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Living with Landslide Risk

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ABSTRACT: Landslides represent a major threat to human life, property and constructed facilities, infrastructure and the environment in most mountainous and hilly regions of the world. Statistics from the Centre for Research on the Epidemiology of Disasters (CRED) show that landslides are responsible for at least 17% of all fatalities from natural hazards worldwide. The socio-economic impact of landslides is underestimated because landslides are usually not separated from other natural hazard triggers, such as extreme precipitation, earthquakes or floods. Many lives could have been saved if more had been known about the risks and risk mitigation measures had been implemented. The paper summarizes key aspects in the assessment of geological hazard and risk and exemplifies these with the risk associated with landslides and use appropriate risk mitigation strategies. Reducing the impact of landslide with mitigation measures is both an economical and social necessity.

1. INTRODUCTION

"Geo-hazards", or natural hazards that are driven by geological features and processes, pose severe threats to humans, property and the natural and built environment. Between 1975 and 2008, the EM-DAT database of natural disasters (EM-DAT, 2010) recorded 8,866 disasters causing 2.3 million fatalities. In the same period, the internationally recorded economic losses were US$ 1,530 billion. Since 2008, the loss of approximately 140,000 people in Myanmar during the tropical cyclone Nargis, the collapse of more than five million buildings and damage to 21 million more in the Wenchuan earthquake in China (UNISDR, 2009a), and the loss of over 200,000 people and the virtual collapse of a nation after the Haiti earthquake have been stark reminders that the risk associated with tropical cyclones, floods, earthquakes, droughts and other natural hazards needs to be mitigated. Over the last 100 years, the increase in the known number of deaths appears to be due to the increase in the exposed population in this time scale and the increased dissemination of the information, and not to an increase in the frequency and/or severity of natural hazards.

The economic consequences of geo-hazards show an even more dramatic increasing trend (Munich Re, 2007). Some of the reasons for this increase are obvious, others less so. The post-disaster effects can be especially severe in a vast, densely-populated area where sewer systems fail and disease spreads. Slums spring up in disaster-prone areas such as steep slopes, which are prone to landslides or particularly severe damage in an earthquake. Many of the world's fastest growing cities are located on coastal land or rivers where climate variability and extreme weather events, from cyclones to heat waves to droughts, pose increasing risks of disaster.

Well-documented studies show that developing countries are more severely affected by natural disasters than developed countries, especially in terms of lives lost (UNDP 2004, UNISDR 2009a and IFRC 2004). Table 1 presents the IFRC (2001) data for 1991-2000.

Table 1 Natural disaster between 1991-2000 (IFRC 2001)

Country classification	No. of disasters	No. of lives lost
Low and medium developed countries	1838	649,400
Highly developed countries	719	16,200

Of the total number of persons killed by natural disasters in this period, the highly developed countries accounted for only 5 % of the casualties. In absolute numbers, the material damage and economic loss due to natural hazards in highly developed countries by far exceed those in developing nations. However, this reflects the grossly disproportionate values of fixed assets, rather than real economic vulnerability.

Mitigation and prevention of the risk posed by natural hazards have not attracted widespread and effective public support in the past. However, the situation has changed dramatically over the past decade. It is now generally accepted that a proactive approach to risk management is required to significantly reduce loss of lives and material damage associated with natural hazards. The wide media attention on major natural disasters during the last decade has clearly changed people’s mind in terms of acknowledging risk management as an alternative to emergency management. A milestone in recognition of the need for natural disaster risk reduction was the approval of the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters" (ISDR 2005). This document, approved by 164 UN countries during the World Conference on Disaster Reduction in Kobe, January 2005, clarifies international working modes, responsibilities and priority actions for the coming 10 years.

2. TERMINOLOGY

The terminology used in this paper is generally consistent with the recommendations of ISSMGE Glossary of Risk Assessment Terms (listed on TC32 web page: http://www.engmath.dal.ca/tc32/). The important terms used in the context of this paper are:

Danger (Threat): Natural phenomenon that could lead to damage, described by geometry, mechanical and other characteristics. Description of a threat involves no forecasting.

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Mathematically, risk is defined as Risk = Hazard × Potential worth of loss.

Vulnerability: The degree of loss to a given element or set of elements within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss).

In UNISDR terminology on Disaster Risk Reduction (2009b), "disaster" is defined as "a serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources. The term "natural disaster" is slowly disappearing from the disaster risk management terminology because without the presence of humans, one is only dealing with natural processes. These only become disasters when they impact a community or a society.

Quantitatively risk can be evaluated from the following expression:

$$R = H \cdot V \cdot E \qquad (1)$$

where R = risk associated with a particular danger
H = hazard
V = vulnerability of elements at risk
E = expected cost of total loss of elements at risk

3. RISK FRAMEWORK

Risk management broadly refers to coordinated activities to assess, direct and control the risk posed by geohazards to the society. It integrates the recognition and assessment of risk with the development of appropriate strategies for its mitigation. The risk management process is a systematic application of management policies, procedures and practices to the tasks of communicating, consulting, establishing the context, identifying, analyzing, evaluating, monitoring and implementing risk mitigation measures (Draft ISO / IEC 31010 Ed. 1.0: Risk Management - Risk Assessment Techniques).

Risk management frameworks have the common objective of answering the following questions (modified from Lee & Jones, 2004):

- What are the dangers and their magnitude? [Danger Identification]
- How often can the dangers of a given magnitude occur? [Hazard Analysis]
- What are the elements at risk? [Elements at Risk Identification]
- What is the potential damage to the elements at risk? [Vulnerability Assessment]
- What is the probability of damage? [Risk Estimation]
- What is the significance of the estimated risk? [Risk Evaluation]
- What should be done? [Risk Management]

Figure 1 illustrates such an integrated process for the assessment and management of the risk associated with a landslide. The process is iterative. It is often required to go back to an earlier step to reassess in light of new information. Figure 2 provides one example of a framework for risk management.

Fell *et al*. (2005) made a comprehensive overview of the state-of-the-art in landslide risk management. Several risk formulations have been proposed, and Düzgün and Lacasse (2005) list a large number of these. A large body of literature also exists on earthquake risk management.

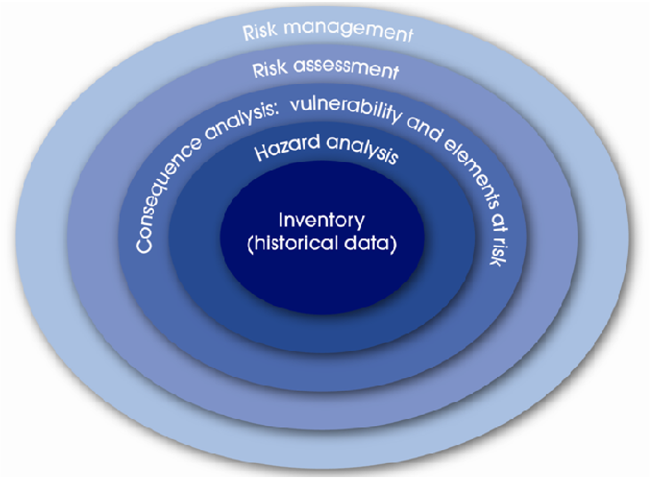

Figure 1 Integrated risk management process including risk assessment, starting with inventory of landslides at a location

In the following sections, methodologies for answering one or more of the above questions are discussed. The discussion is exemplified for landslide risk, but similar methodologies are also in use for earthquakes and tsunamis.

The first step in any decision-making process for disaster risk reductions is a quantitative risk assessment.One typically assesses risk based on a number of plausible scenarios. For example, in the case of a landslide, the following steps would be used: (1) define scenarios for triggering the landslide and evaluate its probability of occurrence; (2) compute the run-out distance, volume and extent of the landslide for each scenario; (3) estimate the losses for all elements at risk for each scenario; and (4) estimate the risk. Risk assessment is part of an integrated risk management process.

4. RISK MANAGEMENT

4.1 Acceptable risk

One of the most difficult tasks in risk assessment/ management is the selection of risk acceptance criteria. As guidance to what risk level a society is apparently willing to accept, one can use ‘F-N

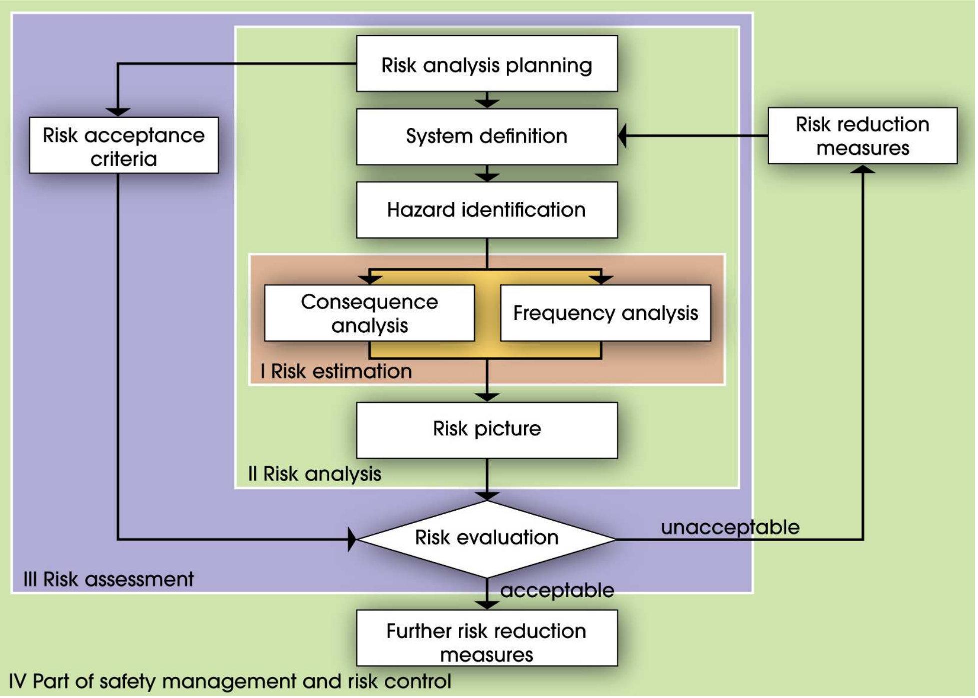

Figure 2 Risk estimation, analysis and evaluation as part of risk management and control (NORSOK Standard Z-013, 2001)

curves'. The F-N curves relate the annual probability of causing N or more fatalities (F) to the number of fatalities, N. The term "N" can be replaced by other quantitative measure of consequences, such as costs. The curves can be used to express societal risk and to describe the safety levels of particular facilities. Figure 3 presents a family of F-N-curves. Man-made risks tend to have a steeper curve than natural hazards in the F-N diagram (Proske, 2004).

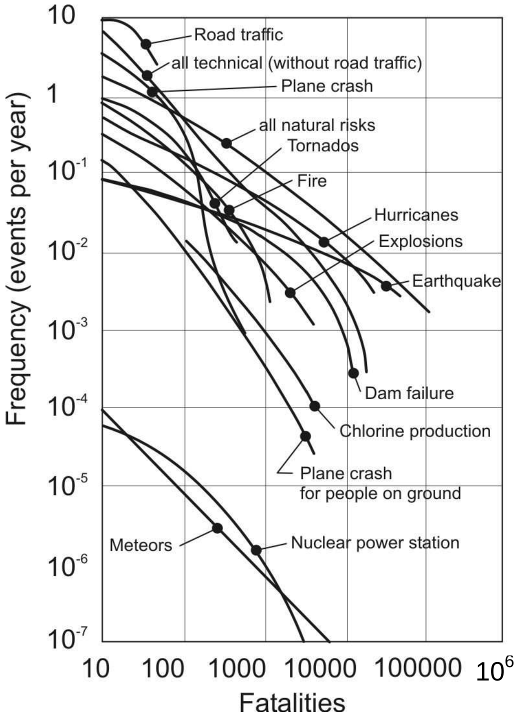

Figure 3 F-N curves (Proske, 2004).

F-N curves give statistical observations and not the acceptable or tolerable thresholds.

Who should define acceptable and tolerable risk level: the potentially affected population, government, or the design engineer? Societal risk to life criteria reflect the reality that society is less tolerant of events in which a large number of lives are lost in a single event, than if the same number of lives is lost in a large number of separate events. Examples are public concern at the loss of large numbers of lives in airline crashes, compared to the much larger number of lives lost in road traffic. Figure 4 presents an interim risk criterion recommendation for natural hillsides in Hong Kong (GEO, 1998). Acceptable risk refers to the level of risk requiring no further reduction. It is the level of risk society desires to achieve. Tolerable risk presents the risk level reached by compromise in order to gain certain benefits. A construction with a tolerable risk level requires no action/expenditure for reduction, but it requires control and risk reduction if possible.

Risk acceptability depends on several factors such as voluntary vs. involuntary exposure, controllability vs. uncontrollability, familiarity vs. unfamiliarity, short/long-term effects, existence of alternatives, type and nature of consequences, gained benefits, media coverage, availability of information, personal involvement, memory, and level of trust in regulatory bodies. Voluntary risk levels tend to be higher than involuntary risk levels. Once the risk is under personal control (e.g. driving a car), it is more acceptable than the risk controlled by other parties. For landslides, natural and engineered slopes can be considered as voluntary and involuntary risk. Societies experiencing geo-hazards frequently may have a different risk acceptance level than those experiencing them rarely. Informed societies can have better preparedness for natural hazards.

Although the total risk is defined by the sum of specific risk, it is difficult to evaluate its sum, since the units for expressing each specific risk differ. Individual risk has the unit of loss of life/year, while property loss has the unit of loss of property/year (e.g. USD/yr). Risk acceptance and tolerability have different perspectives: the individual's point of view and the society's point of view or societal risk.

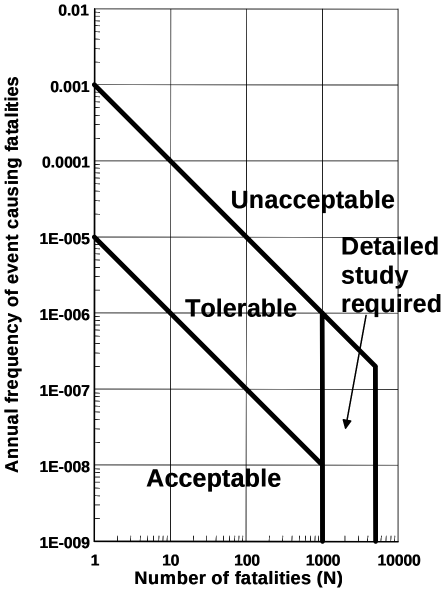

Figure 4 Hong Kong criteria (GEO, 1998).

4.2 Risk mitigation

The identification of the optimal risk mitigation strategy involves: (1) hazard assessment (how often risk management do the geohazards happen?), (2) analysis of possible consequences for the different scenarios, (3) assessment of possible measures to reduce and/or eliminate the potential consequences, (4) recommendation of specific remedial measures and if relevant, reconstruction and rehabilitation plans, and (5) transfer of knowledge and communication with authorities and stakeholders.

5. RISK IN DEVELOPING COUNTRIES

One can observe a positive trend internationally where preventive measures are increasingly recognized, both on the government level and among international donors. There is, however, a great need for intensified efforts, because the risk associated with natural disasters clearly increases far more rapidly than the efforts made to reduce this risk.

Three pillars are essential for the reduction in risk associated with natural hazards in developing countries are suggested (modified from Kjekstad, 2007):

Pillar 1: Identification of high-risk areas, and quantification of hazard and risk

Hazard and risk assessment are the central pillar in the management of the risk associated with natural hazards. Without knowledge and characteristics of hazard and risk, it would not be meaningful to plan and implement mitigation measures.

Pillar 2: Implementation of risk mitigation measures, including early warning systems

Mitigation means implementing activities that reduce the adverse effects of extreme natural events. In a broad perspective, mitigation includes structural and geo-technical measures, effective early warning systems, and political, legal and administrative measures. Mitigation also includes efforts to influence the lifestyle and behaviour of endangered populations in order to reduce the risk. The Indian Ocean tsunami of 2004, which killed at least 230,000 people, would have been a tragedy whatever the level of preparedness. However, even when disaster strikes on an unprecedented scale, there are many factors within human control, such as a knowledgeable population, an effective early warning system and constructions built with disasters in mind. Such measures can help limit the number of casualties.

Improved early warning systems have been instrumental in achieving disaster risk reduction for floods and tropical cyclones. Cuba has demonstrated that such reduction is not necessarily a question of expensive means. However, the recent tropical cyclone Nargis is a sad reminder that much remains to be done in decreasing the risk to tropical cyclones.

Meteorological forecast in region where cyclones generally occur is quite effective, but early warning and response remains insufficient in unexpected regions. As a consequence the focus on Early Warning System (EWS) development should take into account climatic changes and/or exceptional situations.

Pillar 3: Strengthening national and local coping capacity

Most of the developing countries lack sufficient coping capacity to address a wide range of hazards, especially rare events like tsunamis. International cooperation and support are therefore highly desirable. A number of countries have over the last decade been supportive with technical resources and financial means to assist developing countries where the risk associated with natural hazards is high. A key challenge is to ensure that the joint efforts are need-based, sustainable and well anchored in the countries' own development plans. Another challenge is coordination which often has proven to be difficult because the agencies generally have different policies and the implementation periods of various projects do not overlap. A subject which is gaining more and more attention is the need to secure 100 % ownership of the project in the country receiving assistance.

The capacity building initiatives should focus on four fields:

– Risk assessment and risk communication, i.e. the identification, evaluation and possibly quantification of the hazards affecting the country and their potential consequences, and exchange of information with and awareness-raising among stakeholders and the general public;
– Risk mitigation, i.e. laws, rules, guidelines and interventions to reduce exposure and vulnerability to hazards;
– Disaster preparedness, warning and response, i.e. procedures to help exposed persons, communities and organizations be prepared to the occurrence of a hazard; when hazard occurs, alert and rescue activities aimed at mitigating its immediate impact;
– Recovery enhancement, i.e. support to disaster-stricken populations and areas in order to mitigate the long-term impact of disasters.

6. RISK MANAGEMENT FOR LANDSLIDES

6.1 Landslide threat

Landslides represent a major threat to human life, property and constructed facilities, infrastructure and natural environments in most mountainous and hilly regions of the world. Statistics from The Centre for Research on the Epidemiology of Disasters (CRED) show that landslides are responsible for at least 17 % of all fatalities from natural hazards worldwide. The socio-economic impact of landslides is underestimated because landslides are usually not separated from other natural hazard triggers, such as extreme precipitation, earthquakes or floods. This underestimation contributes to reduced awareness and concern of both authorities and general public about landslide risk.

As a consequence of climate change and increase in exposure in many parts of the world, the risk associated with landslides is growing. In areas with high demographic density, protection works often cannot be built because of economic or environmental constraints, and is it not always possible to evacuate people because of societal reasons. One needs to forecast the occurrence of landslide and the hazard and risk associated with them. Climate change, increased susceptibility of surface soil to instability, anthropogenic activities, growing urbanization, uncontrolled land-use and increased vulnerability of population and infrastructure as a result, contribute to the growing landslide risk. According to the European Union Strategy for Soil Protection (COM232/2006), landslides are one of the eight main threats to European soils.

Water plays a major role in triggering of landslides. Figure 5 shows the relative contribution of various landslide triggering events in Italy. Heavy rainfall is the main trigger for mudflows, the deadliest and most destructive of all landslides.

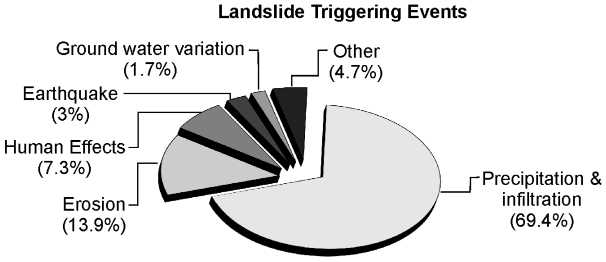

Figure 5 Landslide triggers in Italy (CNR-GNDCI AVI Database of areas affected by landslides and floods in Italy).

Many coastal regions have cliffs that are susceptible to failure from sea erosion (by undercutting at the toe) and their geometry (slope angle), resulting in loss of agricultural land and property. This can have a devastating effect on small communities. For instance, parts of the north-east coastal cliffs of England are eroding at rates of 1 m/yr.

Due to climatic changes and potential global warming, an increase of landslide activity is expected in the future, due to increased rainfalls, changes to hydrological cycles, more extreme weather, concentrated rain within shorter periods of time, meteorological events followed by sea storms causing coastal erosion and melting of snow and of frozen soils in high mountain regions like the Alps and the Himalayas. The growing landslide hazard and risk, the need to protect people and property, the expected climate change and the need to manage the risk have contributed to set the agenda for the profession to assess and mitigate the landslide risk.

6.2 Landslide hazard assessment

6.2.1 Specific slopes

Hazard assessment for a specific slope usually involves a probabilistic analysis of the slope, while hazard assessment for a region generally requires the computation of frequency of the landslides in the region. For regional analyses, data to be collected are in the form of maps related to geomorphology, geology, land-use/cover and triggers. For specific slopes, the required data for hazard analysis includes slope geometry such as height, width, inclination of slope and potential failure plane, shape and length of failure plane etc. Strength parameters for possible triggers such as rainfall intensity, water level, severity of dynamic loads e.g. earthquake magnitude, acceleration and/or other characteristics. The probabilistic models used for a specific slope vary depending on the failure mechanism (e.g. flows, falls or slides) and the slope-forming material (e.g. soil or rock).

Analyses of specific slopes use deterministic (factor of safety, numerical analyses) and/or probabilistic methods, e.g. first order, second-moment (FOSM), first order reliability method (FORM), point estimate methods, and Monte Carlo Simulation (MCS) (Ang & Tang 1984). Recent trends combine different approaches for an improved model of the hazard(s). An uncertainty analysis is essential prior to the calculation of slope failure probability as it allows a rational calculation of total uncertainties associated with different sources of uncertainty (e.g. in parameters and models). The quantification and analysis of uncertainties play a critical role in the risk assessment.

The stability situation for natural and man-made slopes is often expressed by a factor of safety. The factor of safety is defined as the ratio of the characteristic resistance (resisting force) to the characteristic load (driving force). The approach does not address the uncertainty in load and resistance in a consistent manner. The choice of "characteristic" values allows the engineer to implicitly account for uncertainties by using conservative values of load (high value) and resistance parameters (low value). The choice is somewhat arbitrary. Duncan (1992 and 1996) provided an overview of deterministic slope stability analysis method. The overview included the factor of safety approach, equilibrium methods of slope stability analysis (Janbu's generalized method of slices, Bishop's method, Spencer's method, Morgenstern and Price's method among others), techniques for searching for the critical slip surface, both circular and non-circular, three-dimensional analyses of slope stability, analyses of the stability of reinforced slopes, drained and undrained conditions, and total stress and effective stress analyses. Slopes with nominally the same factor of safety could have significantly different safety margins because of the uncertainties involved. Duncan (2000) pointed out that "Through regulation or tradition, the same value of safety factor is often applied to conditions that involve widely varying degrees of uncertainty. This is not logical."

To evaluate the hazard associated with the failure of a specific slope, the stability assessment must be put into a probabilistic format using one of the techniques mentioned earlier (FOSM, FORM, MCS, etc.). An overview of the available methods for doing probabilistic slope stability assessment for individual slopes is provided in Nadim *et al*. (2005).

6.2.2 Regional assessment

Landslide hazard and risk assessment is often required on a regional or national scale and it would not be feasible to do a stability assessment for all potentially unstable slopes in the study area. Therefore other techniques based on Geographical Information Technology (GIT) are employed in these situations. An example of this type of hazard assessment is the study done by Nadim *et al*. (2006) in the Global Hotspots study for the ProVention Consortium. That model, which is currently being updated for the Global Risk Update project of UNISDR (2009a), assesses the landslide hazard by considering a combination of the triggering factors and susceptibility indicators. The principles of the model are demonstrated in Figure 6.

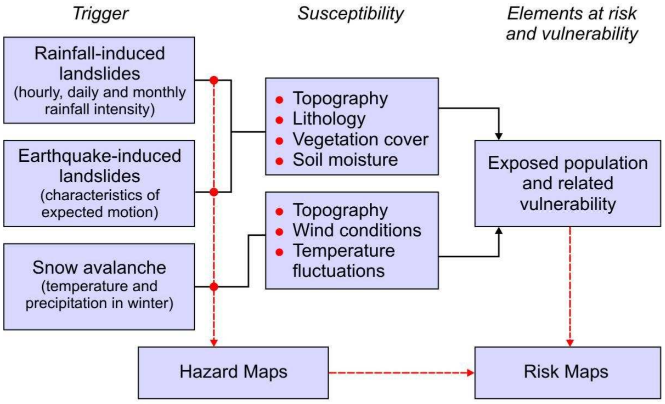

Figure 6 Schematic approach for landslide hazard and risk evaluation (Nadim *et al*., 2006).

In the latest version of the model, a landslide hazard index was defined using six parameters: slope factor within a selected grid cell, lithology (or geological conditions), soil moisture condition, vegetation cover index, precipitation factor, and seismic conditions. For each factor, an index of influence was determined and the relative landslide hazard level $H_{landslide}$ was obtained by multiplying and summing the indices. The landslide hazard indices were then calibrated against the databases of landslide events in selected (mostly European) countries to obtain the frequency of the landslide events, i.e. the landslide hazard. Figures 7a and 7b show respectively the landslide hazard map for parts of Latin America and for Europe obtained by using the updated version of the model by Nadim *et al*. (2006).

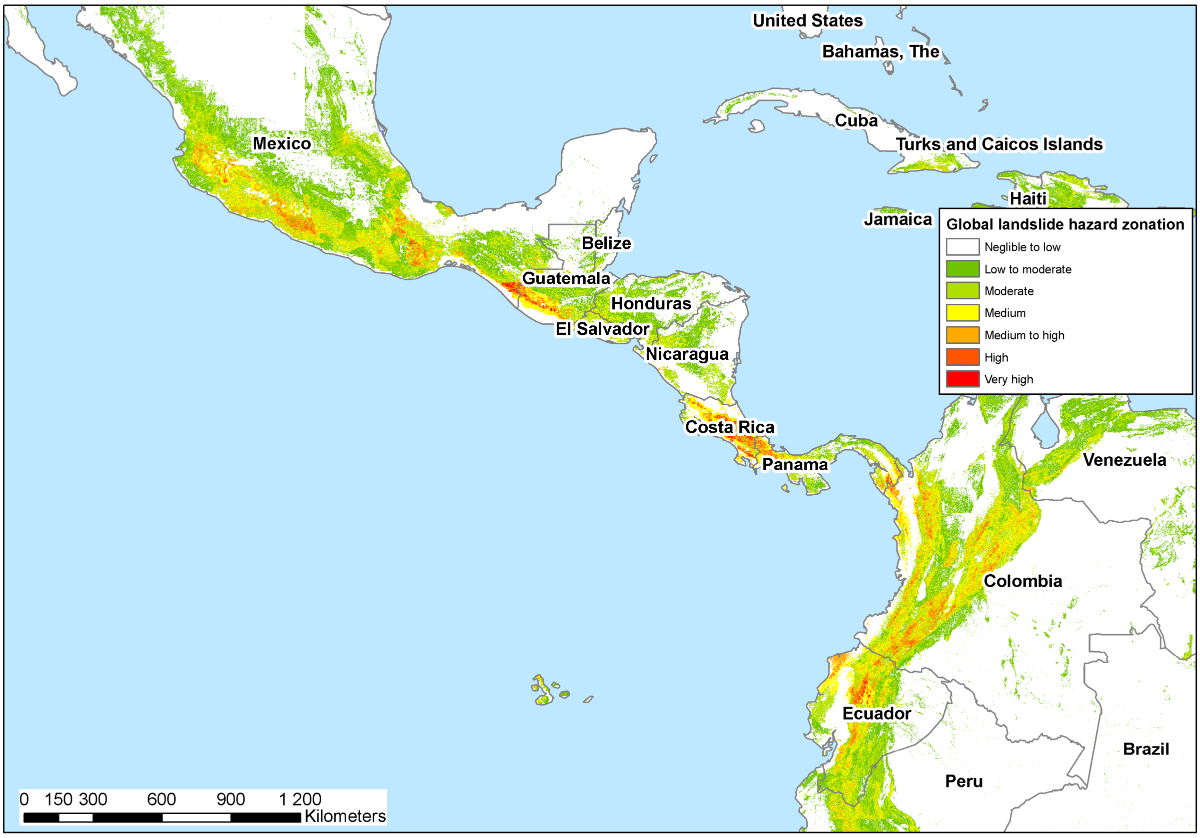

Figure 7a Landslide hazard map for parts of Latin America developed by NGI for the GAR 2009 report (UNISDR 2009a)

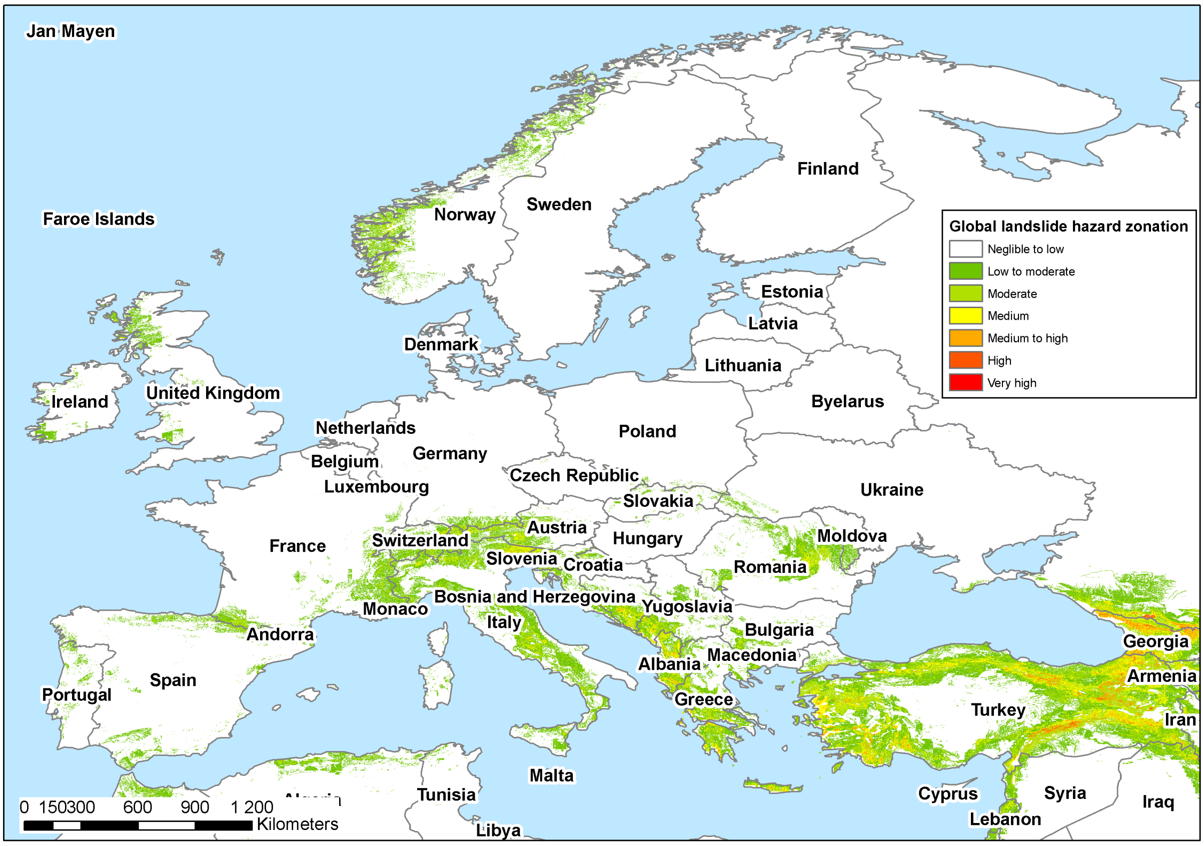

Figure 7b Landslide hazard map for Europe developed by NGI for the GAR 2009 report (UNISDR 2009a).

6.3 Landslide risk assessment

The most complete description of the possible losses (or risk) is quantitatively in terms of a "probability distribution", which presents the relative likelihood of any particular loss value or the probability of losses being less than any particular value. Alternatively, the "expected value" (i.e., the probability weighted average value) of loss can be determined as a single measure of risk. A general scenario-based risk formulation is given by Nadim & Glade (2006):

$$E[loss] = \sum_{allS} \sum_{allC} C \cdot P[C|S]\, P[S] \qquad (2)$$

where C is a particular set of losses (of a collectively exhaustive and mutually exclusive set of possible losses), S is a particular scenario (of a comprehensive and mutually exclusive discrete set of possible scenarios), P[S] is the probability of occurrence of scenario S, P[C | S] is the conditional probability of loss set C given that scenario S has occurred, and E[Loss] is the "expected value" of loss. "Loss" may refer to any undesirable consequence, such as loss of human life, economic loss, loss of reputation, etc., in terms of its direct and indirect effects (e.g. local damage of railway tracks and related interruption of industrial traffic), its effects on different social groups (e.g. individuals, community, insurance, government) as well as its short- and long-term influences on a society (e.g. fatalities could include all children of a community, the tourist industry might collapse).

Most often the focus is on the loss of human life. The expected number of fatalities depends on many factors, for example on which week-day and what time of the day the landslide occurs, whether a warning system is in place and working, etc. The potentially affected population could be divided into groups based on for example the temporal exposure to the landslide: people living in houses that are in the path of the potential landslide, locals in the area who happen to be passer-bys and tourists and/or workers who are coincidentally at the location during certain periods of the day of the year.

Figure 8 summarizes a general procedure for risk assessment for landslides. The key issue is the identification of potential triggers and their probability of occurrence, the associated failure modes and their consequences. The triggering mechanisms could be natural, such as earthquake, tectonic faulting, rainfall, temperature increase (e.g. caused by climate change), excess pore pressures or man-made. Generally, one should consider several scenarios of plausible triggers, estimate the run-out distance and extent triggered by these events, and estimate the upper and lower bounds on the annual probability of occurrence of the scenarios (Roberds, 2005). This scenario-based approach involves the following steps:

– Define scenarios for landslide triggering
– Compute the run-out distance, volume and extent of landslide for each scenario
– Estimate the loss for the different landslide scenarios
– Estimate the risk and compare it with tolerable or acceptable risk levels.

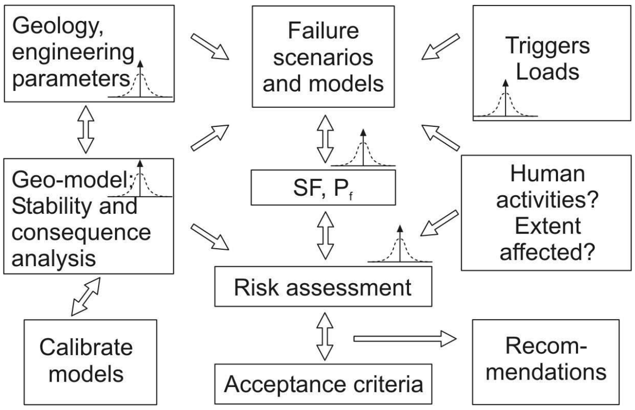

Figure 8 Procedure for risk assessment of slopes.

6.4 Landslide risk mitigation

Landslide risk mitigation measures can be classified as structural and non-structural. Structural measures for landslides include, but are not limited to: slope stabilisation, drainage, erosion protection, channelling, vegetation and ground improvement, barriers such as earth ramparts, walls, artificial elevated land, anchoring systems and retaining structures; buildings designed (and placed) in locations to withstand the impact forces of landslides and to provide safe dwellings for people, and escape routes. Non-structural measures include land-use planning and other consequence-reducing measures. Consequence-reducing measures include, but are not limited to: retreat from hazard, land-use planning, early warning, public preparedness, (escape routes, etc.) and emergency management. The risks may also be pooled through insurance mechanisms.

It is important, when evaluating mitigation measures, to weigh benefits of the measures to be implemented and the possible negative effects these measures may have. Decision-making will rest in finding an optimal solution.

6.5 Early warning systems

Faced with natural hazards, especially landslides, society's only recourse is to learn to live with them. It is therefore important to understand and predict landslide behaviour. One can live with a threat, provided the risk associated with it is acceptable or provisions are made to reduce the risk to an acceptable level. The role of landslide monitoring and warning is to gather information useable for avoiding or reducing the impact of landslide activity. After the recent natural catastrophes around the world, landslide monitoring and especially early warning, have gained enormous interest. The ever increasing need to locate new land areas for urban expansion also requires development in areas with unstable slopes. On the other hand, technological advances in measurement technology as well as data acquisition, transmission and analysis procedures have made monitoring and early warning systems easier to implement.

Monitoring is the key to slope instability assessment, management and mitigation. The objective of a landslide monitoring programme is to collect, record and analyse 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 programmes are implemented for a number of reasons, including providing input for early warning systems.

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

Early warning systems (EWS) mitigate risk by reducing the consequences. The system issues 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 precursor depends on the type of landslide. Typical examples of precursors are intense rainfall, ground vibrations and earthquakes, blasting, acceleration or high rate of movement in the slope, rapid increases in pore water pressure or stream flow at the toe of a slope. Typical instruments in an early warning system are rain gauges, geophones, seismographs, piezometers, inclinometers, extensometers and devices for measuring the movement of slopes.

The reliability of measurements is paramount in any monitoring system, but particularly so in an early warning system. A false alarm generated by an automatic early warning system may pose more of a hazard than the landslide itself. 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 components of an early warning system are the sensors and measuring devices, a real-time data acquisition unit with communication link and software to process and analyse the measurements. The system issues warnings via the communication link automatically when predefined alarm threshold values are exceeded. An early warning system comprises four main activities: monitoring, analysis of data and forecasting, warning and response.

The major problem in designing an early warning system is to be able to specify reliable and effective threshold values. This generally involves some form of forecasting based on past trends in the measurements. Lacasse and Nadim (2008) presented more details on mitigation measures and several examples of mitigation and early warning systems.

6.6 Recent research on landslide risk management: The SafeLand Project

SafeLand (www.safeland-fp7.eu) is a large-scale collaborative project under the European Commission’s 7th Frame Programme. The 3-year project started in May 2009, has a total budget of approximately 8.75 million Euros, involves 27 partners from 12 European countries and is coordinated by the International Centre for Geohazards (ICG), in Norway. SafeLand, titled “Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies”, aims at improving the methods for assessing and managing the landslide risk in Europe, both for today's situation, and including the effects of climate and demographic changes. SafeLand is to (1) provide policy-makers, public administrators, researchers, scientists, educators and other stakeholders with an improved and harmonized framework and methodology for the assessment and quantification of landslide risk in Europe; (2) evaluate the changes in risk pattern caused by climate change, human activity and policy changes; and (3) provide guidelines for choosing the most appropriate risk management strategies, including risk mitigation and prevention measures.

SafeLand recognizes that risk management not only requires an integrated approach involving different specialists in geo-sciences (engineers, geologists, geophysicists, meteorologists) to assess and quantify the risk, but also a close collaboration among geoscientists, social scientists and stakeholders to identify the most appropriate risk mitigation measures. The scientific and technical objectives of the Risk Management part of SafeLand are two-fold: (1) carry out a state-of-the-art review, propose new mitigation and prevention measures, and produce a web-based system toolbox of technically and economically appropriate (and innovative) prevention and mitigation measures based on experience and expert judgment throughout, and outside, Europe; and (2) develop and test a risk communication and stakeholder-led participatory process for choosing prevention and mitigation measures that are most appropriate from the technical, economic, environmental and social perspectives. The Risk Management part will be the culmination of the research in SafeLand and provide the tools required for dealing with landslide risk: a tested and well-documented framework with methodology and procedures for an effective implementation of landslide risk management, a toolbox for the selection of the most appropriate set of mitigation and prevention measures, and participatory stakeholder-led processes for risk communication where risk reduction targets can be explored.

During the first year of the SafeLand project, Risk Management studies have been performed along two axes: (1) preparation of a web-based toolbox for stakeholders with decision-making guidance based on a state-of-the-art study of existing physical mitigation measures, and (2) performing detailed case studies of the influence of political culture, organizational structures and economic context on implementation of landslide risk management tools. Scoping studies documenting the risks and the political history, legal frameworks, policy issues, institutional geography and views of stakeholders on current and future risks have been performed for Norway and Italy, and these will be followed by studies in France, Romania and India. These scoping studies are a key element for the development of a risk-communication and participatory stakeholder-led process for choosing the prevention and mitigation measures that are appropriate from technical, economic, environmental and social perspectives.

6.7 Example of mitigation measures

The city of Drammen, along the Drammensfjord and the Drammen River, is built on a deposit of soft clay. Stability analyses were done in an area close to the centre of the city, and indicated that some areas did not have satisfactory safety against a slope failure. Based on the results of the stability analyses and the factors of safety (FS) obtained, the area under study was divided into three zones (Gregersen, 2005):

– Zone I	FS satisfactory
– Zone II	FS shall not be reduced
– Zone III	FS too low, area must be stabilised.

In Zone III, a counter fill was immediately placed in the river to support the river bank, and the factor of safety checked again. The counter fill provided adequate stability (Gregersen 2008).

In Zone II, no immediate geo-action was taken, but a ban was placed on any new structural and foundation work without first ensuring increased stability. Figures 9 and 10 illustrate four cases (Gregersen 2008; Karlsrud 2008): (1) if an excavation is planned, it will have to be stabilised with anchored sheet-piling or with soil stabilisation, e.g. with chalk-cement piles; (2) new construction or new foundations cannot be done without first checking their effect on the stability down slope; for example, adding a floor to a dwelling may cause failure because of the added driving forces due to the additional loading, and new piling up slope will cause a driving force on the soil down slope.

6.8 Examples of early warning systems (EWS)

6.8.1 EWS in remote location

Lake Sarez is located in the Pamir Mountain Range in eastern Tajikistan. The lake was created in 1911 when an earthquake triggered a massive rock slide (volume: ~2 km^3) that blocked the Murgab river valley. A natural dam, Usoi Dam, was formed by the rockslide which retains the lake. The dam is 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.

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 of people in the Bartang, Panj, and Amu Darya valleys downstream.

There is another natural hazard at Lake Sarez, namely, a large active landslide on the right bank (Figure 11). If this unstable slope should fail and slide into the lake, it would generate a surface wave large enough to overtop the dam and cause a severe flooding downstream. Experts who have studied the hazards agree that the most probable scenario at Lake Sarez is failure of the right bank slope and overtopping of the dam (DiBiagio and Kjekstad, 2007).

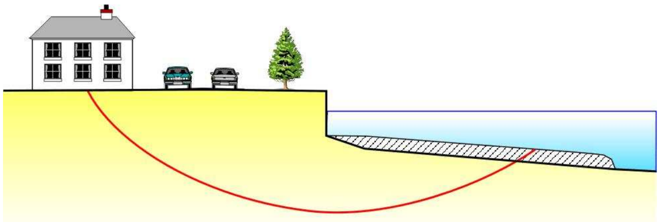

Figure 9 Mitigation in Zone III in Drammen

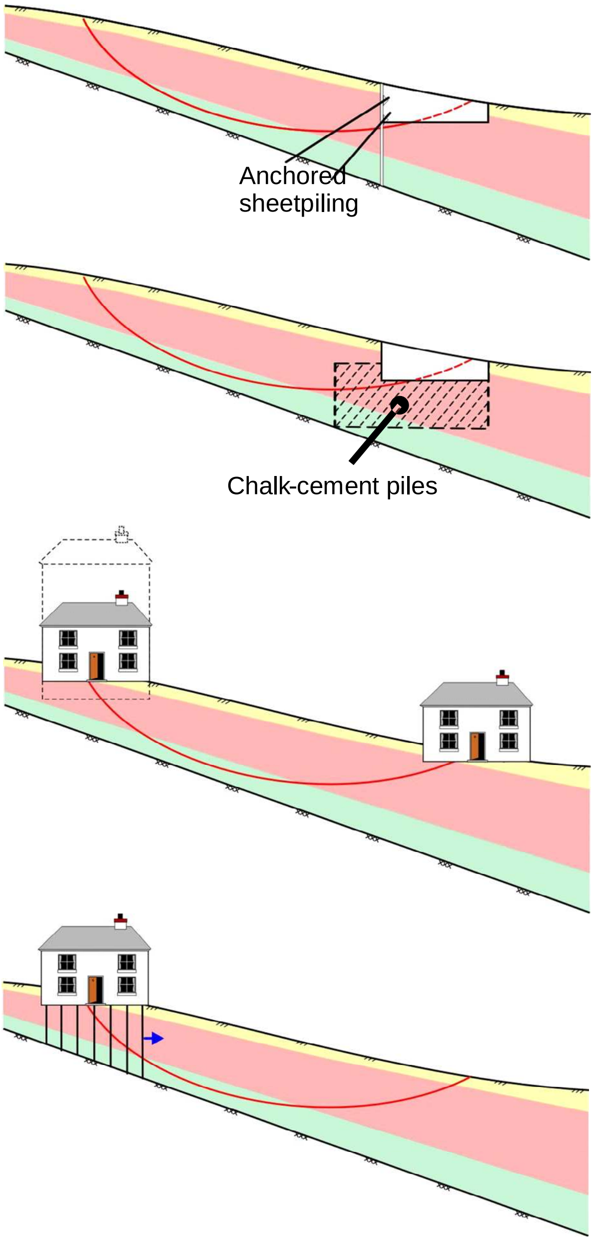

Figure 10 Hazard, mitigation and preventive measures in Zone II in Drammen (Gregersen, 2008; Karlsrud, 2008)

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.

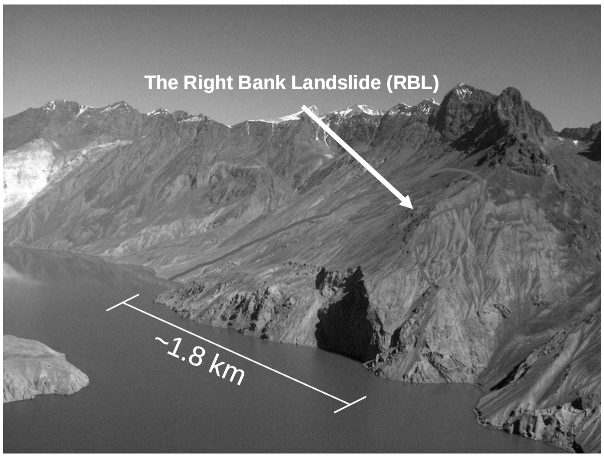

Figure 11 Active landslide on the right bank of Lake Sarez (Photo SECO, State Secr. for Economic Affairs, Switzerland)

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 has been in operation since 2005. The system has 9 remote monitoring units linked to a central data acquisition system at a local control centre near the dam. Data is transmitted via satellite to the main control centre in Dushanbe, Tajikistan's capital. Alerts and warning messages are sent from Dushanbe to 22 communities connected to the system. The local control centre is manned 24 hours per day, every day. The measurements included in the monitoring program are listed in Table 2.

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 3. Alarm states and emergency warning plans are summarized in Table 4.

At the start, some initial operational and maintenance were encountered, but these have been resolved underway. The principal problem has been insufficient 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 Defence who now has responsibility for operation of the system. The plan is to keep the early warning system in operation until 2020 which is the target date for completion of the mitigation works. The least expensive mitigation measure to reduce the risk is to permanently lower the lake level by about 120 m using a diversion tunnel around the landslide.

Table 2 Early warning system measurements at Lake Sarez (Stucky, 2007)

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

Table 3 Threshold values for Level 1 and Level 3 alarm states at Lake Sarez (Stucky 2007)

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

6.8.2 EWS for tsunamigenic rock slide

Rock falls and rockslides are among the most dangerous natural hazards in Norway, mainly because of their tsunamigenic potential. The three most dramatic natural disasters in Norway in the 20th century were tsunamis triggered by massive rockslides into fjords or lakes (Loen in 1905 and 1936 and Tafjord in 1934), causing more than 170 fatalities (Bjerrum and Jørstad 1968; Anda and Blikra 1998). As public attention on natural hazards increases, the potential rockslides in the Storfjord region in western Norway have earned renewed focus. A massive rockslide at Åknes could be catastrophic as the rock slide-triggered tsunami is a threat to all the communities around the fjord. The Åknes/Tafjord project was initiated in 2005 by the municipalities, with funding from the Norwegian government, to investigate rockslides, establish monitoring systems and implement a warning system and evacuation plan to prevent fatalities, should a massive rockslide take place.

Table 4 Alarm states and emergency warning plan at Lake Sarez(DiBiagio and Kjekstad, 2007)

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	Early Warning System Local operating personnel	Origin of warning	Early warning system Local operating personnel
Destination of warning	Local control centre and Dushanbe	Destination of warning	Local control centre 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	Early Warning System Local control centre or Dushanbe	Origin of warning	Dushanbe
Destination of warning	Local control centre and all villages downstream	Destination of warning	Local control centre and all villages
Action	People in villages evacuate to predefined safe areas	Action	Back to Level 0

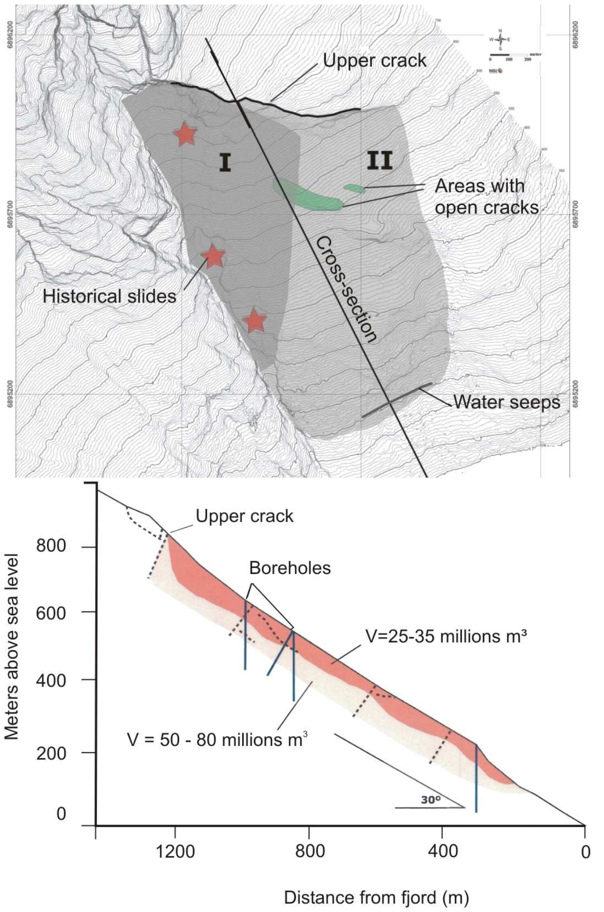

Figure 12 Sliding volume scenarios. Surficial area (left) and cross-section (right) (modified from Blikra et al. 2007)

Area I:Volume 10-15 millions m^3, displacement=6-10 cm/yr
Area II: Volume 25-80 millions m^3, displacement=2-4 cm/yr

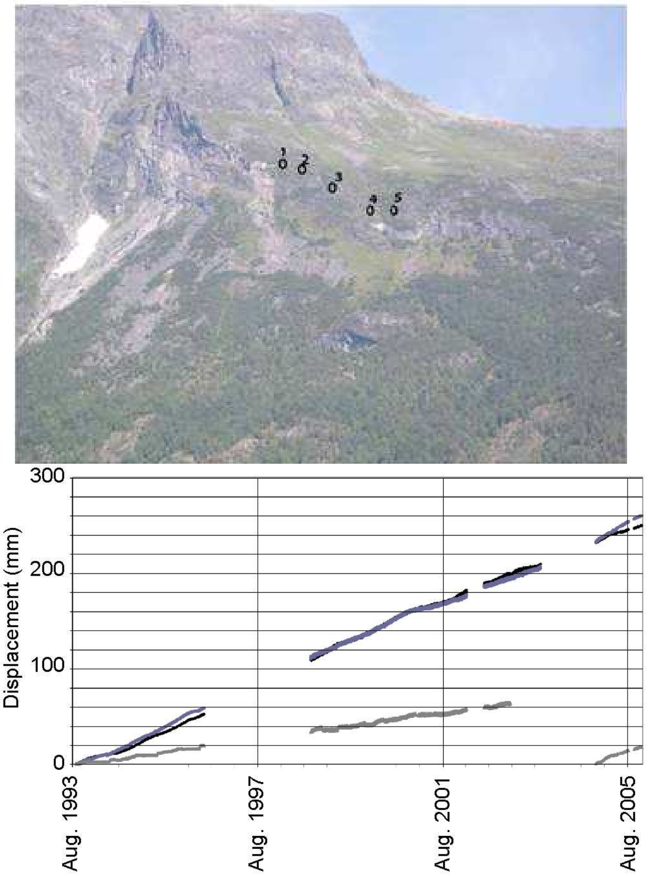

Figure 13 Location of extensometers and displacements from extensometer 1, 2, 3, 4 and 5 at the top scarp at Åknes (Kveldsvik *et al.* 2006)

Åknes is a rock slope over a fjord arm on the west coast of Norway. The area is characterised by frequent rockslides, usually with volumes between 0.5 and 5 millions m^3. Massive slides have occurred in the region, e.g. the Loen and Tafjord disasters. Bathymetric surveys of the fjord bottom deposits show that numerous and gigantic rockslides have occurred many thousands of years ago. The Åknes/ Tafjord project (www.aknes-tafjord.no) includes site investigations, monitoring, and an early warning system for the potentially unstable rock slopes at Åknes in Stranda County and at Hegguraksla in Norddal County. The project also includes a regional susceptibility and hazard analysis for the inner Storfjord region, which includes Tafjord, Norddalsfjord, Sunnylvsfjord and Geirangerfjord. The potential disaster associated with a rockslide and tsunami involves many parties, with differing opinions and perceptions.

As part of the on-going hazard and risk assessment and validation of the early warning system, event trees were prepared by pooling the opinion of engineers, scientists and stakeholders. The objective was to reach consensus on the hazard and risk associated with a massive rockslide at Åknes (Lacasse *et al.* 2008).

Observed displacements

Experience from Norway and abroad shows that rockslide events are often preceded by warning signs such as increased displacement rate, micro-tremors and local sliding. Accelerating rate of displacement several weeks and even months before a major rockslide event is typical. Slope movements have been detected at Åknes down to 60 m depth (Figure 12). New borehole data suggest movements down to 100 m. Important uncertainties lie in the most likely failure depth and location, and whether the slide will occur as one large 30-60 millions m^3 sliding event or a succession of several 'small' slide events. Figure 12 presents the Åknes slope and two slide scenarios. Figure 13 shows some of the displacements observed at the upper crack. Water seeps ("springs") are seen emerging on the downstream slope (Kveldsvik et al. 2008). The displacements in Figure 13 appear to move linearly with time. The total annual displacements vary from less than 2 cm up to about 10 cm.

Instrumentation and monitoring

The large variations in weather and atmospheric conditions in the fjord and mountain areas pose unusual challenges to the instrumentation. For example, the hazard due to snow avalanche and rock bursts is high in most of the area to be monitored. Solar panels do not provide sufficient electricity, and energy has to be obtained from several sources to ensure a stable and reliable supply. Significant effort is underway to deploy robust instruments and improve data communication during periods of adverse weather. An Emergency Preparedness Centre is located in Stranda. The monitoring data will be integrated into a database that will form the basis for future analyses. Based on the experience with similar projects and the specific needs in Storfjord, the overall monitoring system was equipped with:

<u>Surface monitoring</u>

- GPS-network with 8 antennas
- total station with 30 prisms
- ground-based radar with 10 reflectors
- 5 extensometers measuring crack opening
- 2 lasers measuring opening of the 2 largest cracks
- geophones that measure vibrations

Monitoring in borehole
- inclinometers measuring displacements
- piezometers measuring pore pressure
- temperature
- electrical resistivity of water

Meteorological station
- temperature
- precipitation and snow depth
- wind speed
- ground temperature
- radiation

Light Detection and Ranging (LiDAR) mapping and radar measurements were also done. Several independent systems were installed to ensure continuous operation at all times, and different communication systems were implemented to ensure continuous contact with the Emergency Preparedness Centre in Stranda.

Modelling of tsunami following rock slide
The tsunami wave propagation due to an Åknes rock slide was modelled numerically for two rock slide scenarios: slide volume of 8 million m^3 and 35 million m^3. Run-up values were estimated for 15 locations in the Storfjord region (Eidsvig and Harbitz 2005; Glimsdal and Harbitz 2006; Eidsvig et al. 2008). The results of the simulation for three locations are shown in Table 5. Preliminary results of tsunami modelling suggest an inundation height of up to 35 m at Hellesylt for rockslide volume of 35 million m^3 at Åknes. The modelling of the tsunami caused by the rockslide includes several uncertainties. To reduce the uncertainties, physical modelling is presently underway in university laboratories in Oslo and Trondheim (University of Oslo and the Norwegian University of Science and Technology (NTNU) in Trondheim. The model tests are run to improve the understanding of the initial wave pattern generated by the sliding rock masses. A rock slide of 30 million m^3 will pose a serious threat to coastal areas of several communities in the Storfjord region. It may also cause serious damage further out along the fjord.

Table 5 Estimated run-up heights in the Åknes area

Location	**Run-up heights 8 millions m^3**	**Run-up heights 35 millions m^3**
Hellesylt	8-10 m	25-35 m
Geiranger	8-15 m	20-40 m
Stranda	1-3 m	3-6 m
Fjøra	1-2 m	5-7 m
Tafjord	3-5 m	12-18 m

Early warning and emergency preparedness
The Åknes/Tafjord early warning and emergency preparedness system was implemented early 2008. As part of this system, the Emergency Preparedness Centre in Stranda is in operation continuously (24 hours, 7 days). Alarm levels and responses are under development. The aim is to establish guidelines for monitoring and alert levels as a function of observed displacement rates on the extensometers, in the case of impending failure. Figure 14 and Table 6 present an example of the alarm and response system. The system is in constant evolution. The evaluation of the alarm status is done on the basis of an integrated interpretation of all measurements available, and their evolution over time (Blikra et al. 2007; Blikra, 2008).

Table 6 Sketch of alarm levels and response at Åknes (see Figure 14 for colour code)

Alarm level	Activities and alarms	Response
Level 1 Normal situation	Minor seasonal variations No alarm	EPC staff only Technical maintenance
Level 2 Awareness	Important seasonal fluctuations for individual and multiple sensors Values<excess thresholds for Level 2	Increase frequency of data review, compare different sensors Call in geotechnical/geological/monitoring expert
Level 3 Increase awareness	Increased displacement velocity, seen on from several individual sensors Values<excess thresholds for Level 3	Do continuous review, do field survey, geo-expert team at EPC full time Inform police and emergency/preparedness teams in municipalities
Level 4 High hazard	Accelerating displacement velocity observed on multiple sensors Values<excess thresholds for Level 4	Increase preparedness, continuous data analysis Alert municipalities to stand prepared for evacuation
Level 5 Critical situation	Continuous displacement acceleration Values>excess thresholds for Level 4	Evacuation

EPC = Emergency Preparedness Centre in Stranda

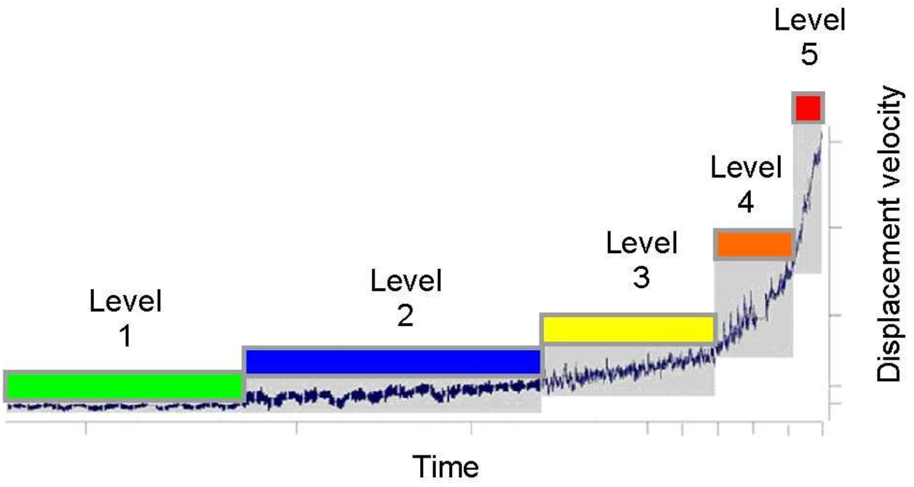

Figure 14 Illustration of the alarm levels as function of displacement velocities (vertical axis: displacement rate in mm/day; horizontal axis: relative time before failure)

The Åknes/Tafjord early warning and emergency preparedness system was implemented early 2008. As part of this system, the Emergency Preparedness Centre Stranda is in operation continuously (24 hours, 7 days). Alarm levels and responses are under development. The aim is to establish guidelines for monitoring and alert levels in the case of impending failure.

7. CONCLUDING REMARKS

Reducing the impact of landslide with mitigation measures is both an economical and social necessity. The frequency of landslide disasters is increasing due to extreme weather, increased population and increased vulnerability. The situation calls for intensified focus action on mitigation measures, both for hazard and risk.

The management of the risk associated with landslides and other geo-hazards involves decisions at local, regional, national and even transnational levels. Lack of information about the risk appears to be a major constraint to providing improved mitigation in many areas. The selection of appropriate mitigation strategies should be based on a future-oriented quantitative risk assessment, coupled with useful knowledge on the technical feasibility, as well as costs and benefits, of risk-reduction measures.

Technical experts acting alone cannot choose the "appropriate" set of mitigation and prevention measures in many risk contexts. The complexities and technical details of managing geo-hazards risk can easily conceal that any strategy is embedded in a social/political system and entails value judgments about who bears the risks and benefits, and who decides. Policy-makers and affected parties engaged in solving environmental risk problems are thus increasingly recognizing that traditional expert-based decision-making processes are insufficient, especially in controversial risk contexts. Risk communication and stakeholder involvement have been widely acknowledged for supporting decisions on uncertain and controversial environmental risks, with the added bonus that participation enables the addition of local and anecdotal knowledge of the people most familiar with the problem. Precisely which citizens, authorities, NGOs, industry groups, etc., should be involved in which way, however, has been the subject of a tremendous amount of experimentation. The decision is ultimately made by political representatives, but stakeholder involvement, combined with good risk-communication strategies, can often bring new options to light and delineate the terrain for agreement.

The human impact of geo-hazards is far greater in developing countries than in developed countries. Capacity building initiatives focusing on organizations and institutions that deal with disaster risks and disaster situations can greatly reduce the vulnerability of the population exposed to natural disasters. Many of these initiatives can be implemented within a few years and are affordable even in countries with limited resources.

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