excavation will mean that some cut slopes will have actual factors of safety of more than 1.1 and others will have less. This is usually the most pragmatic approach and is based on the acceptability of localised failures during construction. Those failures that do occur during construction can be cleared away and mitigated, as necessary. This approach is not acceptable for cuttings at high risk sites (e.g. beneath existing building structures and housing areas, bridge approaches and deep cuttings), where a designed factor of safety is required.

5.5.2.4 Table 5.5 shows provisional design gradient/height relationships for soil cut slopes. The table is derived from observations made in Nepal. It should be noted that these figures are only meant as a guide. The design of any cut slopes will require a site-specific assessment.

Table 5.5 Prescriptive cut slope gradients for soil slopes

Soil Type	Water Table	Cut Slope Gradient (V/H)		
		Cut Height (metres)		
		0 – 3 m	4 – 6 m	7 –10 m
Clayey Silts (transported)	Low Moderate High	1.5 1.3 1.0	1.0 1.0 0.8	0.8 0.5 NA
Silts	Low Moderate High	1.0 1.0 1.0	≤ 0.8 ≤ 0.8 0.8	≤ 0.8 ≤ 0.8 NA
Coarse –grained Colluvium	Low Moderate High	1.0 1.0 1.0	1.0 1.0 0.8	0.8 ≤ 0.8 NA
Silt clays (residual)	Low Moderate High	1.5 1,2 1.0	1.5 1,2 1.0	1.0 1.0 NA

Taken from Overseas Road Note 16 (1997)

Designing cut slope angles in rock

5.5.2.5 A rock mass may display one or more modes of failure depending on various factors such as:

a) presence or absence of discontinuity sets;
b) orientation and dip of discontinuity sets relative to the natural or cut slope;
c) discontinuity spacing;
d) shear strength of discontinuity surfaces or infill;
e) persistence of discontinuities.

5.5.2.6 In analysing the stability of a rock slope, the most important factor to be considered is whether the stability of the slope is likely to be controlled by potential failure of the rock mass itself, or along persistent discontinuities. In most cases, observed failures occur along single discontinuities, where the geometry of the rock mass beneath the slope face becomes critical. The geometrical relationship between the discontinuities in the rock mass and the slope and orientation of the excavated face will determine whether parts of the rock mass are free to slide or fall, giving rise to three dominant mechanisms of failure:

a) planar sliding along a discontinuity (planar failure);

b) sliding along the intersection of two discontinuities (wedge failure);

c) toppling failure.

5.5.2.7 The second most important factor is the shear strength of the potential failure surface, which may consist of a single discontinuity plane or an irregular path along several discontinuities and involving some fracture of the intact rock material. Further discussion on the different modes of failure are given in the publications referenced at the back of this document.

5.5.2.8 As with soil slopes, on low cost roads rock slopes should be assessed during design in general terms, not on a slope-by-slope basis. At high risk sites discontinuity mapping and stereonet analysis should be employed. Design charts can be used to assess whether or not a slope is critical and therefore requiring a more detailed assessment. In general, for low cost road construction and operation, minor individual rock blocks are of little significance, and consequently the following recommendations are based on rock failures greater than 10 m^3 in volume.

Recommended procedure for rock slope analysis

5.5.2.9 To make an initial assessment of the rock slopes on site it is important to take into account the broad properties of a rock mass (as discussed above). To do this it is important to determine both the different rock types present and the nature by which the rock mass will fail.

Rock type

5.5.2.10 The strength of intact rock is dependent on rock type. Table 5.6 lists the different rock types commonly found in the Himalayas grouped on the basis of strength, with group G1 forming the strongest group, and G4 the weakest.

Table 5.6 Rock type groups

Group	**Rock Types**
G1	Gneiss, Granite, Granodiorite
G2	Quartzite, Diorite and Gabbro
G3	Sandstone, Breccia, Hornfels, Rhyolite, Andesite, Basalt and Tuff
G4	Siltstone, Mudstone, Schist, Slate and Phyllite

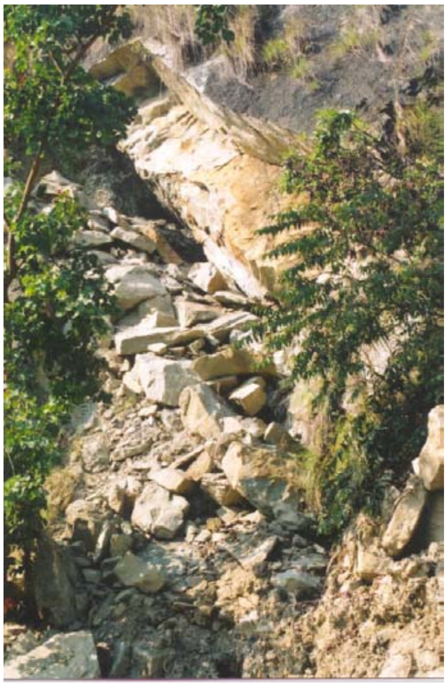
Analytical methods

5.5.2.11 Before cut slope angles can be designed, an initial assessment of the nature of the rock mass should be undertaken in order to determine the likely mode of potential failure and therefore the most appropriate method of analysis to be used. This initial assessment should determine areas on site where the rock could fail as a result of either non-structural (i.e. rock mass) failure or structurally – controlled failure.

Analytical method 1
Non-structurally – controlled failure in rock

Highly fractured rock mass without continuous joint surfaces.

Analytical method 2
Structurally – controlled failure in rock



Combination of planar sliding and toppling along persistent discontinuities.

Non-structural failures (analytical method 1)

5.5.2.12 This case applies to blocky or disintegrated rock masses, dominated by closely spaced, interlocking joints, with more than four sets of discontinuities, including thinly laminated or foliated, tectonically sheared weak rocks, where the failure occurs through the rock mass rather than along persistent discontinuities. Reliable estimates of the strength and deformation characteristics of rock masses are required for almost any form of analysis used for the design of slopes in these materials. The Geological Strength Index (GSI) provides an estimate of the strength of jointed rock masses, based upon an assessment of the interlocking rock blocks and the condition of the surfaces between these rock blocks. Table 5.7 shows the different cut slope gradients determined from using both the GSI and other analytical slope stability methods. The values in the table are typically for cut slopes approximately 10 m in height. This table should not be used for intact or massive rock as failures within these types of rock masses tend to be determined by discontinuities (see structurally-controlled failure below).

Table 5.7 Cut slope angles for rock masses without structural control

Rock Mass Description	Discontinuity Roughness			
	VERY ROUGH Very rough, fresh unweathered surfaces	**ROUGH** Rough, slightly weathered, iron stained surfaces	**SMOOTH** Smooth, moderately weathered and altered surfaces	**SLICKENSIDED** Slickensided, highly weathered surfaces with compact coatings or fillings of angular fragments
Intact or Massive –Massive in situ rock masses with very few and widely spaced discontinuities	**Discontinuity-controlled failures (see analytical method 2)**			
Blocky/Very Blocky – Interlocked undisturbed to partially disturbed rock mass with multifaceted angular blocks formed by three orthogonal discontinuity sets	G1 & G2 60° to 65° G3 & G4 50° to 60°	G1 & G2 60° to 65° G3 & G4 50° to 60°	G1 & G2 50° to 60° G3 & G4 45° to 50°	G1 & G2 45° to 50° G3 & G4 40° to 45°
Blocky/Disturbed – folded and/or faulted with angular blocks formed by many intersecting discontinuity sets	G1 & G2 45° to 50° G3 & G4 40° to 45°	G1 & G2 45° to 50° G3 & G4 40° to 45°	G1 & G2 40° to 45° G3 & G4 35° to 40°	G1 & G2 40° to 45° G3 & G4 35° to 40°
Disintegrated – poorly interlocked, heavily broken rock mass with a mixture of angular and sub rounded rock pieces	G3 & G4 35° to 40°	G3 & G4 35° to 40°	G3 & G4 35° to 40°	G3 & G4 35° to 40°

The cut slope angles in the above table are derived from analytical methods that do not reflect the entirety of ground conditions found on site and should be used as a guide only. They are based on a 10 m high cut in slightly to moderately weathered rock.

Structurally-controlled failures (analysis method 2)

5.5.2.13 For intact or massive rock masses, where large volumes of the rock mass are bounded by a limited number of widely-spaced discontinuities, potential slope failure mechanisms usually fall into one of three categories (as discussed previously):

a) planar instability;
b) wedge instability;
c) toppling.

5.5.2.14 In order to assess stability on an individual slope-by-slope basis discontinuity data needs to be collected for each slope. This data should then be plotted up on a stereonet allowing analysis of the discontinuities with respect to the slope geometry (kinematic analysis).

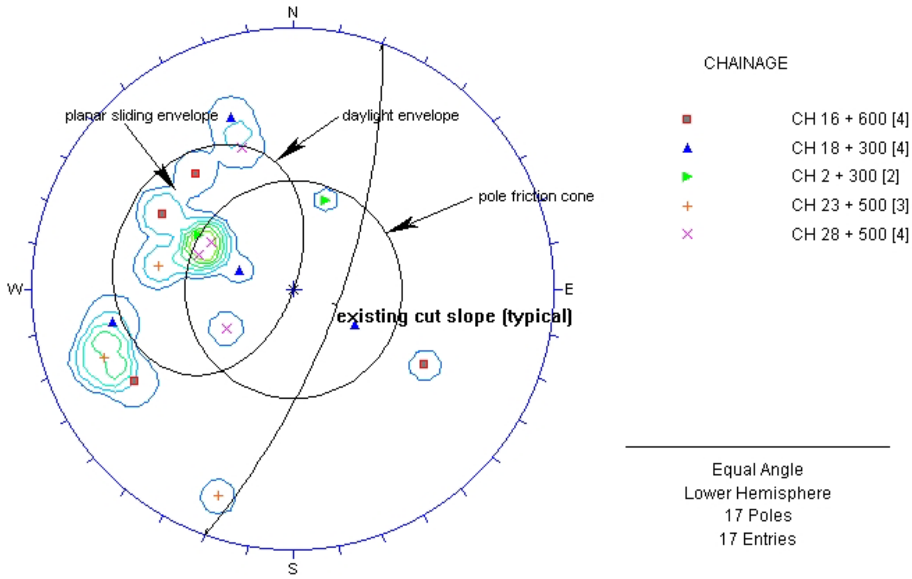


Diagram showing a stereonet for a rock slope. In this particular stereonet the slope is being analysed for planar failure.

5.5.2.15 However, in the case of low cost rural roads it is not practicable to design each individual slope using stereonet analysis. Therefore, for the purpose of these guidelines, Table 5.8 has been compiled giving a range of cut slope angles for different combinations of rock type and structure. The table incorporates both rock type and discontinuity parameters, by combining different rock types into groups based on a) relative strength (as in Table 5.6), b) discontinuity versus slope geometry and c) whether or not the discontinuities are closed or infilled. With respect to b), a discontinuity angle of 30° has been adopted as this represents the basic friction angle of the discontinuity when closed. The presence of any infill material along the discontinuity acts to decrease the friction angle, leading to lower factors of safety and therefore lower permissible cut slope angles. The table itself has been developed from the analysis of individual rock slopes in Nepal approximately 10 m in height.

Table 5.8 Cut slope angles for slopes with a structural control

Rock Type Group	Discontinuity Dipping out of Slope at an Angle > 30° to the Horizontal		Discontinuity Dipping out of Slope at an Angle < 30° to the Horizontal		Discontinuity Dipping into slope	
	Closed	**Infilled**	**Closed**	**Infilled**	**Closed**	**Infilled**
Group 1	65 – 80	40 – 45	80 – 85	45 – 50	80 – 85	80 – 85
Group 2	60 – 75	40 – 45	70 – 80	45 – 50	75 – 85	75 – 85
Group 3	60 – 70	40 – 45	70 – 75	45 – 50	75 – 80	75 – 80
Group 4	55 – 70	40 – 45	65 – 75	45 – 50	70 – 80	70 – 80

This table is intended only as a guide. Each rock slope will require its own site assessment in confirmation of cutting angles

Other important considerations

5.5.2.16 The design tables shown above are for guidance only. The cut slope angles are based on observations on data from slightly to moderately weathered rock masses in Nepal. Lower cut slope angles will apply where rock masses are highly weathered, and completely weathered rock masses should be analysed as soil. Individual cut slopes should be assessed on a slope-by-slope basis taking into account other factors such as groundwater, height of slope, the weathering grade of the material and any land use effects.

5.6 Slope Stabilisation and Erosion Protection

5.6.1 Soil slope stabilisation techniques

5.6.1.1 Figure 5.3 illustrates the principal measures available for stabilising soil slopes. Table 5.9 provides comments on the application and limitations of the various techniques. Illustrations of slope stabilisation and slope erosion protection schemes are shown in the accompanying photographs.

5.6.2 Rock slope stabilisation techniques

5.6.2.1 Some of the more common techniques for treating rock slopes are illustrated in Figure 5.4 and commented on in Table 5.10. Some illustrations are given in the accompanying photographs.

Table 5.9 Soil slope stabilisation techniques

Requirement	Technique	Where?	Limitations
Avoid problem	Realign road	Anywhere, if feasible	High cost; may create similar problems; slow to implement
	Completely or partially remove unstable material	Only if small quantities are involved and at shallow depth	Only feasible for minor, shallow slips; may create further instability
	Construct bridge to allow debris to move beneath structure	Mainly at re-entrants	High cost, slow to implement; requires confidence that re-entrant margins are not prone to further instability
	Construct catch wall	Mainly steep slopes in weathered rock if sufficient space at toe	Must be capable of containing slip debris; slip may become more extensive upslope
Reduce driving forces	Regrade slope	On any slope where reduction in cut slope angle is feasible	Unlikely to be feasible in steep terrain, surface will need erosion protection
	Drain surface	Anywhere	Will only reduce surface infiltration, therefore combine with other techniques
	Drain subsurface	Anywhere where water table is above slip surface	More effective when sliding mass is relatively permeable
Increase resisting forces by application of an external force	Construct breast/retaining wall	Anywhere	Moderate cost; must be founded below slip surface; may need to be combined with other techniques
	Construct toe berm	Anywhere if space available	Usually requires significant space at toe
	Install anchors	For slope stability, used mainly to increase FoS of unfailed slopes	High cost; specialist installation equipment needed, potential corrosion/monitoring problems
Increase resisting forces by increasing internal strength	Drain subsurface	Anywhere if water table is above slip surface	More effective when sliding mass is moderately permeable
	Install soil nailing	Usually used to steepen cut slope angle e.g. for road widening	High cost; specialist installation equipment needed. Applicable to unfailed slopes mostly.
	Use bio-engineering	Anywhere where slip surface is very shallow (<1m maximum)	Not suitable for steep slopes and deep-seated failures. Planting mix must include deep and strong-rooted shrubs.

Photographs showing different soil slope stabilisation and erosion protection measures

Shotcrete surface erosion protection

Mortared masonry retaining wall with mass concrete ribs for support

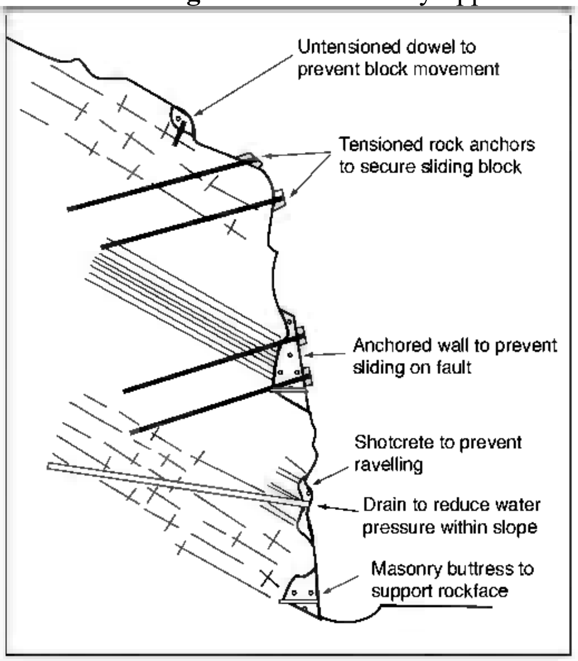
Gabion toe wall used to stabilise a shallow landslide (though poorly constructed)

Installing soil nails

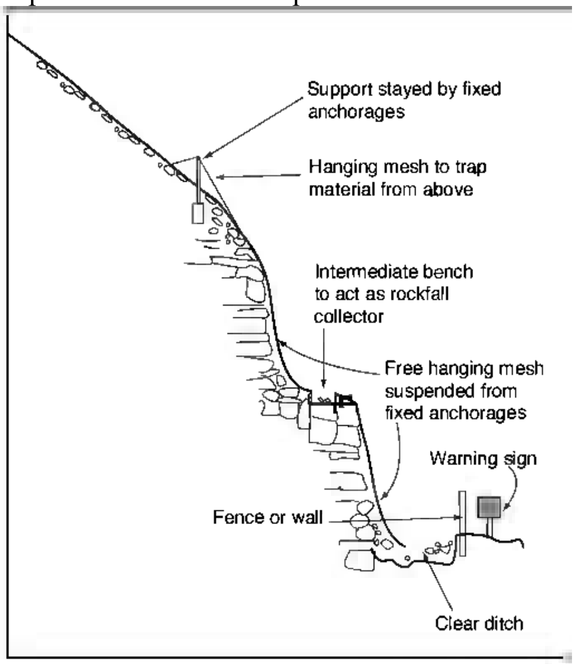
Bio-engineered surface erosion protection with masonry toe wall

Gabion toe wall with hand placed rock backfill for stability and surface protection

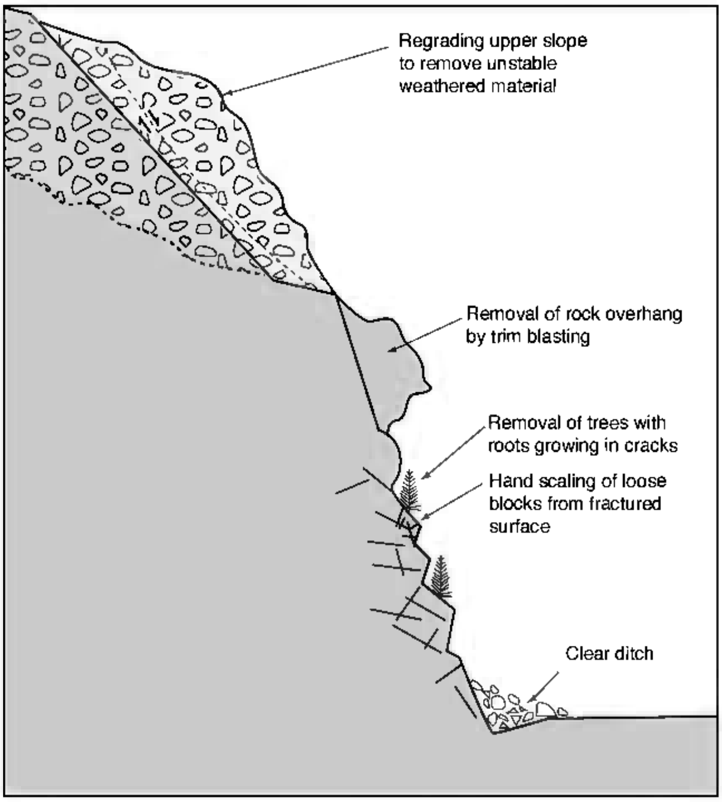
Figure 5.4 Commonly-applied rock slope stabilisation techniques



Reinforcement methods



Rockfall control methods



Removal methods

Table 5.10 Rock slope stabilisation techniques

Requirement	Technique	Where?	Limitation
Stabilisation – Reinforcement	Rock bolting	Any potentially unstable block that can be bolted and tensioned back to stable material	High cost; installation using specialist equipment; long term corrosion/creep problems
	Dowels	Any potentially unstable block that can be kept in place by passive dowel	Use usually restricted to blocks 1-2m thick
	Tied-back walls	Where multiple rock bolting is required to provide load spread	Same as for rock bolting
	Shotcrete	Closely fractured or degradable rock face	Specialist equipment required
	Buttresses	Cavity on rock face	Potential access problems
Stabilisation – Drainage	Drainage	Any rock face where water pressures in fissures create instability	Drilling equipment necessary for drain holes. Drain holes may not function very well in fractured rock
Stabilisation – Removal	Regrading	Instability at crest of rock face	Potential access problems; difficult in very steep terrain
	Trimming	Overhangs, steep slopes	Controlled blasting techniques required
	Scaling	Loose rock on surface	Labour intensive; potential access and safety problems
Protection	Catch ditch	Base of slope where space permits	Shape of ditch dependent on height and slope of rock face
	Mesh	Loose/weak rock on surface	Will not retain major blocks; good anchorage required at top of face
	Barrier	Base of slope where space permits	Needs to be robust to halt movement onto road
	Shelter	At base of high unstable face where other measures not feasible	Very high cost
	Tunnel	If relocation only solution	Very high cost

Illustrations of measures for rock mass support

Masonry buttresses to prevent further degradation of weathered weak strata interbedded with stronger strata →

Example of a mass concrete buttress used to stabilise a sliding rock block

5.6.3 Retaining Structures

5.6.3.1 The range of retaining wall options available for slope stabilisation is illustrated schematically in Figure 5.5 and listed in Table 5.11. Table 5.11 differentiates between externally and internally applied systems. Externally applied systems relate mostly to conventional structures such as gabion and masonry breast and retaining structures, while internally applied systems involve some form of soil or rock mass reinforcement. Since many of these options are typically too expensive for low cost rural road applications, economic considerations will tend to dictate the frequency and type of wall selected. Nevertheless, at locations of high risk or active instability there may be no alternative but to select a high cost option. For instance it is not practical to construct a masonry structure where there is a high risk of rock or boulder fall; a reinforced concrete structure is necessary to minimise the damage from falling rock. An anchored structure may be the only solution in steep terrain with adverse jointing.

5.6.3.2 Before commenting on the various wall types shown in Table 5.11, it is necessary to comment on one of the most important aspects of wall construction, this being verification of founding levels. The difficulties in accessing, investigating and defining wall foundation levels during the design is a matter of fact. Only rarely will precise levels have been defined by trial pitting or drilling and even then spatial variations will affect these levels. It is essential that wall foundation levels are verified during construction. Since walling is often used to retain debris deposits and these generally contain a basal layer of large rock debris, it is essential that machine excavation is carried out where at all possible. Care must be taken to avoid constructing an expensive wall on weak material, especially if in situ (original ground) material underlies this at shallow depth.

During excavation of storm-damaged walling in Nepal and the Philippines it has been observed that many walls have been founded on boulder debris or on uncompacted excavated spoil material placed on sloping ground. In many cases an in situ material was proved within 500mm to 2000mm of the original founding level. It is assumed that the insufficiencies in the original foundations were due to a much greater reliance on hand excavation and budget limitations which combined to restrict founding depths.

Figure 5.5 Typical retaining wall cross-sections

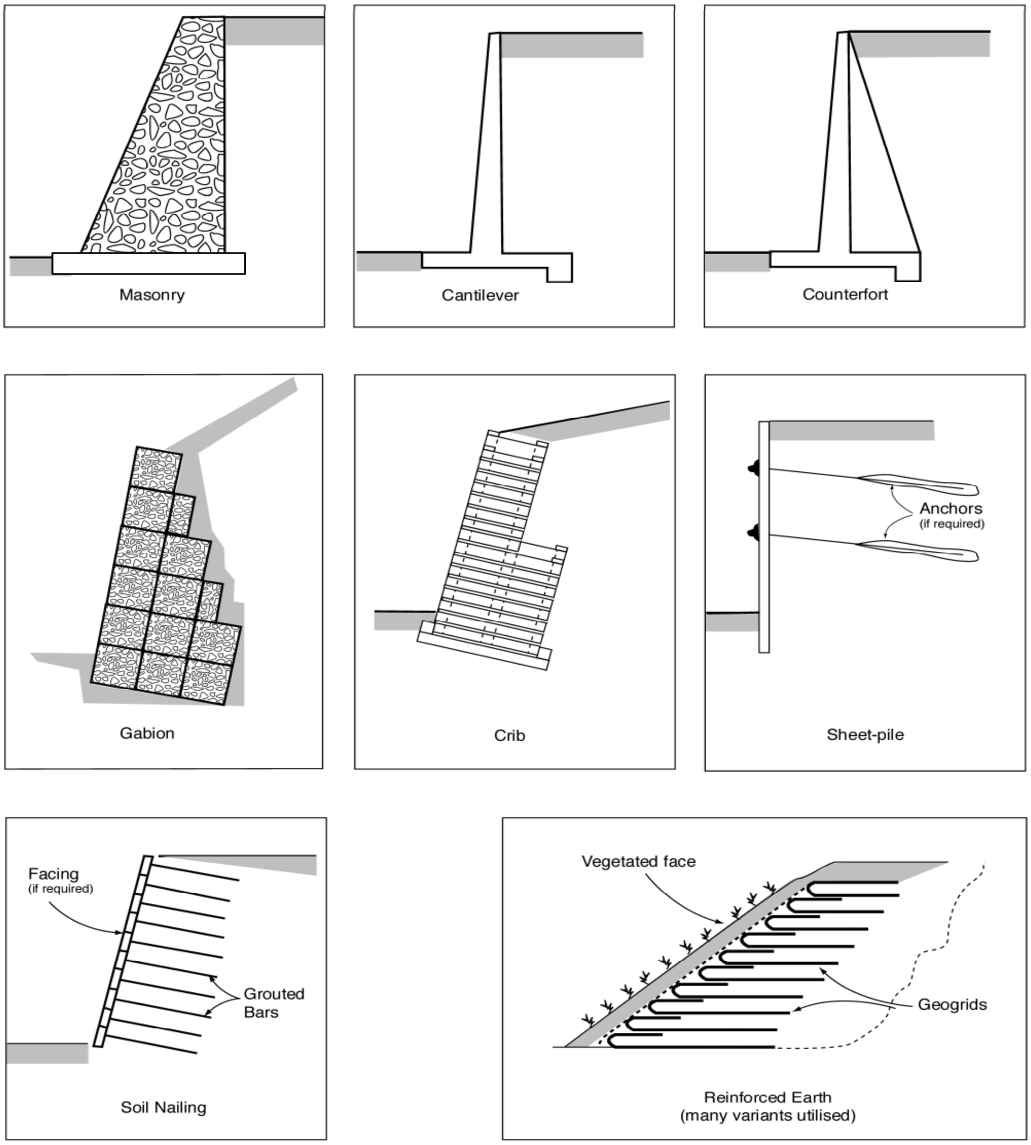


Table 5.11 Types of retaining structures, their advantages and disadvantages

System	Type	Advantages	Typical dimensions	Limitations
Externally stabilised	Masonry	Technique well known	Base width B Height H, B=0.6H Maximum height unless stepped =8m	Unable to accommodate movement without distress
	Mass concrete	Simple to construct	Base width B Height H, B=0.6H Maximum height =7m	Large quantities of concrete required
	Reinforced concrete - cantilever	Generally occupies less width	B=0.5H uneconomic above 8m height	Requires reinforced concrete construction; good foundations
	Reinforced concrete - counterfort	As above	B=0.5H	As above, but can be constructed to greater heights
	Gabion	Technique well-known; can accommodate limited movement without distress; permeable	B=0.6H	Moderate durability; not recommended as retaining walls below and immediately adjacent to paved road surface due to flexibility
	Crib	Attractive, environmentally-friendly appearance	B=0.5H	Possible problems of durability if timber cribs are used
	Composite grid	Generally occupies less width	B=0.4H	Requires reinforced concrete construction and masonry; good foundations;
	Sheet pile	Occupies very limited space, no temporary excavation works required	Anchors need to be outside 45˚ to 55˚ line from toe	High cost; requires specialist installation equipment; impermeability may create problems
	Slurry walls		Anchors need to be outside 45˚ to 55˚ line from toe	
	Bored-in-place piles		0.8m to 1m diameter, difficult and expensive to install through boulder debris	Very high cost; requires specialist installation equipment
Internally stabilised	Strips and grids	Can accommodate limited movement without distress; easy to construct	Minimum strap length 3m, preferably minimum 5m. Difficult to tie in to end taper	Occupies large space behind wall face
	Soil nailing	Used extensively when steepening existing cut slopes	Prescriptive 3m to 5m length at typically 3m spacing	Requires specialist installation equipment and only suitable for soils which dilate prior to failure (not suitable in loose soils)[1]

[1] soil nails mobilise shear resistance between soil particles and the soil nail. For slope movements to develop in medium dense to dense soils (typically residual or completely decomposed rock soils), dilation must occur which increases the shear resistance thereby resisting further movement. In soils which have experienced tectonic shear and high seismic stresses, the soil particles tend to be loosely packed and thus shear resistance provided by soil nails is low, rendering them generally ineffective.

Gabion walls

5.6.3.3 Gabion walls are quite commonly used on rural roads. They are usually adopted where seepages and continued earth movements are anticipated. Gabion walls can be used as breast or toe walls and as retaining walls. In some circumstances it may be impracticable to halt movement entirely as it may be brought about by unexpected groundwater conditions, for example, that were not catered for in design. Also, weak or unstable foundations may result in a degree of structural settlement which may be unavoidable in practice. In these cases the implications of continued small movements and settlement in the road pavement must be considered. Especially in these circumstances particular care should be exercised in the procurement and construction of such walls. There are large cost savings to be made by contractors in using substandard locally available weathered rock to fill the baskets. This may lead to large local deformations of the structure under load, putting at risk the performance of the structure itself. In addition, where fine-grained soils are retained or are used as backfill, especially where significant groundwater or surface water runoff is expected, it is important that a graded stone filter or filter geotextile is placed behind the gabion structure in order to reduce erosion of the backfill.

Mortared masonry retaining wall to retain loose granular colluvium

Gabion retaining wall to support a shallow failure in colluvium

Masonry walls

5.6.3.4 Masonry walls have performed extremely well on the whole, in those cases where they have been properly designed and constructed. Masonry walls can be utilised as thin-section breast walls, gravity retaining walls and as headwalls for culvert inlets and outlets. Masonry is much less expensive and simpler to construct than concrete and can be used wherever the foundation is in rock, weathered rock or dense soil. In order to ensure a load spread, especially in dense soil and weathered rock, a 200mm thick concrete footing is usually incorporated. This footing also provides a starting surface for construction of the masonry. Key stones are embedded in the top of the footing to provide shear resistance. Quality control of masonry walling is essential. Stone must be durable and free from micro-fissures and should be of specification shape and size. Cement mortar must be of the required compressive strength and mixed and placed in accordance with the specification. In this regard it is essential to have a minimum compressive strength (17.5N/mm^2) and compliance testing needs to be carried out.

In many mountain areas mortared stonewalling is a traditional skill. With use of proper materials walling of a very high quality can be obtained. Nevertheless it is often observed that weak rock and improperly mixed mortar are utilised and that there is sometimes an over-reliance on unskilled labour in order to cut costs. These trends should be prevented through close supervision.

Concrete walls

5.6.3.5 Concrete walls of various types are less commonly used than gabion or masonry walls although their use becomes more frequent in areas where hard durable stone is not freely available. Concrete walls are generally used for the same foundation conditions as masonry walls and may be gravity retaining walls or reinforced cantilever or counterfort walls. The latter normally become cost-effective for wall heights exceeding 6 metres, with a counterfort section becoming more efficient for increasing heights. Concrete walls are preferred to masonry walls in locations susceptible to rockfall due to their greater robustness.

Composite walls

5.6.3.6 Composite walls consisting of a mix of dry stone or of masonry and reinforced concrete are utilised in certain circumstances to suit site specific situations. Grids of reinforced concrete infilled with panels of grouted masonry have been utilised where the required wall heights are 5m or greater and where space for gravity structures is insufficient. Reinforced concrete buttresses and reinforced concrete base slabs can be utilised to provide additional load-spreading capacity where localised weaker ground is encountered. In all these applications, care must be taken in detailing site specific walls so that drainage is not compromised and the factors of safety against overturning and sliding are sufficient.

Reinforced concrete composite walls with mortared masonry infill panels

5.6.3.7 Some of the less typical wall types are discussed briefly below. However, they are unlikely to be used in the majority of low cost rural road construction schemes due to their expense.

5.6.3.8 *Anchored retaining walls*. Special mention must be made of anchored retaining walls. Anchored walls have been constructed successfully on a number of road projects at critical locations, either with composite reinforced concrete/gabion or with reinforced concrete walls. Situations can arise where the importance of the road and the instability problem are so great that a conventional solution is not appropriate. However, the main problem with anchored retaining walls is that not only do they require specialist installation equipment to install the anchors, but the anchors themselves must be adequately protected against corrosion for the design life of the structure. They are also very expensive and accordingly are normally used sparingly.

5.6.3.9 *Crib walls*. Crib walls can consist of timber or concrete members pinned together to form a gravity structure. This form of structure is less common as it appears to have no advantage over gabion and reinforced earth structures for which proprietary materials and designs are available. In particular the use of timber for long-term structures requires very stringent quality control.

5.6.3.10 *Soil nailing*. Soil nailing, if protected with a structural facing can be termed an anchored revetment. It has very limited applications due to its high cost, but might be considered to protect an enforced steep cut below a high risk site, such as housing or an electricity pylon.

5.6.3.11 *Reinforced earth walls*. Although these are used extensively around the world, they do not appear to have been used very frequently, if at all, in the low cost rural road sector. The most likely reasons for this are the lack of technical expertise, the need to import reinforcing strips or geogrids, the requirement for good compaction, and the difficulties in working in confined spaces and non-uniform sites. Reinforced earth walls utilising geogrids or gabion mesh would appear to be a potential option for rural roads, particularly for new road construction where the limitations on working space are not so stringent as those for the rehabilitation or widening of existing roads. Reinforced earth can be used in both rock and soil slope situations.

5.6.3.12 *Buttressed walls*. Masonry buttressed walls can be used to provide additional support to a wall undergoing minor distress, provided a good founding layer can be located for the buttresses. However, experience of such applications shows that during excavation adjacent to the existing wall, previous unsatisfactory construction often dictates that the structure must be completely rebuilt. These walls may also be designed to act as supports to reinforced concrete road slabs, thus providing additional road width in critical locations. Their application is mainly as reinstatement of erosion damage where the ground conditions are not adverse.

5.6.4 Slope drainage

5.6.4.1 Drainage control during construction and maintenance is critical to the stability and management of the site. Uncontrolled runoff can create major erosion problems within very short periods and it is therefore imperative that the contractor implements a coherent surface water management scheme during construction. This scheme needs to be functional throughout the construction period. A common mistake is to assume that heavy rain only falls during the wet season. This is routinely shown to be incorrect in mountain environments, where localised intense rainstorms can occur at any time of the year.

5.6.4.2 Efficient drainage must form an important element in the permanent works as well. In many instances staged road construction in rural locations is carried out under drip-fed funding. Delays between the completion of earthworks and construction of drainage often result in significant erosion, which creates or becomes the catalyst for major instability.

5.6.4.3 Slope drainage, applied to stabilise landslides and unstable slopes, as described in Table 5.9, can often result in a marked improvement in the stability of a slope. However, the cost of such drainage severely limits its use and it is only implemented where it can be proved to be critical to stability. The most common forms of drainage are open drains or trench drains, often formed in a herringbone fashion. Counterfort drains and horizontal drains, being more expensive, are usually limited to major problem locations. Table 5.12 describes some of the functions and limitations of slope drainage types and brief description is given in the following paragraphs. Figure 5.6 shows some outline designs.

Table 5.12 Types of slope drainage, their function and limitations

Function	**Type**	**Advantage**	**Limitation**
Interception of surface runoff	Unlined cut-off drain	Cheap	May create line of instability beyond crest; may be prone to erosion
	Lined cut-off drain	Less prone to erosion and leakage	Requires frequent inspection for damage/blockage; inspection access may be difficult
Interception of high/perched water table	Herringbone drain	Able to intercept water up to a max of approx 1.5m depth below slope face; good for intercepting surface seepage or springs; can accommodate some slope movement	May only have limited effect on overall slope stability for deep-seated failures. Good quality control during construction is essential
	Counterfort drain	Able to intercept water up to 3m depth below slope face; can act as a stabilising buttress if base is below slip surface	Usually needs to be machine dug; difficult to construct in boulder material
Interception of deep water table	Horizontal drain	Only feasible method of intercepting groundwater at depth	Moderately costly; track drilling equipment required; may not always be successful
Diversion or improvement of watercourse or gully	Lined channel or cascade	May be necessary if existing watercourse is direct cause of instability	Usually very expensive and often difficult to construct
Reduction of erosion in gully	Check dam	Relatively cheap, often necessary below re-entrant retaining walls	Effective only for a limited length of gully in steep terrain

5.6.4.4 *Cut-off drains*. In the context of slope stability and erosion control, cut-off drains are sometimes used to reduce surface runoff at the crest of a cut slope or slope failure. In order to reduce the likelihood of continuing slope movements breaching the drain, they are sometimes located many tens of metres above the failure crest. The problem with cut-off drains is that unless they are regularly maintained, they can create their own instability problems (e.g. due to a blockage or breach). Since they are usually situated in locations of difficult accessibility where they cannot be seen from the road, maintenance is easily forgotten. On balance, it is not recommended that cut-off drains be constructed unless regular maintenance can be assured and there is a demonstrable advantage in constructing them.

5.6.4.5 *Herringbone drains*. Herringbone drains are constructed herringbone fashion on slope faces to collect surface seepages and surface runoff. They are often quite shallow (about 1m deep). In order to function as intended, it is recommended that the upslope face is lined with a geotextile, that the lower face and invert is lined with heavy-duty polythene, and that the drain itself is filled with free-draining gravel. Care needs to be taken to ensure that the construction of the drain does not lead to further instability, and to ensure that the drain can still function in the event of minor downslope movements. In the event of large anticipated flows, a perforated high-density polypropylene pipe may be necessary at the base of the drain.

5.6.4.6 *Counterfort drains*. Counterfort drains are used to depress a high water table. These drains are constructed at right angles to the toe of the slope and are often dug to a depth of 3m or more at intervals of 3-10m depending on the permeability of the subsoil. Ideally the sides should be lined with a geotextile and the invert with polythene. A perforated high-density polypropylene pipe is likely to be necessary for large flows.

5.6.4.7 *Horizontal drains*. Horizontal drains are used to intercept groundwater and seepage at depth. They require the use of specialist drilling and installation equipment that may not always be available, and they are not easy to install. The drains usually comprise minimum 40mm diameter polyethylene pipes up to 40m long installed in fan-shaped pre-drilled holes inclined 5 degrees upwards. The pipes are perforated and wrapped in a geotextile to reduce the likelihood of clogging. In theory, if not in practice, they should be capable of being flushed with water and eventually removed and renewed. The biggest problem with this type of drain is that it is costly to install and is not always successful unless the subsoils are very permeable or the drain is able to intercept seepage lines at depth. Additionally, the drains are only able to cope with very minor continuing slope movements. Although there are a number of sites where such drains have performed very successfully, in general they are not recommended for use on rural road networks except in conjunction with other measures at major landslide sites.

5.6.4.8 *Sub- soil drains.* In wet areas it is often good practice to improve drainage of the road and the slopes below by installing a French drain beneath the side drains. These drains are commonly 2m deep with a perforated polypropylene pipe in the base that discharges into the adjacent culvert inlet

5.6.4.9 *Lined channels or cascades*. Although really beyond the scope of these guidelines, lined channels or cascades are likely to be necessary if a watercourse or gully is a direct cause of the instability in the first place. A lined channel may be necessary to divert an existing watercourse from the failed area, or to train the watercourse within defined limits. The lining itself may be impermeable (cemented masonry and/or concrete) or permeable (gabion). The drainage structure may comprise cascades and check dams (see below). As a general rule, gabion structures are preferred since they are flexible.

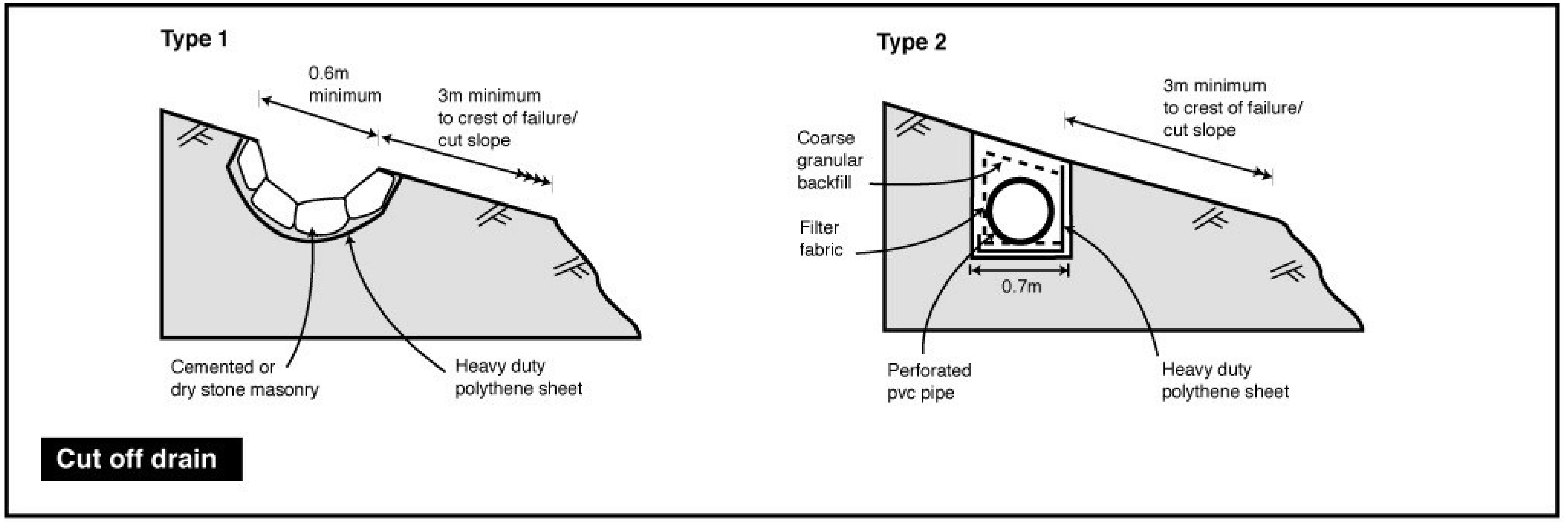
Cement masonry lined channel founded beneath failure surface and hence undisturbed

Masonry cascade channel constructed on a relatively stable slope.

Damaged gabion cascade channel located on a slow moving landslide

5.6.4.10 *Check dams*. Check dams are necessary where excessive stream scour would otherwise occur. They are often particularly necessary below valley side retaining walls where an earlier failure has created a preferred drainage path. Check dams are preferably constructed in gabion and must be properly keyed into the gully sides, although if weathered rock has been exposed by down-cutting a masonry check dam may be more appropriate. The extremities should be raised at least 250mm to minimise the possibility of end scour. The dams should be backfilled, and an apron or gabion mattress provided at the toe on the downstream side to dissipate the flow energy. In situations where erosion is just beginning to initiate a live check dam

Figure 5.6 Typical drainage structure layouts



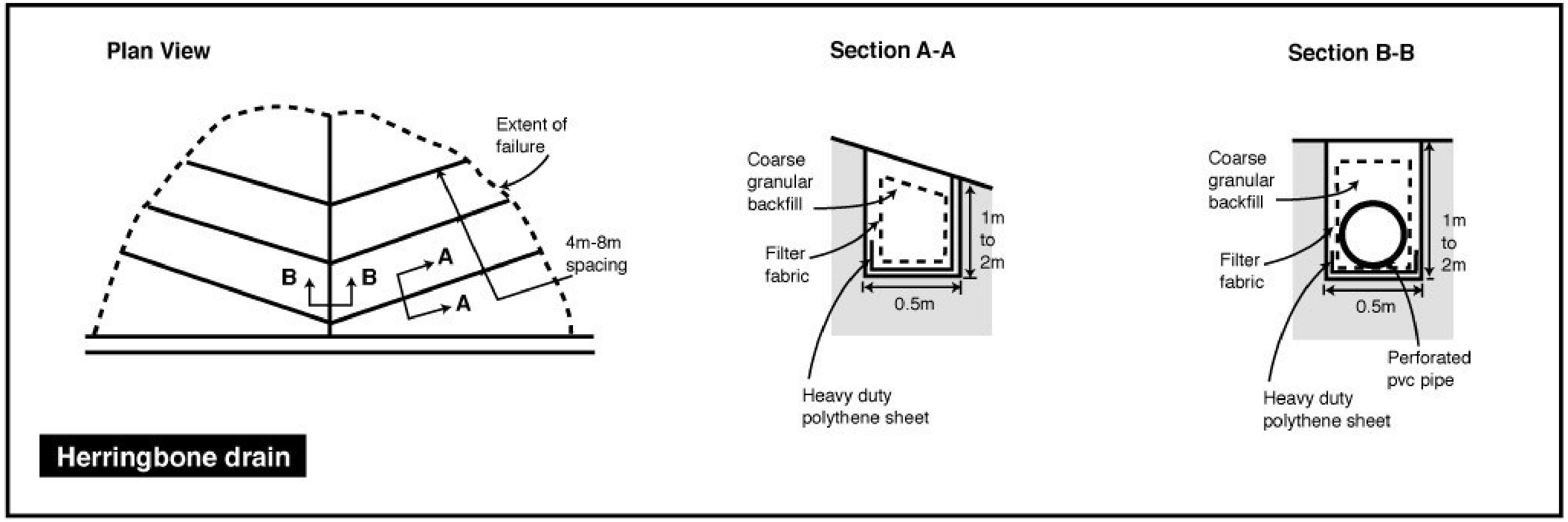
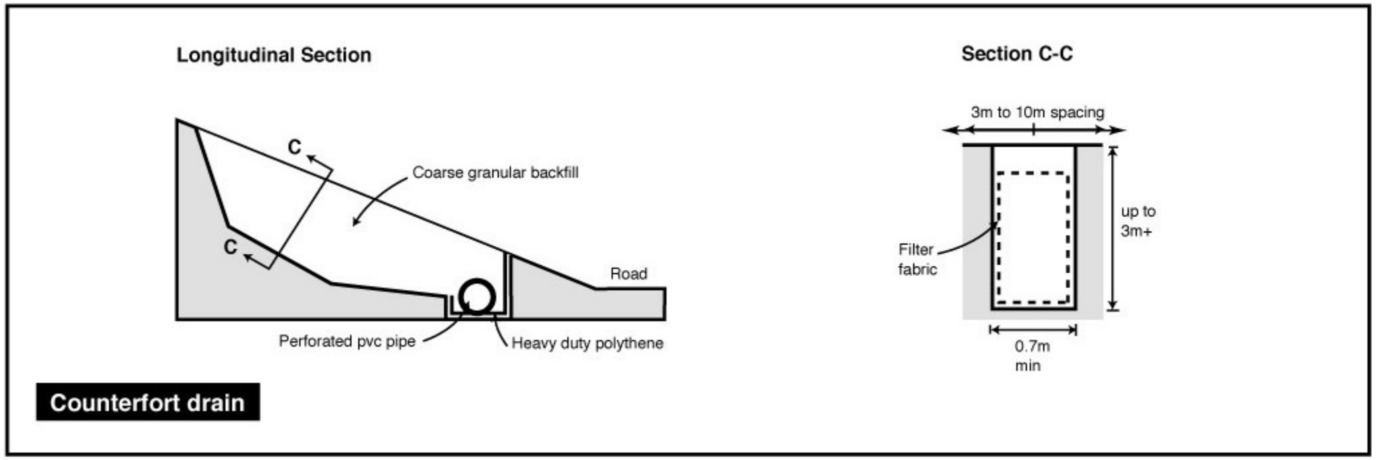
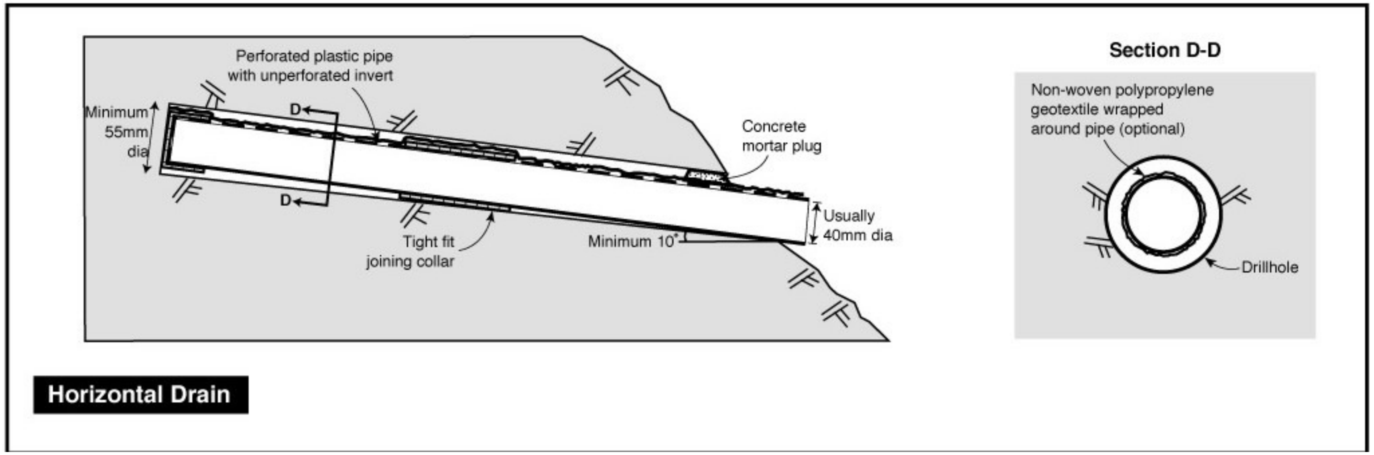


Figure 5.6 (continued) Typical drainage structure layouts





consisting of a bundle of live wood cuttings can be staked into the ground and backfilled with soil and rock as a low-cost solution.

5.6.5 Spoil disposal

5.6.5.1 The disposal of surplus excavated material and landslide debris is a major issue in the design, construction and maintenance of mountain roads. It is often not practical to use excavated materials as fill, either because of excessive haul distances, or because of unsuitability. It is therefore of the utmost importance to select suitable disposal locations as close to the sources of spoil material as possible. In decreasing order of preference, these are:

a) on level ground or terraces;
b) in dry valleys;
c) on the tops of spurs;
d) at steeper locations protected by resistant bedrock;
e) at locations that are as far away from the edge of the road as possible and where property and public safety are unaffected.

5.6.5.2 Wherever possible, the following recommendations should be observed:

a) never place spoil material downslope in a 'sinking' area. At the very least remove it to the boundary of the area before side casting;
b) try to use a number of suitable dumping locations rather than a single location, to reduce the risk of slope overload;
c) avoid the disruption of natural water courses, since this may result in major erosion;
d) avoid tipping spoil material over retaining walls, unless it is quite obvious that the wall is founded on non-erodible material, i.e. rock.

5.6.5.3 In practice the above guidelines are often difficult to achieve. In many mountainous regions agricultural land is in short supply and often areas meeting the above criteria have already been selected for agriculture. Landowners are rarely willing to handover such areas for short-term spoil disposal purposes. Therefore, available spoil disposal areas are limited and are often areas of marginal stability that require very careful consideration. Consultation with landowners may be necessary to satisfy them that adverse environmental affects, such as instability and contamination of agricultural areas or water sources, will not occur.

5.6.5.4 In areas of significant potential instability it is essential that spoiling is carefully considered and haulage of spoil to approved spoil disposal areas is allowed for in the specifications and bills of quantities. It is often the case that acceptance of significant haulage of material may be the preferred option in order that destabilisation of roadside slopes does not occur. In this case, a few large spoil disposal locations, where mitigation and protection structures and drainage can be afforded due to the benefits of scale, may be the most effective solution. In some circumstances there may be scope for the creation of usable community areas at larger spoil disposal areas, and at the consultation stage the need for platforms for health, school or recreation purposes may be identifiable.

5.6.5.5 It is preferable for at least a moderate degree of spoil compaction to be carried out, especially at the larger sites in order to reduce settlement and erosion problems later. Otherwise as a minimum, upon completion of a spoil disposal operation, efforts should be made to compact the spoiled material surfaces, reshape if necessary, and carry out appropriate bio-engineering methods to increase resistance to erosion.

5.6.5.6 In view of the importance of efficient and stable disposal of spoil it is recommended that identification of spoil disposal areas is carried out as part of the design and that consultations encompass this activity during the environmental assessment phases of a project. Monitoring of this activity should be included in the Environmental Management and Audit Plan.

5.6.5.7 Finally, as proper management of spoil disposal has a significant cost, funding must be provided through appropriate items in the bills of quantities. This should not be hidden as a contractor's overhead to be covered in general earthworks items, as this is likely to encourage the contractor to avoid his responsibilities and the associated additional costs.

5.7 Conclusions and Future Developments

5.7.1 The observations and recommendations made in this chapter are not new: they are known to most civil engineers working in the rural road sector. The problem appears to be one of a lack of opportunity to apply best practice to locate, design and construct rural roads in such a way as to minimise landslide problems. This may be due to lack of funds, it may be due to lack of access to the required data and information, or it may be due to the importance of other factors in governing the approach adopted.

5.7.2 There is a large volume of literature that deals with the stabilisation of slopes and the application of bio-engineering works to slope and drainage protection. However, there is very little published guidance on how to approach feasibility and design studies in such a way as to take adequate and due consideration of existing and potential landslide problems. There are few engineering guidelines on how to evaluate geology, geomorphology, and how best to make the most of desk study and remote sensing data. Geologists are aware of these procedures, but in so many low cost road programmes there is too little geological or geomorphological consideration given to the development of the design.

5.7.3 This chapter has sought to make the reader aware of the benefits of geological and geomorphological considerations being incorporated into the planning and implementation of mountain road projects. Particularly for new roads, the benefits of following the advice contained in this chapter can help avoid unnecessary stability problems, minimise environmental impacts and maximise the performance and sustainability of the completed road.

5.7.4 In order that the advice can be followed the following actions and procedures are recommended:

a) skills should be developed through training of land conservation officers or engineers at a regional or local level in the implementation of the procedures detailed in this document. This should be initially through a centralised training officer or consultant directing and periodically auditing outputs, leading to a gradual handover of responsibility. As there is a need for exchange of experience and rationalisation of approach based on feedback, there should continue to be periodic audits and review meetings at a national level;
b) skills training needs to concentrate on encouraging a proactive approach in the implementation of techniques and approaches explained in this document. The engineering principles are not new. However, the inclusion of geomorphological/geological/geotechnical considerations in the planning and route selection process, and the detailing of appropriate and cost-effective slope works, walling and drainage measures, are the key to a sustainable design. Such

a design can only be obtained by a rational and balanced approach based on an understanding of the natural processes affecting the road and road corridor;

c) consultation with stakeholders should be a key component of the environmental assessment. This process should include assessment and agreement on spoil disposal areas, resourced through inclusion of adequate provision in the bills of quantities.

Appendix 1

FIELD RECOGNITION OF LANDSLIDES

FIELD RECOGNITION OF LANDSLIDES

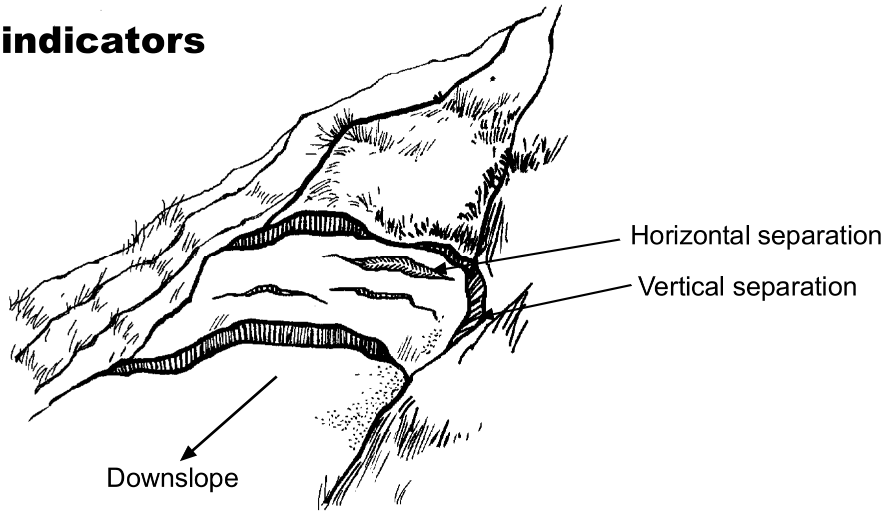
The table below provides a description of some of the more common indicators of landslides and slope movement on the ground. Sketches and photographs that provide further illustration (where practicable) follow the table.

No	*Landslide Indicators*	*Description*
	Active Landslides	
1	Tension cracks	Often orientated in an arc and are continuous, they may show vertical displacement from one side of the crack to the other.
2	Slip scarps	Steps across terraces and other slopes
3	Disturbed/displaced terracing	Lines of vertically/laterally displaced terracing often mark the margins of ground movement
4	Hummocky ground	Slope surface is irregular and often formed by a series of low amplitude hummocks
5	Cracking to structures and paved surfaces	This can be due to local settlement of fill and foundations, so supporting evidence is required, unless effects are extensive
6	Dislocation of drainage structures	Either directly observed or seen as seepages
7	Springs and seepages	Giving rise to marshy ground
8	Trees leaning backwards or with curved trunks	Both wind, steep topography and ground movement can give rise to non-vertical tree trunks, so care is required in their interpretation.
	Relict Landslides	
9	Spoon-shaped landforms	Steep upper scarp often semi-circular, lower angled, possibly tongue-shaped deposit
10	Chaotic debris forming landslide deposits	Boulders often protrude above the surface
	Hummocky ground	Slope surface is irregular and often formed by a series of low amplitude hummocks
11	Steep soil slope located in depression between rock outcrops	Most first-time failures (ie non-colluvium landslides) in mountain areas occur in soils and fail along the weathered rock boundary
12	Lack of mature soil profile, indicative of the ground having been disturbed	The normal profile of weathered rock giving way to relatively dense in situ soil is replaced by a structureless, and usually loose, soil, frequently grey in colour
13	Disturbed vegetation, or uncharacteristic vegetation pattern	This indicator could be land use related, so it needs to be interpreted with care. Alder is frequently among the first to colonise recently failed slopes.
	Colluvium vulnerable to movement	
14	Steeply sloping ground in colluvium	Boulders often protrude above the surface, with poor vegetation cover
15	Slopes where water is seen to collect	Marshy waterlogged ground in colluvium
	Future first time failures	
16	Slopes underlain by adverse geological	Dip slopes will fall into this category. Smooth and persistent joint surfaces can often be seen forming

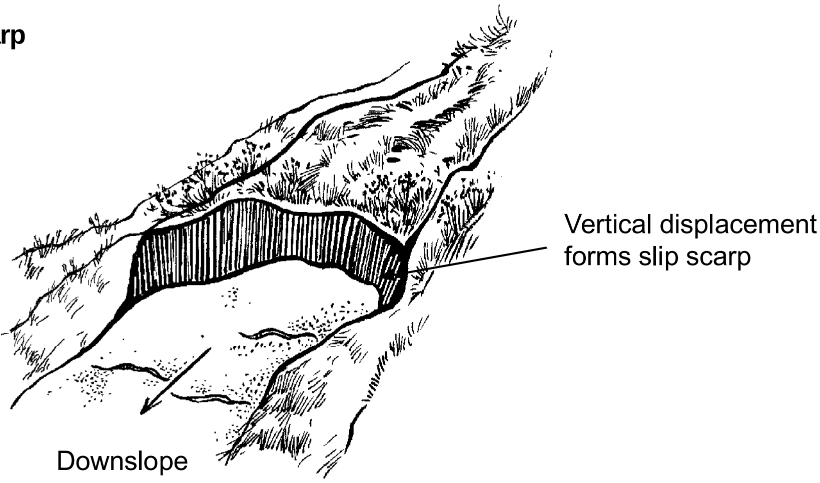
	structures and rock types prone to failure	segments of slopes, and these could be potentially prone to failure
17	Outcrops, slopes and deposits adjacent to active fault zones	Without geological field survey these zones can usually only be determined from published geological mapping
18	Slopes likely to be prone to river or stream scour at their base	This should be observable on the ground or from aerial photography
	Debris flows from upstream	
19	Large landslide scarps present on the catchment slopes above with little or none of the landslide debris remaining	Indicates that the majority of debris was removed instantaneously, possible as a debris flow in the drainage system below.
20	Relict or slow moving landslide masses located adjacent to or above drainage lines could rapidly become debris flows downstream if instantaneous failure were to occur.	This requires a knowledge of existing and potential landslides located on the catchment slopes above.

Active landslide indicators

1. Tension cracks



2. Slip scarp

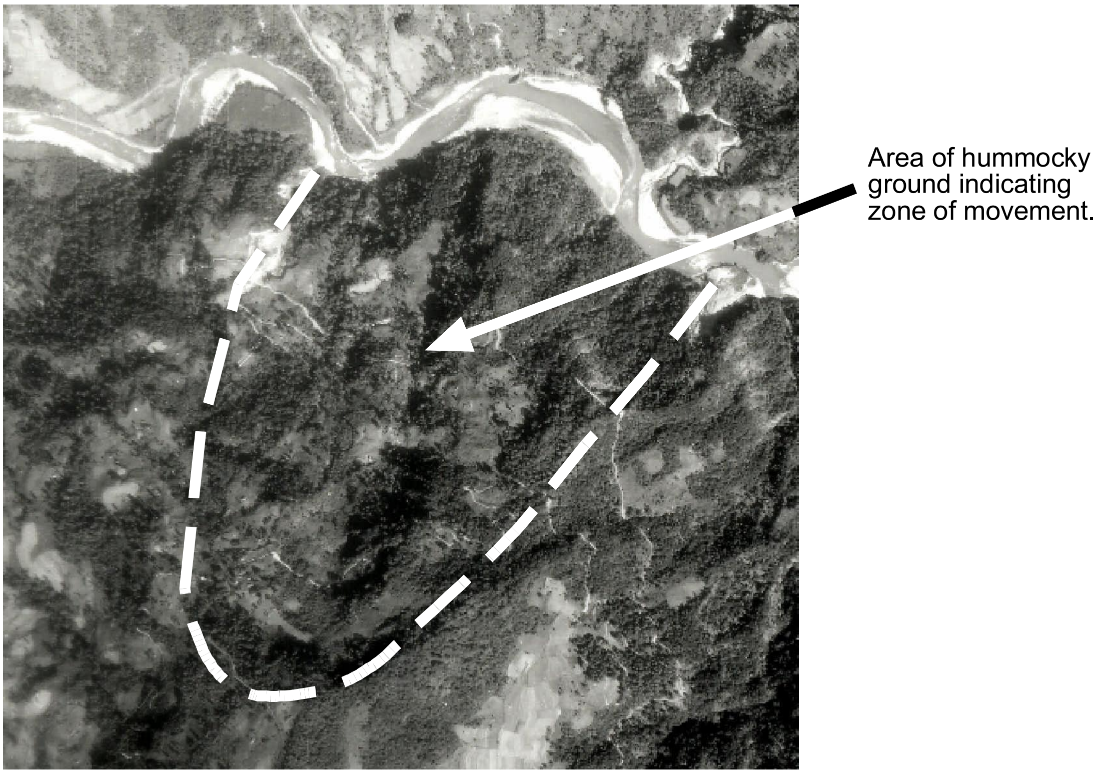


3. Disturbed / displaced terracing

Large landslide scar in foreground undercutting agricultural terraces

Appendix 1 Landslide indicators

4. Hummocky ground



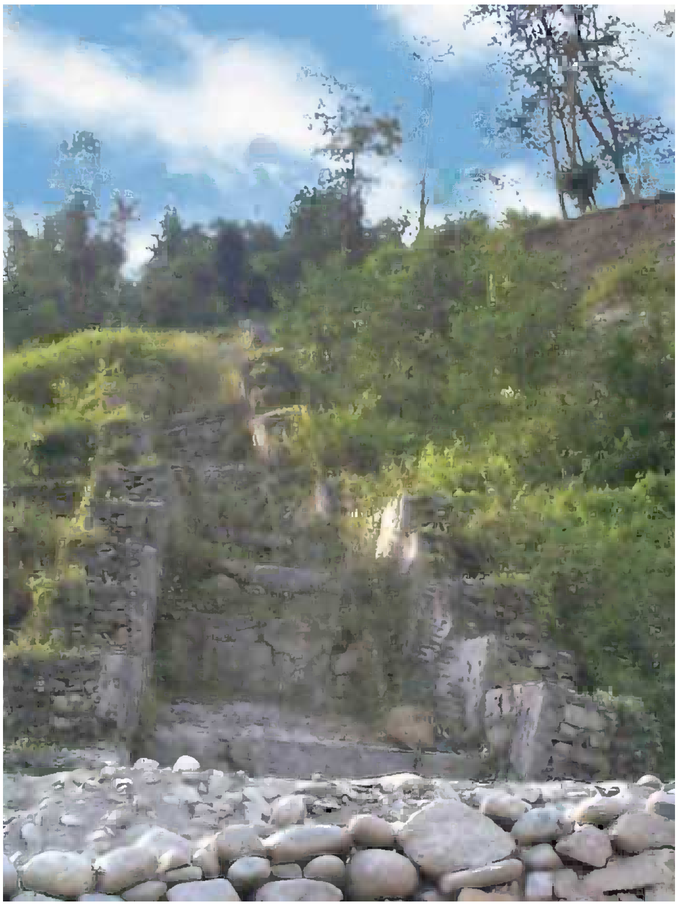
Aerial photograph showing hummocky ground evidence of recent and ongoing ground movements.

5. Cracking to structures and paved surfaces

Severe cracking in a mortared masonry toe wall.

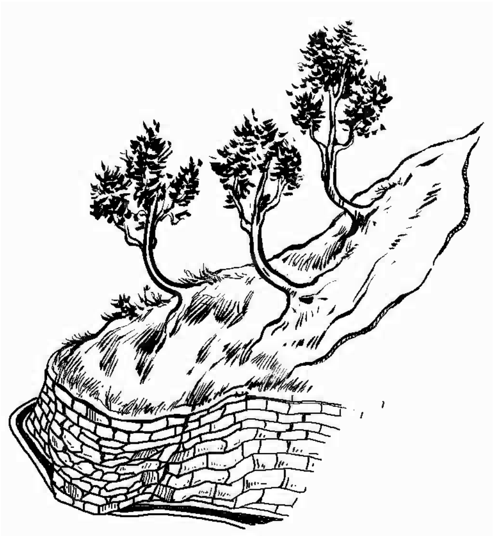
Appendix 1 Landslide indicators

Severe cracking to road, as a result of undercutting by a landslide.



Gabion cascade channel deformed as a result of a slow moving deep seated landslide.

6. **Dislocation of drainage structures**
7. **Trees leaning backwards or with curved trunks**



Ongoing slow -moving ground movementsin slope above road.

Appendix 1 Landslide indicators

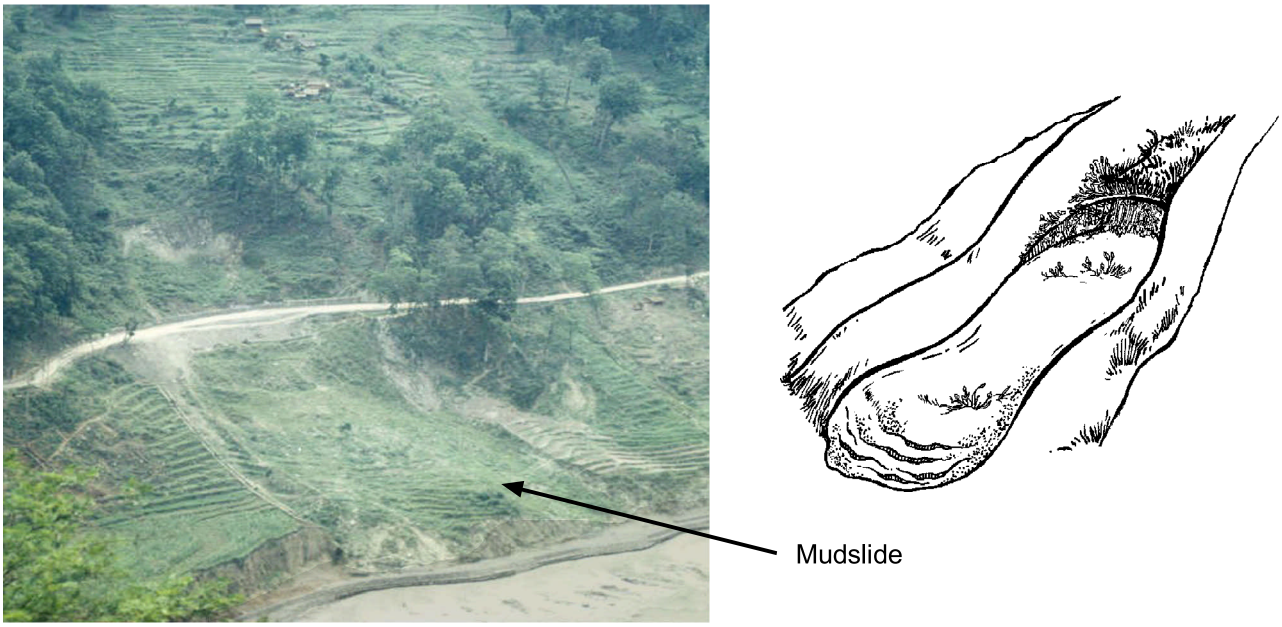
8. Overriding front of landslide flow.

9. Exposed shear surface.

Appendix 1 Landslide indicators

Relict landslide indicators

10. Spoon-shaped landforms



Typical mudslide with spoon-shaped topography

11. Chaotic debris forming landslide deposit

Landslide debris from channelised debris flow.

Landslide debris blocking road.

12. Steep soil slope located in depression between rock outcrops

Surface and shallow sub-surface water converges to saturate slope

13. Disturbed vegetation, or uncharacteristic vegetation pattern

Uncultivated slopes and patchy vegetation can indicate past instability

Colluvium vulnerable to movement

14. Steeply sloping ground in colluvium

Steep slope in colluvium formed by old rock failure.

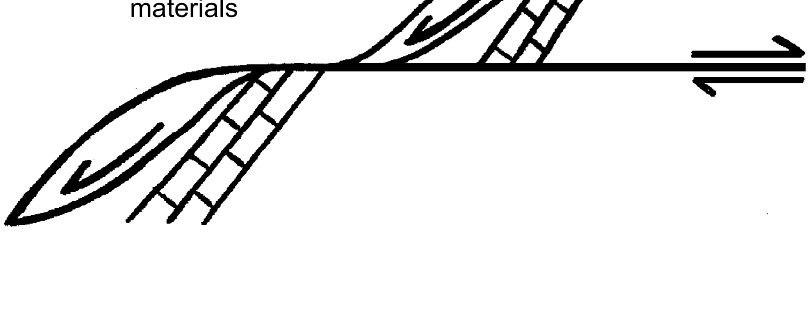
15. Slopes where water is seen to collect

Future first time failures

16. Slope underlain by adverse geology

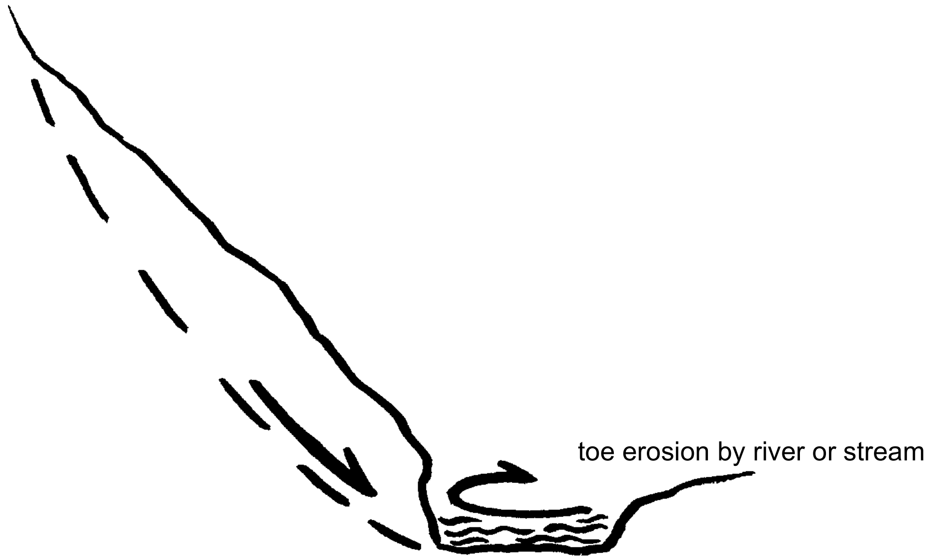
Adversely orientated joints or planes of weakness

17. Slopes adjacent to active fault zone.



Appendix 1 Landslide indicators

18. Slopes likely to be prone to river or stream scour at their base



Relict debris flows from upstream

19. Large landslide scarps with little landslide debris remaining in the source area

Large landslide scar, with the majority of the failed material deposited below the road, away from the source area.

20. Relict or slow- moving landslides above drainage lines

Relict or slow-moving landslide could fail catastrophically becoming debris flow in main channel.

Appendix 2

REMOTE SENSING FOR LANDSLIDE STUDIES IN THE RURAL ACCESS SECTOR

REMOTE SENSING FOR LANDSLIDE STUDIES IN THE RURAL ACCESS SECTOR

Main sensor characteristics

LANDSAT 7ETM+

The Landsat 7ETM+ instrument is the latest in a long line of Landsat instruments owned and operated by NASA. This instrument has good spatial resolution by imagery standards, but it is only useful for mapping landslides of over 45 m in length and width. An advantage is the excellent spectral resolution, which optimises it for the mapping of soils, vegetation, land cover and geological analyses, and which provide a capability for automatic identification and classification of landslides. In order to analyse the imagery expensive software is required. However, this is partially offset by the low cost of the imagery itself.

As with all imaging satellites, Landsat cannot image the ground when the sky is cloudy. However, since archive imagery usually contains a number of scenes for any given area, this is not usually a problem. Unfortunately, Landsat 7ETM+ does not have a stereographic capability. Landsat imagery is only available in archived form, i.e. it cannot be commissioned. The Landsat 7 instrument broke in May 2003 meaning that the quality of imagery available since this date is rather low. However, archive imagery collected before this date is still available.

SPOT IV

The French satellite SPOT IV provides affordable imagery with a spatial resolution that allows the mapping of landslides with a length and width of 30 m. The four spectral bands allow soil, vegetation and terrain analysis to be undertaken, and some limited automatic identification and classification of landslides can be achieved. A good archive of imagery is available, and the instrument can be tasked to collect imagery on demand, although care must be taken with the problems of cloudiness. A great advantage of the SPOT IV instrument is the availability of stereoscopic capability.

IRS

The Indian satellite IRS has very similar capabilities to those of SPOT IV, but with slightly better resolution in panchromatic mode. A potential advantage of this instrument is the low cost of imagery to countries adjacent to India (currently excluding Pakistan).

IKONOS

The launch in late 1999 of the IKONOS satellite marked a large step forward in the availability of high resolution imagery for civilian users. With a 1 m resolution in panchromatic mode, it provides imagery that is similar in quality to aerial photography but with lower levels of distortion. This is supplemented with 4m multispectral capability, potentially allowing automatic classification of landslides. In addition, the instrument has a stereographic capability. However, the advantages of this instrument are currently not being realised due to the high costs of the imagery, although these are now being reduced markedly. The stereo capability of this instrument is now available.

Quickbird

The Quickbird satellite was launched in 2001 into a low earth orbit. It currently represents the highest resolution commercial satellite – in panchromatic mode it has a resolution of 0.61m, whilst in multispectral mode it has a resolution of 2.44 m. The instrument has a stereographic capability.

Unfortunately the cost of the imagery is high, limiting its use, although it is possible to buy archive imagery of smaller areas than for IKONOS, reducing the cost. Quickbird is likely to remain the most capable of all satellite instruments until at least 2004.

Radar satellites

Radar imagery has the advantage of being unaffected by weather as the microwave beam passes through cloud effectively unimpeded. The two main radar systems currently in use (Radarsat and ERS-1/2) provide an expensive product that is of relatively little use in landslide mapping. This is because the images are produced from the back scatter of the microwave beam and are thus not of visible quality. However, the potential application of radar imagery lies in the recent development of interferometry, in which comparison of sets of images taken at different times allows the detection of displacements of the surface of the order of 3 mm. This provides the potential for the detection of landslide movements. However, at present the technology remains under development. The recent successful launch of the ESA ENVISAT instrument is likely to lead to the rapid development of this technology in the near future.

Other instruments

Some other instruments have had limited use in landslide studies, especially on a local basis. Such instruments include ROCSAT in Taiwan, and JERS-1 in Japan. However, their use is extremely limited. Increasingly, spy satellite imagery is becoming available, most notably from the Russian KOSMOS instruments, which have a ground resolution of 2 m. Whilst these are undoubtedly extremely capable instruments, and the imagery from them is very affordable, numerous problems have been encountered in purchasing the images. As a result, these sources of data have rarely been used, at least outside of the Former Soviet Union.

The recent successful launch of the Orbview 3 satellite, following the loss of Orbview 4 as a result of launch vehicle failure in 2001, has now added a third instrument with capabilities that at least match those of IKONOS and Quickbird. If so, this may well reduce the price of imagery of this quality, rendering it usable for landslide studies.

Appendix 3

LANDSLIDE SUSCEPTIBILITY MAPPING PROCEDURES DEVELOPED BY THE LRA PROJECT

Landslide Susceptibility Mapping Procedures Developed by the LRA Project

1. Introduction

A technique was developed for assessing landslide susceptibility utilising primarily desk study data from six study areas, three in Nepal and three in Bhutan. Landslide density has been used as the indicator of landslide susceptibility. It is important to utilise a quantifiable parameter, such as landslide density, as it has a definite meaning. The study concluded that only two factors were consistently significant in explaining the distribution of landslides in all six study areas:

a) slope angle
b) rock type

The analysis that gave rise to this conclusion was based on a comparison between mapped landslide distributions and ten geological, topographical and land use parameters mapped from desk study 13 data sources for each of the six study areas, comprising a total area of 2,200 km^2. Guidance notes detailing the different stages of this two-fold susceptibility scheme are provided in Section 2 of this appendix. While the susceptibility analysis based on slope angle and rock type alone has proved successful, it is based on an averaging of conditions over all six study areas and ignores site specific relationships brought about by geological structure and geomorphology. Consequently a separate study was carried out to assess landslide susceptibility at a more detailed level (the four-fold susceptibility scheme), at the scale of the individual study areas. This study included the analysis of the following parameters derived from published mapping and aerial photograph interpretation:

a) rock type
b) slope angle
c) geological structure
d) terrain classification

Guidance notes detailing the various data sources and processes required to carry out this more detailed susceptibility analysis are provided in Section 3 of this appendix.

These notes should allow the reader to carry out similar landslide susceptibility assessments in their areas of interest. Both susceptibility assessments require the use of a Geographical Information System (GIS) for rapid data handling, although the procedures can be applied manually. A GIS is a powerful computer-based tool for the storage, management and analysis of spatial data. Section 4 of this appendix discusses the role of GIS, the benefits of using it and the general principles behind the system.

2. The Two-fold Susceptibility Scheme

2.1 Introduction

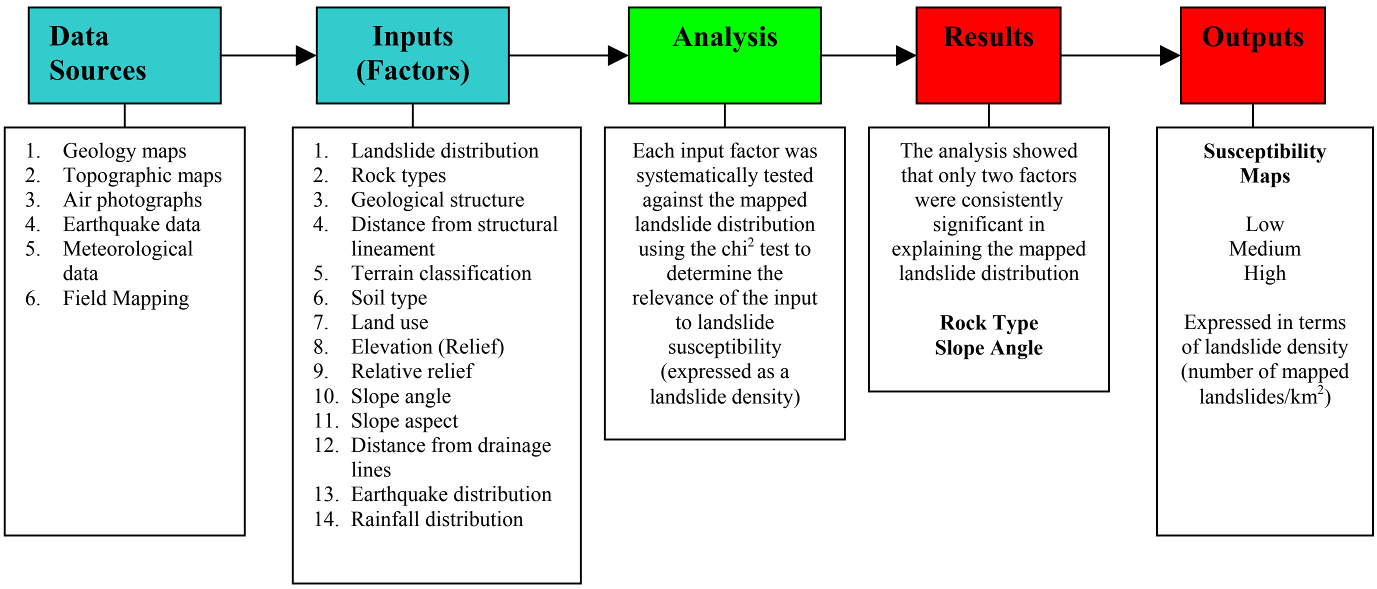
This susceptibility assessment technique incorporates only two factors:

a) slope angle
b) rock type

These two factors were found to be consistently significant in explaining the distribution of landslides in all six of the study areas within the LRA project. Although this appears relatively simple, a total of 13 factors were initially analysed, details of which are listed below.

Factor	Source
Rock type	Published/unpublished geological maps (with field verification)
Geological structure	Published/unpublished geological maps (with field verification)
Distance from structural lineaments	Derived using GIS
Terrain classification	Aerial photograph interpretation (API)
Soil type	API (with field verification)
Land use	Published maps and/or field mapping
Elevation (relief)	Derived from contour data using GIS
Slope angle	Derived from contour data using GIS
Slope aspect	Derived from contour data using GIS
Earthquake distribution	Downloaded from the United States Geological Survey website. Additional data was obtained from the Department of Mines and Geology, Nepal
Rainfall distribution	Data provided by Department of Hydrology & Meteorology, Nepal

The different factors listed above were tested against the mapped landslide distribution within each of the six areas using the GIS software. The aim was to identify the dominant factors that control the landslide activity within the study areas. The flow chart below shows how these different factors were assessed and integrated to derive the final susceptibility maps.



The following information details each of the different stages of the analysis. Results from the six study areas within the LRA project have also been included for reference.

2.2 Types of software used

A suitable GIS software package (ArcView 3.2 was used for the LRA project) should be used to store and analyse all of the collected data. Background information, and discussion on the benefits of using GIS software, are contained in Section 4 of this appendix.

2.3 Available desk study information

The following desk study data should be available for most study areas in both Nepal and Bhutan. If these data sources are not available for a particular study area, recourse will need to be made to time-consuming field data collection, in which case the cost-effectiveness of the susceptibility approach will need to be reviewed.

a) topographical maps
b) geological maps
c) aerial photographs
d) satellite imagery

2.4 Methodology

The twofold susceptibility technique compares different combinations of rock type and slope angle with the mapped landslide distributions. In order to carry out the analysis the following details need to be derived:

a) location of existing landslides
b) rock types in the study area
c) slope angle distribution in the study area

The landslide distribution for a particular study area can only be effectively assessed from aerial photographs. If no aerial photographs are available then susceptibility maps can still be produced by matching the different combinations of rock type/slope angle (for the area of interest) with the same combinations taken from the results of the susceptibility analysis of the six study areas analysed as part of the LRA study, assuming that the rock types match those in the study areas in question. If aerial photographs do not exist and the rock types found in the area of interest do not match those used in the LRA project, then recourse will have to be made to large scale satellite imagery (see Chapter 2) and field mapping.

If aerial photographs are available then the landslide distribution can be established and actual landslide densities can be calculated for the different combinations of rock type/slope angle. Field validation is imperative to ensure that the landslides interpreted from aerial photographs are valid and that the calculated densities reflect the true distribution of landslides.

2.4.1 Location of existing landslides

For a landslide to be incorporated into the analysis, both the source area and deposit/debris trail should be visible from aerial photographs. If the aerial photographs (AP's) for the site are relatively old then it is important to record any landslides that post-date the AP's during the field verification. This creates a landslide inventory for the study area, and it is important to locate the landslides as accurately as possible on the topographic maps, as this inventory will provide the basis of the analysis.

Each landslide source area and deposit should be digitised separately and then entered into the GIS. Each landslide should be represented as a point located at the landslide source.

2.4.2 Rock types

The first stage of the analysis is to prepare a list of rock types or rock type groups for the study area. These can be digitised from published geological mapping. In both Nepal and Bhutan, 1:50,000 scale mapping was available, although significant modification was required during the field verification exercises in some areas.

2.4.3 Calculating slope angles

In theory, under natural conditions, the susceptibility of a slope to landslides should increase with an increase in slope angle. The slope angle distribution for an area can be generated automatically by using the GIS software if contour data is available digitally. The topographic map should be digitised and entered into the GIS as a digital layer, making sure each contour is labelled with its elevation value. From this digital topographic layer it is possible to create a Digital Elevation Model (DEM) of the study area. A DEM is a 3-D digital model, and it is worth bearing in mind that it is only as accurate as the topographic data used to create it. The DEM forms the basis from which the slope angle distribution within the study area can be derived. This is done automatically by using an in-built function within the GIS software. It is best to generate the slope angle layer using 5º slope angle intervals (0º to 90º). Each slope interval will then need to be grouped. It is best to group these into four slope angle ranges, for example:

a) 0º to 20º
b) 21º to 30º
c) 31º to 40º
d) 41º to 90º

A separate GIS layer should be created for each slope angle range.

2.4.4 GIS methodology

The methodology by which the landslide distribution is compared with the rock type and slope angle distribution is detailed below:

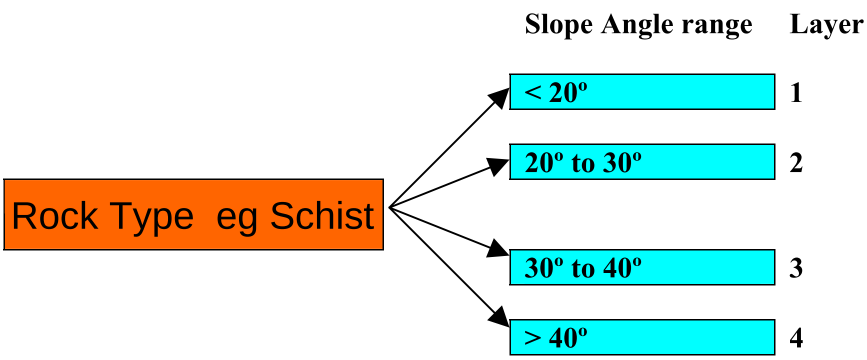
a) Step 1. Combining rock type with slope angle

b) Step 2. Comparing the landslide distribution with the results from Step 1 (calculation of landslide density).

These steps are carried out using the GIS software. For specific details on how to use the software (ArcView in the case of the LRA project) refer to the notes in Section 4 of this appendix.

Step 1. Combining rock type with slope angle

Each rock type identified within the study area should be categorised by slope angle. An in-built function within the GIS allows subdivision of each rock type into the different slope angle ranges, creating four separate layers for each rock type (refer to the diagram below).



The surface area of each layer can now be calculated. The GIS software has an inbuilt function that allows the surface area to be calculated automatically, this should be expressed in terms of km^2.

Step 2. Comparing the landslide distribution

The landslide distribution can now be compared systematically with each layer. The number of landslides that fall within each layer (generated from Step 1) should be counted. The number of landslides within each layer should then be divided by the surface area of the layer. This number is effectively the landslide density, which is expressed as the number of landslides per km^2, per layer. Once the landslide density of each layer is determined it is then possible to group different layers with similar landslide densities, into e.g. High, Medium and Low susceptibility layers. Examples of the ranges of landslide densities adopted for the LRA study are listed below.

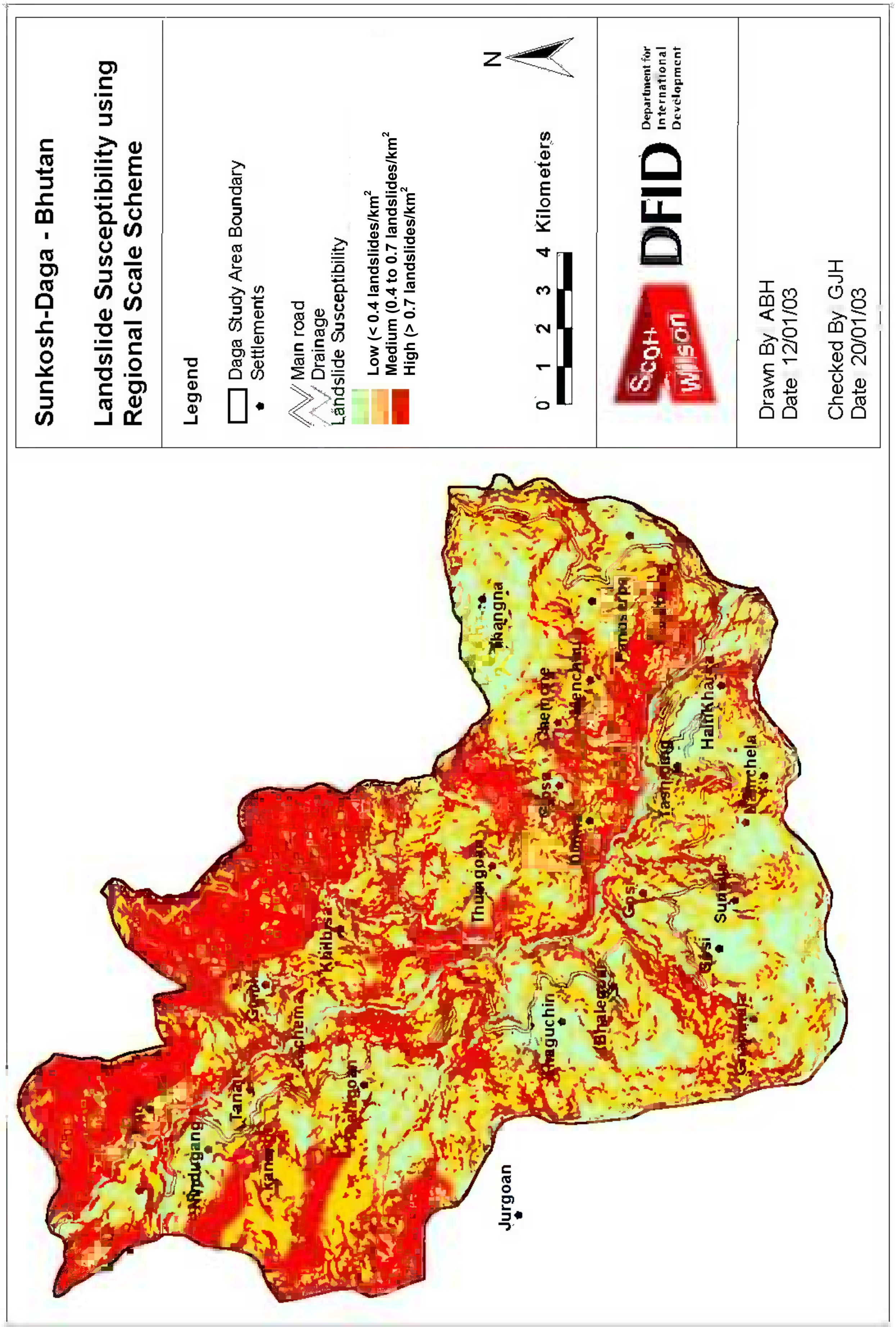
a) Low 0 to 0.39 landslides/km^2
b) Medium 0.4 to 0.69 landslides/km^2
c) High > 0.7 landslides/km^2

As discussed previously, if no aerial photographs are available for the chosen site, then it becomes very difficult to derive the landslide distribution. If this is the case then it is still possible to assess the landslide susceptibility of the area by matching the different combinations of rock type/slope angle (established in Step 1) with the same combinations taken from the results of the susceptibility analysis of the six study areas analysed as part of the LRA study. NB this can only be done if the same rock types apply. The results from the LRA study are shown in the table below.

The twofold landslide susceptibility rating list

Susceptibility Class	Rock Type	Slope Angle	Indicative landslide density (landslides/Sq km)
Low Landslide Susceptibility (Rating of 1)	Granite	0° - 20°	0.00
	Granite	20° - 30°	0.00
	Granite	30° - 40°	0.00
	Granite	> 40°	0.00
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	0° - 20°	0.00
	Slate/shale with Limestone &/or Quartzite	0° - 20°	0.00
	Quartzite & Phyllite	0° - 20°	0.16
	Mica Schist & Gneiss	0° - 20°	0.20
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	20° - 30°	0.20
	Mica Schist and other minor rock types	0° - 20°	0.22
	Gneiss & Mica Schist	0° - 20°	0.25
	Mica Schist & Phyllite	20° - 30°	0.26
	Mica Schist & Quartzite	0° - 20°	0.27
	Gneiss	0° - 20°	0.30
	Phyllite (with Quartzite &/or Limestone)	0° - 20°	0.30
	Limestone/Dolomite with Quartzite, Phyllite &/or shale	30° - 40°	0.36
	Quartzite & Phyllite	20° - 30°	0.36
Moderate Landslide Susceptibility (Rating of 2)	Limestone/Dolomite with Quartzite, Phyllite &/or shale	> 40°	0.40
	Mica Schist & Phyllite	0° - 20°	0.43
	Phyllite (with Quartzite &/or Limestone)	20° - 30°	0.46
	Mica Schist and other minor rock types	20° - 30°	0.48
	Mica Schist & Gneiss	20° - 30°	0.53
	Quartzite & Phyllite	30° - 40°	0.54
	Gneiss	20° - 30°	0.55
	Mica Schist	0° - 20°	0.56
	Slate/shale with Limestone &/or Quartzite	30° - 40°	0.59
	Mica Schist & Quartzite	20° - 30°	0.60
	Slate/shale with Limestone &/or Quartzite	20° - 30°	0.60
	Quartzite & shale &/or Sandstone	20° - 30°	0.62
	Quartzite & shale &/or Sandstone	0° - 20°	0.65
	Gneiss & Mica Schist	20° - 30°	0.66
	Slate/shale with Limestone &/or Quartzite	> 40°	0.67
High Landslide Susceptibility (Rating of 3)	Quartzite & Phyllite	> 40°	0.72
	Mica Schist	30° - 40°	0.75
	Mica Schist	20° - 30°	0.77
	Fine grained Sandstone (siltstone/mudstone)	0° - 20°	0.78
	Mica Schist	> 40°	0.80
	Mica Schist & Gneiss	> 40°	0.81
	Gneiss	30° - 40°	0.82
	Mica Schist & Phyllite	30° - 40°	0.83
	Phyllite (with Quartzite &/or Limestone)	30° - 40°	0.88
	Mica Schist and other minor rock types	30° - 40°	1.00
	Gneiss & Mica Schist	30° - 40°	1.00
	Mica Schist & Gneiss	30° - 40°	1.02
	Gneiss	> 40°	1.02
	Medium to coarse grained Sandstone	0° - 20°	1.03
	Quartzite & shale &/or Sandstone	30° - 40°	1.15
	Mica Schist & Quartzite	30° - 40°	1.19
	Quartzite & shale &/or Sandstone	> 40°	1.45
	Phyllite (with Quartzite &/or Limestone)	> 40°	1.55
	Mica Schist & Quartzite	> 40°	1.58
	Mica Schist and other minor rock types	> 40°	1.58
	Medium to coarse grained Sandstone	20° - 30°	1.64
	Gneiss & Mica Schist	> 40°	1.89
	Medium to coarse grained Sandstone	> 40°	2.15
	Medium to coarse grained Sandstone	30° - 40°	2.48
	Mica Schist & Phyllite	> 40°	2.62
	Fine grained Sandstone (siltstone/mudstone)	20° - 30°	2.91
	Fine grained Sandstone (siltstone/mudstone)	30° - 40°	3.33
	Fine grained Sandstone (siltstone/mudstone)	> 40°	6.85

Example of a susceptibility map created using the twofold analysis technique



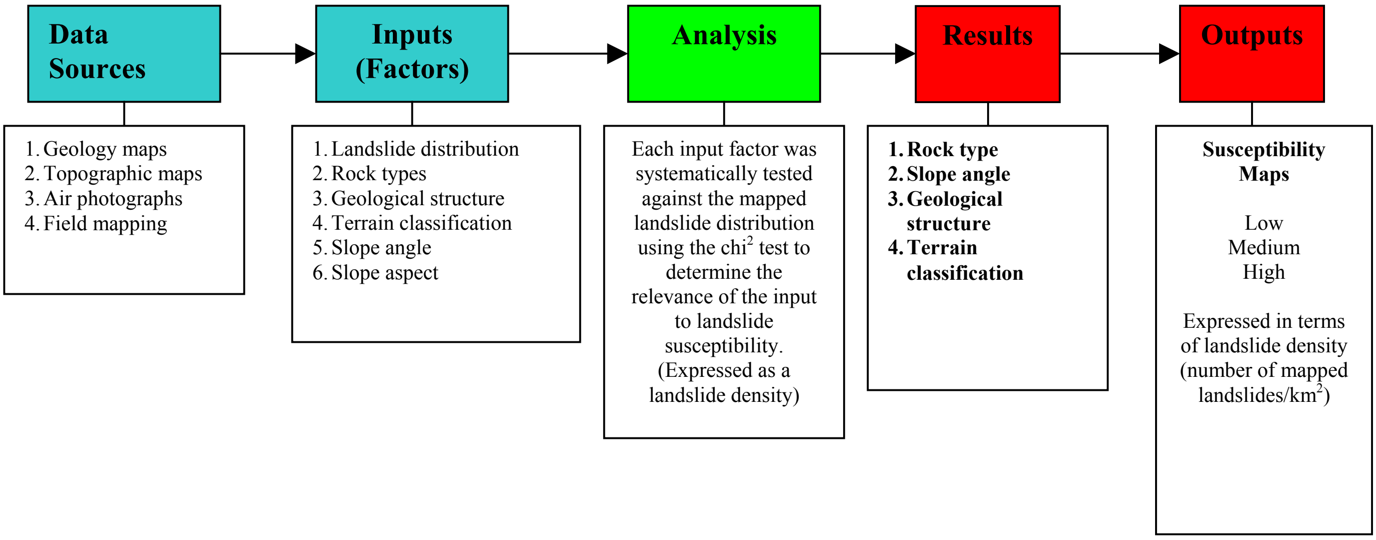
3. The Four-fold Susceptibility Assessment

3.1 Introduction

This susceptibility assessment technique incorporates the following factors:

a) rock type
b) slope angle
c) geological structure
d) terrain classification

These factors are derived essentially from desk study data sources, including detailed aerial photograph interpretation. Field validation is imperative to ensure that the factors derived from aerial photographs are valid. The flow chart below shows how these different factors are assessed and integrated to derive the final susceptibility map.



The following information details each of the different stages of the analysis. Results from one of the six study areas within the LRA project (Sunkosh – Daga study area) have also been included for reference.

3.2 Types of software used

As with the two-fold susceptibility analysis, a suitable GIS software package (ArcView 3.2 was used for the LRA project) should be used to store and analyse all of the collected data. Background information and discussion on the benefits of using GIS software are contained in Section 4 of this appendix.

3.3 Available desk study information

The following desk study data should be available for most areas in both Nepal and Bhutan. As with the two-fold analysis, if these data sources are not available for a particular study area, then recourse will need to be made to time-consuming field data collection, in which case the cost-effectiveness of the susceptibility approach will need to be reviewed.

a) topographic maps
b) geological maps
c) aerial photographs
d) satellite imagery

3.4 Methodology

A detailed aerial photograph interpretation (utilising the topographic maps, geological maps, and any satellite imagery) is required to determine the following information:

a) the location of existing landslides
b) terrain classification
c) rock types
d) structural geological trends

Discussion on how to derive the above information is given in the following sections of this appendix. Once the aerial photograph interpretation (API) has been carried out, a field visit to the site should be planned in order to allow the API to be field checked. Field validation is imperative, not just for checking the validity of the API, but also for understanding the different factors that contribute towards landslide development in the study area.

3.4.1 Location of existing landslides

For a landslide to be incorporated into the analysis, both the source area and deposit/debris trail should be visible from aerial photographs. If the aerial photographs (AP's) for the site are relatively old then it is important to record any landslides that post date the AP's during the field verification.

Each landslide source area and deposit should be digitised separately and then entered into the GIS. For the analysis each landslide will need to be attributed with the following information:

a) Landslide ID – unique identification number given to each landslide
b) Slope angle – taken from the Digital Elevation Model (DEM) generated by GIS from the contour data (should be field verified if possible)
c) Slope aspect – taken from the DEM (should be field verified if possible)
d) Landslide material type, i.e. rock, colluvium and in situ soil – derived initially from terrain classification (should be field verified if possible)

This information is then linked to a unique point located at the uppermost point (crown) of the landslide source area. The above data, although registered to the landslide crown, should be derived by averaging the attributes of the entire source area.

3.4.2 Terrain classification

The terrain classification is predominantly carried out from API with field verification of at least 10% of the study area. A simple terrain classification scheme should be used, incorporating the following three terrain classes:

a) colluvium

b) in situ soil
c) rock-dominated terrain (essentially in situ rock)

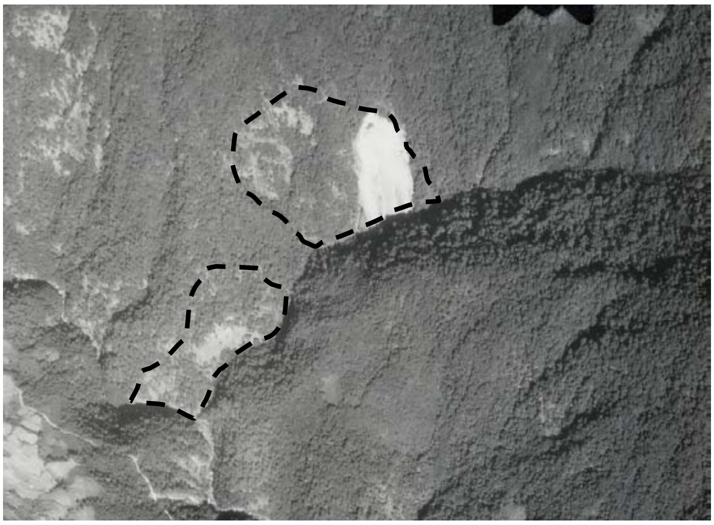
These three terrain classes are identified on the basis of topographic position and morphology, with material properties confirmed during field verification:

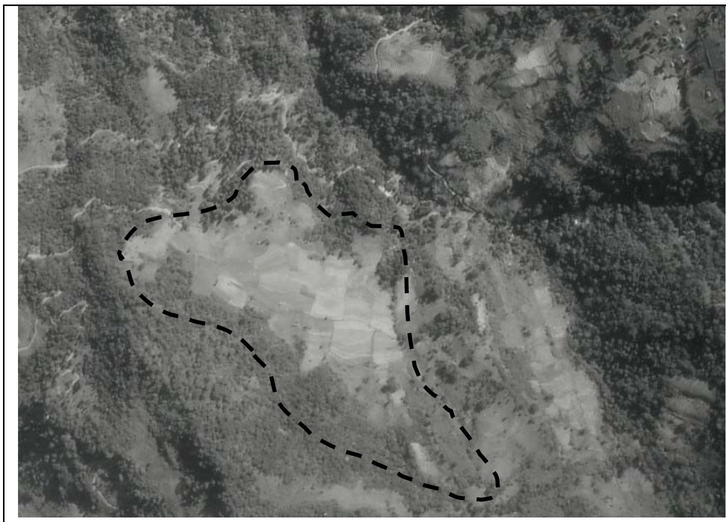
Colluvium – material transported by hill slope processes. Colluvium tends to form low to moderately inclined slopes (typically 10º to 25º), which display an irregular, undulating morphology when viewed in aerial photographs. Areas of colluvium are often un-cultivated, which tends to be an indication of relatively recent instability. In the field, the material tends to form a poorly graded mass of boulders and cobbles within a finer grained matrix. Frequently, individual boulders may be visible on the ground surface in the aerial photographs.

In situ soil – material derived from the insitu weathering of parent rock, which generally retains the original rock structure. Residual soil is also included in this category. Insitu soil tends to form on slope angles typically 0º to 25º, including ridge and spur lines. Areas of in situ soil display a smooth rounded morphology (when viewed in aerial photographs), with slopes typically cultivated.

Rock-dominated terrain – areas of ground that are dominated by insitu rock (i.e. rock is either at, or near the ground surface). Rock tends to form steep slopes (typically > 40º), which have a thin veneer (typically < 1m in depth) of either colluvium or in situ soil overlying the rock. Areas of rock display a steep angular morphology, when viewed in aerial photographs.

Summary of the different terrain types.

 	**Colluvium** Slope angles typically 10º to 25º. Irregular, undulating morphology, vegetated but typically un-cultivated. Colluvium may be derived from a single landslide event or from an amalgamation of material from several landslide events over time. Colluvium may exhibit several forms: channelised – linear ribbon like deposits of colluvium along drainage lines, hillslope – colluvium forming relatively planar slopes, frequently with a lobate form, which tends to give the surface a rounded “hummocky” appearance. Vegetation is often irregular and slopes frequently un-cultivated. Residual colluvium – relatively old, weathered colluvium forming a series of lobate-shaped features, which have an irregular and undulating morphology
	**In situ soil (residual soil)** Residual soil is classified as a soil derived from the tropical weathering of in-situ rock. Areas of residual soil are characterised by featureless, slightly undulating low angle slopes (typically < 25°). Soils are red or red-brown in colour when viewed in colour aerial photographs, or seen in the field. Residual soil can be found in a variety of topographic positions: on rounded spurs and ridge lines and mid-slope benches.

	
	**Rock-dominated terrain** Slope angles typically > 40º. Steep angular morphology. Can be heavily vegetated (not cultivated) towards the lower end of the slope angle range, with rock outcrops dominating the steeper end of the slope angle range.

3.4.3 Combining the terrain classification with underlying rock type

It is important at this stage to understand how the different materials, derived from the terrain classification, behave with respect to landslide processes. Colluvium is derived from mass movement processes, and therefore reactivation of this material tends to be governed by factors unrelated to both geological structure and underlying rock type.

In situ soil by definition retains the original texture, fabric and structure of the parent rock type, but essentially acts as a soil. As this material retains the original rock structure, landslides (within this material) tend to slide along planar, unfavourably orientated surfaces that are weathered remnants of geological structures.

Landslides within areas of rock-dominated terrain (i.e. rock close to, or at ground surface) tend to be governed by both rock type and geological structure. The two-fold analysis has shown that landslide susceptibility varies greatly between different rock types, i.e. schist is more susceptible to landslides than granite, generally because schist has a distinct tectonic foliation, which can promote both weathering and instability. On this basis, areas classified as rock-dominated terrain (from the terrain classification) should be further classified by rock type, with the rock type taken from the existing geology map.

By combining the terrain classification (in situ soil and colluvium) with rock-dominated terrain, sub-classified by rock type, a more detailed terrain classification can be derived. This terrain classification then forms the basis of the subsequent GIS based susceptibility analysis. The table below shows examples of the different terrain types derived for two study areas in Bhutan.

Sunkosh – Daga Terrain Types	**Damchu - Chhukha Terrain Types**
Colluvium	Colluvium
In situ Soil	In situ Soil
Rock-Phyllite	Rock-Quartz & Schist
Rock-Schist & Quartzite	Rock-Gneiss & Schist
Rock-Augen Gneiss	Rock-Limestone
Rock-Schist	

3.4.4 Geological structure – determining the dominant structural orientations within the study area

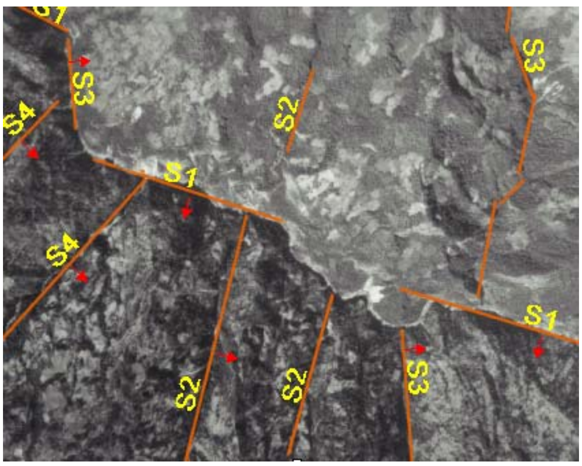
As discussed previously, geological structure appears to have an influence on landslide initiation by forming the plane along which the failing mass slides. In order to incorporate this into the susceptibility analysis, the dominant structural orientations within the study area have to be determined. These should be determined primarily from aerial photographs making sure to incorporate any data present on existing geological maps.

The aerial photographs should be used to determine the dip direction of the dominant structural orientations (lineaments). To do this it is important to utilise both the aerial photographs and the topographic map. The main orientations of the drainage lines should be marked on the topographic map. Dominant structural lineations identified on the aerial photographs (photolineaments) should also be recorded. Where possible the dip direction of each lineament should be determined. This is done by observing linear areas of rock outcrop and by drawing cross sections 90º across the strike of the lineation.

Each lineation should then be grouped and classified on the basis of its dip direction. For example: lineation group S1 (dip direction range = 200º to 210º), lineation group S2 (090º to 100º).The abbreviation S1 refers to all those lineations or geological structures that have a dip direction corresponding to between 200º and 210º. A dip direction range is used so that localised variations in dip direction can be incorporated, an example is shown below.

Aerial Photograph of Sunkosh – Daga area

Aerial Photograph of Sunkosh – Daga area with the main structural lineations shown

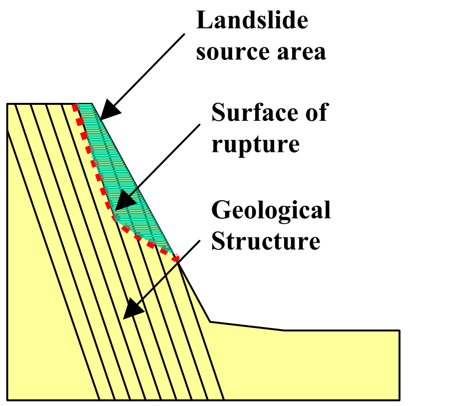


The table below shows a comparison between the dominant structural orientations recorded from API and those recorded in the field, for the Sunkosh Daga study area in Bhutan. This shows that the level of accuracy achieved from API is sufficient to facilitate this type of analysis.

Structure	**Sunkosh – Daga**	
	API-Measured Dip Direction	**Field-Measured Dip Direction**
S1	200º to 210º	210º
S2	090º to 100º	090º
S3	065º to 075º	060º
S4	140º to 150º	150º
S5	330º to 340º	340º

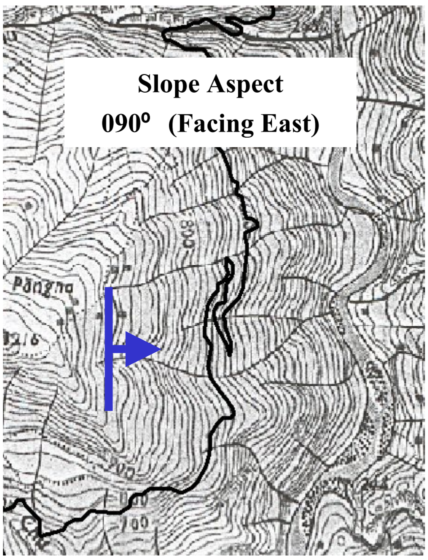
3.4.5 Applying geological structure to the GIS-based susceptibility analysis

Typical rock slope stability analysis methods analyse the kinematics (geometry) of the slope with respect to the orientation of the geological structures present in the slope. In typical rock slope analyses, for planar sliding to occur, the dip direction of the geological structure must be approximately coincident with the slope aspect, and the discontinuity, along which the failed mass slides, must "daylight" out of the slope face (the dip of the discontinuity must be less than the dip of the slope face). However, site observations have shown that, unlike typical rock slopes, landslides can also fail along discontinuities that do not daylight out of the slope (where the discontinuity has a steeper dip than the slope angle), but which have a similar dip direction to the slope aspect.

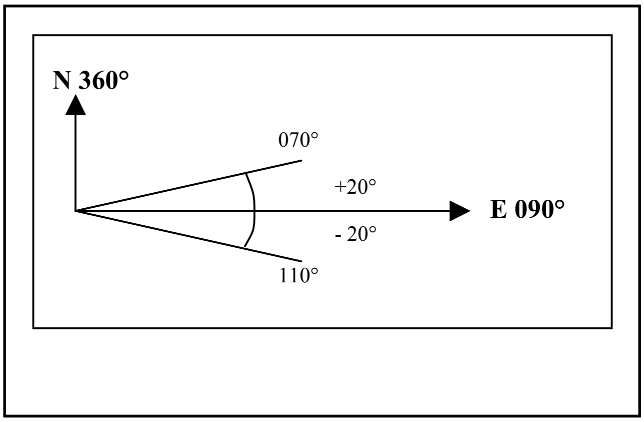


Dip direction of structure corresponds to the aspect of the slope

This is generally a function of the weathered nature of the rock mass, e.g. the landslide may initially slide along the structural discontinuity, with the surface of rupture tending to break through to the slope surface, as the failure surface continues to propagate (see the above diagram). This creates a planar central part of the source area, and a more concave surface towards the toe of the source area. Field observations from previous studies have shown that, for structurally controlled landslides to occur, the failed mass needs to slide more or less straight out of the slope, and that the dip direction of the sliding plane should lie within approximately +/- 20° of the dip direction of the slope.



To incorporate the geological structures identified from API in the previous section, +/- 20º should be added to the dip direction of each discontinuity set, (e.g. a discontinuity set with a dip direction of 090º would have a dip direction range of between 070º to 110º). This 40º range is termed the structural window (refer to the diagram below).



Based on the previous discussion it should be assumed that slopes within the study area with aspects corresponding to one of the structural windows, will be more susceptible to landslides than those slopes outside a structural window. Below is a table showing the structural windows derived for the Sunkosh Daga study area in Bhutan.

Sunkosh Daga area structural windows

Structural Set (Lineation Group)	**From API/Field Verified Data**		**Combined Structural Windows**
	Dip Direction of Discontinuity Set	**Structural Window Dip Direction +/- 20º**	
S1	210º	190º to 230º	190º to 230º
S2	090º	070º to 110º	040º to 170º
S3	060º	040º to 080º	
S4	150º	130º to 170º	
S5	340º	320º to 360º	320º to 360º

3.4.6 Establishing slope angles

In theory, under natural conditions the susceptibility of a given slope material to landslides should increase with an increase in slope angle. Therefore it is important to derive the slope angle distribution within the study area, as this forms one of the parameters required for this susceptibility assessment. The slope angle distribution can be generated automatically by using the GIS software. To do this the topographic map should be digitised and entered as a GIS layer. From the digital topographic map it is possible to create a Digital Elevation Model (DEM) of the study area. The DEM forms the basis from which the slope angle distribution within the study area can be derived. This is done automatically using an in-built function within GIS. The slope angles within the study area will need to be grouped, it is best to group these into four slope angle ranges:

0º to 20º
21º to 30º
31º to 40º
41º to 90º

3.4.7 Establishing slope aspect

The slope aspect distribution within each study area is generated in much the same way as the slope angle distribution. The slopes within the study area should be categorised into 10º aspect ranges, from 0º to 360º: a total of 36 ranges. Once the aspect ranges have been established, those slope aspect ranges which correspond to a structural window should be grouped and classified as “IN” (inside a structural window) and “OUT” (outside a structural window).

3.5 Data analysis

The mapped landslide distribution should now be compared systematically with the factors discussed in the previous sections:

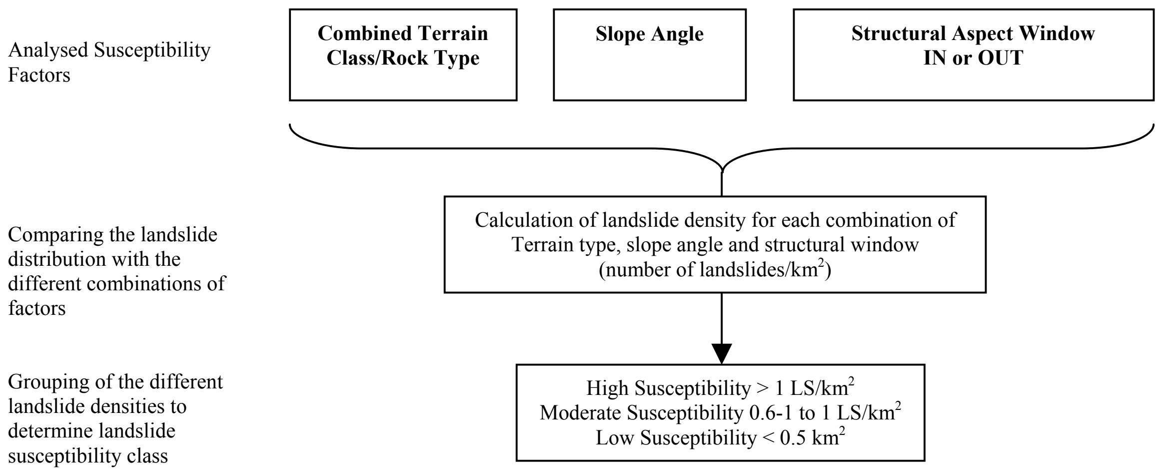
- combined rock type and terrain classification
- slope angle
- structural window and slope aspect

3.5.1 GIS Methodology

The methodology by which the landslide distribution is compared with the above susceptibility factors is detailed below:

- Step 1. Combining terrain classification and rock type with slope angle
- Step 2. Combining terrain class, rock type and slope angle with structural window
- Step 3. Calculation of landslide density

These stages are carried out using the GIS software. For specific details on how to use the software refer to the notes in Section 4 of this appendix. The diagram below shows how each of the different susceptibility factors are combined.



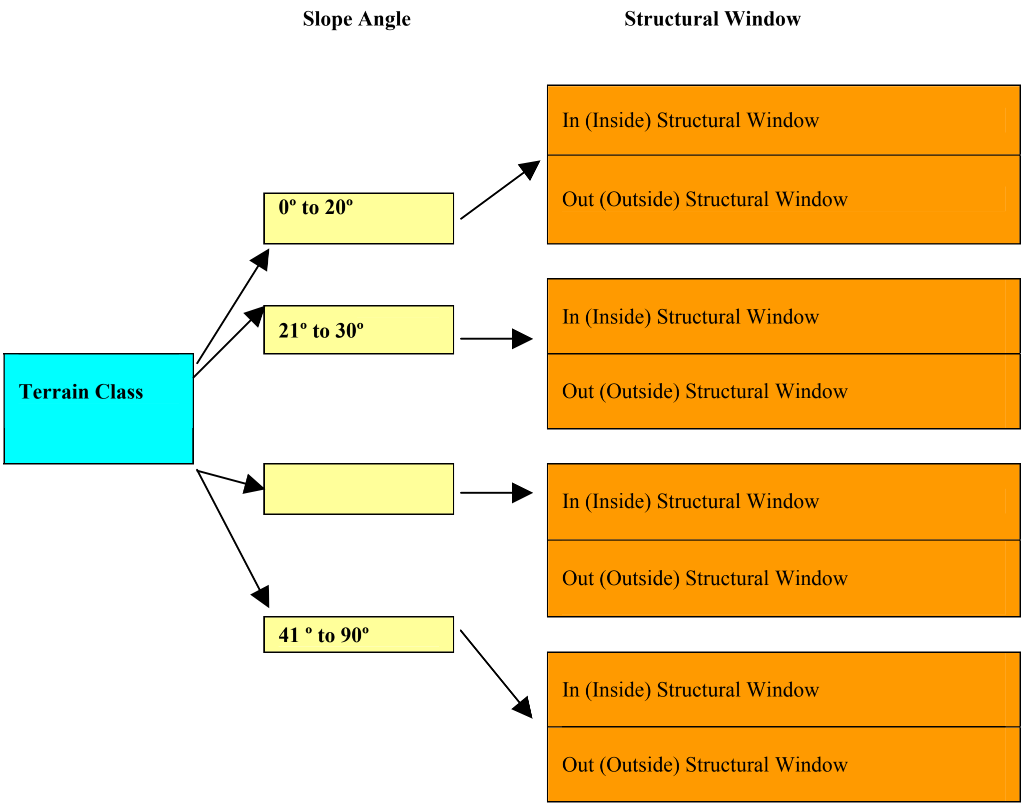
3.5.1.1 Step 1. Combining terrain class, rock type and slope angle

By combining the terrain classification with the underlying rock type a more detailed terrain classification is established. The resultant terrain types should then be categorised by slope angle, using the slope angle ranges from the two- fold analysis (< 20º, 21º to 30º, 31º to 40º and > 40º). This should be carried out for each terrain type in the study area.

3.5.1.2 Step 2. Combining terrain class, rock type, slope angle and structural windows

Each of the terrain types that were categorised by slope angle in Step 1, should be further sub-categorised on the basis of structural window, i.e. those areas of combined terrain type/slope angle that are IN (inside) and OUT (outside) a structural window should be categorised, producing eight permutations of slope angle and structural window for each terrain type*. The flow diagram below shows the different combinations derived for each terrain type. To illustrate this, the table below shows those terrain units developed for the terrain type of in situ soil.

Surface areas should now be calculated for each of the terrain type / slope angle/IN - OUT structural window combinations.



*NB - Colluvium as discussed previously does not tend to fail as a result of structural control, therefore it was not categorised by structural window, only slope angle.

Terrain Unit	Terrain Type	Slope Angle	Slope Aspect
1	Insitu Soil	0º to 20º	**In** Structural Aspect Window
2	Insitu Soil	21º to 30º	**In** Structural Aspect Window
3	Insitu Soil	31º to 40º	**In** Structural Aspect Window
4	Insitu Soil	41º to 90º	**In** Structural Aspect Window
5	Insitu Soil	0º to 20º	**Outside** Structural Aspect Window
6	Insitu Soil	21º to 30º	**Outside** Structural Aspect Window
7	Insitu Soil	31º to 40º	**Outside** Structural Aspect Window
8	Insitu Soil	41º to 90º	**Outside** Structural Aspect Window

3.5.1.3 Step 3. Calculation of landslide density

A landslide density can now be calculated for each of the different terrain type/slope angle/structural window combinations. The number of mapped landslides can be counted within each of the different combinations of factors. The number of landslides is then divided by the surface area occupied by each of the respective factor combinations to yield landslide density.

Those terrain units with similar landslide densities should then be grouped to produce the susceptibility maps. Results from Sunkosh Daga study area in Bhutan using this susceptibility technique are shown below.

3.6 Results from Sunkosh Daga, Bhutan

The first table shows the calculated landslide density for the example terrain type – In situ soil, categorised by slope angle only (two- fold analysis method). The second table shows the same terrain type categorised by slope angle, as well as structural window (four- fold analysis method). The results in these tables show that the range in calculated landslides densities is much higher for the four- fold method, thus providing greater resolution in landslide density and hence susceptibility.

Sunkosh – Daga study area (two- fold analysis)

Terrain Type	Slope Angle	Number of Landslides (%)	Density (No. landslides/km^2)
In situ Soil	0º to 20º	8.0	0.5
In situ Soil	21º to 30º	17.7	0.9
In situ Soil	31º to 40º	10.2	1.4
In situ Soil	41`º to 90	3.5	1.5

Sunkosh – Daga study area (four- fold analysis)

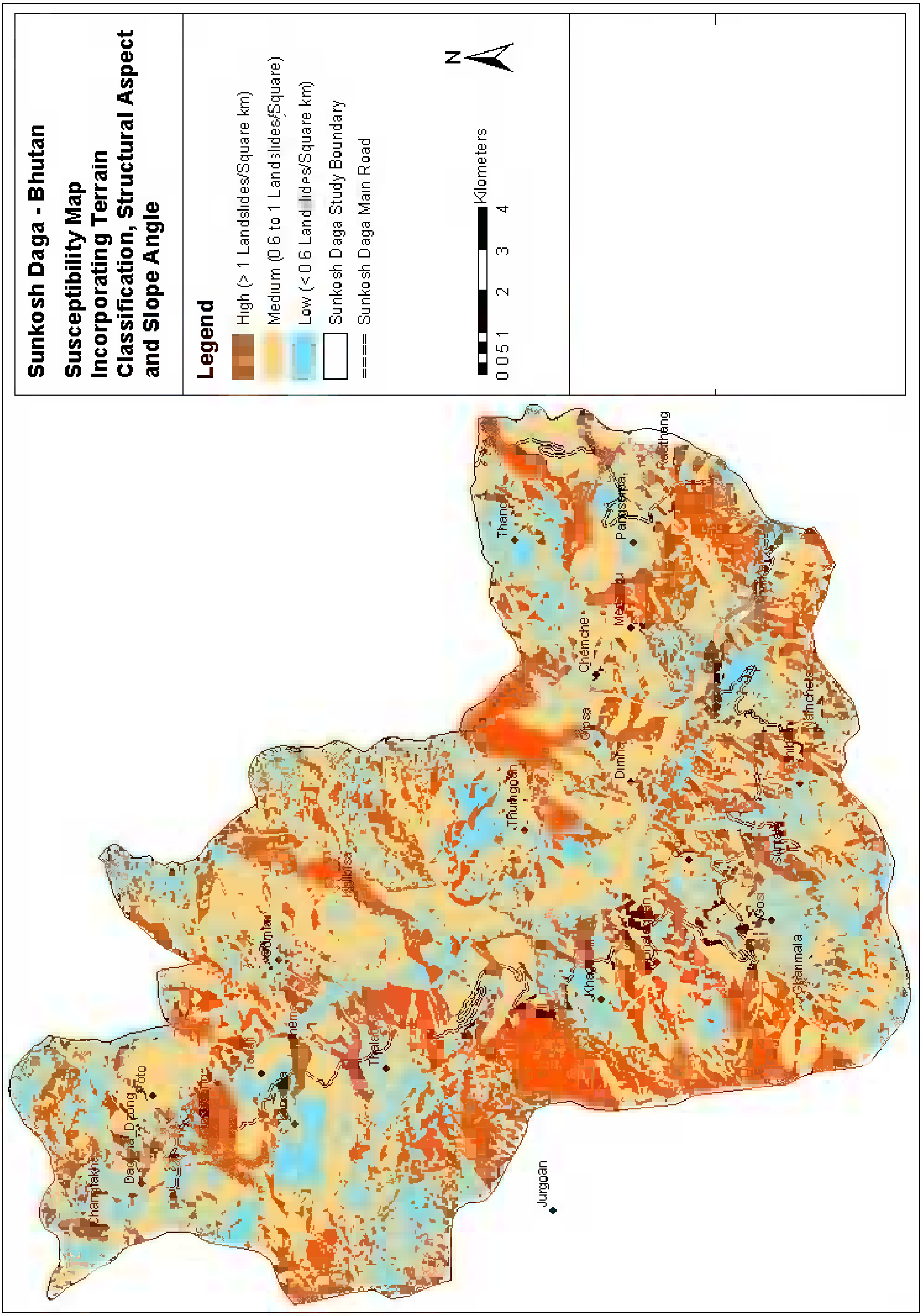
Terrain Type	Slope Angle	Structural Window	Number of Landslides (%)	Density (No. landslides/km^2)
In situ Soil	0º to 20º	IN	8.0	1.0
In situ Soil	21º to 30º	IN	11.9	1.1
In situ Soil	31º to 40º	IN	7.1	1.8
In situ Soil	41º to 90	IN	2.7	1.9
In situ Soil	0º to 20º	OUT	0.0	0.0
In situ Soil	21º to 30º	OUT	5.8	0.6
In situ Soil	31º to 40º	OUT	3.1	0.9
In situ Soil	41º to 90	OUT	2.7	0.9

The different terrain units were grouped in order of increasing density. Those combinations with a density 0 – 0.5 landslides/km^2, were grouped and given a LOW susceptibility ranking, combinations with a density of between 0.6 to 1.0 landslides/km^2 were given a MODERATE ranking, and those combinations with densities > 1 landslide/km^2 were ranked as HIGH.

The table below shows the results of the susceptibility analysis for the Sunkosh Daga study area. Note that these guidelines are derived for a specific area. Details and applications will change from one area to another. Furthermore, groundwater and seepage water factors were not considered due to lack of data at desk study.

Terrain Type	Slope Angle Class	Aspect	No of landslides	Density (No./km^2)
Rock Phyllite	0-20	In	0	0.0
Rock Schist	0-20	In	0	0.0
Rock Phyllite	40-90	In	0	0.0
In situ Soil	0-20	Out	0	0.0
Rock Augen Gneiss	0-20	Out	0	0.0
Rock Phyllite	0-20	Out	0	0.0
Rock Schist	0-20	Out	0	0.0
Rock Schist & Quartzite	0-20	Out	0	0.0
Rock Phyllite	20-30	Out	0	0.0
Rock Phyllite	30-40	Out	0	0.0
Rock Phyllite	40-90	Out	0	0.0
Rock Schist & Quartzite	40-90	Out	0	0.0
Colluvium	0-20	N/A	2	0.1
Rock Augen Gneiss	20-30	Out	1	0.2
Rock Schist & Quartzite	40-90	In	1	0.3
Rock Schist	20-30	Out	2	0.4
Rock Augen Gneiss	40-90	Out	1	0.5
Coll	45-90	N/A	4	0.6
Coll	20-30	N/A	17	0.6
Rock Schist & Quartzite	30-40	Out	3	0.6
Coll	30-45	N/A	10	0.6
Insitu Soil	20-30	Out	13	0.6
Rock Schist & Quartzite	20-30	Out	5	0.6
Rock Schist	30-40	Out	3	0.7
Rock Schist	40-90	Out	2	0.8
Insitu Soil	40-90	Out	2	0.9
Insitu Soil	30-40	Out	7	0.9
Insitu Soil	0-20	In	18	1.0
Rock Schist	20-30	In	6	1.0
Rock Augen Gneiss	30-40	Out	4	1.0
Rock Schist & Quartzite	20-30	In	13	1.1
Insitu Soil	20-30	In	27	1.1
Rock Augen Gneiss	20-30	In	8	1.2
Rock Schist & Quartzite	0-20	In	5	1.2
Rock Augen Gneiss	40-90	In	5	1.5
Rock Augen Gneiss	0-20	In	3	1.6
Rock Augen Gneiss	30-40	In	9	1.6
Rock Schist & Quartzite	30-40	In	14	1.8
Insitu Soil	30-40	In	16	1.8
Insitu Soil	40-90	In	6	1.9
Rock Schist	30-40	In	9	2.0
Rock Schist	40-90	In	6	2.2
Rock Phyllite	20-30	In	2	2.2
Rock Phyllite	30-40	In	2	2.5

Example susceptibility map created using the four- fold analysis technique



4. Using Geographical Information Systems

A Geographical Information System (GIS) is a powerful computer-based tool for the storage, management and analysis of spatial data. Until recently GIS was a tool that was only really usable by specialists due to the complexity and cost of the required software and hardware. However, in recent years the availability of powerful, low cost computers and the development of user-friendly software systems have meant that GIS is now a tool that is applicable to a wide range of projects. In the first part of this guideline the fundamentals of GIS are described and reviewed. In the second part the use of GIS for landslide susceptibility mapping is described.

The Landslide Risk Assessment (LRA) Project has demonstrated the value of using a GIS for handling and analysing large volumes of spatial data, and in particular for carrying out rapid assessments of landslide susceptibility over large areas. It has also become clear that GIS is a very powerful tool for the assessment of infrastructure and population vulnerability, and it is thus a very useful tool for planning purposes.

The LRA Project has involved six study areas – three in each of Nepal and Bhutan. For each study area a GIS database has been developed to manage a wide variety of data, including topography, geology, geomorphology, land use, regional seismicity and infrastructure. This data has been obtained from a number of sources, including published and unpublished maps and report, aerial photograph interpretation, satellite image analysis and field mapping. In the LRA project the aim was to examine the factors that were significant in the occurrence of landslides in each study area. The GIS allowed this to be assessed. The results obtained from these analyses have been used to create a set of landslide susceptibility maps for each of the six study areas.

One advantage of a GIS is the ability to produce maps that are of a very high graphical quality. Unfortunately this can lead to a feeling that the information that they are portraying is absolutely accurate. This may not always be the case. Output data can only be as good as the data that has been used as an input. If the input data quality is poor then the output will be poor. In addition, it is critically important that the user understands what the computer is actually doing when it undertakes an analysis. It may therefore be necessary to have a GIS specialist working in conjunction with a field specialist so as to utilise the experience, skills and knowledge of both.

4.1 Benefits and limitations

The key benefits of GIS include:

a) the ability to store, manipulate and assess large amounts of data
b) the capacity to undertake complex mathematical analyses of data
c) the ability to work at multiple scales
d) the ability to create both statistical and map outputs

In the specific example of landslide susceptibility, hazard and risk mapping studies for rural infrastructure planning, a GIS offers the ability to:

a) manage the large volumes of data
b) identify the factors involved in landslide susceptibility
c) produce outputs indicating the levels of susceptibility, hazard and risk across the study area

However, GIS has a number of limitations, most notably:

a) GIS systems can be complex
b) a high quality GIS can take a considerable amount of time to set up
c) the acquisition costs of the hardware and software can also be high

4.2 General principles

The aim of a GIS is to represent the real world in a digital form. To do this it uses three types of spatial data:

- Point data, in which an object is represented by a single point in space. A house might be represented in this way if a large area is being mapped, or a point might be used to represent the location of a single geological measurement.
- Line data, in which an object is represented by a line in space. A line can be used to represent the course of a road or a river, or the line of geological structure such as a fault.
- Polygon data, in which an object is represented by a space. A polygon might be used to represent a landslide, land use or a geological unit.

Clearly, as a GIS is being set up it is important to decide how to represent each type of data. To a certain degree this will depend upon the scale at which the mapping is being undertaken and the end use of the system. So, for example, a detailed local study might represent a house as a polygon whilst a regional study might represent it as a point.

In all cases the user can add data to the point, line or polygon to describe its characteristics. This data is known as 'attribute data', which is usually held as an attribute table within the GIS. So, for example, a landslide map can be digitised as a series of polygons into the computer. An attribute table can then be added to this data showing the area, volume, and failure mechanism for each landslide that has been mapped.

Within the LRA project information has been stored about the study areas as a series of 'factor layers' within the GIS. Each stores information about a particular aspect of the study site. So, for example, one layer stores information about the spatial distribution of the geological units in the form of polygons. Another holds information about the location of all of the houses in point format. Note, however, that some information may be represented by more than one factor layer. For example, the geological information might consist of a map of the geological units (polygon data), a map of the structural data that was collected (point data), and the faults and folds (line data).

4.3 Data input

Clearly, a key requirement of GIS is that data must be generated and entered into the system.

There are a number of different ways of entering data:

a) tablet digitising: a digitising tablet can be used to trace an existing paper map into the computer. This can be a very time-consuming process;

b) on-screen digitising: here a map containing the required data is scanned into the computer, and the information is then converted to line, point or polygon form, either by hand or automatically;
c) importing: in some cases data is already available in GIS format and can be imported directly into the system;
d) attribute data: information about an object can be entered directly into the computer
e) direct measurement: in some cases data might be entered directly into the GIS. For example, a modern EDM surveying system can often generate topographical data that can be transferred directly into the GIS.

4.4 Database management

A GIS can generate large volumes of data in a short period of time. Some of this data may be revisions of earlier data or results from analyses. Unless care is taken this data can quickly become very difficult to manage. It is therefore essential to have a set of database management conventions or protocols within a project. All those who are working with the database must strictly adhere to these conventions as closely as possible. These conventions should prescribe the file and folder names that should be used, and there must be a clearly defined file structure.

A good management convention will make it easy to find the most recent version of a particular data layer within the GIS. This is particularly important when more than one person is working with the data. To assist in this a metadata file should also be kept, recording the data that is contained within the GIS database, the file names that have been used, the reasons for any revisions, and any problems that have been encountered. It should also record when the data was created or revisions made and who did the work. This file could also contain information about when backups of the data have been made. It is very important that the metadata file is regularly checked and kept up to date.

4.5 Analysis and interpretation

The strength of GIS is the ability to undertake complex analyses of the spatial relationships of the data. These functions include:

a) querying, which allows the user to select areas with specific properties
b) buffering, which allows the user of define a zone around a specific point or object
c) overlaying functions, which allow the user to combine data layers using mathematical or logic functions

4.6 Field validation

The data held within the GIS is a digital representation of the real world. Any interpretations and analyses undertaken using the data should, where possible, be verified in the field. The field validation can often also be used as part of a quality assurance check on the data, which should be undertaken by someone who is familiar with the terrain.

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Glossary

Glossary

Arcuate Formed in the shape of an arc.
Artefact A feature on an image which is produced by the optics of the system or by atmospheric correction-Image-processing procedure that compensates for effects of selectivity scattered light in multispectral images.
Backscatter In radar, the portion of the microwave energy scattered by the terrain surface directly back toward the antenna.
Band A wavelength interval in the electromagnetic spectrum. For example, in Landsat images the bands designate specific wavelength intervals at which images are acquired.
Beam A focused pulse of energy.
Brightness Magnitude of the response produced in the eye by light.
Classification Process of assigning individual pixels of an image to categories, generally on the basis of spectral reflectance characteristics.
Colour composite image Colour image prepared by projecting individual black-and-white multispectral images, each through a different colour filter. When the projected images are superposed, a colour composite image results.
Contrast The ratio between the energy emitted or reflected by an object and its immediate surroundings.
Contrast enhancement Image-processing procedure that improves the contrast ratio of images. The original narrow range of digital values is expanded to utilize the full range of available digital values.
Contrast ratio On an image, the ratio of reflectances between the brightest and darkest parts of an image.
Contrast stretching Expanding a measured range of digital numbers in an image to a larger range, to improve the contrast of the image and its component parts.
Digital image An image where the property being measured has been converted from a continuous range of analogue values to a range expressed by a finite number of integers, usually recorded as binary codes from 0 to 255, or as one byte.
Daylighting Where a joint surface in rock or a landslide slip surface intersects the slope it is said to ‘daylighty’ at that location. Daylighting enables kinematic feasibility for slope failure.
Digital image processing Computer manipulation of the digital-number values of an image.
Digital number (DN) Value assigned to a pixel in a digital image.
Electromagnetic spectrum Continuous sequence of electromagnetic energy arranged according to wavelength or frequency.
False colour composite (FCC) A colour image where parts of the non-visible EM spectrum are expressed as one or more of the red, green, and blue components, so that the colours produced by the Earth's surface do not correspond to normal visual experience. Also called a false-colour image. The most commonly seen false-colour images display the very-near infrared as red, red as green, and green as blue.
Filter, digital Mathematical procedure for modifying values of numerical data.
Grey scale A sequence of grey tones ranging from black to white.
Hue In the IHS system, represents the dominant wavelength of a colour.
HIS Intensity, hue, and saturation system of colours.
Image Pictorial representation of a scene recorded by a remote sensing system. Although image is a general term, it is commonly restricted to representations acquired by non-photographic methods.
In Situ Slope material, usually rock, that is located in its original position, i.e. it has not failed or been otherwise removed or transported
Intensity In the IHS system, brightness ranging from black to white.
IR Infrared region of the electromagnetic spectrum that includes wavelengths from 0.7µm to 1 mm.
Kernel Two-dimensional array of digital numbers used in digital filtering.
Kinematic Feasibility Where the geometry of single or intersecting joint surfaces combined with that of the slope surface allows failure to take place.

Landsat A series of unnamed earth-orbiting NASA satellites that acquire multispectral images in various visible and IR bands.
light-Electromagnetic radiation ranging from 0.4 to 0.7µm in wavelength that is detectable by the human eye.
Mid-infrared (MIR) The range of EM wavelengths from 8 to 14 µm dominated by emission of thermally generated radiation from materials; also known as thermal infrared.
MSS Multispectral scanner system of Landsat that acquires images of four wavelength bands in the visible and reflected IR regions.
Multispectral classification Identification of terrain categories by digital processing of data acquired by multispectral scanners.
Multispectral scanner Scanner system that simultaneously acquires images of the same scene at different wavelengths.
NASA National Aeronautical and Space Administration.
Near infrared (NIR) The shorter wavelength range of the infrared region of the EM spectrum, from 0.7 to 2.5 µm. It is often divided into very-near infrared (VNIR) covering the range accessible to photographic emulsions (0.7 to 1.0m), and the short-wavelength infrared (SWIR) covering the remainder of the NOR atmospheric window from 1.0 to 2.5m.
Nondirectional filter Mathematical filter that treats all orientations of linear features equally.
Panchromatic film Black and white film that is sensitive to all visible wavelengths.
photograph-Representation of targets on film that results from the action of light on silver halide grains in the film's emulsion.
Pixel Contraction of picture element.
Primary colours A set of three colours that in various combinations will produce the full range of colours in the visible spectrum. There are two sets of primary colours, additive and subtractive.
Radar Acronym for radio detection and ranging. Radar is an active form of remote sensing that operates in the microwave and radio wavelength regions.
Ratio image-An image prepared by processing digital multi-spectral data as follows: for each pixel, the value for one band is divided by that of another. The resulting digital values are displayed as an image.
reflectance-Ratio of the radiant energy reflected by a body to the energy incident on it. Spectral reflectance is the reflectance measured within a specific wavelength interval.
Remote sensing Collection and interpretation of information about an object without being in physical contact with the object.
Resolution Ability to separate closely spaced objects on an image or photograph. Resolution is commonly expressed as the most closely spaced line-pairs per unit distance that can be distinguished. Also called spatial resolution.
Sensor Device that receives electromagnetic radiation and converts it into a signal that can be recorded and displayed as either numerical data or an image.
Spall Usually associated with rock masses. Weathered or fractured rock falls away under gravity or pressure release.
spectral reflectance-Reflectance of electromagnetic energy at specified wavelength intervals.
SPOT-Systeme Probatoire d'Observation del la Terre. Unmanned French remote sensing satellite orbiting in the late 1980s.
Stereo pair Two overlapping images or photographs that may be viewed stereoscopically.
supervised classification-Digital-information extraction technique in which the operator provides training-site information that the computer uses to assign pixels to categories.
Synthetic-aperture radar (SAR) Radar system in which high azimuth resolution is achieved by storing and processing data on the Doppler shift of multiple return pulses in such a way as to give the effect of a much longer antenna.
Synthetic stereo images Stereo images constructed through digital processing of a single image. Topographic data are used to calculate parallax.
texture-Frequency of change and arrangement of tones on an image.

Thematic Mapper (TM) A cross-track scanner deployed on Landsat that records seven bands of data from the visible through the thermal IR regions.
Thermal IR IR region from 3 to 14 μm that is employed in remote sensing. This spectral region spans the radiant power peak of the earth.
unsupervised classification-Digital information extraction technique in which the computer assigns pixels to categories with no instructions from the operator.
UV Ultraviolet region of the electromagnetic spectrum ranging in wavelengths from 0.01 to 0.4m.
Vertical exaggeration In a stereo model, the extent to which the vertical scale appears larger than the horizontal scale.
Wavelength Distance between successive wave crests or other equivalent points in a harmonic wave.