Proceedings

2nd Regional Training Course

Asian Program for Regional Capacity Enhancement for Landslide Impact Mitigation

(RECLAIM Phase II)

Phuket-Thailand,
29 January – 02 February 2007

Implemented by
Asian Disaster Preparedness Center (ADPC) and
Norwegian Geotechnical Institute (NGI)

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Contents

7. *Landslide Hazard Mitigation Strategy in Indonesia. Case Study: Landslide Induced by an Earthquake in Indonesia,* Dr. Surono, Center for Volcanology and Geological Hazard Mitigations Bandung, Indonesia

8. *Good Practices in Landslide Risk Management: Nepal,* SDE Ram Prasad Pathak, Naresh Man Shakya and Binod Prasad Sapkota, Department of Roads (DoR), Nepal

9. *Landslides in Nepal and their Prevention by Bio-Engineering,* Engr. Deo Raj Pokharel Department of Water Induced Disaster Prevention (DWIPD), Nepal

10. *State of the practice in slope mitigation measures: Focus on the Philippines* Mark Albert H. Zarco, Sandra G. Catane, and Rhodora M. Gonzalez University of the Philippines Diliman, Philippines

11. *Ready Project: Hazards Mapping And Assessment For Effective Community Based Disaster Risk Management Project, A Case Study of CARAGA Region, Northeastern Mindanao, Philippines,* Dr. Blanche T. Gobenciong, Office of Civil Defense, National Disaster Coordinating Council

12. *Search for a Conducive Policy Environment for Landslide Risk Reduction,* Mr. N.M.S.I. Arambepola, Asian Disaster Preparedness Center (ADPC), Bangkok, Thailand

Background

The incidents of landslides, other types of mass movements and flash flooding have accounted for considerable human losses, damage to social and economic assets, natural resources, and environment in many countries in Asia. During the past few years, such events have had significant negative impact on the development initiatives, poverty reduction goals in countries such as Bhutan, India, Indonesia, Nepal, Philippines, Sri Lanka and Thailand. Despite advances in science and technology, losses continue to result in human sufferings, property losses and sentimental degradation. As population increases and societies become more complex, the economic and societal losses due to such event will continue to rise. Increasing anthropogenic activities in the mountain areas also add to the existing vulnerability of communities living in landslide prone areas.

However, little efforts have been made by the stakeholder institutions to understand the social and technical dimensions and to develop cost effective landslide mitigation solutions. Information needed for implementation of such initiatives aimed at understanding the social and technical dimensions, have not yet been fully taken up by the professionals in developing countries of Asia. The reason may well be the inadequate involvement and encouragement by key players of developmental planning and implementation to obtain the services of technical professionals in decision making and also their reluctance to integrate risk based mitigation practices in the process of development planning and environmental protection.

Moreover, the service sector such as human settlement development, water, power and road development authorities do not have adequate knowledge in landslide mitigation work and when the planning decisions are taken, the landslide proneness and issues related to reduction of impacts in generally not considered. In most cases, the impact of landslides is visible when the services are disrupted, and again due to lack of provision of sufficient maintenance and repairs budget, the developed of the affected area(s) are impeded. Hence, the traditional ways of imparting training to the three groups, viz. professionals involved in landslide mitigation, service sectors and decision-makers will not be effective. A more effective approach would be to discuss the issues in a comprehensive manner encouraging exchange of knowledge, through face-to-face contact, /discussion in capacity building and knowledge management.

Therefore, ADPC in collaboration with Norwegian Geo-technical Institute (NGI) has developed the program for Asian Program for Regional Capacity Enhancement for Landslide Impact Mitigation (RECLAIM) with the idea of promoting a dialogue between decision makers and professionals about the theoretical and practical aspects and issues related to landslide hazard mitigation. The program activities are designed to be implemented in three-years involving national partners from Bhutan, India, Indonesia, Nepal, the Philippines, Thailand and Sri Lanka.

The project aims to build the national capacity on landslide disaster mitigation by

- Identifying cost effective methodologies and practices adopted by national partners
- Execution of Landslide Mitigation Demonstration Projects, (LMDPs) in 2 countries as a source of committing efforts and partly funds for applied mitigation, advocacy and awareness creation purposes.
- Through sharing of experience of partner agencies in target countries in Asia.

Program Objectives

Long-term objective:

The main long-term objective of the program is *"Reduction of landslide disaster vulnerability and prevention of loss of lives and damages to properties human settlements, infrastructure, and critical facilities in the target countries"*.

Short-term objectives:

- **The first short-term objective**

To provide target countries with a cadre of specialists and decision makers with up-to-date knowledge on landslide disaster mitigation practices and to integrate this knowledge in routine development work initiated by national and local governments

- **Expectations related to first short-term objective:**
    - To provide the scientists and geo-technical engineers involved in landslide studies and services a forum for academic discussion on landslide disaster mitigation;
    - To promote good practices on landslide mitigation and risk management models in the target countries;
    - To introduce cost effective mitigation and preparedness practices through 2 Landslide Mitigation Demonstration Projects,(LMDPs) in two selected countries, tentatively on Philippines and in Thailand.
    - To facilitate introduction of new concepts into the risk assessment and land use planning process and construction in landslide prone areas
    - To promote participatory approach of all stakeholders including decision makers in the search for solutions for current problems in landslide risk mitigation
    - To promote sustainable development and environmental protection through landslide disaster impact reduction and integration of concepts of risk based mitigation planning in development practice at all levels

- **The Second short term Objective**

An increased collaboration between Norwegian Institutes and Institutes in Asia for development of cost effective strategies for landslide risk mitigation through new joint programs for demonstration of practices of landslide mitigation and preparedness and opportunities for sharing of experience and learning applications in the subject area.

- **Expectations related to Second short term Objective**
    - To promote bi-lateral programs and joint research between Norwegian Institutions and Asian Partners for sharing of experience and learning applications in the subject area.
    - To initiate a network where the participants facing the same challenges can benefit from interaction with each other during as well as after the program has been completed.

RECLAIM Phase I

In the project kick-off meeting which was held in Bangkok, Thailand on September 2004, the country partners from all the 6 target countries presented the country reports highlighting the growing risk and vulnerability in landslide prone mountain areas. As per the records presented at the meeting there is more and more evidence that frequent extreme weather, increased development activities, population growth contribute to increased vulnerability creating a more unfavourable situation in the years to come.

The 1st International Seminar on Landslide Risk Management held in Colombo, Sri Lanka on 6 June 2005, followed by Regional Training Course on Landslide Risk Mitigation in Bandarawela, Sri Lanka conducted on 7-11 June 2005.
Presenters in both events from the target countries had highlighted the urgent need to implement practical solutions for mitigation of growing landslide risk. The larger landslide risks in the target counties, as well as in many other developing counties, is due to a number of factors. The most important one is the increased vulnerability of population living in prone areas, in terms livelihood of inhabitants, its buildings and its land use, lack of resources for planning and mitigation actions and lack of knowledge to make correct and timely decisions. Even if such technical information is available, it may be dispersed through different sources without an operational procedure for sharing this information and take appropriate decision at correct time.

The participants who had attended the 1st Regional Training in Sri Lanka highlighted the importance of undertaking demonstration projects (LMDPs) to enhance the knowledge and skills of local professionals on investigation, instrumentation and structural mitigation of areas identified to be landslide prone. Especially this is a very important aspect for human settlements threatened by landslides in terms of reducing the casualties and destructions due to potential events in future. NGI has extensive experience in all three areas of landslide mitigation practice and in developing rainfall prediction models to predict landslide initiation. The transfer of knowledge can be maximized if RECLAIM project can support demonstration activities in selected countries to benefit from the technical expertise of NGI. It will not only help to transfer of state of the art of landslide risk control but also to demonstrate the cost effectiveness of the mitigation practices.

RECLAIM Phase II

The fundamental basis for the phase II of the project is to highlight the need for a gradual change in attitude towards proactive approaches of preventive measures to reduce losses. The regional implementing partners NGI and ADPC have demonstrated the ways of interactive training methodology and have stressed the need for continuity for actions as creating trust and changing attitudes cannot happen overnight. Attitude change is the primary challenge in order for behavioral change to occur subsequently. The curriculum outline for a national training course had been developed and a generic module and training material for national training was expected to be developed under the Phase II of the program.

One good example where such expertise can be of valuable resource is the landslide event in Philippines, which occurred on n 17th of February 2006.The massive landslide, which rumbled down mountainside of eastern Philippines, was responsible for burying a village in the Province of Leyte. The incident took place at 1045hrs in Barangay Guinsaugon, Municipality of St. Bernard. Ten days of heavy rain aggravated the mudslide engulfing hundreds of houses and a school packed with more than 200 students and teachers. The February 25th (latest) statistics reported that 140 dead bodies had been recovered while 972 people were still missing and are feared dead. The Government of Philippines has made a request after the recent disaster event to ADPC to consider inclusion of Philippines as a project beneficiary country of RECLAIM to benefit from the experience of other participating countries especially from the expert knowledge of NGI.

Therefore the program under Phase II would expand its scope and in size to provide hands on experience to professional staff attached to local partner agencies, while continue to provide a platform for having further interaction and discussions between decision makers, planners and professionals with theoretical and practical knowledge on the issues related to landslide risk minimization. The traditional way of training will not be able to provide a platform for the above three groups to discuss the issue and to share knowledge. Training is only a first step and more value has to be added to the skills gained through practical experience and should make use of other tools such as simulations, risk mapping, and more interactive dialogues between stakeholders including potential at risk communities, for value addition and to enhance the learning process. It is believed that through a fruitful interaction between above stakeholder groups it should be possible to obtain positive results during the next phase of the program.

The suggested approach of providing hands-on experience and skill enhancement through demonstration activities would provide good cost-effective models, which can be replicated elsewhere to solve the landslide problem in the target countries. The experience will be documented systematically and integrated as training material in Regional and national training courses planed in the phase II of the project.

The key areas of activity of RECLAIM Phase II are as follows:

- Preventive measures to reduce the consequences of landslide disasters
- Demonstration activities of suitable mitigation measures in selected landslide prone areas
- Strengthening capacity of local institutions to deal with management of risk
- Suitable development and building of safer communities
- Strengthening regional networks

Program components under phase II of the project:

- Capacity building at regional level
- Sharing of experiences in risk identification and risk reduction measures
- Development of national training capacity
- Organize and facilitate Landslide Mitigation Demonstration Projects (LDMPs) in two participating countries: Philippines and Thailand

Implementing Institutions

ADPC

Established in 1986, and with a present staff of 50 employees, ADPC is recognized as a focal point for promoting disaster awareness and fostering institutionalized disaster risk management policies and practices in the Asian region. Asian Urban Disaster Mitigation Program (AUDMP) involving 9 countries in Asia is one of the largest programs undertaken by ADPC. The AUDMP funded by USAID/OFDA and implemented during the period 1995-2005, focused on selected type of hazards in each country with the purpose of capacity building both for individuals and participating organizations. The 9 countries that participated were Bangladesh, Cambodia, India, Indonesia, Loa PDR, Nepal, Philippines, Sri Lanka and Thailand. Since October 2005 ADPC will be implementing a Program for hydro-meteorological disaster mitigation in Asia and the program is funded by USAID/OFDA.It will be targeted to be implemented in Bangladesh, Pakistan, Philippines, Sri Lanka and Vietnam. Experience gain in both programs will be very useful for the implementation of the program presented in this proposal and ADPC will be able to find synergy between programs to enhance the effectiveness and optimize the resource utilization.

NGI

Established in 1953, and with a present staff of 150 employees at its headquarter in Oslo, NGI is a well known international centre for research and consulting within geo-technical and geo- environmental engineering. It is organized as private independent foundation. Within the field of natural hazards like landslides, flooding aspects and earthquake engineering, NGI has served clients in most part of the world. Of particular relevance for the proposed program are the recent projects that NGI has undertaken in Venezuela, Nicaragua, El Salvador, Madagascar, The Caucasus Region, India, Bhutan and Hong Kong to assist on landslide preventive measures. With the newly established International Centre for Geohazards (ICG) at NGI's premises, the resource base within this discipline has grown significantly.

Participating Institutions

Bhutan

Department of Geology and Mines (DGM), Ministry of Trade and Industry *(Lead Partner)*
Departments of Roads and Agriculture

India

Indian Institute of Remote Sensing (IIRS) *(Lead Partner)*
Central Road Research Institute
National Disaster Management Division (NDMD), Ministry of Home Affairs

Indonesia

Centre for Volcanology and Geological Hazard Mitigation
Research and Cooperation Bureau, Gadjah Mada University (GMU)

Nepal

Geo-environment Unit, Department of Roads *(Lead Partner)*
Department of Water Induced Disaster Prevention (DWIDP)
Department of Narcotic Control and Disaster Management, Ministry of Home Affairs

Philippines

University of the Philippines (Department of Engineering Sciences at the UP College of Engineering) *(Lead Partner)*
National Disaster Coordinating Council (NDCC)
Department of Environment and Natural Resources (DENR)

Sri Lanka

National Building Research Organization (NBRO) *(Lead Partner)*
Road Development Authority (RDA), Ministry of Highways
Disaster Management Center (NDMC)

Thailand

Department of Mineral Resources (DMR), Ministry of Natural Resources and Environment *(Lead Partner)*
Department of Disaster Prevention and Mitigation
University of Kasetsart

Agenda

Day 1: Monday, 29 January 2007		
0900-0930	Registration of Participants	
0930-1030	Opening Ceremony	
1030-1100	Tea Break	
1100-1130	Introduction of participants	
1130-1230	Expectation from the participants and administrative announcement	
1230-1330	Lunch Break	
1330-1430	Flash Flooding and Landslide Problems in Thailand-Recent Experience	Mr. Tawsaporn Nuchanong, Department of Mineral Resources (DMR) Thailand
1430-1530	Approach for Site Investigations for Managing Landslide Risks	Prof. Warakorn Mairaing, Kasetsart University, Thailand
1530-1600	Coffee/Tea Break	
1600-1645	Risk Mapping: Case Study from Thailand	Dr. Suttisak Soralump, Kasetsart University, Thailand
1645-1730	Landslide Mitigation Demonstration Project: Patong Municipality Thailand	DMR & Kasetsart University
1800	Welcome Dinner	
Day 2: Tuesday, 30 January 2007)		
0830-1230	Field Visit in Patong, Municipality - Landslide Risk in Patong - Landslide Remediation Measure - Tsunami Early Warning System - Inspection by groups, some potential risk area and study by groups	
1230-1400	Lunch Break	
1400-1530	Discussion on the field visit and group work	
1530-1600	Coffee/Tea Break	
1600-1730	Group Presentations	
Day 3: Wednesday, 31 January 2006		
0900-1030	Early Warning, Instrumentation and Monitoring of Landslides	Dr. Elmo DiBiagiao, NGI Norway
1030-1100	Coffee/Tea Break	
1100-1215	Risk Assessment in Landslide Prone Areas Method Adopted by Sri Lanka	Mr. MIDH Wijewickrama, NBRO, Sri Lanka

1215 -1300	Two simplified qualitative methods for landslide risk assessment	Mr. Oddvar Kjekstad, NGI Norway
1300-1400	Lunch Break	
1400-1530	Probabilistic Assessment of Landslide Risk and Mapping of Risk and Vulnerability	Invited Lecturer: Dr. Fowze, AIT Thailand
1530-1600	Coffee/Tea Break	
1600-1730	Risk Assessment in Landslide Prone Areas Approach Adopted by Bhutan	Mr. Dorji Wangda, DGM Bhutan
Day 4: Thursday, 1 February 2006		
0900-1000	Seismic Action Induced Landslides	Dr. Champati Ray, IIRS India
1000-1030	Buildings in steep slopes, how can slide instabilities be avoided?	Mr. Tore Valstad, NGI, Norway
1030-1100	Coffee/Tea Break	
1100-1130	Landslide Risk & Remediation Techniques for Road Construction	Dr. P.K. Nanda, Central Road Research Institute, India
1100-1200	Landslide Risk & Remediation Techniques for Road Construction	Mr. Jayamanne, Road Development Authority, Sri Lanka
1200-1300	Application of Geoinformation (RS/GIS) for Landslide/Disaster Risk Assessment and Management", an experience in rapid assessment for landslide induced by earthquake of Jogjakarta region	Dr. Sudibyakto, GMU, Indonesia
1300-1400	Lunch Break	
1400-1500	Landslide Hazard Mitigation Strategy in Indonesia Case Study : Landslide Induced By Earthquake in Indonesia	Dr. Ir. Surono, Center for Volcanology and Geological Hazard Mitigation, Indonesia
1500-1600	Good Practices in Landslide Risk Management	Mr. Ram Prasad Pathak, DOR, Nepal
1600-1630	Coffee/Tea Break	
1630-1730	Bio-engineering Methods Use in Landslide Mitigation	Mr. Deo Raj Pokharel, Department of Water Induced Disaster Prevention (DWIPD) Nepal
1800	Depart for Farewell Dinner	
Day 5: Friday, 2 February 2007		
0900-0930	Landslide Problem in the Philippines: Experience of Recent Event CARAGA Landslide Project Experience	Dr. Sandra G. Catane, University of the Philippines Dr. Blanche O. Gobenciong, NDCC

0930-1030	Landslide Mitigation Demonstration Project	Dr. Rhodora Gonzalez, University of the Philippines
1030-1100	Coffee/Tea Break	
1100-1200	Conducive Policy Environment for Mainstreaming Landslide Risk Management in Local Government Level	Mr. NMSI Arambepola, ADPC Thailand
1200-1300	Panel Discussion on Policy Environment (Country Experience)	DDPM, DMC-Sri Lanka, NDCC-Philippines, NDM-India
1300-1400	Lunch Break	
1400-1530	Discussion on National Training	Mr. Muhibuddin Bin Usamah, ADPC, Thailand
1530-1600	Coffee/Tea Break	
1600-1700	Follow up actions and discussion on the candidate themes for the next (3rd) regional training	
1700	Conclusion	

List of Participants

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Technical Presentation

1. *Early Warning, Instrumentation and Monitoring Landslides,*
   Elmo Di Biagio and Oddvar Kjekstad,
   Norwegian Geotechnical Institute, Oslo, Norway

2. *Landslide Hazard and Risk analysis of Kandy Municipal Council area, Sri Lanka,*
   M.I.D.H.Wijewickrama, Landslide studies and services division, National building research organization, Ministry of housing and construction, Sri lanka

3. *Examples of Two Simplified Qualitative Methods For Landslide Risk Assessment,*
   Oddvar Kjekstad, Tore Valstad,Odd Gregersen and Ulrik Domås,
   Norwegian Geotechnical Institute, Oslo Norway

4. *Spatial Modelling of Seismicity Induced Landslides,*
   P. K. Champati Ray, R. C. Lakhera and V.K. Singh,
   Indian Institute of Remote Sensing, Dehradun, India

5. *Landslide Risk and Remediation Techniques for Road Construction*
   Dr. P K Nanda
   Central Road Research Institute, New Delhi – 110 020

6. *Landslide Risk & Remediation Techniques for Road Construction in Sri Lanka*
   J Jayamanne and D P Mallawaratchie, Road Development Authority, Sri Lanka

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Early warning, Instrumentation and Monitoring Landslides

Elmo DiBiagio and Oddvar Kjekstad
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Abstract

Recent landslide disasters as well as the ever increasing need to locate new sites for urban expansion have resulted in a world-wide increase in the use of instrumentation and monitoring techniques to assist in evaluating the stability of slopes.

The paper will present a general review of the current state-of-the-art of instrumenting slopes. This will include a discussion of the parameters that need to be monitored and a survey of available technology and equipment for remote monitoring from space as well as for surface and subsurface measurements.

A step by step approach to design and implementation of monitoring programs will be presented for the most common slope stability problems encountered by engineers and urban planners. The importance of reliable communication, proper data management and analysis tools will be pointed out. Common problems encountered in monitoring programs will be discussed.

The role of Early Warning Systems in mitigating risk will be discussed. Threshold values for triggering events needed to issue alerts and alarm annunciating will be discussed and illustrated by means of case studies. Examples of Early Warning Systems will be presented.

Early Warning, Instrumentation and Monitoring Landslides

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Nature abhors sloping landforms

Natural slopes will eventually fail or be eroded away

We learn in school that "Nature abhors a vacuum". That idiom, which can be credited to the Greek philosopher Aristotle (350 B.C.) expresses the idea that empty space is unnatural as it goes against the laws of physics. For people involved in slope stability and landslide problems an appropriate revision of the expression would be: "Nature abhors sloping landforms". It is indeed true that in the geological time scale, natural slopes are only temporary topographical features. If given enough time, all slopes will eventually become horizontal or near horizontal surfaces under the combined actions of natural processes such as weathering, erosion, freezing and thawing, earthquakes and of course gravity. This is part of the geologic cycle whereby older mountains are worn down creating new depositions of geologic material at another location and subsequent formation of new mountains. We must, therefore, accept the fact that all natural slopes will eventually fail or be eroded away. The major uncertainty is of course the time element, i.e., when will this happen? For these reasons, we must learn to live with the constant threat of landslides.

Living with landslide

Our only recourse is to learn to live with landslides. To do this we must be able to understand and predict landslide behavior.

One can live with the threat of a potential landslide providing the risk associated with it is acceptable to society or provisions can be taken to reduce the risk to an acceptable level. Whether it is possible to do this or not depends on our ability to correctly evaluate the stability of the slope which in turn depends on how much qualitative and quantitative information we have about the slope and how well we understand the failure mechanisms for landslides. Without an adequate knowledge basis, it is not possible to do so.

The role of landslide monitoring is to gather information useable for avoiding or reducing the impact of landslide activity. That is why landslide monitoring has become such an important activity.

The current level of interest in monitoring landslides can be illustrated by the number of references available on the Internet. A search of the phrase *Landslide monitoring* yielded 25000 references or *Hits* as the result of an Internet search is referred to. Another search showed that there are approximately 250 Microsoft Power Point presentations dealing with landslide monitoring on the Internet. Two of the principal reasons for the current high level of landslide monitoring activities are:

- Recent landslide disasters as well as the ever increasing need to locate new land areas for urban expansion have resulted in a world-wide need for improving our knowledge of the problems associated with unstable slopes and how to be better prepared to cope with them.
- It has become easier to implement monitoring programs because of technological advancements in measurement technology as well as data acquisition, transmission and analysis procedures.

Landslide monitoring

Monitoring is the key to slope instability assessment, management and mitigation.

The objective of a landslide monitoring program is to collect, record and analyze in a systematic and purposeful manner qualitative and quantitative information required to evaluate specific problems associated with the slope or landslide being studied. The information may comprise maps, photographs, boring logs, topographical data, weather data and visual observations. In most cases, monitoring will also include installation of instruments and taking physical measurements.

Landslide monitoring programs are implemented for a number of reasons. Four of the most common applications are listed below.

- To detect and classify landslides, to provide information needed to evaluate slope stability, calibrate prediction models and carry out risk and consequences analyses or to moderate construction activities that may lead to a slope failure.
- To provide input for Early Warning Systems.
- To protect workers clearing away slide debris or carrying out remedial works in a post landslide area, and
- To verify the effectiveness of mitigation measures taken to reduce the risk associated with an unstable slope.

Monitoring programs vary considerably depending on the risk a potential unstable slope poses. Programs can range from only visual inspections to extensive programs comprising observations from orbiting satellites and arrays of sophisticated instruments installed at the site.

The challenges in monitoring landslides are considerable. There are many different types of landslides; thus, different approaches to monitoring and instrumentation are required. Generally there is a limited knowledge of site conditions and historical information about the stability of the area under study. Often one is not aware of a landslide problem before movement is detected. Triggering events can occur anytime. And last but not least, physical limitations and economic constraints limit what can be monitored.

Guidelines for designing a monitoring program

A successful monitoring program depends on three points, namely (1) know why monitoring is necessary, (2) know what to monitor and (3) know how to do it.

Monitoring programs will differ in methodology and scope because landslides also differ widely in size and type of movement associated with them. For example, six common types of landslide movements are: rockfalls, topples, rotational, sagging, spread and flows. Obviously, the approach to monitoring movements may be quite different for each of these. In addition, monitoring programs may have different objectives depending on the problem being investigated. A monitoring program designed to study a natural slope may differ significantly from one designed to monitor construction of a manmade slope or to investigate a post-disaster landslide.

The most important step in the design of a successful landslide monitoring program is to identify and understand the objective of the program. Once the objective is known and understood, the appropriate data to be collected can be correctly specified. This important initial step is often not given enough consideration.

Steps in designing a monitoring program for landslides

- Get as much site characterization information as possible, including maps, geological and topographical data, historical records of previous slides and aerial extent of a potential sliding mass.
- Perform a stability analysis or model study and risk evaluation to get a better understanding of the hazard
- If a monitoring program is considered helpful or necessary, define the objective of the monitoring program and select the type of measurements to be included in the program. Assign priority to the measurements.
- On the basis of cost, availability and reliability information decide on the measurement methods to be used and select the appropriate instruments

- Determine the optimum number of instruments and locations. If available, use theoretical or empirical models to optimize the number and placement of instruments.
- Decide on the preferred method of data acquisition, e.g. manual or automatic recordings.
- Arrange for proper installation, protection and marking of instruments and reference points in the field
- Plan for data flow, data management and analysis. Insure that there are sufficient funds to properly analyze the measurement data.
- Plan for an adequate level of maintenance of the monitoring system.

Monitoring methodology and equipment

As a general rule of thumb, one should use the simplest methods possible.

Monitoring implies observations and physical measurements. A landslide monitoring program will normally comprise one or more of the following:

- Visual observations to look for evidence of instability and to determine the areal extent of a slide
- Remote sensing for classification and detection of movement over large surface areas
- Surface measurements for site characterization and monitoring displacements
- Subsurface measurements for site characterization, monitoring displacements and pore water pressure, and
- Environmental data, particularly magnitude and intensity of rainfall

Landslide monitoring techniques range from simple and inexpensive manual measurements and visual observations; to costly and sophisticated surveillance techniques using satellites and automatic systems comprising a large numbers of electronic instruments. As a general rule of thumb, one should use the simplest methods possible. Many landslide related measurements can be made manually without the recourse to expensive and complex equipment. Some examples are:

- Photographic records of permanent reference points and terrain features to track surface changes
- Surveying techniques for measuring vertical and horizontal movements of reference points
- Observation wells to monitor ground water level instead of using pressure transducers installed in boreholes.

Visual observations

Technology will never replace completely the human observer, in particular when it comes to recognizing terrain features that indicate slope instability. Visual observations of topographical features, geology, soil type and hydrological conditions are an important part of site characterization studies.

Regularly scheduled visual inspections combined with photographic records may detect signs of incipient failure of a slope. Visual inspections should be carried out immediately after a triggering event such as an earth quake or extreme precipitation. Some of the features that may be observed prior to a landslide are (Source: USGS - Features That May Indicate Catastrophic Landslide Movement):

- Springs, seeps, or saturated ground in areas that have not typically been wet before.
- New cracks or unusual bulges in the ground, street pavements or sidewalks. Soil moving away from foundations.
- Ancillary structures such as decks and patios tilting and/or moving relative to the main house.
- Tilting or cracking of concrete floors and foundations.
- Broken water lines and other underground utilities.
- Leaning telephone poles, trees, retaining walls or fences
- Offset fence lines.
- Sunken or down-dropped road beds.
- Rapid increase in creek water levels, possibly accompanied by increased transport of soil particles (turbidity).
- Sudden decrease in creek water levels though rain is still falling or just recently stopped.
- Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb.

Geophysical methods for site exploration

Geophysical measurements such as cross-hole tomography surveys using ground penetrating radar or seismic methods may be combined with conventional borings to determine soil and rock properties and stratigraphy.

Geophysical methods for subsurface mapping that can be carried out from the surface such as, resistivity and seismic surveys or ground penetrating radar have the advantage that costly borings are not necessary.

Another advantage of geophysical site investigations is that the equipment is relatively light-weight and readily transported to sites where access with conventional drilling equipment is difficult or not justifiable because of the cost. Consequently, for some projects geophysical survey methods may be an acceptable alternative to conventional borings.

Remote sensing of terrain features and landslide activity

Satellite-borne remote sensing

Remote sensing implies collection of information from a distant vantage point. The term is generally associated with Earth Observation (EO) satellite data, but it also applies to aerial photography and ground-based detectors and other devices that are remotely located from the geographical area being observed.

Satellite and radar imagery can be used for detection and classification of landslides. Satellite stereophotogrammetry consists of acquiring a stereo pair of images of the same ground scene within a relatively short period of time. These images can be processed to get 3-dimensional topographical features and changes can be determined from repeated observations over time.

The most important satellite imaging system currently being used for landslide detection and monitoring is Interferometric Synthetic Aperture Radar (InSAR), Figure 1.

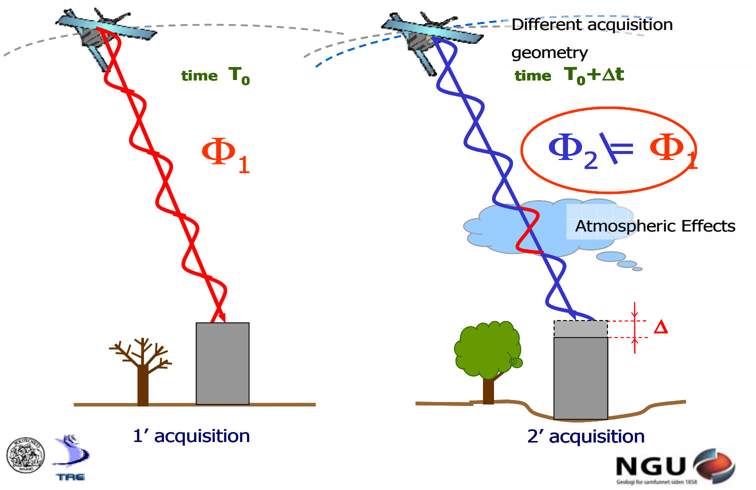

Figure 1 InSAR concept for monitoring surface displacements

For landscapes with terrain features that are more or less stable over a period of time and good reflectors of radar signals, such as buildings or other engineered structures, or undisturbed rocks and ground surfaces, it is possible to make high precision measurements of the change in the position of the reflectors by subtracting or "interfering" two radar scans made of the same area at different times. This is the principle behind InSAR, see Figure 1.

Under ideal conditions, it is possible to measure displacements with an accuracy of the order of 5 to 10 mm. Interferograms, formed from patterns of interference between the phase components of two radar scans made from nearly the same orbital position but at different times, have demonstrated dramatic potential for high-density spatial mapping of ground-surface displacements

One important advantage of InSAR is that there is a large inventory of archived InSAR images dating back over approximately 10 years. These images can be compared with current images to get a historical record of landslide movements. An example is shown in Figure 2. One disadvantage of InSAR is that observations are only possible when the InSAR satellite passes over the area under study. Normal repeat time is of the order of 20 to 30 days depending on the satellite being used.

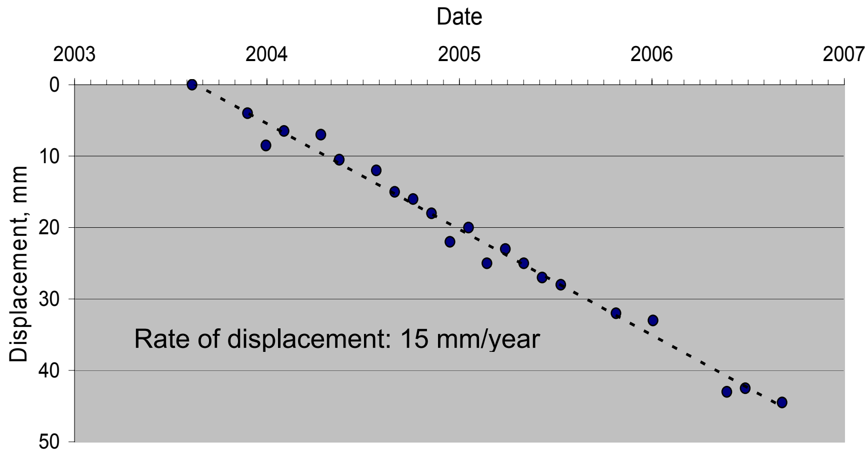

Figure 2 *Historical displacement of a point on a landslide calculated in September 2006, using 3 years of archived InSAR images*

Land-based remote sensing

One disadvantage of satellite-based InSAR is that measurements can only be made when the satellite orbit passes over the area of interest. A much shorter repeat time is desirable for most studies of active landslide and for warning systems in particular. Therefore, considerable work is being done on the development of ground-based interferometric radar systems for monitoring displacement of unstable slopes. The use of such equipment is becoming more common. An example of land-based InSAR displacement measurements of a rock slope in Norway is shown in Figure 3.

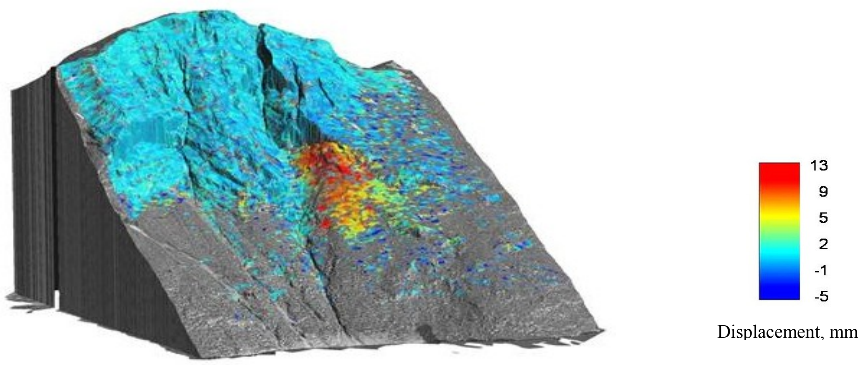

Figure 3 *Displacements of an unstable rock slope at Åknes, Norway The measurements were made using surface-based InSAR equipment*

Other land-based monitoring techniques used for landslide monitoring are: digital photogrammetry, EDM (Electronic Distance Measurements), motorized surveying equipment for automatic point to point measurements and automatic terrestrial scanning laser equipment.

Surface measurements of landslide activity

Measurements on the surface of a slope are used primarily for mapping, site characterization studies and to determine if the slope is unstable. Monitoring surficial displacement is the easiest way to observe the history of a landslide. Instruments deployed on the surface are also used for detection of landslide triggering events. Typical surveillance methods for monitoring the surface of a slope or active landslide are listed and described briefly in Table 1.

Table 1 Surveillance methods and instrument for monitoring surface activity

Objective or parameter measured	Surveillance method	Instrument type	Site installation work required
Monitor displacements of reference points on the slope	Geodetic survey, leveling or triangulation	Surveyor's level or theodolite	Pertmanent reference monuments
	Geodetic survey	Total Station or motorized theodolite	Installation of fixed targets or prisms
	Direct measurement of displacement between 2 points	Extensometers, joint meters, mechanical or electrical	Fixed installations and protection
	Differential GPS	GPS receiver with software	Fixed or portable installations
Measure rotation of points on slope	Surface mounted tiltmeter	Various types available	Fixed to rigid body or monument
Stream flow	Gauging station	Various types of level sensors calibrated against stream flow	Suitable structure for installing instruments
Detect triggering event	Geophone	Electronic instrument	Permanent installation
	Seismograph	Electronic instrument	Permanent installation
	Rainfall intensity	Rain gauge	Permanent installation
	Flood water level detection	Liquid level limit switches	Suitable structure for installing instruments

For most slopes, measurements of the magnitude, direction and velocity of displacements are the most reliable indicators of slope instability. Survey monuments and traditional surveying techniques are used for point measurements of displacements. These methods are labor intensive; thus, it is more common now to use motorized survey equipment such as so-called Total Stations that can be programmed to automatically survey an array of reference prisms installed on the surface of the slope. Other point-based measuring instruments are extensometers and joint meters for measuring width of tension cracks and surface deformations. Surface mounted tiltmeters are helpful in determining whether a slide is a rotational slide or not.

Satellite based GPS measurements are becoming more and more common for point-based monitoring of surface displacements. GPS measurements can be automated. GPS measurements require no line of sight between monitoring stations. Measurement can be taken during unfavorable weather conditions.

A technique for improving the accuracy of the Global Positioning System is Differential GPS (DGPS). The basic concept of DGPS is the use of 2 receivers, one at a known fixed location and one mobile station. Error corrections are transmitted by radio from the fixed location to the mobile unit, see Figure 4.

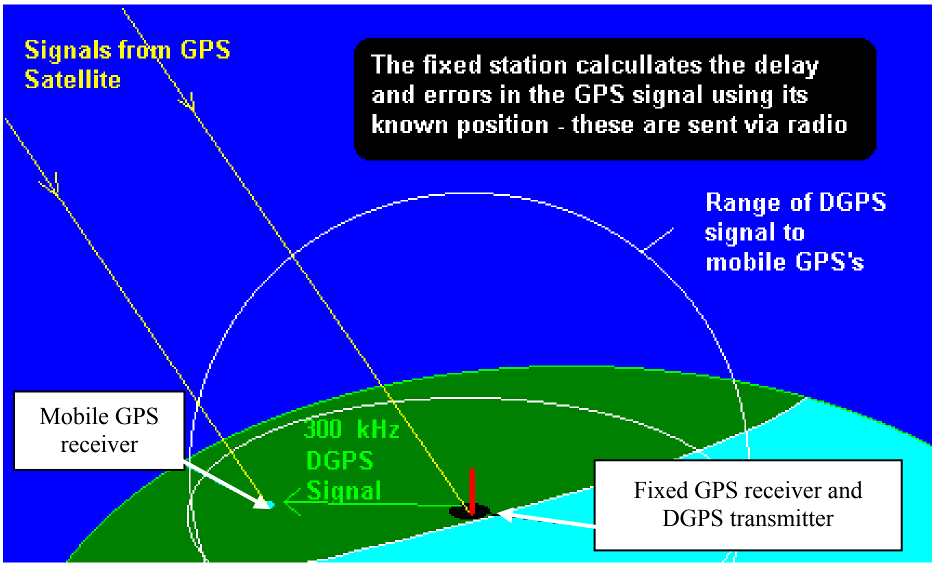

Figure 4 Differential GPS measurement concept

Area-based techniques for monitoring surface features are digital photography, photogammetry and terrestrial laser scanning. The last method is commonly used for creating Digital Surface Models (DSM).

Early warning systems may use precipitation gauges and surface mounted geophones or accelerometers to detect landslide triggering events. Likewise, stream flow measurements may be required if there is a possibility that a landslide will be triggered by high velocity channel flow at the surface or erosion at the toe of a slope

Subsurface measurements of landslide activity

The objectives of subsurface measurements are primarily for site characterization and to determine the vertical extent of the unstable mass and to locate the failure plane. Typical surveillance methods and instruments commonly installed in boreholes for subsurface measurements are tabulated in Table 2.

Table 2 Surveillance methods and instruments commonly installed in boreholes for subsurface measurements

Objective or parameter measured	Surveillance method	Instrument type	Site installation work
Monitor subsurface displacement profiles and slide velocity, locate failure planes	Moveable Inclinometer probe	Various types available	Inclinometer casing installed in boreholes
	In-place inclinometers	Various types available	Inclinometer casing installed in boreholes
Detect initial subsurface movement and failure plane	TDR, Time Domain Reflectrometry	Special equipment	Coaxial cable in a grouted or backfilled borehole
Ground water level	Direct measurement	Measuring tape fitted with sensor to detect water level	Observation well
	Pressure sensor	Various types of electrical sensors	Observation well
Pore water pressure	Direct measurement of piezometric head	Measuring tape fitted with sensor to detect water level	Open standpipe or observation well
	Pressure sensor	Various types of electrical or pneumatic piezometers	Piezometers installed and sealed in borehole

Inclinometers measurements are extremely useful in detecting movements and locating the boundaries of an unstable slope. Borehole inclinometer survey probes and in-place inclinometers are used to profile the moving mass and locate the failure plane. Manual surveying a borehole with an inclinometer probe is very labor intensive and requires a site visit for every set of readings. For this reason, it is becoming more common to install instead a permanent string of inclinometers in the borehole, so-called "In-place Inclinometers". The advantage of using in-place inclinometers is that the measurements can be automated to provide real time data.

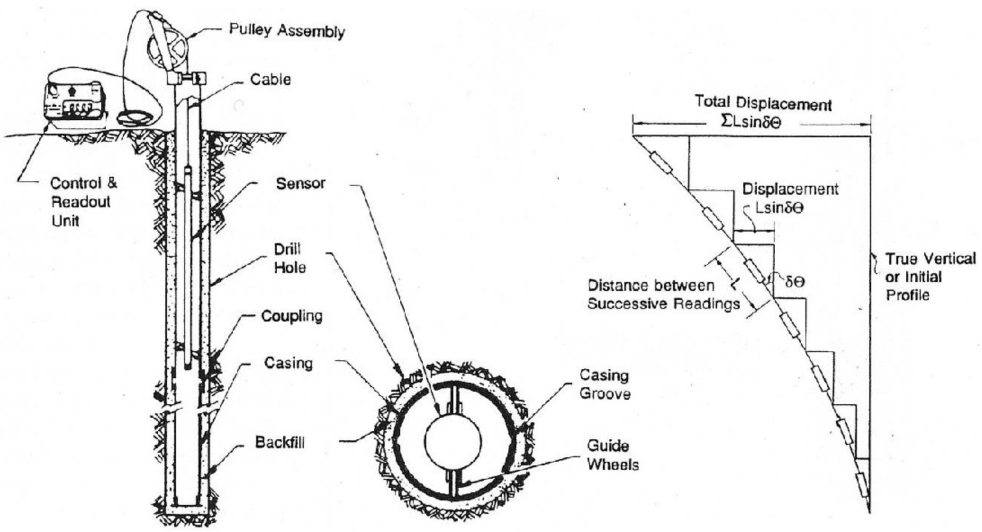

Figure 5 Borehole inclinometer installation

Observation wells and piezometers are used to determine the subsurface ground water regime and in particular for monitoring changes in pore water pressure. The stability of many types of slopes depends largely on the shear strength of the material along the sliding surface, which in turn is a function of the ambient pore water pressure. The higher the pore pressure, the lower the shear strength. For this reason, pore water pressure is a key indicator of slope stability.

Time Domain Reflectometry (TDR), Figure 6, is frequently used to localize the moving zone in a landslide. It is a simple and reliable method developed originally by electrical engineers to precisely locate faults in communication cables. The technique involves sending an electromagnetic pulse through the cable. If the pulse encounters a deformation or break in the cable, part of the signal is reflected back to the source and the time of flight can be used to determine the distance to the fault. When used to monitor a landslide, a coaxial cable is embedded in a grouted borehole. The cable serves as a continuous sensor which, when pulsed, can be used to detect fracturing and relative movement at any location along its length. The principal use is to detect the location of the failure plane and identify the zone of movement in a landslide.

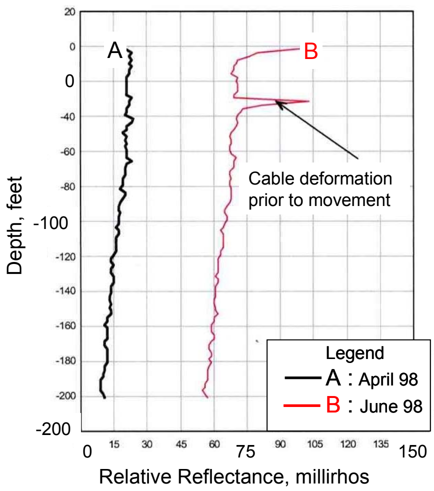

Figure 6 *TDR monitoring station and measurement data (Kane and Beck, 1999)*

Selection of instruments

The best approach is to ask for advice from reputable instrument suppliers.

Instruments must be reliable and capable of functioning for long periods of time without repair, calibration or replacement. Instruments must be capable of responding rapidly and precisely to changes so that a true picture of events can be maintained at all times. Fortunately, there is a large selection of well-proven commercially available equipment to choose from. Unfortunately, economic constraints generally limit the scope of instrumentation used in landslide monitoring programs.

It is not always obvious what instrument or measurement concept is best suited for the given geotechnical application. This type of knowledge is obtained primarily by trial and error from past experience. Some performance and reliability data for instrumentation can be found in the literature. However, there is little negative performance data because of a general reluctance to write about unsuccessful instrumentation case histories. The best approach is to ask for advice from reputable instrument suppliers. Be sure, however, to specify the operating and environmental conditions for the intended use of the instruments, accuracy requirements and how long the instruments are to function. Indicate also the qualifications of the people who will be installing and using the equipment.

Displacement of the slope is undoubtedly the most important measurements in a landslide monitoring program. Fortunately, there are a number of well-proven surveillance techniques to choose from. Table 3 summarizes the precision of the measurements obtainable with the methods currently used to monitor movements of slopes.

Table 3 Summary of methods used in measuring surface displacements and their precision (Mikkelesen 1996)

Method	Typical operating range	Components of displacement	Typical precision
GPS (Differential)	Variable (< 20 km)	δx, δy, δz	5-10 mm
EDM	Variable (1-14 km)	δ(Distance)	1-5 mm + 1-5 ppm
Total Station	< 3.5 km	δx, δy, δz	1mm + 1 ppm
Wire extensometer	<10 - 80 m	δ(Distance)	0.3mm/30m
Surveying triangulation	< 300 - 1000 m	δx, δy, δz	5 - 10 mm
Surveying traverses	Variable	δx, δy, δz	5 - 10 mm
Geometrically leveling	Variable	δz	2 - 5 mm/km
Terrestrial photogrammetry	Ideally < 100 m	δx, δy, δz	20 mm from 100 m
Aerial photogrammetry	Altitude < 500 m	δx, δy, δz	100 mm
Note: 1 ppm means one part per million or 1 additional millimeter per kilometer of measured line			

Data acquisition systems

Selection of a data acquisition system for a landslide monitoring program is no longer a complicated or difficult decision to make. Almost anything is possible using current state-of-the-art technology. Communication links provide real-time links and data flow to the user, an important requirement for landslide monitoring systems in particular for early warning systems. A typical data acquisition system suitable for landslide monitoring comprised entirely of commercially available components is shown in Figure 7.

Landslide monitoring systems may have to be kept in operation for many years. During this period the original instruments may be damaged and replaced or recalibrated from time to time. Likewise, the scope of monitoring program may be expanded by the addition of more instruments. Under these conditions it is absolutely necessary to keep accurate records of the serial numbers, valid calibration data and other information needed to convert raw instrument readings to engineering values. This important detail is often not given enough attention. One approach for dealing with this problem when using an automatic data acquisition system, is to record the pertinent instrument data together with the instrument readings. For example, the instruments' channel number, serial number, calibration data, elevation, etc., can be stored in a configuration file within the data acquisition system. The configuration file is then read as a block of information and recorded as a header for every set of instrument readings recorded by the data logger. Thus, the valid calibration data is always recorded together with the instrument readings. The only requirement otherwise is to keep the configuration file updated at all times. This procedure adds some extra volume of data storage but this is generally not a serious problem because the total volume of data recorded by a landslide monitoring system is small.

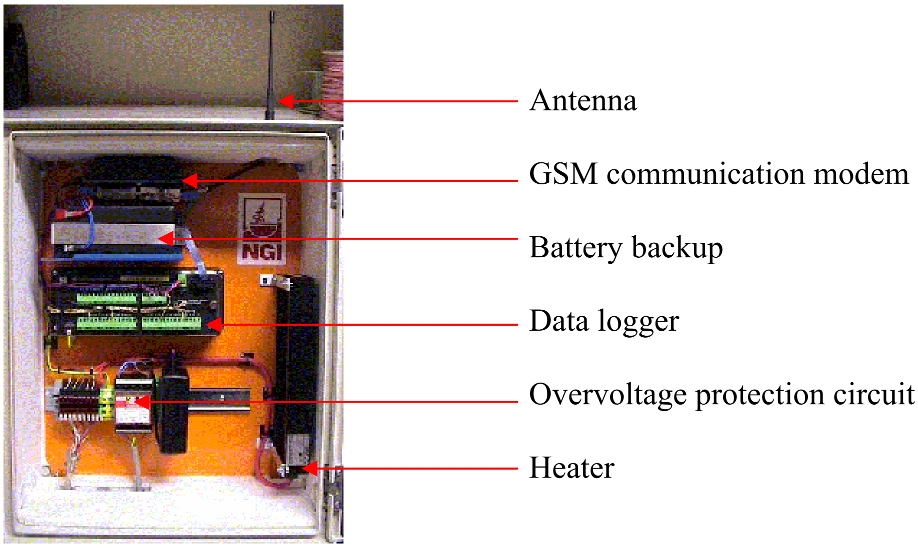

Figure 7 *Typical data acquisition system with communication link over the GSM mobile telephone net*

The major problems with automatic data acquisition systems for some potential users, are the high initial cost and the need for highly trained personnel to operate and maintain the equipment.

Installation and operational problems

Three frequently encountered problems in the operation of landslide monitoring systems are outlined below. These need to be given serious thought in the design, installation and operation of the equipment.

Damage caused by electrical storms
Electrical storms are one of the main causes of instrument failures for geotechnical instrumentation projects. Instruments installed on a slope will generally require long cable runs to connect them to the data acquisition equipment. During electrical storms there can be very high induced voltages in these cables. These induced voltages may be high enough to damage either the instruments or the data acquisition system or both. This is particularly a problem for installations at high elevations as is often the case when monitoring landslides. Failure can also be caused during electrical storms by high voltages transients in mains power lines connected to the data acquisition equipment. Therefore, adequate overvoltage protection circuits for the instrument cables and mains connections must be included in the monitoring system.

Adequate power supplies
Landslide monitoring systems in remote areas very often rely entirely on battery power. Experience has shown that lack of power is one of the major causes of system failures during the long-term operation of these installations. Battery power supplies must be designed with sufficient reserve and equipped with reliable charging equipment for the specific geographical and climatic location. Adequate maintenance and training in the proper use of these components is paramount to successful operation.

Vandalism
Monitoring systems are frequently unattended and located in remote areas. Vandalism is often a serious problem. Instruments and auxiliary equipment must be installed and protected in such a way as to minimize damage due to vandalism.

Early warning systems (EWS) for landslides

A false alarm generated by an automatic Early Warning System may pose more of a hazard than the landslide itself.

Early warning systems mitigate risk by reducing the consequences. To do this, the system must issue alerts or warnings early enough to give sufficient lead time to implement actions to protect persons and/or property.

Early Warning Systems for landslides are monitoring systems specifically designed to detect events that precede a landslide in time to issue an imminent hazard warning and initiate mitigation measures. The key to a successful early warning system is to be able to identify and measure small but significant indicators that precede a landslide.

The relevant precursors depend, of course, on the type of landslide. Typical examples of precursors are intense rainfall, ground vibrations and earthquakes, blasting, acceleration or high rate of movement of the slope, rapid increases in pore water pressure or stream flow at the toe of a slope. Typical instruments in a EWS are, therefore, rain gauges, geophones, seismographs, piezometers, inclinometers, extensometers and devices for measuring movement of slopes.

Reliability of measurements is paramount in any monitoring system, but particularly so in an early warning system. Thus, redundancy and alternate measurement methods should be considered to avoid false alarms. The consequences of false alarms in a warning system are so serious that every possible action must be taken to eliminate them. One important step in this process is to include data quality control measures in data acquisition and processing to insure that erroneous data is not used in analysis and forecasting of landslide activity. Another step is to make maximum use of human intelligence and "engineering judgment" in decision making - a process that, unfortunately, does have practical limitations in a fully automatic warning system.

The principal components of a EWS are the appropriate sensors and measuring devices, a real-time data acquisition unit with a suitable communication link and software to process and analyze the measurements. The system must issue warnings via the communication link automatically if predefined alarm threshold values are exceeded.

An EWS comprises four main activities: monitoring, analysis of data and forecasting, warning and response. A block diagram of a typical EWS is illustrated in Figure. 8.

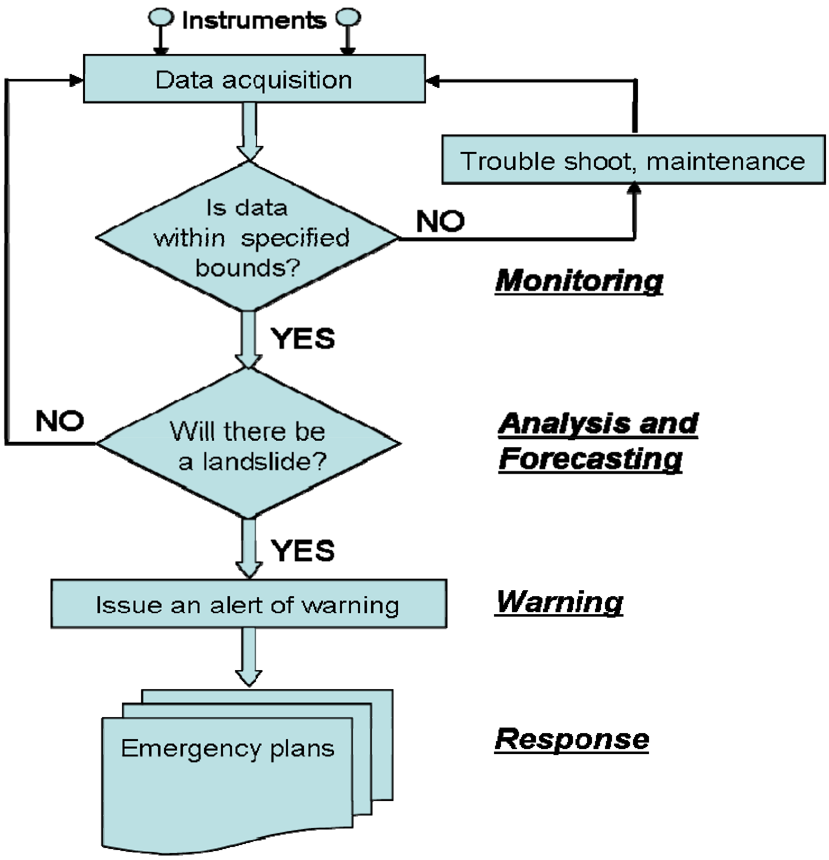

Figure 8 Block diagram of a typical EWS

The major problem in designing a EWS is to be able to specify proper threshold values. This will generally involve some form of forecasting based on past trends in the measurements. Engineering judgment will also be an important element in the process of forecasting and setting alarm limits. In all cases the system must be so flexible that the threshold parameters can be changed as more and more information is obtained on the performance of the monitoring system and the behavior of the slope being monitored.

Examples of early warning monitoring systems

The Val Pola landslide monitoring system (1987)

A warning system for protecting personnel working in a landslide.

The 28 July 1987 Val Pola landslide in Valtellina in northern Italy was the most destructive and expensive landslide in recent times in Italy, Figure 9. The landslide was triggered by erosion following a week-long period of above normal rainfall combined with unseasonable glacier melt water. The runoff and subsequent erosion resulted in debris flows which created a large alluvial fan in the valley below. The debris buried a small village and formed a landslide dam approximately 70 m high that blocked the Adda River forming a lake behind the dam. The landslide claimed 27 lives. Property damages and remedial works cost approximately 400,000,000 Euro.

Figure 9 Val Pola landsline in Valtellina, northern Italy 1987

The avalanche path was 750 m wide and 1600 m long. The elevation difference from crest to valley floor was 1200 m. The slide material was gneiss, granite and debris from an older landslide.

The most critical post-landslide scenario was the rising water level in the lake which if allowed to increase uncontrolled would lead to overtopping and erosion of the landslide dam and a major flood downstream in the very densely populated valley. For this reason, the first remedial work was installation a temporary high-capacity pumping station to control the lake level by pumping water over the landslide dam, Figure 10. At the same time, work was started on construction of two diversion tunnels to permanently divert the Adda River around the landslide dam.

Figure 10
Pumping station Capacity (11m cubic meters/sec)

Figure 11
Wire extensometer mounted over a tension crack

After the initial landslide there were numerous tension cracks and steep scarps at the crest as well as unstable slopes along the sides of the avalanche path as shown in Figure 11. Remedial work had to be carried out under the constant threat of new landslides. The work in the valley below engaged many workers over a long period of time. For this reason an extensive early warning system was installed to protect the people working in the valley.

A list of the instruments in the monitoring system is shown in Table 4. In addition approximately 400 m of inclinometer casings were installed in boreholes for manual measurements of movements with inclinometer probes. There were seven data acquisition nodes like the one shown in Figure 12, each equipped with telemetry links to a central control station.

Table 4
Instruments in the Val Pola monitoring system

Instruments	**Nr.**
Extensometers (Electrical)	58
Extensometers (Manual)	67
Piezometers	46
Seismometers	20
In-place inclinometers	11
Temperature sensors	10
Rain gauges	9
Hydrometers	6
Snow gauges	1
Geodetic station	1

Figure 12 Data acquisition node

There Val Pola monitoring system was installed during an emergency. This is frequently the case when a landslide occurs. There is little time for design and procurement of components. One has to improvise using whatever equipment is available. That is not always the best starting point for an important monitoring program. Fortunately, the Val Pola system was able to provide the information needed to keep a running assessment of the stability of the landslide area. It has been in continuous operation since 1987; however, the scope has been reduced gradually as remedial works were completed and the need for data decreased. The original cost of the system was approximately 10,000,000 Euro.

Some lessons learned from the Val Pola monitoring project are listed below.

- Standard instrumentation is in general able to provide data of sufficient quality for evaluation of landslides.
- The reliability of instruments is in general more important than accuracy and resolution because a small decrease in instrument performance is negligible compared to the uncertainties in the behaviour models used to evaluate the data.
- Great care must be taken to insure adequate protection of instruments against environmental and mechanical damage, and electrical damage during thunder storms.
- A microseismic network is a powerful tool for qualitative global monitoring of landslides, but considerable experience and long-term observations are necessary for a quantitative analysis of the data.
- Radio telemetry is well suited for data transmission under adverse operating conditions. And, when distances are large, radio telemetry may be significantly less expensive than communication over cables.

Lake Sarez Risk Mitigation Project (Tajikistan)

A sophisticated EWS in a very remote location.

Lake Sarez is located in the Pamir Mountain Range in eastern Tajikistan. It was created in 1911 when an earthquake triggered a massive rock slide (volume: ~2 km3) that blocked the Murgab river valley. The natural dam, Usoi Dam, formed by the rockslide which retains the lake is located at an altitude of 3200 meters. With a height of over 550 meters, it is by far the largest dam, natural or man-made, in the world, Figure 13.

Lake Sarez, impounded by this natural dam, is now about 60 km long and has a maximum depth of approximately 550 m and a volume of 17 km^3. The lake has never overtopped the dam but the current freeboard between the lake surface and the lowest point of the dam crest is only about 50 m. The lake level is currently increasing about 30 cm per year. If this natural dam were to fail, a worst-case scenario would be a catastrophic outburst flood endangering thousands and thousands of people in the Bartang, Panj, and Amu Darya valleys downstream.

There is another natural hazard at Lake, namely, a large active landslide on the right bank, Figure 14. If this unstable slope would fail completely and slide into the lake, it would generate a surface wave large enough to overtop the dam and cause a severe flood downstream. Experts who have studied the hazards agree that the most probably risk scenario at Lake Sarez is failure of the right bank landslide and subsequent overtopping of the dam.

Figure 13
Satellite photograph of Lake Sarez and Usoi Dam

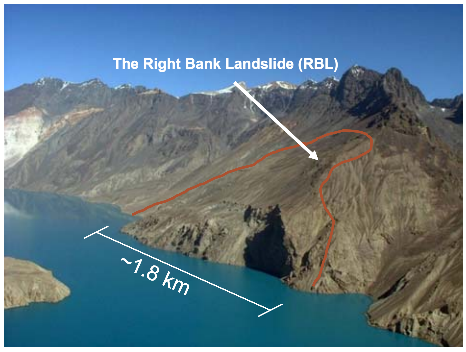

Figure 14
The active landslide on the right bank of Lake Sarez

In 2000, an international "Lake Sarez Risk Mitigation Project (LSRMP)" was launched under the auspices of the World Bank to deal with the risk elements posed by Usoi dam and Lake Sarez. The two main objectives of the project were to find long-term measures to minimize the hazard and to install an early warning system to alert the most vulnerable communities downstream.

The Early Warning System for Lake Sarez, Figure 15, has been in operation since late 2005. The system has 9 remote monitoring units linked to a central data acquisition system at a local control center near the dam. Data is transmitted via satellite to the main control center in Dushanbe the capital of Tajikistan. Alerts and warning messages are sent from Dushanbe to 22 communities connected to the system. The local control center is manned 24 hours per day, every day.

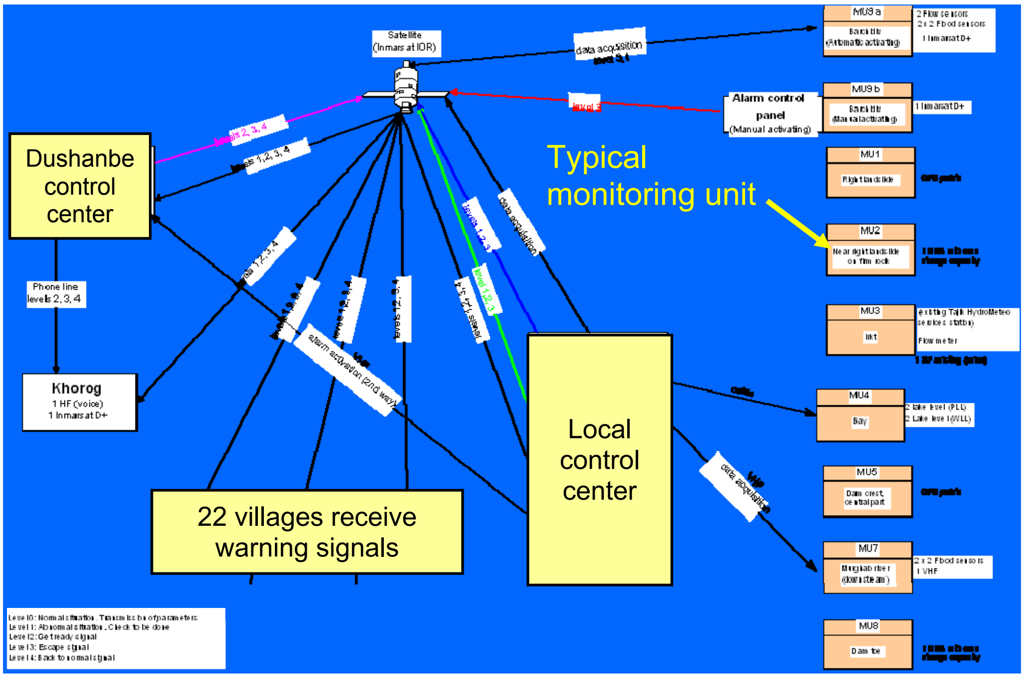

Figure 15 *Overview of the Early Warning System*

The general layout of the EWS and communication links are shown in Figure 15. As can be seen, it is a large and sophisticated system. The measurements included in the monitoring program are listed in Table 5.

Table 5 Measurements included in the EWS at Lake Sarez

Measurement	Methodology
Lake elevation	Pressure transducer in the lake
Detection of large surface wave	Pressure transducer in the lake
Seismic event	Strong motion accelerometers
Surface displacements	GPS
Flow in Murgab river downstream	Radar type level sensor
Turbidity in the outflow water	Turbidity meter
Flood conditions down stream	Level switches
Meteorological data	Complete weather station

At present the warning system comprises three alarm levels. Each level is based on monitored data and/or visual observations. Threshold values for triggering alarms include both maximum measured values and rate of change with time. These are listed in Table 6. Alarm states and emergency warning plans are summarized in Table 7.

Table 6 Threshold values for Level 1 and Level 3 alarm states

Level	Source	Threshold value
1	Seismic acceleration Lake level elevation, Rate of change of lake level River flow downstream Manual alarm input	a > 0.05 g H > 3270 m above sea level dH/dt > 25 cm/day Q > 300 or Q < 10 m3/sec Unusual visual observation
3	Height of detected wave on lake Flood sensor River flow down stream Rate of change of river flow Manual alarm	Wave height > 50 m Q > 400 m3/sec Q > 400 or Q < 5 m3/sec dQ/dt > 15 m3/sec/hour Major observed event

Table 7 Alarm states and emergency warning plan

Level 0 –Normal state		**Level 1 – Abnormal state but not critical**	
Definition	All systems operating properly No abnormal conditions detected	Definition	Abnormal situation due to a natural phenomenon or technical problem
Origin of warning	EWS and Local operating personnel	Origin of warning	EWS and Local operating personnel
Destination of warning	Local control center and Dushanbe	Destination of warning	Local control center and Dushanbe
Action	Daily operation and maintenance	Action	Inspection, checking, repair and observation
Level 3 –Escape Signal		**Level 4 –Back to normal signal**	
Definition	Abnormal condition detected based on several sources	Definition	Normal conditions confirmed after a Level 3 alarm
Origin of warning	EWS, Local control center or Dushanbe	Origin of warning	Dushanbe
Destination of warning	Local control center and all villages downstream	Destination of warning	Local control center and all villages
Action	People in villages evacuate to predefined safe areas	Action	Back to Level 0

The system has been in operation since late 2005. As expected some initial operational and maintenance problems have been encountered, but these have been resolved under way. The principal problem has been lack of sufficient power in some of the remote villages. The system satisfied the specified one-year error-free test program and has been formally turned over to the Ministry of Defense who are responsible for operating the system.

The present plan is to keep the EWS in operation until 2020 which is the target date for completion of mitigation works. The least expensive mitigation measure to reduce the risk is to permanently lower the lake level approximately 120 m using a diversion tunnel around the landslide.

Early warning systems for debris landslides

Debris slides strike quickly and move rapidly with little warning.

Debris landslides are fast moving relatively fluid masses of soil and water that can flow for long distances even on slopes of only a few degrees. They destroy or burry objects in their paths and are particularly dangerous to life and property because they can strike with little warning

Debris slides can be triggered by two main mechanisms:

- Shear failure due to build-up of pore water pressure which reduces the shear resistance of the soil along a potential sliding surface
- Erosion caused by high velocity channel runoff of surface water in gullies or depressions in the terrain.

Both failure mechanisms are directly related to rainfall. Studies of historical records of debris landslides show that it is the maximum intensity of rainfall within a short period of time that determines whether a slide will occur or not. Thus, rainfall-duration intensity is a critical factor in predicting debris slides. It follows, therefore, that rainfall is the best and perhaps the only realistic input to an Early Warning System for debris slides. There are several methods to predict critical rainfall intensities that can trigger debris slides. The most reliable method is to correlate rainfall records to observed debris slides in the geographical area of interest.

If one is faced with the problem of installing a EWS for debris slides or shallow landslides, one must know the critical intensity-duration threshold values that trigger slides. If this correlation does not exist, it can be created using a regional landslide inventory database and rainfall records from the local meteorological office. Figure 16 illustrates an example of such a correlation study carried out by NGI in Nicaragua (Heyderdahl et al, 2003). Figure 17 is a similar correlation plot constructed in this manner for Eastern Jamaica. Figure 17 shows for example, that a rainfall intensity of 36 mm/hour over a one-hour period is required to trigger a landslide.

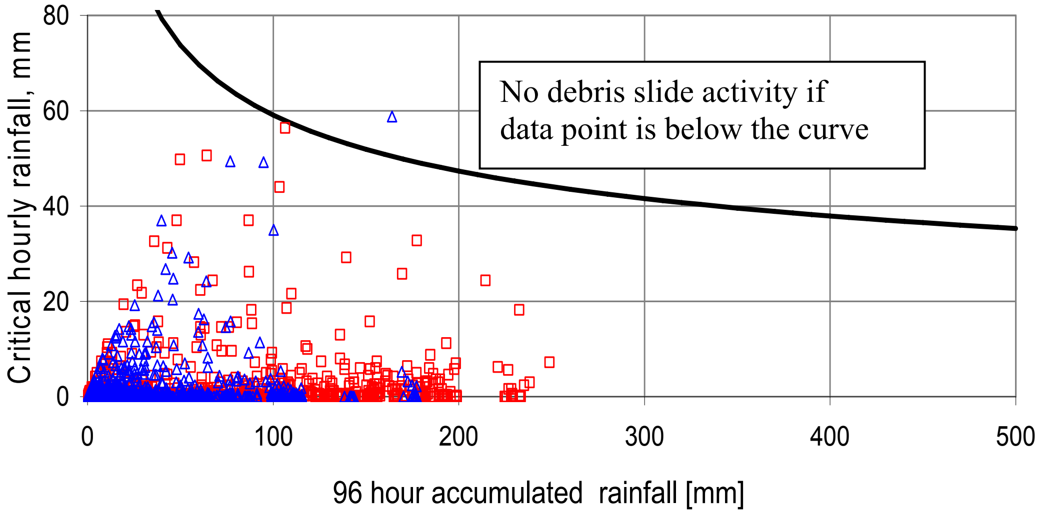

Figure 16 Threshold hourly rainfall triggering debris slides as a function of 96 hour accumulated rainfall, Nicaragua

The equation for the curve in Figure 16 is: $i_c = 258 \cdot R_{96hrs}^{-0.32}$

where i_c is the critical hourly rainfall (mm/hour) and R_{96hrs} is the accumulated rainfall the last 4 days (mm/ 96 hours). Figure 16 and equation above are given only to illustrate the concept. Before using the correlation plot, the position of the curve in the diagram has to be verified using data from observed debris slides that have occurred in the same area.

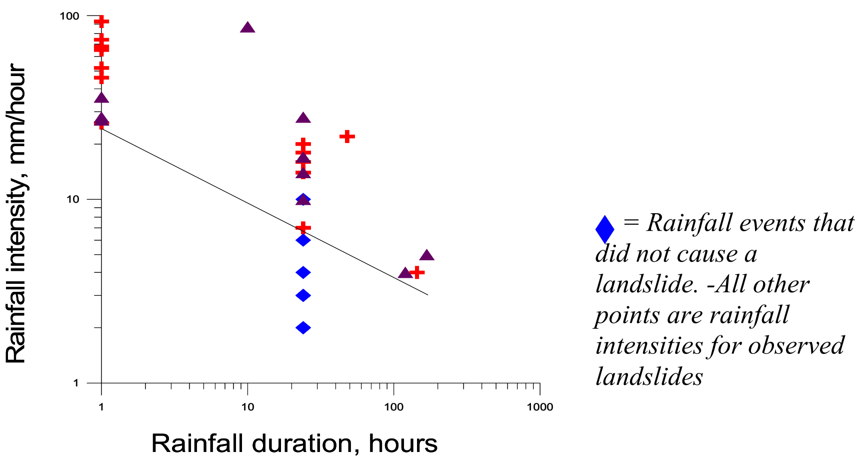

Figure 17 Rainfall intensity – duration threshold values, Eastern Jamaica (Source: Mr. Rafi Ahmad, Univ. of West Indies at Mona)

If there is no landslide inventory available for a correlation study, the best approach is to search in the literature for the critical rainfall intensity studies reported for similar geographic and climatic areas. Start with these values and modify them as more information is obtained from the EWS measurements and observed slides in the vicinity of the site being monitored.

Statistical methods are also used to determine critical rainfall intensities. Statistical data from Norway indicates that debris slides can be expected if the accumulated rainfall in one day is greater than 8% of the annual rainfall. It has been possible to greatly simplify critical rainfall threshold values in Hong Kong using the large database of rainfall and landslide statistics accumulated over many years of observations. EWS warnings are now issued in Hong Kong on the basis of two simple triggering conditions namely: when rainfall exceeds 70 mm in one hour or when rainfall exceeds 100 mm in 24 hours.

Conclusions

Engineers and geologists have the theoretical and empirical tools required for landslide hazard assessment, management and mitigation. Landslide monitoring programs incorporating physical measurement and human observations provide the information needed to use these tools. That is why landslide monitoring has become such an important activity world-wide. Without physical measurements and visual observations, landslide assessment would be reduced to intelligent guessing.

The challenges in monitoring landslides are considerable. There are many different types of landslides; thus, different approaches to monitoring and instrumentation are required. Fortunately, well proven methods and equipment are readily available today to successfully monitor landslides of all types. Economical constraints limit what can be done, not available technology or equipment.

Reliability of measurements is paramount in any monitoring system but particularly so in an early warning system. Thus, redundancy and alternate measurement methods should be considered to avoid false alarms. The consequences of false alarms in a warning system are so serious that every possible action must be taken to eliminate them.

Early Warning Systems intended to issue real-time alerts and warnings of an impending catastrophic event are the most difficult monitoring systems. The difficulty is not due to lack of reliable equipment or suitable measurement technology. The real challenge is to identify and correctly measure the relevant precursors that precede a landslide. For this reason, landslide prediction and real-time warning will continue to be a complex and difficult task.

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Landslide Hazard and Risk analysis of Kandy Municipal Council area, Sri Lanka

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Abstract

The Kandy is one of the most famous and historic city in Sri Lanka, 172km away from Colombo, Capital of the country. Kandy has been declared as a world heritage city by UNESCO in 1980s and the unique character of Kandy arising from the harmonious blending of the natural and man made features, which made it a place possessing a rich in historical, architectural, religious, socio-cultural and environmental aspects. Mean annual rainfall of the Kandy area is about 2,000mm -2500mm which manly receive from Southwest (April-June) and Second Inter monsoons (October-November). With the population growth and migration of people from other suburb areas to Kandy, due to mild climate and many other reasons there is a heavy demand for the lands and houses in the area around Kandy. According to that, areas previously (traditionally) reserved for forests are been gradually converted into residential areas without a proper guidance during the constructions. The land plot sizes are decreased and density of houses increased enormously. The people who migrated from other areas are not well aware about the traditional construction techniques in Kandy area and that, coursed a heavy constructions in steep slopes, deep and steep cuttings and fillings, road constructions etc.

The present study was conducted with assessing the susceptibility of different factors to landslidings through bi-variate statistical model and a preliminary risk assessment considering the buildings in the study area. The attributes, Geology, Deviation angle (angle between dip direction and slope), Slope, Landuse, Landform, distance to streams, Material, are assessed for the susceptibility to landslides and weights of individual classes of attributes were obtained by crossing with previous occurrence of landslide map. To derive the weights Information Value (Yin and Yan, 1998) was used. Success rate was observed, that 90 % landslide areas are falling into 30 % of highest weighted area. The boundaries for the hazard map was selected as highest weight values of 90 %, 97.5 % and 2.5 % of landslide areas as High, Moderate and Low from the success rate analysis results. Runout area of landslide is an important part of a hazard zonation map for further evaluations. Due to the unavailability of a suitable technique to incorporate that into hazard map, manually demarcated the possible runout area through screenscope and 3D model developed by Digital elevation model.

The risk assessment basically focuses to building damages, which can be used to incorporate in to the building construction approval process in Municipal Council of Kandy.

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1. Introduction

Landslide is a natural phenomenon of denudational processes in hilly areas. With the increase of population and decreasing availability of flat lands for settlements, people are forced to construct their houses on hill slopes and close to steep slopes, which are vulnerable to landslides. On the other hand inappropriately designed constructions in hill slopes can adversely affect to the stability and the area can be changed to a high hazardous area which previously stated as less hazardous. Landslide studies resulting zonation maps in hilly areas are an essential requirement nowadays for the development activities in many countries. The occurrence of landslides is a serious constraint towards the economic development, particularly in developing countries.

Various researches were conducted in the field of landslide analysis and zonation practices during the last two or three decades. A number of methods such as, direct mapping, statistical methods and probabilistic methods as well as combinations of those methods are tested during the recent past (Carera.,1983, Varnes.,1984, Selby.,1993, Soeters and Western.,1996., Duncan .,1996).

The present study was conducted with assessing the susceptibility of different factors to landslidings through bi-variate statistical model and a preliminary risk assessment with land value, building density and population density of the Kandy area of Sri Lanka. The risk assessment basically focuses to human losses and building damages, which can be used to incorporate in to the building construction approval process in Municipal Council of Kandy.

1.1 Sri Lanka and Natural Hazards

Sri Lanka is an island with the land area of about 64,740 sqkm, out of 65,610 sqkm of total area which, surrounded by Indian ocean (Fig 1) Highest mountain, Piduruthalagala with the elevation of 2,524m above mean sea level situated in the central part of the island. The island receive rain from mainly two monsoons, Southwest (May-October) and Northeast (December-March) Apart from those, there are two inter monsoons, from October-November (from Southwest) and from March to April (from Northeast)

The temperature in the middle of the country varies from 14°C to 16°C and in the coastal area that varies from 25°C-31°C (*http://www.statistics.gov.lk/Abstract2004/chap1Eng.pdf*)

According to the morphological setting of the island, central, hilly area of the country is seriously affected by landslides and low lands of the inland annually affect by flood and coastal area seriously affected by storms, tsunami etc.

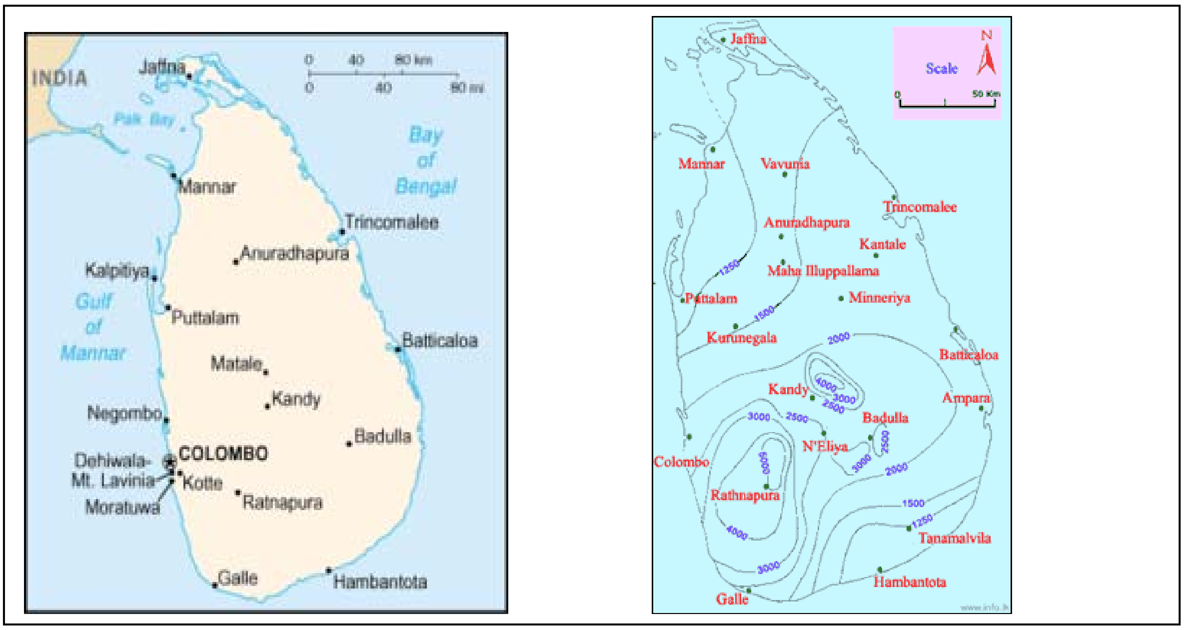

Figure 1: Regional setting and rainfall distribution of Sri Lanka

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According to the morphological setting of the island, central, hilly area of the country is seriously affected by landslides and low lands of the inland annually affect by flood and coastal area seriously affected by storms, tsunami etc.

In recent years, landslides have taken a heavy toll of life and property in Sri Lanka, rendering thousands of people homeless. Landslides are prevalent in several hill country districts, namely Nuwara Eliya, Badulla, Rathnepura, Kegalle, Kandy, Mathale, Galle, Part of Hambantota, Matara and Kaluthara, which cover more than 30 % of the land area of the island (Amaratunge.,1994). These areas occupied more than 40% of the total population of the country

The high risk factor in these areas is repeated by the devastating events in 1986, 1987,1992, 1997 2003 and 2007 which killed more than 1000 people and destroyed houses and property worth millions of rupees - (Sithamparapillai.,1994, Dahanayake.,1998, Arambepola, et.al., 1998 and NBRO Data).

In Sri Lanka, as in several other developing countries, landslides are only recognized by society as problematic, when people and livelihood are affected by death and destruction. During the last decades there has been an unprecedented increase in landslide disasters, mainly because of tremendous increase in unplanned landuse practices. This is basically due to people having had to occupy hazardous areas, which are partially or totally unsuitable for uses to which they have been put, because of population pressures, urbanization, etc.

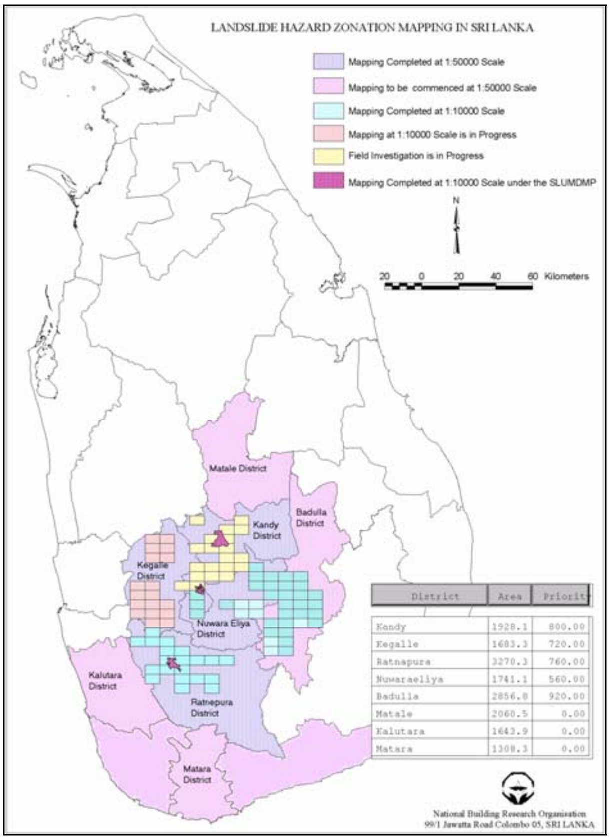

Figure 2: Landslide prone districts and details of ongoing Landslide Hazard Zonation Mapping program

1.2 Previous studies on Landslides Hazards in Sri Lanka

With the landslide incidents of 1986, Sri Lankan government decided to launch a Landslide Hazard Zonation mapping program (LHMP) in the hilly area of Sri Lanka and National Building Research Organization, with the financial and technical assistance with UNDP and UNCHS. The mapping program was started initially in the districts of Nuwara Eliya and Badulla. With the end of the Phase I of the project in 1995, Sri Lankan Government decided to continue the project in other landslide prone districts too. According to that, the program has continued in the districts of Ratnepura, Kegalle, Kandy and Matale. The ongoing districts are Matale and Matara. At the first stage of the project activities, 1:50,000, regional scale zonation maps are prepared considering, geology, landuse, hydrology and slope as attributes. This exercise is basically carryout through remote sensing and random checking in the field is conducted after the completion of initial zonation map for the entire district. The area is categorized in to four categories as *safe*, *landslides are not likely to occur*, *moderately hazardous* and *Most hazardous*. The areas fall into *Most Hazardous* category of 1:50,000 scale zonation maps are selected for further detailed study, which involve detailed Aerial Photo interpretation, extensive field work etc. The scale for the detailed mapping program was selected as 1:10,000 scale and up to now more than 3000 sqkm have been zoned at this scale. (Fig.3).

Awareness of community, governmental, not governmental authorities, school children etc is another activity related to this project. It was noticed that, during the last few years, landslide incidents seem to be increasing in number and severity, however, the human losses are becoming less as a result of awareness created among the residents of the districts, in which the LHMP program was conducted.

1.3 Introduction to Study area

The Kandy is one of the most famous and historic city in the country 172km away from Colombo. Kandy has been declared as a world heritage city by UNESCO in 1980 and the unique character of Kandy arising from the harmonious blending of the natural and man made features, which made it a place possessing a rich in historical, architectural, religious, socio-cultural and environmental aspects.

With the population growth and migration of people from other suburb areas to Kandy, due to mild climate and many other reasons there is a heavy demand for the lands and houses in the area around Kandy. According to that, areas previously (traditionally) reserved for forests are been gradually converted into residential areas without a proper guidance during the constructions. The land plot sizes are decreased and density of houses increased enormously. The people who migrated from other areas are not well aware about the traditional construction techniques in Kandy area and that, coursed a heavy constructions in steep slopes, deep cuttings and fillings road constructions etc.

Figure 3. Hap-hazard constructions in Kandy area

1.4 Previous studies conducted in Kandy area

Under the LHMP project of National Building research organization (NBRO), prioritized area of kandy district (including study area) was mapped at a scale of 1:10,000 and some data collected by NBRO were used for this study too. Apart from that, under Sri Lanka Urban Multi-Hazard Disaster Mitigation project (SLUMDUMP), Kandy municipal area was selected for a risk analysis exercise. That study was conducted by Urban Development Authority (UDA), Center for Housing Planning and Building (CHPB), NBRO and ADPC with the financial assistance of USAID. The mapping and analysis has been conducted at a scale of 1:10,000 and the ultimate product is a Planning Work book for the Municipal Council. As NBRO is preparing landslide hazard zonation maps for pre-identified hazardous areas in the districts at a larger scale, landslide hazard zonation map of this project was the input from NBRO. The project SLUMDUMP had deal with compilation of data related to natural hazards and some relevant data for a risk assessment. Although some data is available in this workbook, those are not sufficient for a detailed quantitative risk analysis.

In general, regarding the possible natural hazards and risk, only very few attempts were observed from the literature.

2. Scope of the Study

With all above facts, necessity arises for a risk analysis which can be used for approval processes, that is mandatory to Municipal Council for granting permission for constructions of buildings and other structures in the hill slopes of Kandy area.
According to that, objectives of the research are,

1). Prepare a Landslide Hazard zonation map at a scale of 1:10,000 by a statistical method and include run-out path and deposition area of debris to the Hazard map.

2). Identify buildings currently at different hazard levels and come to a conclusion for necessary precautionary measures.

With the limited time frame , availability of data and other resources, the risk study had to limit to a basic qualitative study, but results of this effort will energize the authority to look for a more detailed and comprehensive study in future.

3. Data Collection

Data collection was done through 1:20,000 scale aerial photo interpretation and following data layers were derived (*Oresetes Fonticoba and Tamire Hailu, 2001 ITC, MSc. Thesis*)

1. Landslide distribution
2. Landuse
3. Landform
4. Material distribution

Other required following data were collected from various institutes as mentioned bellow,

1. Geology (from Geological survey and Mines Bureau, Sri Lanka)
2. Altimetric Data (Survey department of Sri Lanka)
3. Building foot prints (Survey department / Urban Development Authority)
4. Urban Landuse (Survey department / Urban Development Authority)
5. Infrastructure and lifeline facilities (Urban development Authority / Municipal council of

Kandy)
6. Demographic Data (Census department / Urban development authority)
7. Rainfall data (Metrological Department)

Apart from those data layers, hydrology, Deviation angle (angle between maximum slope and dip direction) map and Material map were prepared through the GIS.
All data collected through aerial photo interpretation were transferred to 1:10,000 scale base maps (ABMP-Survey department). Field verification and required other details were collected during the field work.

4. Rainfall distribution of Kandy area

It is a commonly known fact that nature and type of landslides as well as other mass movements observed in hilly area of Sri Lanka depend significantly on the overburden material, geology, landuse, Geomorphological factors etc. and rainfall intensity, in addition to the man-made factors involved in the process. Therefore before discussing the stability attributes, it is appropriate to examine the possible connection between the landslides as well as mass movements and associated rainfall events. The location of the rain gauge station closest to the area under discussion is the Kings Pavilion rain gauge station close to the city center and records maintained by the same station were used for this discussion. (Source of information – Meteorological Dept. of Sri Lanka).

Mean annual rainfall of the Kandy area is about 2,000mm -2500mm. Rain receive manly from Southwest monsoon (April-June) and Second Inter monsoon (October-November) in an year.

The rainwater movement over a slope depends largely on topography, slope gradient, intensity and duration of rainfall, infiltration capacity and soil permeability. Morgenstern and Matos (1975), Bhandari and Thaylan (1994) pointed out that if the time for the wetting front to reach the critical depth is larger than the duration of rainfall, the landslides would not take place. The studies carried out in NBRO has clearly shown that the peak run-off, which resulted deeper penetration of wetting front, during intense rainfall periods recorded on the days preceding the event, has lead to the occurrences of failures along the surface of wetting front. Many studies have been carried out to established the co-relation between rainfall pattern and landslides in Sri Lanka under different geological conditions and climatic environments. Priyasekara (1986) investigating the landslides which occurred in the Badulla District has indicated an association of landslides with precipitation of the order of 300 mm – 400 mm in two consecutive days (ADPC –documentations)

Daily rainfall data from 1950 was used to examine the frequency of high intensity rainfall periods and correlate that with the landslide occurrences as the exact dates of landslide occurrences were not feasible to known. Most of residents in the identified past landslide areas are new to the Kandy (new settlers from other areas) or original residents are reluctant to give information due to some reasons. Especially, they probably thought, that will be badly affected to the land value or some times they may think that will create unnecessary difficulties for them. Anyhow, according to the information from few residents, it was understood that, during the year 1957, there were many landslides occurred in the area. Unfortunately in the Municipal council or any other institute records on those incidences are not available.

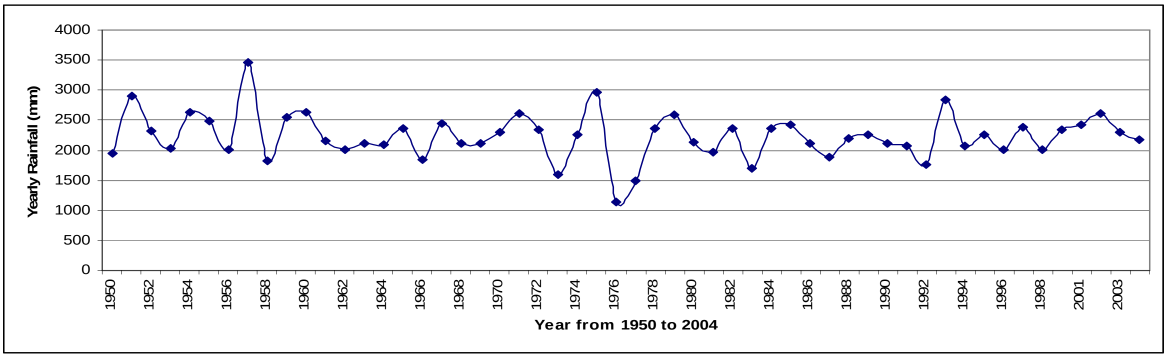

Figure 4. Yearly (total) Rainfall distribution from 1950 to 2004

From the rainfall distribution it is clear that, in 1957 is the maximum rainfall received Kandy area in the past (3470mm). After that, in the years, 1975 (2967mm), 1993 (2838mm) peak rainfall figures indicate most possible landslide occurred periods. In 2002, there were some small scale cut slope failures and one death was reported by a cut slope failure behind a house (rainfall-2620mm) (Fig 4 and 5)

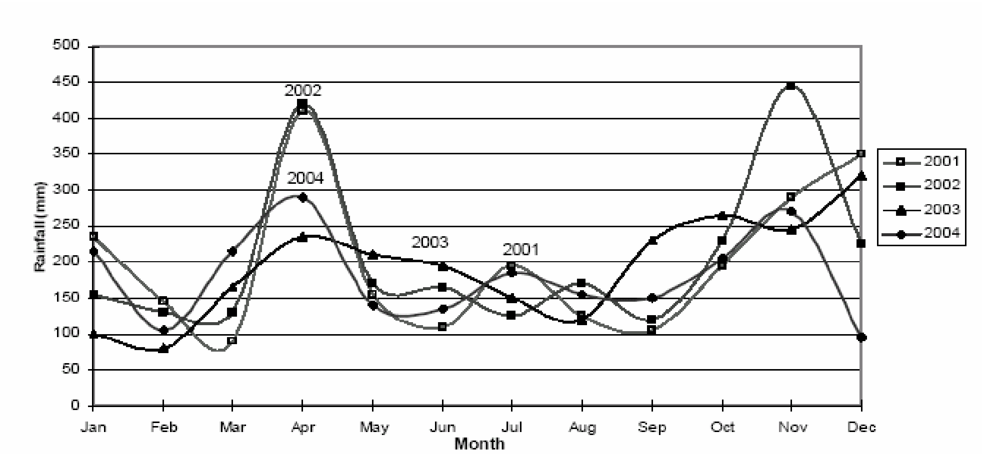

Figure 5 Annual average rainfall distribution from 200-2004 [1] (Adikari et al, 2005)

In November,2007 more than 500 houses were seriously affected by small scale landslides and cut slope failures. Extensive investigations of NBRO conducted, reveivleved that, inappropriate landsuse practices, especially small land plot sizes and non engineered retaining structures and buildings are the main difficulty to reduce risk. In November, 2007 with 75mm maximum rainfall was reported by Meteorological department and it is very clear that, if a higher rainfall like 300mm can create a catastrophic disaster in Kandy area.

5. Hazard Analysis

There are number of methods have been developed in the recent past to asses the susceptibility / probability of landslidings. Those methods are categorized as Inventory, heuristic / knowledge driven, Statistical / data driven and deterministic approaches by Soeters Van Westen (1996), and Van Westen (1997).The application of those methods depends with the working scale, availability of data, user requirement available time and the budget. Remote sensing can be used for the inventory mapping and attribute data collection for all above methods effectively if the spatial resolution is good enough to identify the individual landslides. Stereoscopic viewing capability is an added advantage in the process (Van Wesen, 2004).

In this exercise, Bi-variate statistical method used for the assessing of susceptibility of individual factors for landslides in the Kandy Municipal area (Fig 6- Flow diagram) Weights of individual attributes / classes (discuss later) were derived through information values as introduced by Yin and Yan (1998).

The methodology use by National Building Research Organization(NBRO) is a knowledge driven model and weights for attribute maps and classes are predefined. According to the NBRO materials, the weights are derived through a susceptibility analysis, which was conducted for two landslide prone districts, namely Nuwara Eliya and Badulla. Applicability of same weights for other areas is questionable and, during this analysis same attributes were used as because, intended to evaluate the applicability and accuracy of the NBRO system in Kandy area.

The Statistical Bi-variate methodology, which used for the hazard analysis is simple and through crossing of individual attribute maps with active landslide distribution map (Fig 7 Landslide distribution map.) cross tables were obtained. The attributes considered for the analysis are, Gelogy (lithology, Deviation angle), Overburden material (type), Landuse, Landform, Hydrology and Slope- Fig. 8. Some map layers used in NBRO (e.g. Material, Hydrology and Deviation angle had to be changed or omitted due to some errors and to reduce the fussiness. Weights for individual classes of attribute maps were derived according to the information values. Finally all attribute maps converted in to weights maps and by summation of all weight maps total weight map was obtained.

Area of previous occurrences of landslides as a percentage were plotted against the area of weights categorized from maximum to minimum (Fig 9. Success rate analysis) and also the same success rate analysis used to classify total weight map into different hazard classes.

According to the success rate analysis it was observed that, 90% of previous occurrences of landslide areas fall into 30 % of maximum, weight area. The boundaries for the hazard map was selected as highest weight values of 90 %, 7.5 % and 2.5 % of landslide areas as High, Moderate and Low from the success rate analysis results (Fig. 10 Hazard Map).

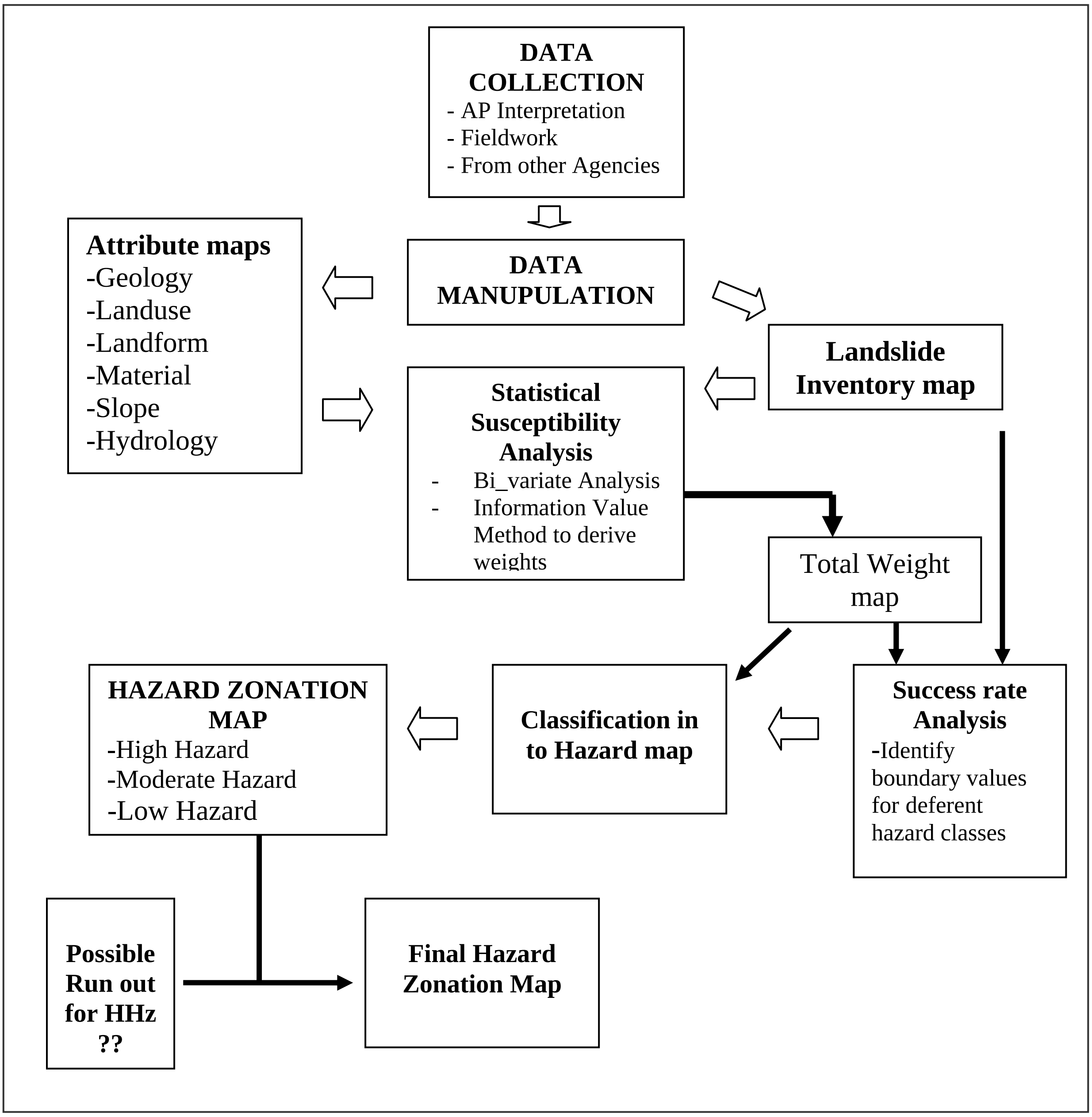

Figure 6 : Steps in susceptibility analysis and Hazard Zonation

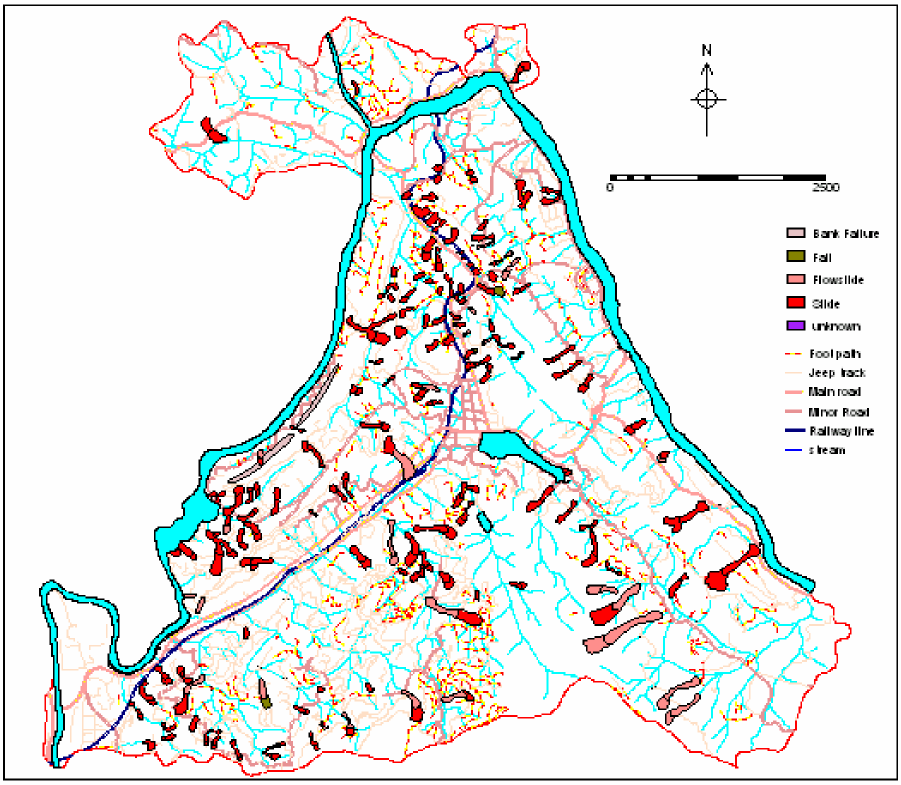

Figure 7 : Landslide distribution map prepared through aerial photo interpretation (active, initiation areas of landslides separated from the database for analysis)

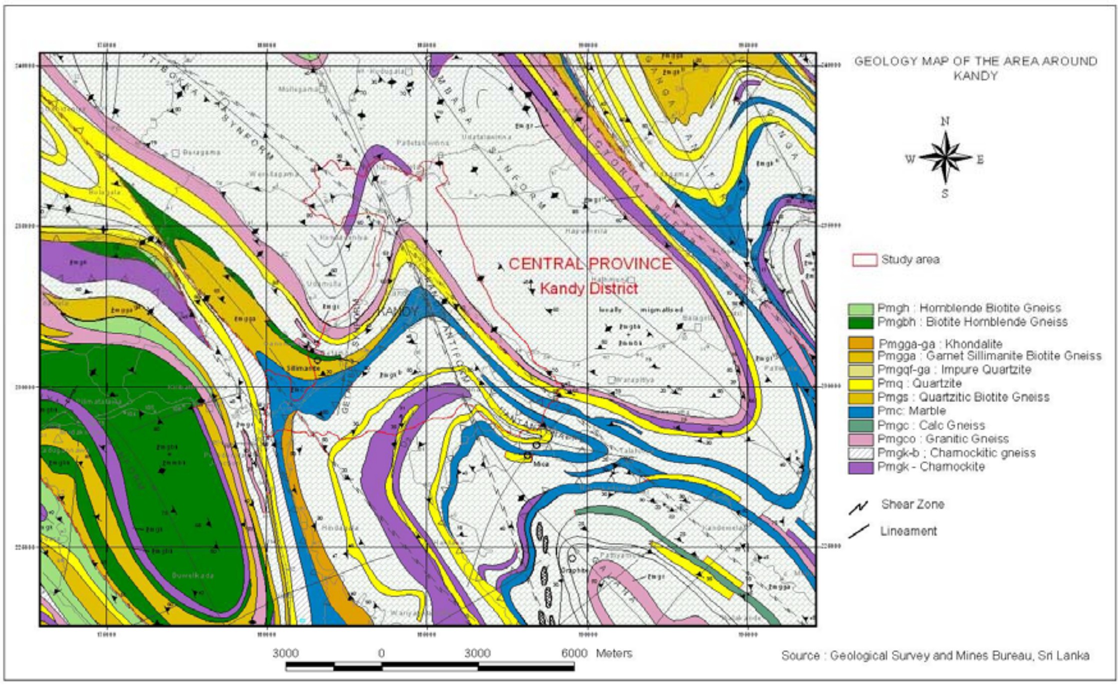

Figure 8 : Geology map of the area around Kandy

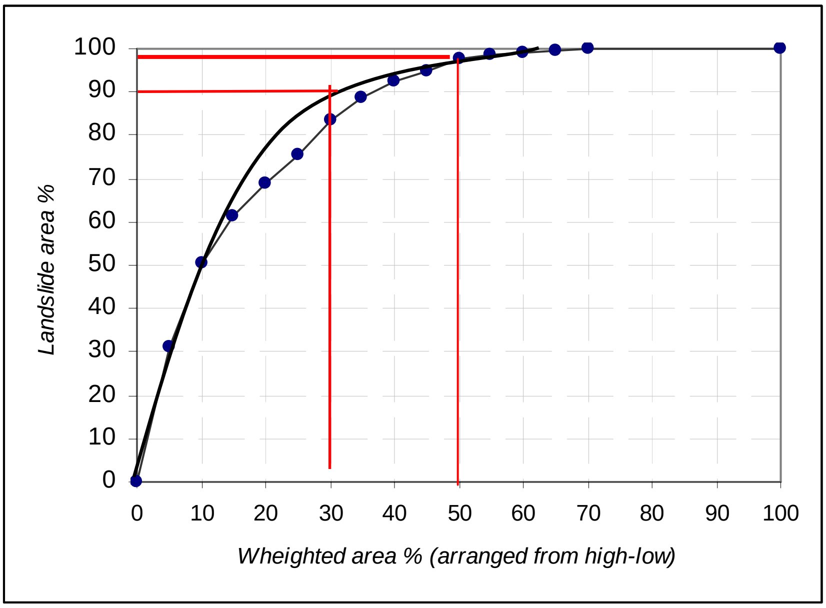

Figure 9 : Results of Success rate analysis used for the classification of total weight map into hazard zonation map (70 % of previous landslide areas fall into 30 % of highest weighted areas).

Structures located in run-out path and deposition area of landslides are also venerable, whether the areas identified as low or moderate by statistical analysis. Also, flat areas in valley bottoms and hill tops area free from initiation of landslides (especially debris flows) except the flow paths of debris. Therefore, identifying of run-out paths and deposition areas were done by 3D model developed through Digital Elevation model and interpreted with using Screenscope manually. The flat areas (slopes <5°) from the slope map has separated after applying a 25m buffer zone to the adjoining steep slopes which are greater than 5°. Those identified flat slopes initially classified as safe and did not consider for the susceptibility analysis.

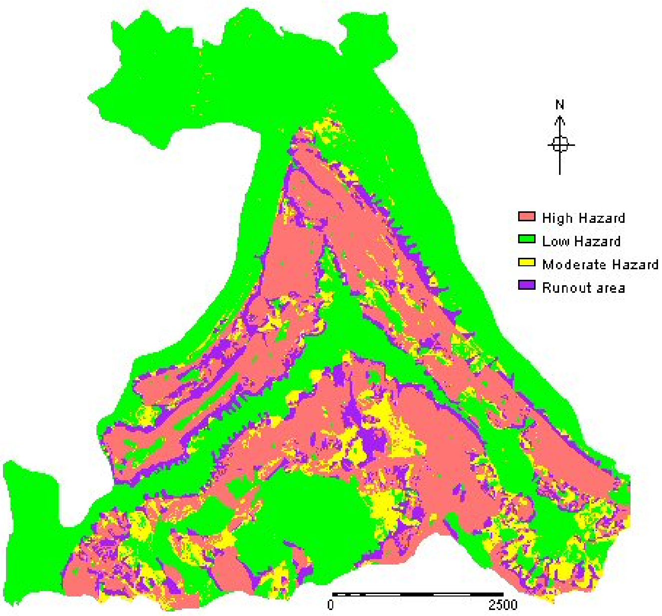

Fig:10 Resulted Final Hazard map with manually digitized runout zones (Violet)

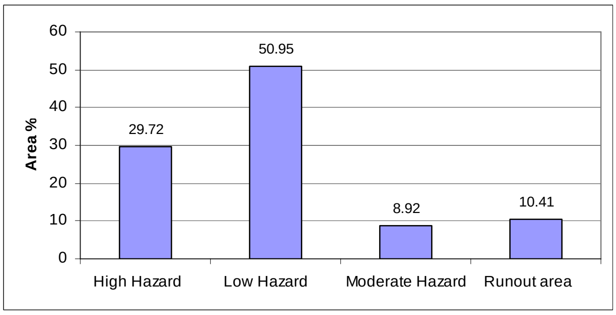

Figure :13 Distribution of hazard classes

4. Risk analysis

Although the requirement is a more comprehensive study in risk analysis for the Kandy area, the available data in various authorities limit the level of detail of the study. The analysis had to be limit only to identify the buildings at risk in municipal are qualitatively. The building foot print map received from Urban Development Authority does not have an attribute table , so the buildings were identified with the local knowledge of the area. This type of data deficiency is very common in Sri Lanka and it is very difficult to find the authorities, who has sufficient data for a particular study.

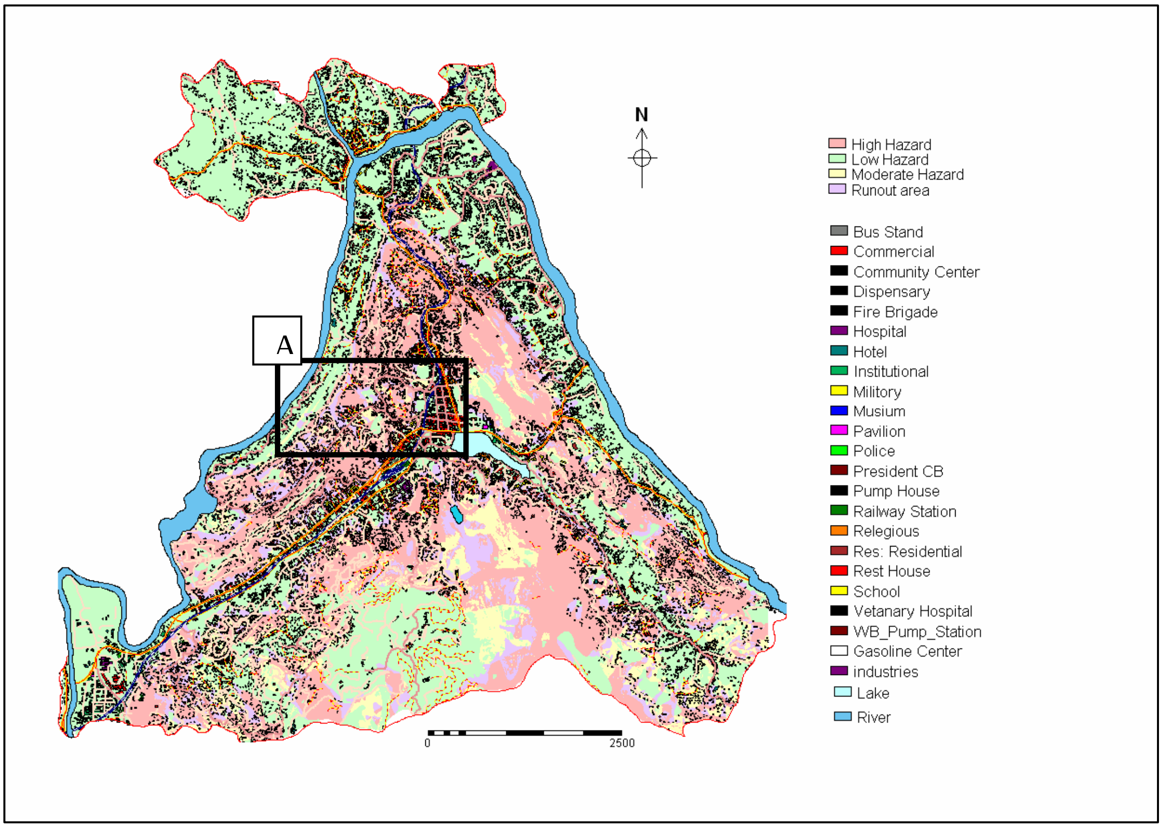

Figure 14; Buildings overplayed on Hazard map

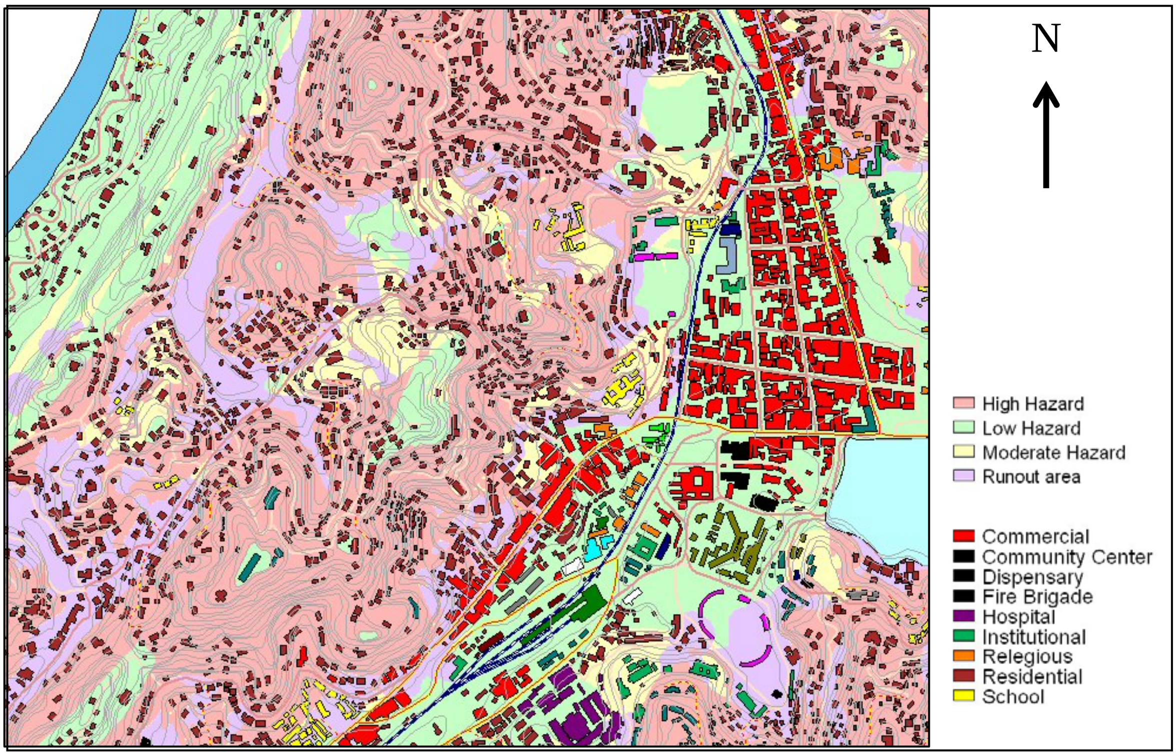

Figure 15; Zoomed area "A" in Fig 14, density of buildings and distribution in different hazard classes.

Hazard Level	**Residential**	**%**	**Commercial**	**%**	**Institutional**	**%**	**Industries**	**%**	**Community Faci. & Services**	**%**	**School**	**%**	**Religious**	**%**
Low	9096	51.1	1005	74.4	248	71.7	12	100	77	62.1	75	27.4	49	64.5
Moderate	1488	8.4	57	4.2	17	4.9	0	0	10	8.1	30	10.9	3	3.9
High	5343	30.0	104	7.7	45	13	0	0	12	9.7	112	40.9	9	11.8
Runout	1858	10.4	13.6	36	10.4	0	0	25	20.2	57	20.8	15	19.7	
Total	***17785***	***89.07***	***1350***	***6.76***	***346***	***1.73***	***12***	***0.06***	***124***	***0.63***	***274***	***1.37***	***76***	***0.38***

Table 1 : Distribution of buildings in different hazard classes

Statistics of the building distribution in different hazard classes (Table 1) shows 40.4 % of residential buildings are in highest hazard zones (30.0 % in High and 10.4% in runout area). Commercial, Industrial and Institutional buildings mostly situated in low hazardous classes and high percentage of school buildings (55.9 %) are in highest hazardous classes.

All the buildings situated on High and Run-out categories in hazard map can be considered as at a highest risk level, the buildings in Moderate hazard category can be categorized as at a moderate risk level and the buildings in low hazards are free from the possible hazards and those at lowest risk levels.

6. Conclusion and recommendations

According to the study conducted, following conclusions can be made,

The hazard map prepared according to the NBRO previous system does not show good prediction power, compared to the results obtained from the statistical analysis. For a better conclusion, the same type of study is recommended to do for some other areas too.

1. The slope facet technique is highly subjective and it is difficult to demarcate uniform level of accuracy for all slope facets, which prepare by different people.
2. Generalization of data during the weighting course a significant inaccuracy (e.g. in Landuse and Landform maps), that has to be re-evaluated.
3. Duplication of data (e.g. in Amount of dip map and Deviation angle map, dip type of slope is duplicating) has to be eliminate.
4. Hydrological factors have to be re-evaluated for susceptibility and if it is possible, important to look for a methodology to include rainfall distribution for the zonation practice.
5. As the NBRO, weighting system is based on data in Nuwara Eliya and Badulla districts, applicability of same method for another area is questionable and that has to be re-considered and if it is possible the methodology has to be improved through statistical analysis.

6. Material distribution map of NBRO has to be improved by introducing a method based on engineering geological classification of material, rather than present classification

7. Landform map must be improved by introducing a geomorphological map.

8. As the temporal data on landslide incidents are important for risk analysis, recommended to look for good methodology / technique to acquire temporal data on incidents (i.e. Remote sensing data). The same base data can be used for landuse monitoring, building developments etc. in the process.

According to the identifying of level of risk for buildings, it was clear that more data on building type, construction materials, occupancy, cost etc. are required for a better assessment. Local authorities should be aware on disaster management concepts and look for a feasibility of implementation and management of a good database on elements at risk is important.

According to the present study, following recommendations can be made based on hazard levels,

1. High hazard and Runout areas
    - Aware of residents about the situation and come to an agreement with them for reduce the hazard. May be by engineering practices, proper landuse practices and limitation of extending their buildings. New constructions on these areas has to be restricted or banned.
    - Maintaining a proper surface and sub surface drainage systems, and for the waist water, introducing a centralized system is essential.
    - Site specific further studies (preferably deterministic) may required for assessing the level of risk in these areas.
    - Monitoring / early warning system is required for these areas.

2. Moderately Hazard areas-
    - Same awareness is required for the residents living in this area.
    - Without prior detailed investigations, new constructions and extensions should not be permitted. A detailed site specific studies may required to asses the suitability of lands for new constructions.
    - Proper landuse practices have to be introduce and when necessary, engineering mitigation measures can be implemented in identified, important areas and buildings (e.g. for Schools, Hospitals etc.).
3. Low hazard area.
    - without restrictions related to landslide hazards, building construction permits can be issued.

As the study risk assessment is more general, a comprehensive study is required for implementing a disaster management plan in the Kandy municipal council. This study can be considered as a starting point for such a detailed study.

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Examples of two Simplified Qualitative Methods for Landslide Risk Assessment

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Abstract

Hazard and risk assessment are the central pillars in landslide management. Knowledge and characteristics of hazard and risk are basic tools to plan and implement mitigation measures

The focus of this paper is on the following two simplified approaches:

- Use of engineering scores, where risk is assessed as the product of the score for estimated hazard level, and the score for estimated damage exposure. Damage is expressed in terms of loss of lives and damage to properties. The product of these scores establishes the relative risk classes presented on maps.

- Use of a GIS-based analysis where the predicted landslide hazard map is overlaid with elements at risk (population and infrastructure) to obtain potential hotspot "risk areas", where the product of the hazard and the damage exposure is high.

The engineering approach is best suited for regional areas, for instance municipalities. The GIS analysis is considered to be applicable both on national and regional levels.

Introduction

Risk assessment and risk mapping cover a wide range of methods, from advanced modelling in probabilistic terms to simplified scoring methods. The term “risk” associated with natural hazards is frequently misused. Risk is strictly the expected degree of loss in a defined area due to a potential damaging phenomenon within a given time period. To carry out landslide risk mapping on a national level by following a strict quantitative or numerical approach is, however, quite demanding and not so frequently used.

Pay-off on landslide risk assessment

The value of proper landslide risk assessment is convincingly highlighted in a recent publication issued by the US National Research Council on Partnership for Reducing Landslide Risk (National Research Council, 2004). The report states that among the different activities in a national landslide mitigation strategy, proper risk assessment is the one with optimum cost-effectiveness. The same message is echoed in a recent report from the thematic network GeoTechnet authorized by the European Commission on socio-economic impacts of natural disasters in Europe (Koehorst et al 2006).

Regional landslide risk assessment for prioritization of preventive actions

In landslide prone areas, on regional level, there is often a need to prioritize in terms of protective measures or establish risk zonation for land use planning. For such purposes risk assessment does not need to be complex, especially if mainly a comparison of risks (ranking of priorities) is required. Even a critical look at recommendations based on judgement forms a type of risk analysis. "Risk" is a combined measure of the probability and severity of an adverse event (consequence). It can be estimated by the product of the probability of the event occurring and the expected consequences.

Two simplified approaches to serve as regional landslide risk assessment will be illustrated, one from Norway and one from Italy.

The Norwegian engineering scores approach

The method has been developed as a part a long term assignment that NGI is undertaking for the Government of Norway to classify and map the risk posed by potential quick clay landslides in Norway. Potential landslide areas are given "engineering scores" based on geotechnical parameters, local conditions, persons or property exposed and engineering judgement. Hazard classes are described as: low, medium and high. Consequence classes are discussed as not severe, severe and highly severe. The resulting risk, based on engineering evaluations and experience, is subsequently divided into five risk classes (Lacasse et al, 2004 and ICG, 2004).

The hazard levels depend on topography, geological and geotechnical conditions, and changes at the site. The evaluation of the hazard is done with the use of Table 1. The weighting given to each hazard in Table 1 (or later to consequence in Table 2) describes its importance relative to the stability of the slope.

Table 1 Evaluation of hazard for quick clay landslides

Hazard	Weight	Score for hazard 3	2	1	0
TOPOGRAPHY					
Earlier Sliding	1	Frequent	Some	Few	None
Height of slope, H [i]	2	>30 m	20-30 m	15-20 m	<15 m
GEOTECHNICAL CHARACTERISTICA					
Overconsolidation ratio (OCR)	2	1.0-1.2	1.2-1.5	1.5-2.0	>2.0
Pore pressure conditions [ii]					
- artesian pressure (kPa)	3	> + 30	10-30	0-10	Hydrostatic
- sub normal pressure (kPa)	-3	> 50	20 - 50	20 - 0	Hydrostatic
Thickness of quick clay layer [iii]	2	>H/2	H/2-H/4	<H/4	Thin layer
Sensitivity, S_t	1	>100	30-100	20-30	<20
NEW CONDITIONS					
Erosion [iv]	3	Active/sliding	Some	Little	None
Human activity					
- Worsening effect	3	Important	Some	Little	None
- Improving effect	-3	Important	Some	Little	None
Maximum possible weighted score		51	34	16	0
Percentage of maximum weighted score		100%	67%	33%	0%

Remarks:

i) For the quick clays in the study, inclination was identical for all slopes (1:3), and slope inclination was not included as a variable. In a general study, slope inclination should be added in the list of hazards.

ii) Relative to hydrostatic pore pressure with ground water table close to surface.

iii) In general, the extent and location of the quick clay are important, and should be added to Table 1.

iv) Erosion at the bottom of a slope reduces stability.

The zones with weighted score between 0 and 17 (up to 33% of maximum score) are mapped as "low hazard" and have low probability of failure by sliding. The zones with weighted score between 18 and 25 (up to 50% of maximum score) are mapped as "medium hazard" and have a higher, though not critical, probability of failure. The zones with weighted score between 26 and 51 are mapped as "high hazard" and have a relatively high probability of failure.

Consequences are commonly evaluated in terms of human life safety, environmental, economic and social effects. The evaluation of the consequences is done with the help of Table 2.

Table 2 Evaluation of consequence for slides

Possible damage	Weight	Score for consequence			
		3	2	1	0
HUMAN LIFE AND HEALTH					
Number of dwellings i)	4	> 5 Closely spaced	> 5 Widely spaced	≤ 5 Widely spaced	0
Persons in industrial building	3	> 50	10-50	< 10	0
INFRASTRUCTURE					
Roads (traffic density)	2	High	Medium	Low	None
Railways (importance)	2	Main	Required	Level	None
Power lines	1	Main	Regional	Distribu-tion network	Local
PRIVATE PROPERTY					
Buildings, value ii)	1	High	Signifi-cant	Limited	0
Consequence of flooding iii)	2	Critical	Medium	Small	None
Maximum possible weighted score		45	30	15	None
Percentage of maximum weighted score		100%	67%	33%	0%

i) Permanent residents, in both sliding area and within run-out distance.
ii) Normally no one on premises, but building(s) have historical or cultural value
iii) Slides may cause water blockage or even dam overflow, flooding may cause new slides; there should be time for evacuation; damage depends on a complex interaction of several factors.

The zones with weighted score between 0 and 6 (13% of maximum score) are mapped as "not severe". In these zones, there would be very few or no permanent residents. The zones with weighted score between 7 and 22 (up to 50% of maximum score) are mapped as "severe". The zones with weighted score between 23 and 45 are mapped as "highly severe". In these zones, there would be a large number of persons, either as residents or temporarily on the premises.

The risk score to classify the mapped zones into a risk class is obtained from:

$$\text{Risk} = \text{Hazard} \times \text{Consequence}$$

$$R_{WS} = H_{WS(\%)} \times C_{WS(\%)}$$

where R_{WS} = Risk weighted score given in % of the max R_{WS}
$H_{WS(\%)}$ = Hazard weighted score in %
$C_{WS(\%)}$ = Consequence weighted score in %

Table 3 gives the risk scores for the five risk classes that have been used.

Table 3 Risk classes for slides based on Risk Weighted Scores

Risk Class	1 (lowest risk)	2	3	4	5 (highest risk)
Risk Weighted Score (R_{WS})	0-166	167-628	629-1905	1906-3203	3204-10,000
R_{WS} (% of max R_{WS})	0-1.7	1.7-6.3	6.3-19.1	19.1-32.0	32.0-100

An example of the resulting zonation map is shown in Figure 1. To assist decision makers in the following up of this zonation and take priority actions in the different risk zones, the following activity matrix shown in Table 4 was constructed.

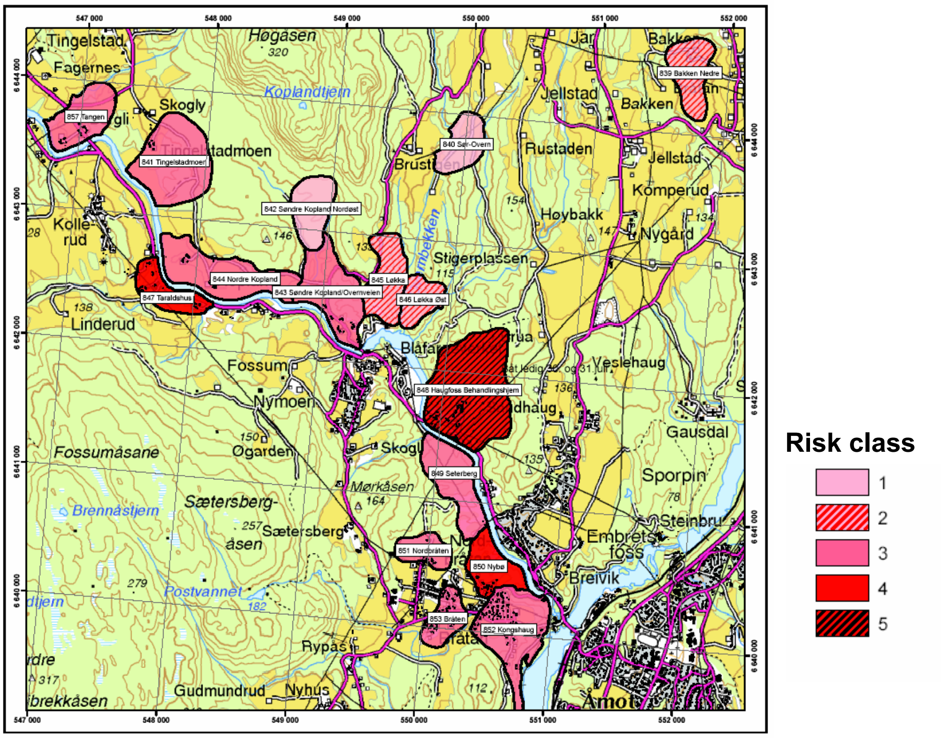

Figure 1 Landslide risk zonation in a highly landslide prone area 150 km North of Oslo

Table 4 Activity matrix as a function of risk class

Activity	Risk class			
	1-2	3	4	5
Soil investigations	None	Consider additional *in situ* tests and pore pressure measurements	Require additional *in situ* tests and pore pressure measurements	Require additional *in situ* tests, pore pressure measurements and laboratory tests
Remediation e.g. erosion protection, stabilizing berm, unloading, soil stabilization, moving of residents	None	None	Consider doing	Required

The Italian risk matrix

Italy is by far the country in Europe with the highest cumulative number of deaths or missing people and the highest expected yearly losses both in terms of mortality and economic losses related to landslides.

The most frequently applied method for assessment of landslide risk on a regional level in Italy has conceptually some similarities with the previously described method used in Norway (Calcaterra et al 2003).

In the Italian legislation classification of the exposed areas are defined by four classes:

R4 = very high risk- possible loss of human lives
R3 = high risk-possible serious injuries to people
R2 = minor risk-minor damage to buildings and infrastructure
R1 = moderate risk- marginal economic and social damage

The risk is defined as the product of the hazard P and the consequences in terms of damage D:

$$R(k) = P(n) \times D(m)$$

The matrix for calculation of the risk is shown in Figure 2.

$R_k = P_n \times D_m$		P_n		
		P_3	P_2	P_1
D_m	D_4	R_4	R_4	R_3
	D_3	R_4	R_3	R_2
	D_2	R_3	R_2	R_1
	D_1	R_2	R_1	R_1

Figure 2 The Italian Matrix for Landslide Risk Assessment

The relative landslide hazard (P) for soil slides-debris/earth flows is defined by three categories:

P3 = high
P2 = medium
P1 = low

Establishment of the relative landslide hazard map is usually carried out following a qualitative approach, where a number of factors expected to control landslides susceptibility are assessed. Among the major factors are geology, geomorphology, slope, land use, soil thickness together with information about historical landslides.

Damage (D) is defined by four levels, D1- D4 (where D4 = very high), is defined as the expected loss of properties or human lives given by the product of exposed value and vulnerability.

Assessment of national landslide risk hotspot areas by a GIS model

Many countries have found it useful to have a national map that shows where in the country landslides are most likely to take place and also where the hotspot risk areas are in terms of potential loss of lives and damage to critical infrastructure. This type of map is useful as input for national strategies for mitigation measures, and for the communication of risk reduction measures with the politician and the public.

The most commonly used approach is a multivariate model where a relevant number of governing factors expected to control landslide occurrence is assessed in a suitable format and pixel size in a GIS program.

Below is shown an example recently carried out for Colombia (NGI 2005).
The model developed for the study is based on a method developed by Mora and Vahrson, (1994). The method was modified for use with the datasets available for global application. The landslide hazard level $H_{landslide}$ is defined by a combination of susceptibility and triggering factors.

$$\mathbf{H_{landslide} = SUSC * TRIG}$$

SUSC is the intrinsic susceptibility factor determined from the combination of:

- $\mathbf{S_r}$ slope factor (slope gradient),
- $\mathbf{S_l}$ lithological factor, and
- $\mathbf{S_h}$ relative soil moisture index.

TRIG represents the active external driving forces and their probability of occurrence as landslide triggers. It is determined from the combination of:

- $\mathbf{T_s}$ seismic trigger indicator, and
- $\mathbf{T_p}$ precipitation (rainfall) trigger indicator.

For each factor, an index of influence is determined by a reference value through a specific weight. By multiplying and summing these indices, one can determine the relative landslide hazard level $H_{landslide}$:

$$\mathbf{H_{landslide} = (S_r * S_l * S_h) * (T_s + T_p)}$$

The slope data were classified on a geographical grid (WGS84). The cells were distributed in the 5 different categories (1 – 5) shown under the category table, Table 6.

Table 6 Slope classification

Range of slopes angle (degrees)	Classification	S_r
0 –6	Very low	1
6 –12	Low	2
12 – 18	Moderate	3
18 – 24	Medium	4
24 – 90	High – Very high	5

Figure 3 shows the slope map with the five classes for Colombia.

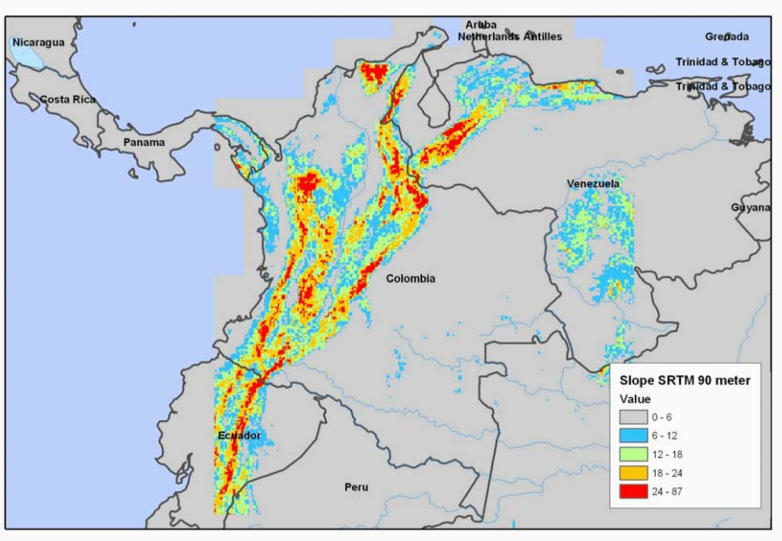

Figure 3 *Slope map for Colombia with the five classes based on a 90x90 m^2 grid*

In terms of **lithological characteristics** rock strength and fracturing are the most important factors to evaluate. The Geological map of the World at 1/25,000,000 scale elaborated by the Commission for the Geological Map of the World and UNESCO (2000) was used. Five susceptibility classes were identified as shown in Table 7.

Table 7 *Lithology and strategraphy*

Lithology and stratigraphy	**Susceptibility**	**S_l**
Extrusive volcanic rocks - Precambrian, Proterozoic, Paleozoic and Archean. Endogenous rocks (plutonic and/or metamorphic) - Precambrian, Proterozoic, Paleozoic and Archean.	Low	1
Old sedimentary rocks - Precambrian, Archean, Proterozoic, Paleozoic. Extrusive volcanic rocks – Paleozoic, Mesozoic. Endogenous rocks - Paleozoic, Mesozoic, Triassic, Jurassic, Cretaceous.	Moderate	2
Sedimentary rocks - Paleozoic, Mesozoic, Triassic, Jurassic, Cretaceous. Extrusive volcanic rocks – Mesozoic, Triassic, Jurassic, Cretaceous. Endogenous rocks – Meso-Cenozoic, Cenozoic.	Medium	3
Sedimentary rocks – Cenozoic, Quaternary. Extrusive volcanic rocks – Meso-Cenozoic.	High	4
Extrusive volcanic rocks – Cenozoic.	Very high	5

The distribution of the five classes is shown in Figure 4.

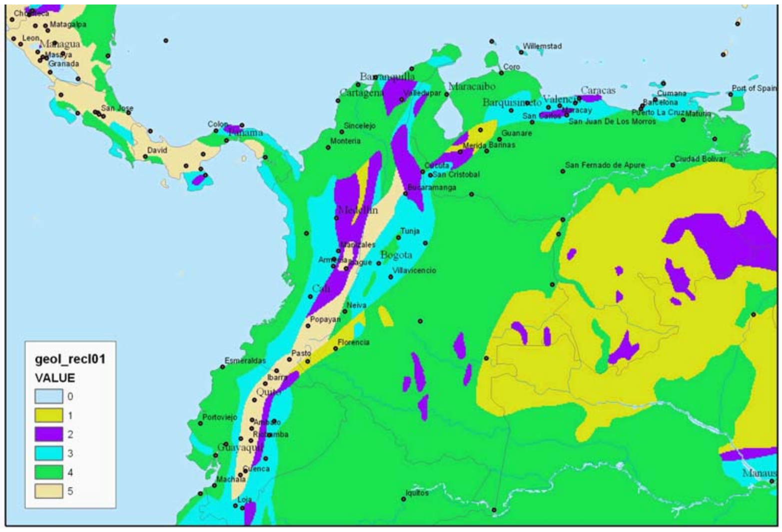

Figure 4 *The distribution of the five classes of lithology (value of 0 represents water)*

The **Soil Moisture Index, S_h** which indicates the mean humidity throughout the year and gives an indication of the state of the soil prior to heavy rainfalls and eventual destabilization was derived from work by Willmott and Feddema, documented by Cort J. Willmott and Kenji Matsuura, at the Center for Climatic Research, Department of Geography, University of Delaware Newark, USA

In the lack of data of the 50 and 100 year expected extreme values of monthly precipitation for Colombia, grided data of monthly precipitation available from a global *1.0°×1.0° latitude/ longitude* grid was used. Estimation of T_p was based on the global 100-year extreme monthly rainfall as derived by Global Precipitation Climatology Centre (GPCC) at the German National Meteoro-logical Service (DWD), Fig 5.

The map of the estimated 100-year extreme monthly rainfall in Colombia is shown in Fig. 5.

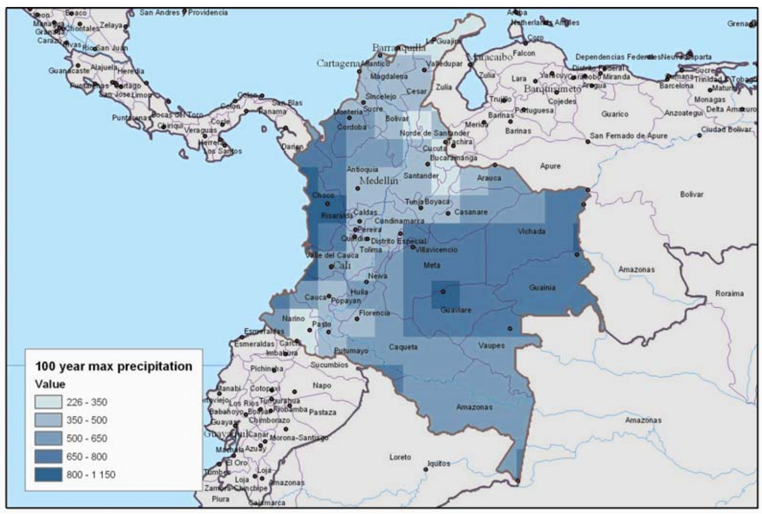

Figure 5 *Expected monthly extreme values in mm, for a 100-years event defining the five classes of T_p*

The seismic trigger indicator, T_s, was derived form data presented in the Global Seismic Hazard program (GSHAP), where peak ground accelerations, PGA_{475}, for a return period of 475 years defined in 10 classes and used directly as input in the GIS analysis.

The value of **relative landslide hazard level, $H_{landslide}$,** obtained from the previous mentioned equation **$H_{landslide}$ = SUSC * TRIG,** is based on experience grouped in three classes as shown in the landslide zonation map in Fig. 6.

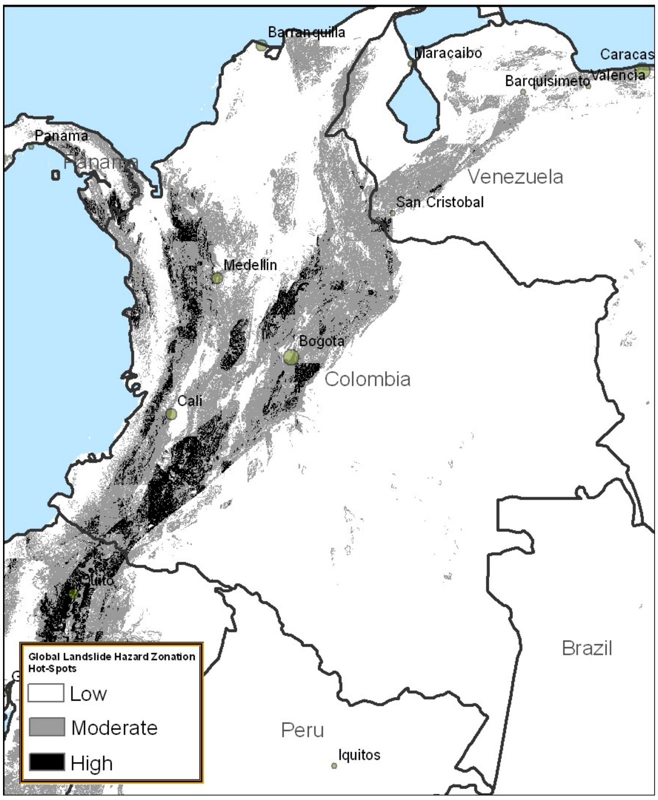

Figure 6 Landslide hazard map of Colombia

Combining the landslide hazard map with the population density map, the GIS model allows for a quick estimation of the percentage of population who live within the landslide prone areas, as well as estimation of land areas that they represent.

In this case it was found that the moderate and high landslide zones cover more than 10 % of the country's land area, and that approximately 20% of the population, or 8.5 million people, live within the these zones. This type of GIS model can easily be expanded to include the exposure of different elements at risk, like roads, rails, buildings and other structures. More comprehensive use of the GIS model has been presented by Dilley et al (2005) and Nadim et al (2006).

Landslide inventory

Landslide inventory is an essential part of the landslide hazard and risk assessment. Unfortunately, inventories for historic landslide events and their consequences are incomplete and even missing in many of the developing countries. The two open international sources for historical landslides are:

- EMDAT-CRED International Data Base, (CRED 2005)
- The DesInventar/LaRed Data base, (DesInventar 2005)

In addition, government agencies, geological surveys, research organisation and universities do hold national databases. The database EMDAT-CRED provides country-wise information on disasters between 1900 and 2006 and information from slides where 10 persons or more were reported killed, 100 persons or more were reported affected, and where appeal for international assistance was issued and/or a state of emergency was declared. DesInventar/LaRed focuses on Latin American countries. The time span covered is much less, but the database contains much more information from the smaller events than is the case in EMDAT-CRED. Both databases suffer from lack of comprehensive information about economical losses associated with the events. In the databases, the smaller events are often not captured, and the events are recorded according to the trigger starting the event rather than the hazard itself that caused the damage. Examples are the debris flows in Venezuela in 1999 and the Las Colinas landslide in El Salvador in 2001: they were recorded in the databases as floods and earthquake respectively, and not as landslide disasters.

Given that reasonable time series do exists, it might be useful to present the historical loss data in a statistical manner, in terms of a loss-frequency diagram. Examples of such plots are shown in Figure 7. The profiles for Colombia and Nepal were derived by NGI in landslide screening studies for the World Bank. Data used originate from respectively DesInventar (2005) and a national database for Nepal, Kahnal (2004). The loss frequency diagram for the other countries shown in Figure 7, originate from work done by Guzzetti, (2000).

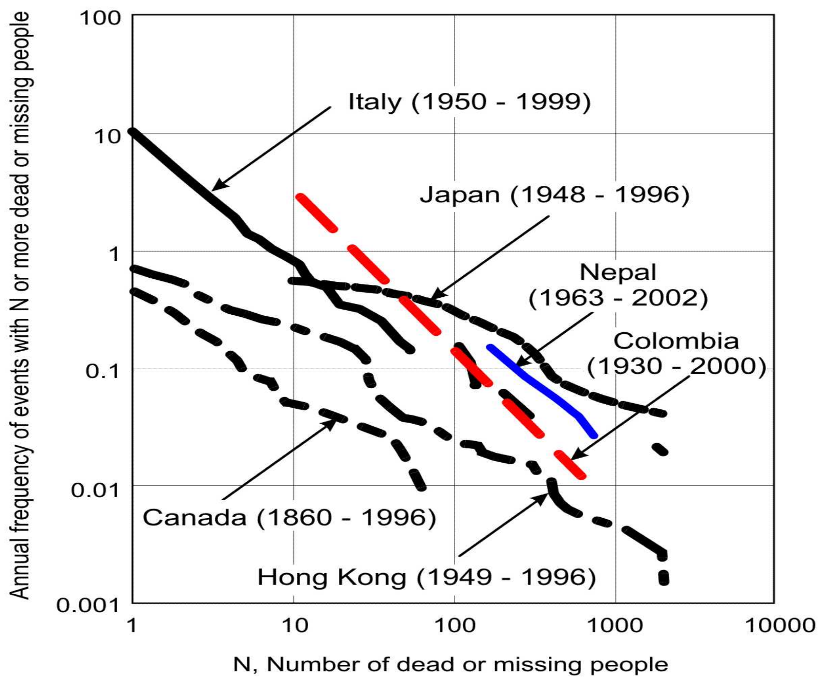

Figure 7 Landslide loss frequency diagram for selected countries

For Colombia, the figure indicates that a) the return period for a single landslide causing more than 180 fatalities is about 10 years and b) a landslide disaster with fatalities of 500 or more may statistically occur every 50 years.
When a reasonable quantity of economic loss data is available, it is useful to prepare a statistical evaluation of economic loss potential by plotting losses versus annual exceedance probability. Such an exercise was carried out by the World Bank for a number of countries in Central Asia, (Push 2005). Key results for selected countries are shown in Table 8.

Table 8 Predicted annual losses in % of GDP caused by floods, mudslides and landslides, data derived from Push, (2005)

Country	**Losses in % of GDP** Annual probability of exceedance equal to **5%**	**Losses in % of GDP** Annual probability of exceedance equal to **20%**
Romania	1.2	0.6
Kyrgyz Republic	1.1	0.01
Tajikistan	24.2	5.8

Unless loss data are available in one form or another, experience has shown that it is difficult to convince decision-makers to invest in mitigation measures, support the build-up of national competence or invest in R&D for improved understanding of the landslide process. It is an important challenge for the geotechnical profession to get involved not only on the technical aspect of landslides, but also in the gathering of loss data from landslide events. Internationally, there is a new initiative taken up by UNDP in collaboration with the ProVention Consortium to invest in a global effort to improve the database for loss data in connection with most types of natural hazards, including landslides, (Dilley 2006).

In a global context, Italy stands out as a leading country for having invested heavily in a comprehensive landslide database, (Guzzetti *et al.* 1994). Work is also in very good progress in many developing countries, for instance in Nepal, Sri Lanka and Nicaragua. An example from Nepal is shown in Fig.8. Comprehensive work carried out for Nicaragua has been reported by Devoli, (2005).

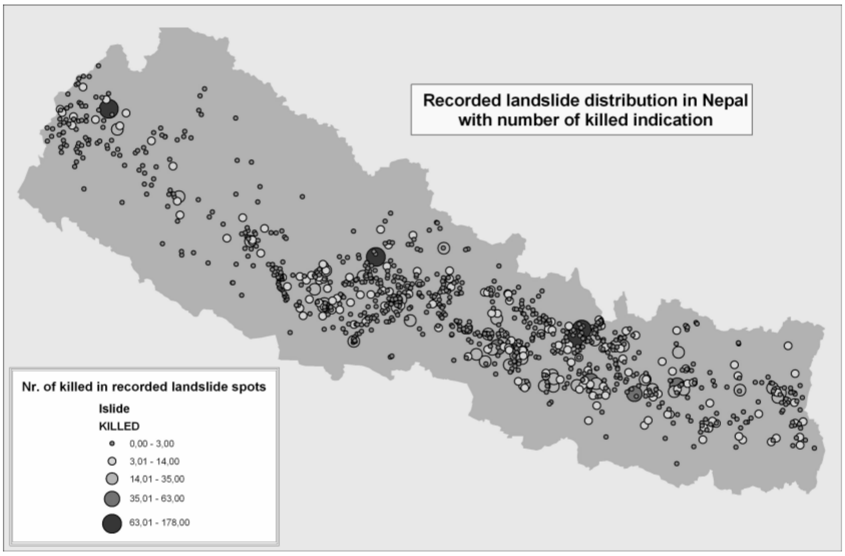

Figure 8 *Recorded landslide distributions in Nepal in the period 1934-2003, (after Khanel 2004)*

Summary and conclusion

Simplified qualitative methods can be useful tools for the practitioners in the assessment of landslide risk. The progress in the application of risk maps has, with few exceptions, been rather slow. Hazards maps are quite often treated as a kind of risk maps, while they actually often are just susceptibility maps. They very often lack the dimension of "probability of occurrence."

The engineering scoring approach can be tailor made to fit with the actual problem. The method can also easily be applied for assessment of risk caused by other hazards so that comparison between different hazards can be done in a consistent manner. In the assessment of scoring and weighting of consequences, it is for instance possible to involve local communities in the process.

Use of GIS has improved dramatically the objectivity and productivity of landslide hazard and risk maps. Both susceptibility factors and triggering factors can be assessed and refined to a relevant level, depending on the scope and scale of the investigation. In principle the method indicated in the paper can be adopted at global, regional, national and sub-national scale. There is, however, a great need for more comprehensive validation of the predicted hazard and risk maps.

In the application of the GIS analysis based on the Mora-Vahrson approach, there are interesting works in progress both in Norway and in Italy to include run-out distance in the calculation model. A successful outcome of this work will be a great improvement.

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Spatial Modelling of Seismicity Induced Landslides

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Abstract

Landslides induced by an earthquake depend primarily on the amount of permanent deformation experienced by the slope due to ground shaking. The present study in one case study area in Himalaya is concerned with the assessment of simplified Newmark's block-on plane model for evaluating the permanent earthquake displacement. The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history. The moderate magnitude Chamoli earthquake that occurred in the Garhwal Himalaya in the early hours of March 29, 1999, caused intense damage to the ground and mountain slopes in Alaknanda river valley and adjoining region. The earthquake has triggered several new landslides and reactivated some of the existing ones. In the present study this model is applied in Chamoli region and its surrounding areas falling in a high landslide hazard zone as well as high seismic zone (Zone V), that have experienced a large number of seismicity induced landslides of varying size and types in the recent past. The model is also applied in another case study area around Uttarkashi with reference to Uttarkashi earthquake of 1991 to study the possibility of deformation developed then resulting in massive landslide after 12 years in 2003. The slope response, ground deformation and possible lateral spreading due to earthquakes in hilly region are also studied with respect to recent earthquake of 2005 in Kashmir. The study concludes that it is possible to make a preliminary assessment of the seismicity induced landslide using Newmark model, however, in the presence of geological heterogeneity and lack of precise geotechnical information such as in situ cohesion and angle of friction, the application of such model needs precise calibration to yield useful results.

Introduction

The hilly tracts of Himalaya are prone to landslides and earthquakes due to ongoing tectonic activities. The seismic events can cause ground acceleration which in turn can activate mass movement processes, especially in high relief areas of Himalaya, aggravating the slope stability problem. Earthquakes having magnitudes greater than 4.0 can trigger landslides on very susceptible slopes near the epicenter, and earthquakes having magnitudes greater than 6.0 can cause widespread landsliding (Keefer,1984). The study area lies in the Chamoli district of Garhwal Himalaya, bounded by latitude $30^0 15'30''$ to $30^0 31'00''$ and longitude $79^0 15'00''$ to $79^0 33'00''$. The Chamoli earthquake of 1999 triggered new landslides and reactivated old landslides (Sah and Bartarya, 2002). The seismic parameters have been derived from source characterization data of USGS and IMD. Parameters on terrain characteristics *viz.* geology, structure, geotechnical properties etc. were derived from IRS-LISS-III, IV and PAN data supported by ground observations and laboratory test. These satellite data products show three types of landslides: old, reactivated and new slides, most of which are rock and debris falls. The database is organized in ARC GIS and result shows simulation of slope response to reference seismic event and its effect on slope stability.

Geological setup

The Garhwal Himalaya is located at the eastern end of the North-west Himalaya in the northern India and is situated in a seismic gap, in the vicinity of the Main Central Thrust that separates the Lesser Himalaya to the South from the Greater Himalaya to the North (Valdiya, 1988). The study area is underlain by Garhwal Group of rocks (Kumar and Agrawal, 1975) consisting of quartzites which are well exposed at Chamoli and extends 2-3 km to the northeast followed by limestone and slate sequences of the Pipalkoti Window, locally known as 'Carbonate Suite of Chamoli' (Gaur et al, 1977). The Carbonate Suite of Chamoli consists of alternating sequence of slates and dolostones that forms the doubly plunging Pipalkoti anticline. It is thrusted over by the thick quartzites of Gulabkoti and the Chinka formations, which are thrusted upon by the Central Crystallines along the Main Central Thrust (MCT), locally trending in NW-SE direction and dipping at 15-20^0 towards north**.** Tectonically, the MCT represents a ductile shear zone at depth, comprising a duplex zone with three distinct thrust planes: MCT I, MCT II and MCT III from south to north. Based on the degree of metamorphism, lithostratigraphy and tectonic setting, these thrust planes are also referred to as Chail (MCT I, lower thrust), Jutogh (MCT II, middle thrust) and Vaikrita (MCT III, upper thrust) (Valdiya, 1980). The Chamoli earthquake appears to be associated with the ongoing deformation along Chail Thrust.

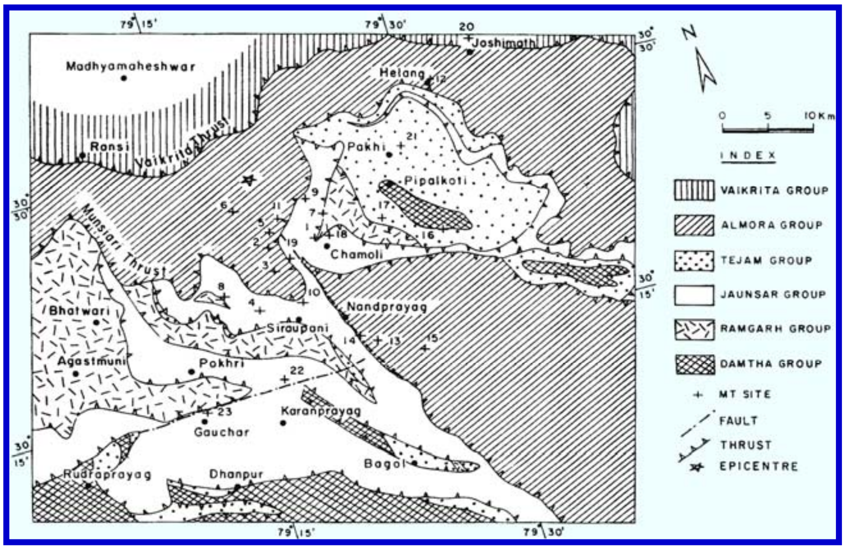

Figure 1. Regional geological map of the study area (After Valdiya, 1980)

Modelling of Seismicity Induced Landslide

Several models have been developed to evaluate the stability of geotechnical structures under earthquake loadings. These models include: the limit equilibrium model that uses the slope safety factor, in which the failure occurs when the safety factor is less than unity; the stress-strain analysis using the infinite element technique, and the block-on-plane model which is based on calculating the cumulative earthquake induced displacement.

Development in the first group of models includes the work of Fellenius (1936), Bishop (1955) and others. The second group of models is more sophisticated and requires accurate input data, as demonstrated by Al-Homoud (1990) and Al-Homoud and Whitman (1995), who used the finite element method to model dynamic behavior of gravity walls under earthquake loading. The third group, block-on-plane model, was introduced by Newmark (1965) to obtain the earthquake induced displacement of embankment slope. Many attempts were made to improve this model, resulting in models for obtaining the earthquake induced displacement (Ambraseys, 1972; Richard and Elms, 1979; Zarrabi, 1979; and Wong and Whitman,1983).

Newmark method of analyzing the dynamic performance of slopes bridges the gap between simplistic pseudostatic analysis and very sophisticated, but generally impractical finite-element modeling. Although Newmark introduced his method to analyze the performance of artificial embankments, Wilson and Keefer (1983) showed that Newmark's method to model the dynamic behavior of landslides on natural slopes yields reasonable and useful results. Jibson (1993) used the Newmark’s sliding block analysis method for predicting earthquake induced landslide displacement. Based on Newmark method, Miles and Keefer (2001) have prepared the seismic landslides hazard map for the city of Berkeley, California in GIS environment.

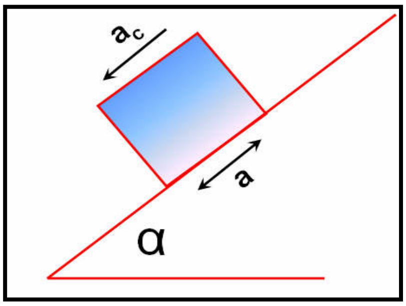

Figure 2. The potential landslide is modeled as a block resting on a plane inclined at an angle (α) from the horizontal. The block has known critical (yield) acceleration (a_c), the base acceleration required to overcome shear resistance and initiate sliding with respect to the base. The block is subjected to a base acceleration (a) representing the earthquake shaking.

Newmark's method models a landslide as a rigid friction block that slides on an inclined plane (Fig-2). The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effects of an earthquake acceleration-time history.

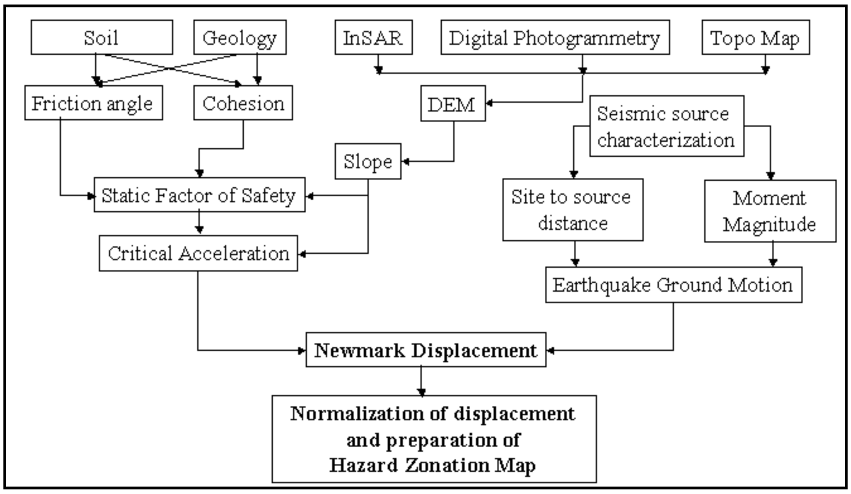

Figure 3. Methodology for seismicity induced landslide hazard zonation using Newmark model.

Newmark analysis can be extended to regional analysis using Geographical Information Systems (GIS). The procedure is summarized by the flow diagram (Fig. 3), where each labeled box, except for earthquake magnitude, represents a map grid. Conducting a conventional Newmark analysis requires selection of an appropriate earthquake record and determination of the critical acceleration (a_c) of the selected slope. Critical acceleration (a_c) can be calculated using the equation:

$$a_c = (FS-1)\sin\alpha \qquad (1)$$

Here, FS is the static factor of safety of the slope and α is the angle of the landslide block, which is typically approximated by the slope angle. The angle for each pixel is approximated by calculating slope from a digital elevation model (DEM), which has been generated using IRS-1C stereo pair. The most common means of calculating the static factor of safety, in the context of spatial analysis, is to apply the infinite slope model to each pixel. Using the infinite slope model, the static factor of safety of a slope (FS) can be expressed as follows:

$$FS = (\acute{c} / \gamma\, d \sin\alpha) + (\tan\varphi' / \tan\alpha) - (m\, \gamma\, w \tan\varphi' / \gamma \tan\alpha) \qquad (2)$$

Where, c' is cohesion ,ϕ' is effective angle of internal friction, γ is material unit weight, γ_ω is unit weight of water, α is the angle of the slope from the horizontal, *d* is normal depth to the failure surface, and *m* is the ratio of the height of the water table above the failure surface to *d*.

The above equation is organized so that the first term on the right side accounts for the cohesive component of the strength, the second term accounts for the frictional component, and the third term accounts for the reduction in frictional strength due to pore pressure. In present analysis pore-water pressure is neglected (m=0) because almost all failures in the Chamoli earthquake occurred in dry conditions; thus, the third component is dropped from the equation.

Conducting a GIS-based Newmark analysis requires characterization of expected regional earthquake ground motions. In this method the required ground motion descriptor is Arias Intensity (*Ia*). Expected mean Arias intensity can be estimated using the following equation (Wilson, 1993).

$$I_a = \frac{\pi}{2g}\int_0^T [a(t)]^2 dt \qquad (3)$$

Where, I_a is Arias intensity in units of velocity, g is the acceleration of Earth's gravity, a(t) is the ground acceleration as a function of time, and t is the total duration of the strong motion. It can also be calculated from the moment magnitude as per the following attenuation law (Wilson and Keefer, 1985) :

$$\log I_a = M - 2\log\sqrt{R^2 + h^2} - 4.1 \qquad (4)$$

Where, I_a is Arias intensity, M_w is moment magnitude, R is closest distance to surface projection of fault rupture, and h is the focal depth of earthquake.

Newmark displacement, an index of seismic slope performance, can be estimated as a function of critical acceleration (dynamic slope stability) and Arias intensity (ground-shaking intensity). In the final step, Newmark displacement is calculated based on the maps of critical acceleration and earthquake ground motion, as per the following equation:

$$\log D_N = 1.521 \log I_a - 1.993 \log a_c - 1.546 \qquad (5)$$

Parameter Derivation and Data Analysis

The Chamoli earthquake of magnitude mb 6.3 / MS 6.6 USGS occurred on 29th march 1999 at 00:35:13.59 hours (local time) near the town of Chamoli in the state of Uttaranchal in northern India. The pre and post event satellite data of IRS-1C/1D PAN (26 March 1999 and 05 April 1999) and LISS-III (26 and 30 March 1999) were georeferenced and digitally enhanced. A comparison of pre and post earthquake data images reveals about 57 new landslides of various dimensions in and around the epicenter region (Chamoli, Ghingran and Gopeshwar). Similar visual assessment of satellite images to map new and reactivated landslides has been reported by Ravindran and Phillip (2002). The earthquake has reactivated old landslides mainly along Alaknanda, Birahi Ganga and Garur Ganga (Fig. 4).

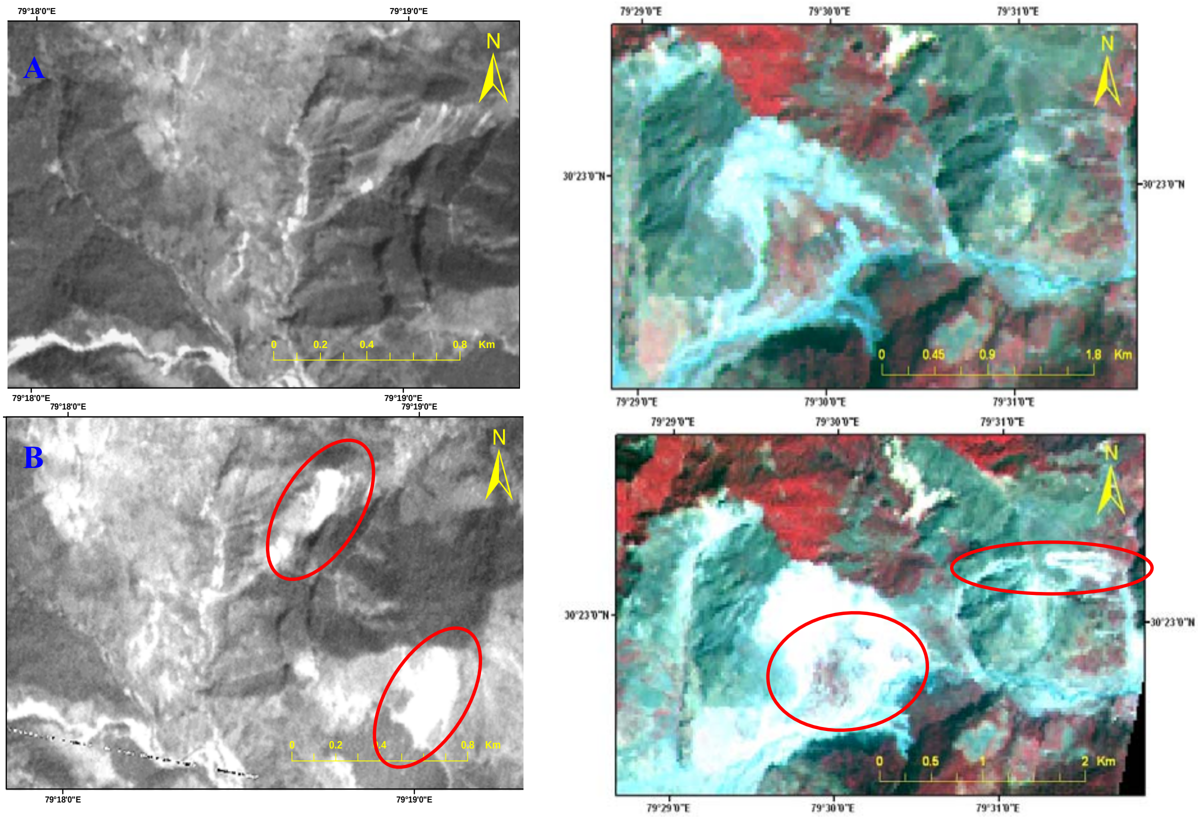

Figure 4. Satellite images (IRS-1C-PAN and LISS-III) acquired before and after earthquake show a) fresh rock fall in quartzite near Gopeshwar, and b)reactivation of old landslides near Gauna Tal.

IRS PAN images acquired before and after the earthquake were used for change detection analysis using synthetic color composites, where in the post event image was assigned to red channel and pre event image was repeated on blue and green channels. Changes related to ground deformation associated with seismically induced landslide were highlighted in red color. Similar attempts have also been made by earlier workers in highlighting surface changes due to earthquakes (Champati ray et al., 2001; and Saraf, 1998). Additionally, thresholding was applied to unimodal histogram of post and pre difference image. The threshold point is selected at a pixel intensity value that maximize the perpendicular distance between the line and the histogram distribution (Rosin, 2001).In spite of image comparison, synthetic color composition and unimodal thresholding, the detection of landslide was not always possible in a straight forward manner. It was still necessary to consider contextual information on slope, shape, size and association to map new and reactivated landslides.

Identification of landslide was primarily based on spectral differences, morphologic features and contextual information. Morphologically defined lineaments, e.g. drainage line or scarps were interpreted to be the trace of high angle faults in those places where the lineament displaces rock units at least along part of the lineament. Different litho units and surficial deposits were interpreted based on available literature and satellite data products. A detailed lithological map of the study area has been generated on 1:25000 scale and geotechnical property of the rock and soil (cohesion, angle of friction and unit weight) were obtained from triaxial test of representative samples from different litho units. Slope gradient has been derived from the DEM generated from IRS-1C Stereo pair. Seismic parameters were taken from data provided by USGS and IMD. The United States Geological survey (USGS) located this moderate magnitude earthquake (M_b=6.3, M_s=6.6, M_w=6.4, M_o=5.2*10^{18}) at 30.490 N, 79.290 E at 12 km depth.

A raster database is organized in Arc GIS and static factor of safety was calculated as per eq. 2. The critical acceleration (a_c) is calculated by combining the factor of safety grid with slope grid to yield the critical acceleration grid which represents seismic landslide susceptibility. Arias intensity is calculated based on moment magnitude distance to epicenter and focal depth as per eq. 4. Newmark displacement has been estimated based on empirical relation combining the critical acceleration and shaking intensity values from the Chamoli earthquake (Figure 5). The modeled displacement is then compared with the inventory of landslides triggered by the Chamoli earthquake and it was observed that 80 % of the area where landslides were triggered due to earthquake was falling in very high to high hazard zone derived from Newmark displacement map.

Surface Deformation and landslides due to Kashmir earthquake of 2005

A devastating earthquake of 7.6 Mw magnitude occurred at 03:50:38 (UTC) on Saturday, October 8, 2005 with an epicenter located at 10 km north-northwest of Muzaffarabad. The epicenter was located very close to one of the most striking structural features, known as Hazara syntaxis, where most of the thrust faults have a sinuous trace as they across the foothills in northern India and into northern Pakistan. These high-resolution data products show three types of landslides: old, reactivated and new slides, most of which are rock and debris falls. Landslides were commonly observed on the steep slopes of two important river valleys of the region i.e. Jhelum and Katha Kazi Nag. During the field investigation, it was observed that ground acceleration has mostly affected regions close to the free face developing lateral spreading features, often aligned in a direction parallel or sub parallel to the causative NW oriented fault plane as well as to the major structural feature of the region (Champati ray et al., , 2005; Thakur et al., 2006).

Satellite data was analyzed from two different sources: archive ETM data available from the site and recent satellite data acquired by NDC, NRSA on October 9, 2005. The 7 bands ETM data and panchromatic data were utilized to assess the seismotectonic set up of the region vis-à-vis the earthquake epicenter (Figure 6).

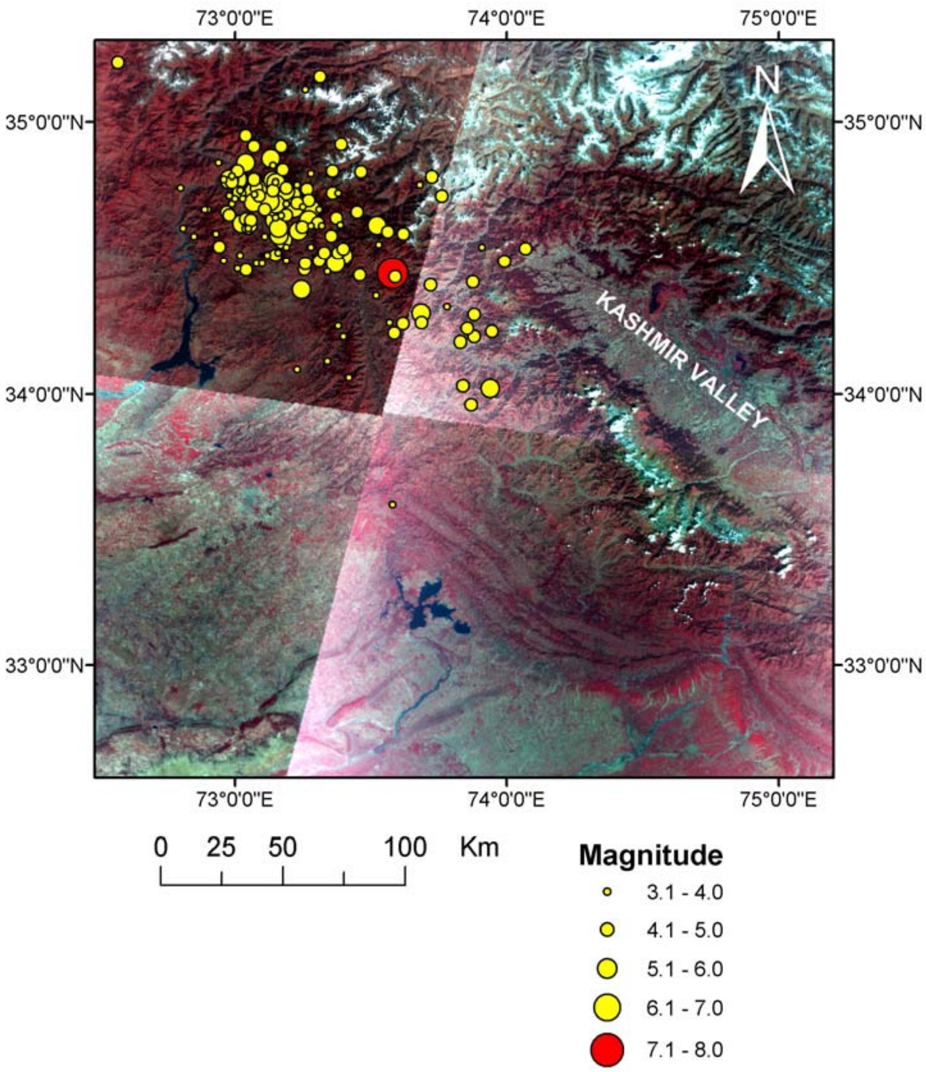

Figure 6. Post earthquake coverage of ETM image of the Pakistan and Kashmir Himalaya showing the main shock and after shocks.

The Cartosat PAN data of 2.5 m resolution and Resourcesat multispetral data of 5.8 m resolutions were geo-referenced and analyzed for land surface change mapping particularly landslides and surface ruptures. The NRSA data was made available within a week time for quick assessment of the damage due to surface deformation. On priority the areas close to Uri were analyzed, wide spread landslides and slope failures in solid rocks, as well as colluvial and alluvial fan and terrace deposits (Fig. 7) were observed. Based on the tonal difference and temporal analysis numerous landslides have been mapped on high-resolution Cartosat as well as Resourcesat data. Although Cartosat data offers better resolution and 3-D perception, the multispectral LISS-IV data found to be superior in many cases due to better tonal discrimination.

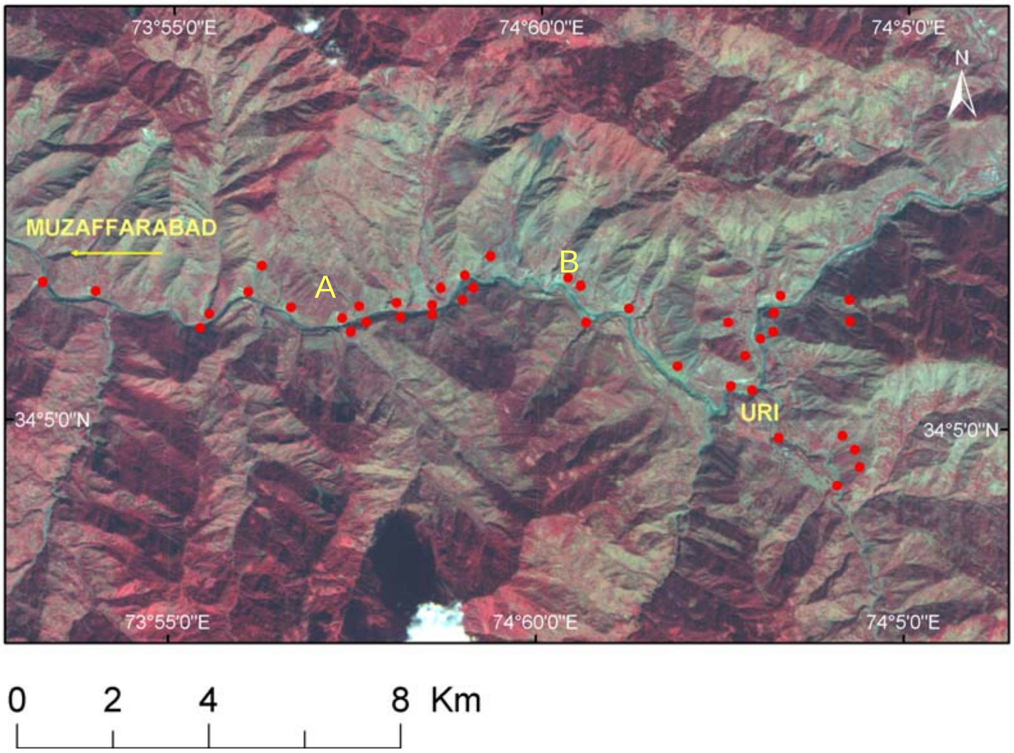

Figure 7. The post earthquake coverage of LISS-IV image showing landslides along the Jhelum River to the east and west of Uri town are indicated by red solid circles. (A) & (B) are prominent landslides in the region.

In the Jhelum valley, in a westward direction from Baramulla to Uri landslides were observed due to failure of the scarp faces of the river terraces and steep slopes in road section at around 8-10 km before Uri. Towards further west, the occurrences of the landslides are found to be more pronounced closer to Punjal Thrust and Murree Thrust. In this region Murree and Punjal Thrust occur very closely to each other separated by a narrow band of quartzite, silt stone and slate. Beyond Murree thrust, the rock types are found to be predominantly steeply dipping with alternating red shale and sandstone, which are vulnerable to landslides due to differential weathering. In areas close to thrust, and vulnerable rocks mostly old slides have been reactivated. Maximum devastation has taken place in areas beyond Uri towards further west, due to high ground acceleration and landslides observed on colluvial wedges (Figs. 8a, b, c and d). In this section, some of the landslides are found to be reactivated old slides. The stream discharges on the right bank of the Jhelum was found to increase due to rupture.

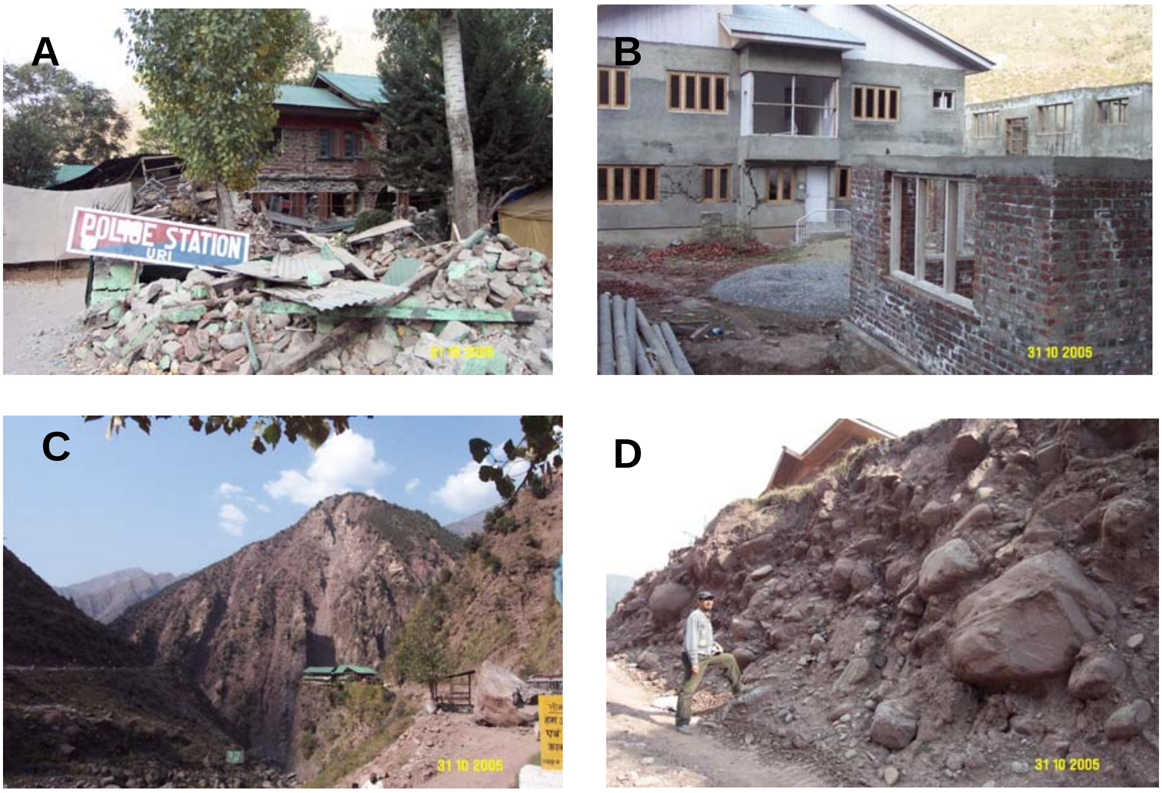

Figure. 8a). Complete collapse of Police station at URI town (34° 04' 36.0", 74° 03' 56.8".), **b).** The earthquake surveyed partially constructed house and at the back ground the large diagonal cracks in the side walls of the house, but the walls have not failed, **c).** The fresh landslide in the steeply dipping hard red color sandstone of Murree Formation, at red bridge (34° 06' 03.3", 73° 57' 29.1"), **d).** Fresh land slide in the thick colluival deposit near Urusu village along the National High way leading to Muzafarabd (34° 06' 25.9", 73° 56' 00.4").

Uttarkashi Landslide: As a consequence of earthquake in 1991 ?

One of the most seismic active regions of the Garhwal Himalaya is devastated by landslides along the Bhagirathi valley, the prominent ones are located near Gyansu, Matli and Maneri. In the recent time particularly the town of Uttarkashi is affected by a huge landslides on Varunavat hill, which started on 24th Sept. 2003 and continued till monsoon period (June-Aug) of 2004 (Champati ray, 2006). It has displaced more than 2000 people and property and business worth 100 million USD has been lost. There is no sign of stabilization yet and similar landslides in the vicinity cannot be ruled out. The composite landslide has destroyed the main business center of the town and has affected around 1 km of one of the most important pilgrim rout to Gangotri, the source region of Ganges. Efforts are being made to realign the road on the southern bank of the river by constructing additional bridges. Therefore, a study area of 185 km^2 has been taken up around Uttarkashi town to monitor the landslides and prepare a landslide susceptibility map in order to guide the future development of the region. Based on the terrain and geological parameters, fuzzy integration based landslide hazard map showed the variation of landslide susceptibility in the region. However, since the area lies in highest seismic hazard zones of India (zone 5), it was necessary to assess the effect of seismic events in the region.

The Uttarkashi area falls in one of the highly active seismic domains of the Himalaya, Garhwal seismic block, defined by Kaurik fault in the west and Alkananda fault in the east. The characteristic of 79 major earthquakes recoded in this region are: 4<Mb<4:25 events, 5<Mb<6:26 events, 6<Mb<7:10 events (Narula et al., 1995). The Uttarkashi earthquake (Ms 7.0) of 20th Oct 1991 has been the highest magnitude earthquake affecting the region, followed by the Chamoli earthquake (Mw 6.6) of 29th March 1999 and most recently on 27th May 2003 an earthquake of magnitude 4.9 has occurred at a distance of 70-80 km from the study area. In the Uttarkashi earthquake, many parts of the area witnessed major landslides, reactivation of old slides. During Chamoli earthquake of 1999, seismicity induced landslides have been reported by Ravindran and Phillip (2002) and Saraf and Sarkar (2002). Rastogi and Chada (1995) have reported around 200 landslides in the entire Uttarkashi region. Landslides mostly occurred as highly jointed quartzite rocks slipped along the slopes of the mountains. In general large number of slides were observed in the highest intensity IX (MSK scale) and VIII zones followed by minor slides in the VI zone. The present study area lies in zone VI very close to zone VII and experienced maximum ground acceleration of 0.3g. Therefore, the ground motions induced by the earthquake have acted as triggering factor in causing slope failures. The slope failure phenomena further aggravated during monsoon period of 1992 when the slope forming material consisting of fractured rocks got fully saturated leading to landslides.

Numerous ground fissures have been reported; maximum length being in the order of 100m with largest opening of 0.55m (Narula et al., 1995). These fractures/ faults have potential to develop landslides in subsequent years. Therefore, in order to assess the possible effect of earthquake on slope stability of the region and with particular reference to the Varunavat landslide, modeling based on permanent –displacement analysis developed by Newmark (1965), Wilson and Keefer (1983), and Jibson (1993), and Jibson et al. (1998) has been applied. The static factor of safety has been calculated for various possible rock types of the region using different effective cohesion and friction angle. For simplicity, a uniform unit weigh of 15.7 kn/m^3 and thickness of the failure plane is considered as 3m for shallow landslides. For a reference slope of 40 degree and Arias intensity (I_a) of 0.970 for Uttarkashi earthquake (Shrikhande et al., 2001), the possible displacement is calculated (Table 1). A similar calculation for 45 degree slope suggests even more displacement and more conditionally unstable slopes in situations similar to present landslide region in Uttarkashi. Thus the vulnerable slopes already affected by Uttarkashi earthquake (1991), Chamoli earthquake (1999) and minor tremors in 2003, are more prone to develop landslides as indicated by Newmark displacement analysis.

Table 1. Possible Newmark displacement due to Uttarkashi earthquake

c'	ϕ'	FS	a_c	D_n
10	35	1.164777	1.037984	0.202222
15	35	1.329928	2.078323	0.110878
20	35	1.495079	3.118663	0.078035

10	30	1.018362	0.115665	1.351096
15	30	1.183513	1.156005	0.184225
20	30	1.348664	2.196345	0.105702
10	27	0.937531	*	
15	27	1.102682	0.646828	0.304519
20	27	1.267833	1.687168	0.132809
10	25	0.886026	*	
15	25	1.051177	0.322382	0.55638
20	25	1.216328	1.362722	0.159774

c' = effective cohesion, ϕ' = effective angle of internal friction, FS = factor of safety, a_c = Critical Acceleration, D_n = Newmark displacement in cm and * indicates conditionally unstable slopes where movement is apparent.

Results and Discussion

The presented case studies reveal that pre and post earthquake event IIRS-LISS-III and PAN satellite data products provide information on changes related to seismicity induced landslides using various change detection techniques. It is possible to map landslides triggered by earthquake except for very small slides and slides in shallow region. Orthorectification is highly essential for high positional accuracy in this rugged terrain. Although an integrated surficial geological map has been used for parameter characterization by analyzing representative field samples, it would be better to have actual angle of friction, on-site cohesion and unit weight for different rock types. Additionally, it was not possible to map thin layers of unconsolidated material on gentle to steep slopes which often fails during earthquakes.

In Newmark's method, displacement depends on the critical acceleration, which, in turn, depends on the static factor of safety. Therefore, a landslide at or very near static equilibrium should have a very low critical acceleration (theoretically, $a_c = 0$ if $FS = 1$) and thus should undergo large displacements virtually in any earthquake. Predicted Newmark displacements do not necessarily correspond directly to measurable slope movements in the field; rather, modeled displacements provide an index to correlate with field performance. For the Newmark method to be useful in a predictive sense, modeled displacements must be quantitatively correlated with field observation. Therefore, with all above limitations, this method can still be used to study slope response in the event of an earthquake.

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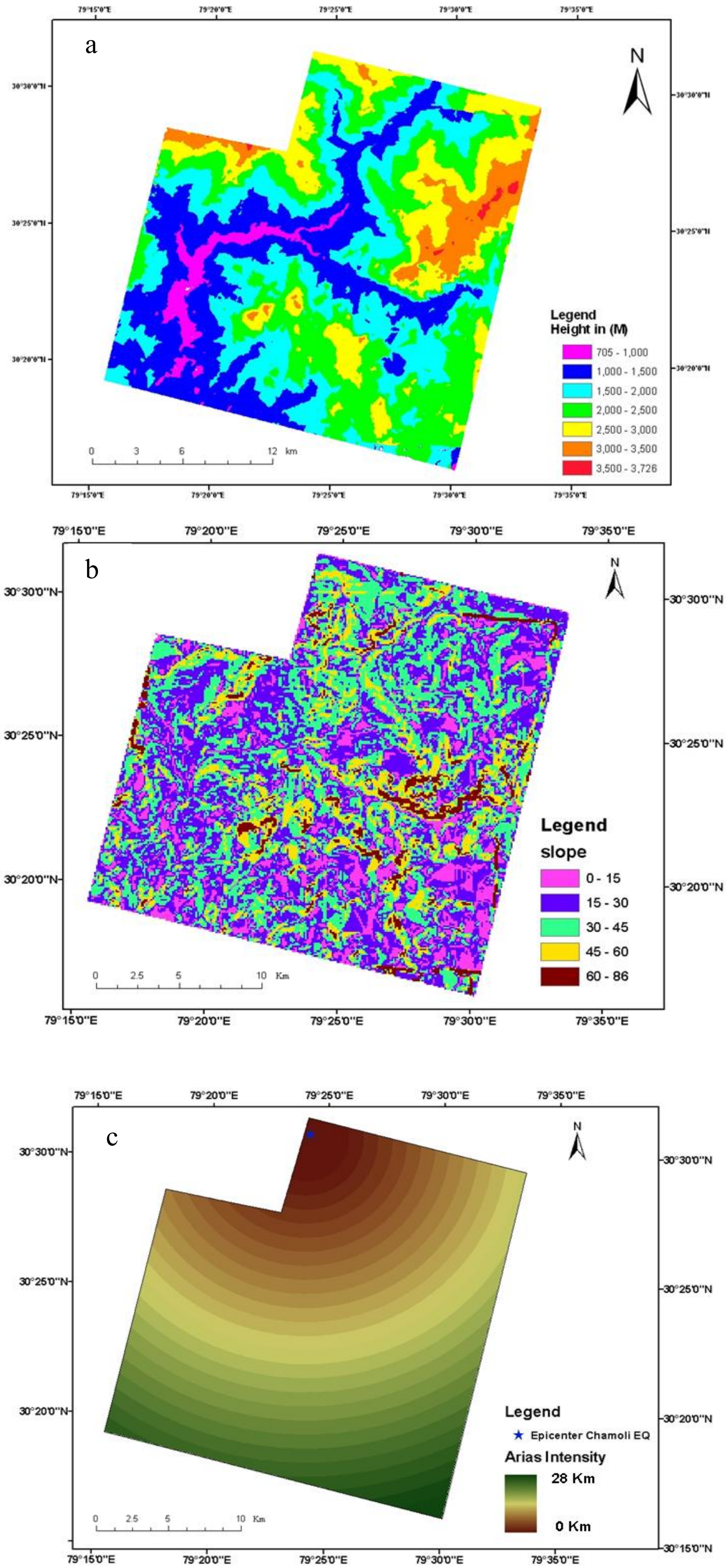
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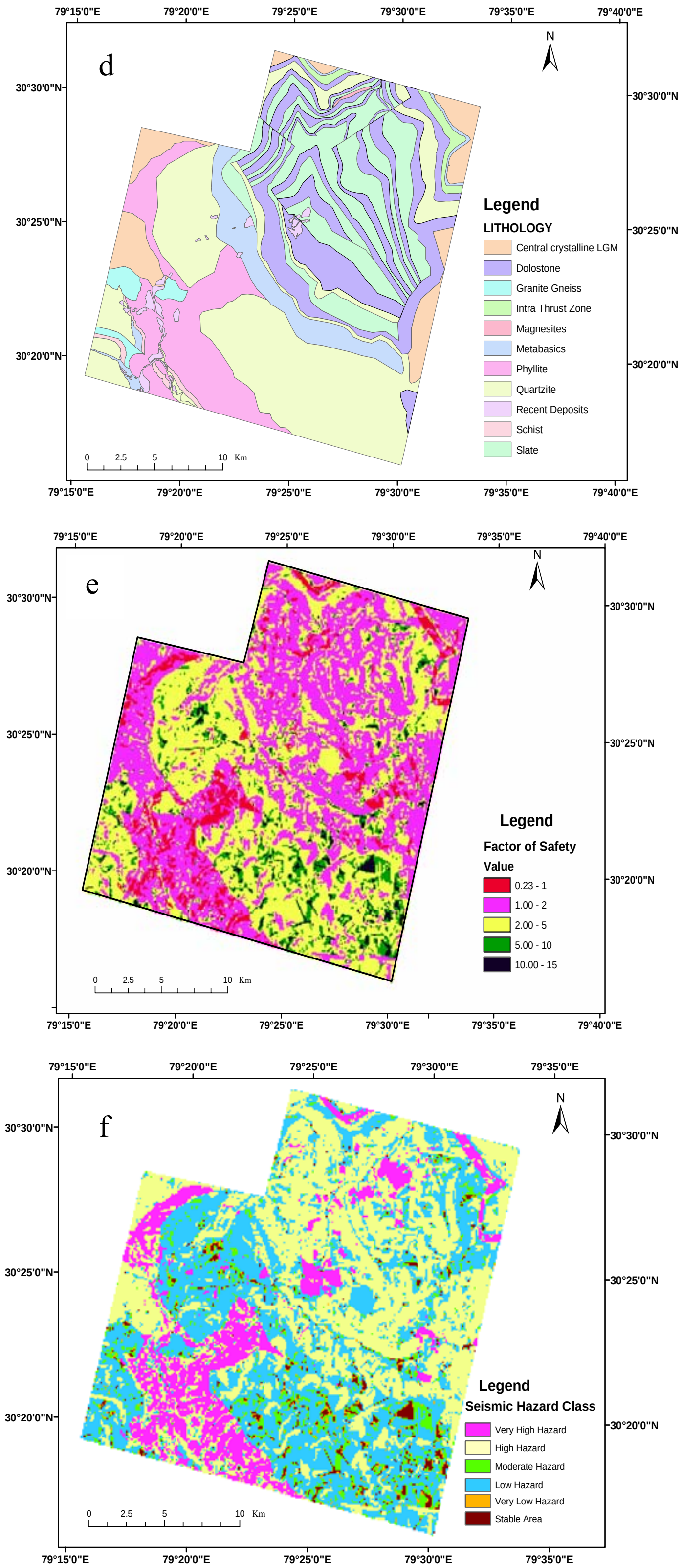

Figure 5. a) DEM generated from IRS-1C Stereo pair, b) Slope map, c) Lithological map, d) Distance buffer from epicenter of Chamoli earthquake, e) Factor of safety map, f) Seismic Landslide Hazard Zonation Map.