Strategies for mitigation of risk associated with landslides

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Abstract

Beyond risk communication and public awareness campaigns, pro-active strategies for the mitigation of risk associated with landslides can broadly be categorised as (1) structural slope-stabilization measures to reduce the frequency and severity of the landslide hazard, and (2) non-structural measures, such as land-use planning and early warning systems, to reduce the hazard consequences, and measures to pool and transfer the risks. Identification of the optimal risk mitigation strategy involves: (1) identification of possible landslide triggering scenarios, and the associated hazard level; (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 measure and if relevant reconstruction and rehabilitation plans; and (5) transfer of knowledge and communication with authorities and society.

Keywords: Landslide; Risk Mitigation, Risk Management, Early Warning System

1.0 INTRODUCTION

Landslides represent a major threat to human life, property and constructed facilities, infrastructure and natural 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. This underestimation contributes to reducing the awareness and concern of both the authorities and the general public about landslide risk.

Climate change, increased susceptibility of surface soil to instability, anthropogenic activities, growing urbanisation, uncontrolled land-use and increased vulnerability of population and infrastructure as a result, all contribute to the growing landslide risk. 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. Furthermore, according to the European Union Strategy for Soil Protection (COM232/2006), landslides are one of the main eight threats to European soils. Many coastal regions have cliffs that are susceptible to failure from sea erosion (by undercutting at the toe) and their geometry (steep 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 coast cliffs of England are eroding at rates of 1m / yr.

Water has a major role in triggering of landslides. Figure 2 shows the relative contribution of various landslide triggering events factor in Italy. Heavy rainfall is the main trigger for mudflows, the deadliest and most destructive of all landslides. Many of the future climate scenarios predict changes of hydrological cycles, more extreme precipitation events, 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 the Alpine regions. These factors are all important in triggering of landslide events and their effects on landslide hazard must be evaluated in any long-term landslide management programme.

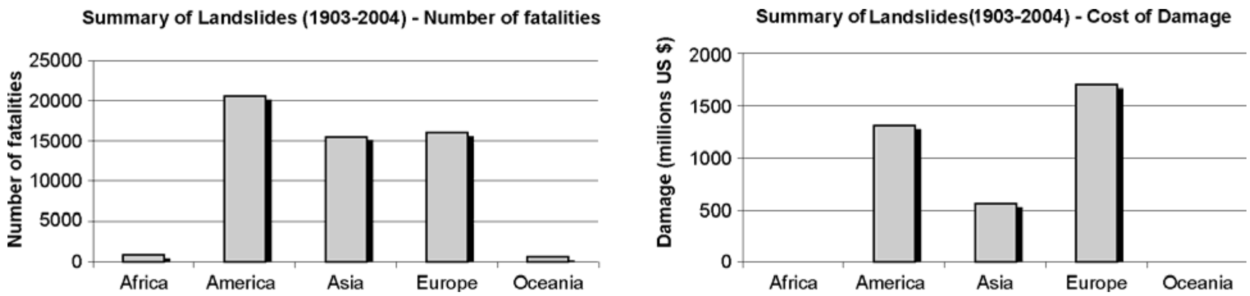

Figure 1 : Fatalities and cost of damage caused by landslides 1903 to 2004 (EM-DAT, OFDA/CRED International Disaster database)

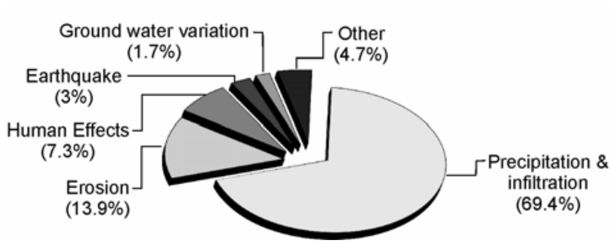

Figure 2 : Landslide triggers in Italy (CNR-GNDCI AVI Database of areas affected by landslides and floods in Italy).

The strategies for the mitigation of risks associated with landslides can broadly be classified in six categories: (1) land use plans, (2) enforcement of building codes and good construction practice, (3) early warning systems, (4) community preparedness and public awareness campaigns, (5) measures to pool and transfer the risks and (6) construction of physical protection barriers. The first six strategies are referred to as non-structural measures, which aim to reduce the consequences of landslides; while the last strategy comprises structural slope-stabilization measures, which aim to reduce the frequency and severity of the landslides.

Identification of the optimal risk mitigation strategy involves: (1) identification of possible landslide triggering scenarios, and the associated hazard level (frequency); (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 measure and if relevant reconstruction and rehabilitation plans; and (5) transfer of knowledge and communication with authorities and society.

In many situations where landslides could affect life and property early warning systems could be designed to monitor and forewarn of impending danger. These systems are discussed in Section 4 of the paper.

Physical protection measures include, but are not limited to, improvement of drainage, erosion protection, vegetation and ground improvement techniques, barriers and walls to reduce the energy or the loads induced by landslides. Physical protection barriers may be used to stop or delay the impact of the landslide, reduce the maximum reach of its impact, and/or dissipate its energy. The barriers could be "soft" structures in the form of dikes or embankments, or "hard" structures like vertical concrete or stone block walls. Any physical protection measure needs to be part of a community's master plan and subject to analyses to assess and circumvent any negative environmental impact. Further discussion of the physical protection measures is provided in Section 5 of this paper.

Risk management integrates the recognition and assessment of risk with the development of appropriate strategies for its mitigation. Landslide risk management typically (but not solely) involves decisions at the local level. Lack of information about landslide risk and how this risk is changing on account of changes in climate, land-use, demography and other factors, 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 and costs and benefits of risk-reduction measures. In many situations, technical experts acting alone cannot choose the most "appropriate" set of mitigation and prevention measures. The complexities and technical details of managing landslide 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 has 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 and theory development. 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 growing hazard and risk, the need to protect people and property, the consequences of the expected climate change and the need for the society to adapt and learn to manage the risk, will set the agenda for the geoscientists who are involved in the assessment and mitigation of landslide risk.

2.0 LANDSLIDE HAZARD AND RISK MANAGEMENT

Many countries have experienced increased vulnerability to landslides and increased awareness of the need for mapping, due to industrial and recreational development over the entire country, infrastructure development, the consequences of interruption in the communication arteries and increase in population. A few major disasters in the past 30 years also helped "convince" the authorities to take preventive measures.

To increase safety, reduce risk, and assist with emergency preparedness, a priority mapping is needed for landslides in clays, rock slides and snow avalanches. Susceptibility mapping has been done continuously in Norway and some other European countries since the late 1970s. The susceptibility, hazard and risk maps are especially useful for the planning of new dwellings, schools, recreation areas, etc. The entire network of communication corridors and military and humanitarian (Red Cross) exercises have need for such maps (Karlsrud et al. 1984; Gregersen 1989).

Risk management integrates the recognition and assessment of risk with the development of appropriate strategies for its mitigation. Figure 3 illustrates in a "bow-tie" diagram the components of hazard and risk mitigation. Risk is the measure of the probability and severity of an adverse event to life, health, property or the environment. Quantitatively, risk is the probability of an adverse event times the consequences if the event occurs. The consequences are obtained by considering the elements at risk and their vulnerability. Mitigation of risk can be done by reducing the frequency (probability) of the adverse event by reducing the vulnerability and/or exposure of the elements at risk, or both.

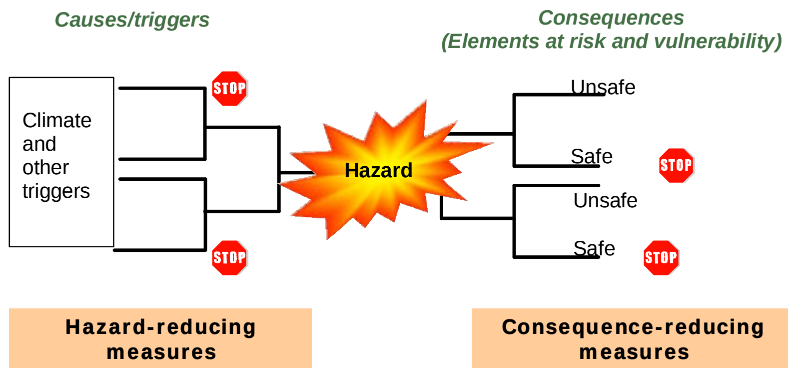

Figure 3 : Illustration of hazard and risk

As mentioned earlier, experts acting alone cannot always identify the most appropriate set of mitigation and prevention measures. Any risk mitigation strategy is embedded in a social/political system and entails value judgments about who bears the risks and benefits, and who decides. Traditional policy approaches that are often shaped by scientific analysis and judgment (e.g. acceptable risk concept) are vulnerable to two major critiques: (1) since they de-emphasise the consideration of affected interests in favour of "objective" analyses, they suffer from a lack of popular acceptance; and (2) because they rely on systematic observation, they often slight the local and anecdotal knowledge of the people most familiar with the problem, and risk producing outcomes that are incomplete. Conflicting values and interests, as well as conflicting and uncertain expert evidence, characterise many landslide risk decision processes. These characteristics become more complex with long time horizons and uncertain information on climate and other global changes.

2.1 Example of assessment of need for risk mitigation

The Building and Planning Act in Norway has been under development since 1924 and the act was put into force for the whole country in 1966. The last revision was done in 1987. The rules were first established for the mapping of snow avalanche hazard. The Building Act is used when a detailed hazard plan is made with corresponding detailed maps. The on-going hazard mapping on survey maps at 1:50,000 scale has been operative since 1979. The building council of the counties has to follow the rules stated in the Act.

Table 1: Safety class in Technical Regulations in the Norwegian Planning and Building Law

Safety class	Maximum nominal frequency (per yr)	Return period (yrs)	Type of construction
1	10^{-2}	100	Garages, smaller storage rooms of one floor, boat houses
2	10^{-3}	1000	Dwelling houses up to two floors, operational buildings in agriculture
3	$< 10^{-3}$	>1000	Hospital, schools, public halls, etc.

The assessment of hazard for natural events is subject to the Norwegian Planning and Building Law. According to the technical regulations in the law, three classes of avalanche and slide frequencies should be taken into account (Table 1). There is also a fourth class, where the consequences are so important that the buildings cannot be placed in a "hazard zone". How one determines a "no-hazard" zone is however not defined. The building regulation states that rebuilding after fires or other kinds of reparation may be done for Class 2, when the nominal yearly frequency is less than 3 x 10^{-3}, i.e. a return period of 333 years or more. By using the word "nominal" as opposed to "real", one admits that the exact calculation of avalanche run-out distance for the given frequencies is not possible, and that the use of subjective judgment is necessary.

As part of the assessment of the risk associated with quick clay slides, the process in Figure 4 is followed, where the proponent needs to determine if there is a hazard and the potential consequences. Later, in the building plans, the proponent needs to document safety or prepare mitigation measures.

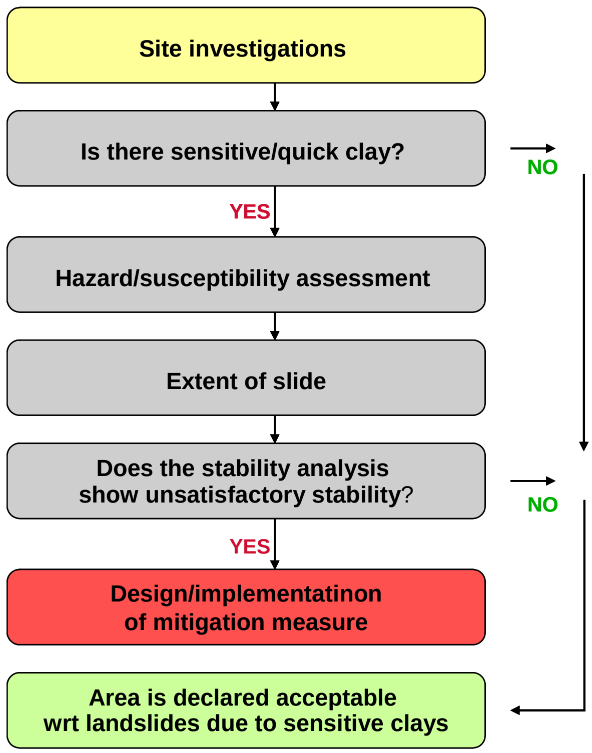

Figure 4 : Implementation of hazard assessment

The Norwegian standard NS 5814 (1991) considers risk analysis, including the necessary steps for planning and execution of risk analysis and guidelines for presentation of results and conclusions. NS 5814 can be used for all types of risks including multi-hazard situations. The planning of the risk analysis includes: initiation, description of problems and objectives, establishment of working groups and establishment of areas of responsibility. The working group shall be familiar with methods for risk analysis and the type of problems at hand. The verification of the work shall be ensured by a competent person not actively involved in the analysis. The execution part of NS 5814 includes: Description of subject for analysis (include limitations and circumstances that are important for safety); Selection of procedures and methods (include uncertainties); Selection of data sources; Identification of undesired events; Causal analysis (based on the selected undesired events, considering measures to eliminate the causes, and if quantitative, including quantification of the probability of undesired events); Consequence analysis (including long and short term consequences and mitigation measures to reduce the consequences; the consequence analysis can be qualitative or quantitative; a quantitative consequence analysis shall contain i) calculation of the extent of damage caused by the undesired events and ii) quantification of the probability of the consequences given the occurrence of the undesired events); Description of risk (based on both the causal analysis and the consequence analysis) and Presentation of results. The NS framework does not include an evaluation of the risk as a function of acceptance criteria and gives no quantitative acceptance criteria. (The standard is presently under review.)

3.0 DECISION-MAKING ON REMEDIAL MEASURES

3.1 Landslide prediction

To make decisions on the need for landslide risk mitigation, an assessment of landslide hazard must be made. This involves landslide evaluation and prediction, which typically include the following stages: i) detection of movement through monitoring, ii) temporal evaluation through analysis of data and numerical simulation, and iii) definition of thresholds identifying critical instability. For site-specific slopes with monitoring by instruments, the slope displacement represents one of the key indicators of actual slope performance. The monitoring may include: in-situ, remote, and surface/subsurface methods. It is important to consider the issues of 'what to measure' and 'where to measure', system uncertainty and reliability etc, in order to avoid misleading results.

Instrumentation systems to monitor landslide behaviour are employed in many different locations, often in conjunction with surface mapping and sub-surface investigations, for a diverse range of landslide types in many different geological settings and landscapes. To determine where protective measures are necessary, landslide inventories and risk assessment maps over large areas are needed. Scientists are today increasingly relying on global satellite data to produce landslide inventories and risk assessment maps over wide areas; remote sensing data from optical and radar sensors (Synthetic Aperture Radar, SAR) are applicable to landslide mapping due to multispectral and textural information, high repetition cycles and global coverage. The integration of SAR and optical images, along with SAR interferometric techniques, are currently used for characterising landslides. New techniques such as DInSAR and high resolution image processing are increasingly exploited for risk assessment studies. DInSAR is a powerful technique to measure from satellite displacements and has been successfully applied to detect subsidence and landslides, earthquakes or volcanic activity. The ground-based radar device such as LISA (Linear SAR) is capable of assessing the deformation field of an unstable slope in the areas characterised by a high radar reflectivity.

Near surface geophysical methodologies (seismic, gravimetric, magnetic, electric and electromagnetic) are often applied to monitor hydrogeological phenomena. New electric and electromagnetic survey techniques have been applied to areas with complex geology (seismic, geothermal, volcanic and landslide areas, etc.).

In many landslide risk areas, it may be too costly to stabilise a landslide area. Mitigation work may too intrusive in sites of cultural heritage, of outstanding beauty, or for other reasons. Early warning systems allow the adoption of strategies for the mitigation of landslide risk not involving the construction of expensive and environmentally damaging protective measures. On an operational basis, hazard/susceptibility maps, movements identification and monitoring need to be coupled with "real time" continuous measurement and with observations on possible "triggering" events. The output should call for action at different levels, involving local, regional, national and even international authorities.

3.2 Monitoring and remote sensing

The objectives of the monitoring of the movement include (1) monitoring for public safety and risk management, (2) health or performance monitoring, (3) regional warning (e.g. landslide), (4) construction quality control and (5) the understanding of the behaviour observed (technical development). Different purposes will have different monitoring and follow-up requirements. One needs to consider the likely modes of failure in data interpretation and the setting of threshold values (e.g. brittle versus ductile failure controlled, among others, by material and mass properties.

The detection of movement is a more direct measure of the potential instability than the other measurements. If only pore pressures are monitored, it may be difficult to foretell how imminently the instability may occur. It is however best to relate the movement monitored to other monitoring data (e.g. pore pressure, rainfall, etc.) to have a more complete appreciation of the slope behaviour.

Table 2 : Remote sensing technologies: strength and limitations, after Hutchinson, J. (2008, Personal communication) and Lacasse (2008).

System		Applications	Resolution	Limitations	Strengths - DEM from all	Future
Photo-gram-metry	Terrestrial	joint survey, scarp and change detection	cm to m, depending on scale	field of view, image resolution, requirement for surveyed positions, vegetation obscurance	rapid, cheap, long term record, stereoscopic - build DEMs and see terrain conditions	digital imagery, use of high resolution scanners and video
	Airborne	landslide inventory and time series analysis				
LiDAR	Ground based - static	landslide monitoring, landslide mapping, topography extraction HR, joint surveys, moisture detection	mm to cm	humidity, distance limitations, angular limitations, reflectivity, vegetation obscurance, too much data?, field of view	multi-return LiDAR allows bare earth model, very high accuracy, high rate of acquisition, perspective views possible	costs will decrease, signal analysis will improve, automated feature extraction?
	Ground based - mobile					
	Airborne - fixed wing					
	Airborne - helicopter					
InSAR	Standard	movement detection and monitoring, time series displacement, HR movement detection (ground based)	mm	visibility and shadowing, need reflectance, doesn't penetrate vegetation, limited to slow movements	large area survey, long term monitoring, return frequency affects use, comparison or combination of ascending and descending paths, movement measurement, rapid mapping of targeted	more frequent passes of satellite, monitoring of faster landslides
	PS			as above. plus only works with stable reflectors, very expensive	as above, plus mm accuracy movement detection	
	Ground based			as above, but can monitor faster movements, but semi-permanent installation and view point is required	as above, plus can pick up larger movements	
Optical satellite images		landslide inventory and time series analysis	10's cm to D11 10's m	expensive, image quality can be poor due to cloud cover	landslide surveys, large area coverage, historical record since 1990's, change detection, rapid mapping of targeted areas	higher resolution satellites to be deployed, more satellites will increase coverage and frequency
Weather Radar		precipitation intensity, early warning from rainfall intensity and accumulation	depending on calibration, km	calibration is required	helps map spatial distribution of weather	enhanced mapping of weather systems, cheaper systems
Others	Thermal, IR			low resolution	vegetation classification, water content, change detection	

Remote sensing tools, such as LiDAR, InSAR or other imagery, are practical and for many of them, affordable tools in landslide hazard assessment programs. Table 2 presents the consensus reached at the Landslide Risk Management Forum Hong Kong in 2007 (Lacasse, 2008) on the strengths and limitations of most of the techniques in use today. Issues of "where", "when", "why" and "costs" influence the selection of technique(s) in practice. In plenum, the session participants agreed with the table presented and the evaluations made.

The interpretation of movement data needs a suitable model for projection of behaviour, e.g. the observational approach, which is typically done empirically or based on common sense instead of theoretical/numerical analyses.

Numerical simulation can be used to set-up a framework to interpret ground movement; with the observed data used to calibrate the model predicting the slope behaviour up to failure. It is best to do the calibration against a slope that has gone to failure. The code will differ from conventional limit equilibrium stability calculations, but will be more complex, and require more input parameters and hence have more uncertainty.

Thresholds need to relate to anticipated mode of failure and time for response. In the case of a brittle failure with little warning signs before collapse with fast-moving debris, the movement monitoring could give result to a false sense of security! One also needs to consider whether there are potential mechanisms under which ductile failures could become brittle failures. Where a slope failure is brittle, an observation of no movement could give a false sense of security.

3.3 Digital mapping

Mapping should be available to enable landslide risk management to be effective. The mapping can consist of (1) susceptibility maps for general land-use planning; (2) hazard maps, which give more information and allow for finer tuning of risk management; (3) risk maps, forming the basis for disaster preparedness and early warning; and (4) risk maps for risk-based design of remedial measures.

Susceptibility mapping is possible and useful, both in terms of source area and run-out area. Establishing hazard maps is difficult, establishing risk is even more difficult. Landslide inventory is essential, and vulnerability information is usually where there is most information missing. It is important to be aware that vulnerability is much more than just the physical vulnerability.

The mapping scale depends on the objectives of the mapping: scale of study, available data, techniques and models used and whether the mapping is static or dynamic (dynamic meaning that the data change with time). At the site investigation level, the mapping seems less useful and can be replaced by engineering design.

The scale of a susceptibility map is dictated by the constraints of the terrain and quality of data. For instance, if the quality of data is not too reliable, only small-scale maps can be prepared. Depending on the scale wanted, one has to choose the adequate data needed.

There are many uncertainties in susceptibility, hazard and risk mapping that need to be dealt with, including landslide inventory, input data (geology, geomorphology, terrain, slope inclination, soil layer thickness, soil properties), models and methods used and temporal changes for the elements at risk. Vulnerability and hazard change continuously.

In considering the vulnerability of a facility, other types of hazard should also be considered in addition to the landslide hazard. Multi-hazard risk is important.

4.0 MONITORING AND EARLY WARNING SYSTEMS FOR LANDSLIDES

Faced with natural hazards, especially landslides, society's only recourse is to adapt and 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 gain 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.

4.1 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 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 programs are implemented for a number of reasons, including providing input for early warning systems.

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.

A successful monitoring program depends on (1) ensuring that the monitoring is necessary, (2) knowing what to monitor and (3) knowing how to do it. Monitoring programs will differ in methodology and scope because landslides also differ, both in size, velocities and type of movement associated with them. For the following types of mass movements, rock falls, topples, rotational, sagging, spread and flows, the approach to monitoring the displacements will be quite different. The most important step in the design of a successful landslide monitoring program is to identify and understand the objective of the program.

Designing a monitoring program for landslides include the following steps:

- Gather as much site information as possible, including maps, geological and topographical data, geotechnical data, records of previous slides and extent of potential sliding mass.
- Perform a stability analysis and hazard assessment to gain an improved understanding of the hazard
- Define the objective of the monitoring program and select the type of measurements to be included in the program, assigning a 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 optimise 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 analyse the measurement data.
- Plan for adequate maintenance of the monitoring system.

As a general rule of thumb, one should use the simplest monitoring methods and equipment 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 and visual observations to costly and sophisticated surveillance via satellites and automatic systems. DiBiagio and Kjekstad (2007) describe the approaches in detail.

4.2 Early warning systems for landslides

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, and to get the exposed population out of the harm's way. 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.

As opposed to a monitoring program, a reliable early warning system needs:

- Understanding of the sliding process
- Historical knowledge of triggers (e.g. rainfall)
- Effective monitoring programme
- Interpretation of data
- Decision-making, including possibility for human intervention
- Public tolerance of false alarms
- Communication system
- Pre-established action plans for implementation
- Feedback loop and adaptability of system and to "new" knowledge

If a landslide occurs or is on the verge of occurring, time is needed for detection through the EWS, notification (authorities -police, -mayor's office, …) and required actions (closure of roads, evacuation, etc.). Societal needs and controls are also a factor. But outmost, communication is the most critical need.

Sharing information on the monitoring system is an absolute requirement for an effective early warning system. The expectations from the general public and the regulator differ. Efficient sharing of information is a challenge. There is generally very little time for the regulator to disseminate the monitoring information. Communication also depends on public tolerance, method used to share the information and the measurements themselves and the perception of their reliability.

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. Figure 5 presents a block diagram of a typical early warning system.
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. Engineering judgment is an important element in the process of forecasting and setting thresholds. The system must also be so flexible that the threshold parameters can be changed as more information becomes available on the performance of the monitoring system and the behaviour of the slope being monitored.

There is the need for more than one alert or action level, related to the assessed/judged probability of failure and the time to develop failure. It is difficult to come up with absolute limits on tolerable slope movement because of the lack of experience. The rate of change of movement is usually of the essential and central focus of the measurements and warning. One must allow sufficient time for response. Risk communication is also essential if monitoring is to be used for risk management decisions.

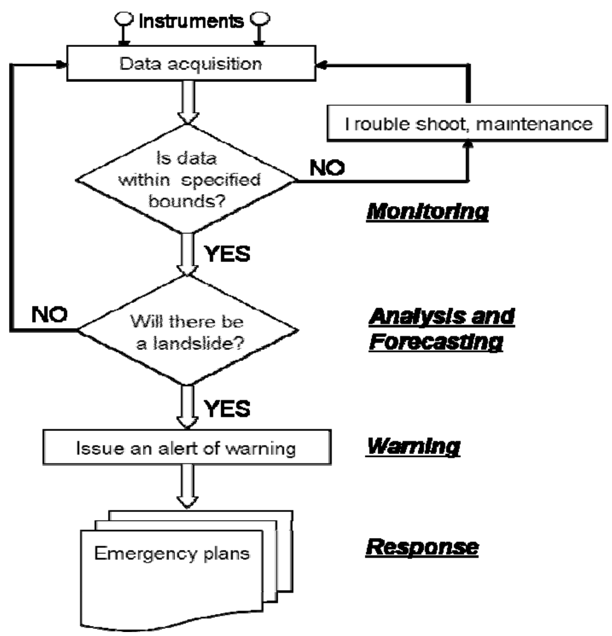

Figure 5 : Block diagram of a typical early warning system (DiBiagio and Kjekstad, 2007).

The issues of false alarms and loss of credibility remain an issue. Based on past experience in Hong Kong, the use of movement monitoring results may be more effective than measurements of groundwater pressure. There are more frequent false alarms when threshold groundwater pressure values are reached because of conservative pore pressure assumptions made in the slope stability analyses.

Early warning systems also benefit greatly from lessons learned. The Val Pola landslide monitoring system developed in 1987 for protecting personnel working in a landslide is such an example. Some of the lessons learned then include (Bruzzi, 1989):

- Standard instrumentation provides data of sufficient quality for the 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 models used to evaluate the data.
- Great care must be taken to ensure adequate protection of instruments against environmental and mechanical damage, electrical damage from thunderstorms and vandalism if relevant.
- 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. When distances are large, radio telemetry may be significantly less expensive than communication over cables.

The technology exists today, both the instruments, systems and models. The profession needs to make all this knowledge work together. It is not the State-of-the-Art that is the limiting factor, it is the application of the State-of-the-Art that needs to be improved (Lacasse, 2008).

Future directions are expected to move towards: (1) making simple visual observation in the field, improving accessibility and enhancing rapid communication; (2) education and awareness; (3) training of public, including having then input information; and (4) improving interpolating solutions.

4.3 Example – EWS for debris flows

Debris flows strike quickly and move rapidly with little warning. Debris flows 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 bury objects in their paths and are particularly dangerous to life and property because they can strike with little warning.

Studies of historical records of debris flows 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 and 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 flows. The most reliable method to predict critical rainfall intensities that can trigger debris flows is to correlate rainfall records to observe debris flows within one geographical area.

To develop an early warning system for debris flows or rainfall-induced landslides, one needs to set the critical duration-intensity threshold values. Figure 6 illustrates an example of such a threshold used in Nicaragua.

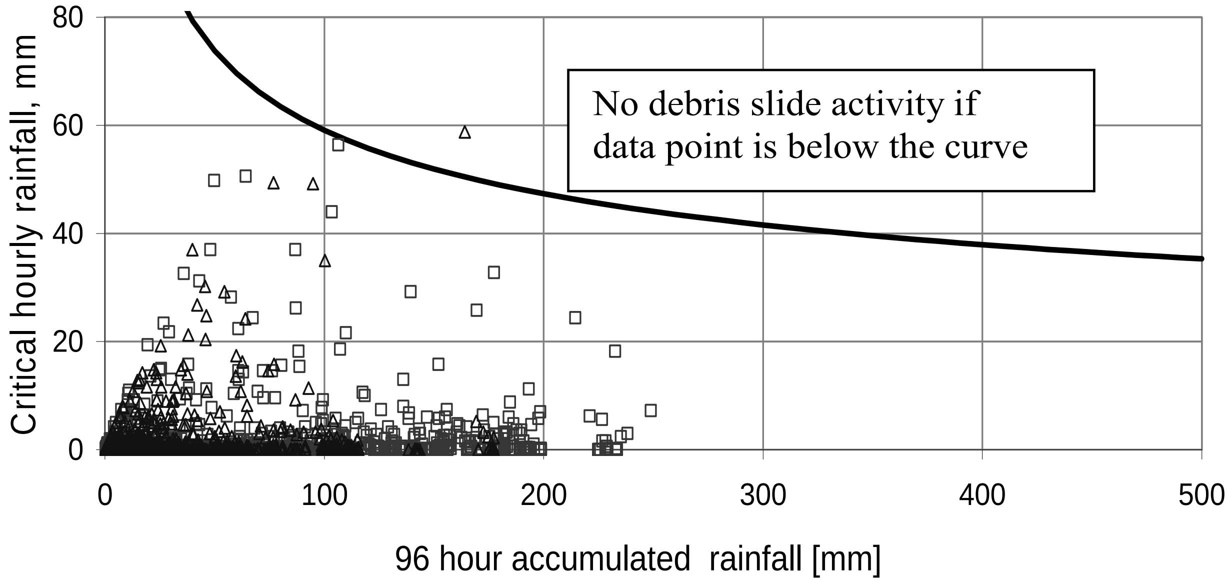

Figure 6 : Threshold trigger for debris flows in Nicaragua for critical hourly rainfall vs. 96-hr accumulated rainfall (Heyerdahl et al., 2003).

If there is no landslide inventory available for a correlation study, the best approach is to search the literature for the critical rainfall intensity studies for similar geographic and climatic areas. These start values can be modified as more information becomes available form the monitoring. 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. Early 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.

4.4 Example – EWS for rockslide-triggered tsunami

Rock falls and rockslides are among the most dangerous natural hazards in Norway and other mountainous countries. The risk posed by rockslides in Norway is mainly due to 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.

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 (Figure 7). 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 (Figure 8) 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.

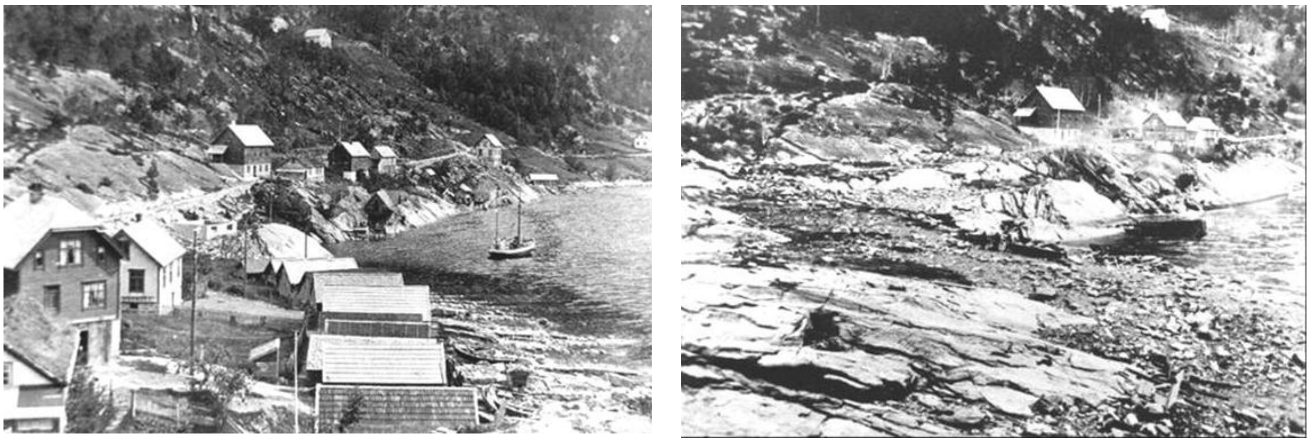

Figure 7 : Municipality of Fjøra in Tafjord, Norway, before (left) and after (right) the tsunami triggered by a massive rockslide into Tafjord in April 1934.

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).

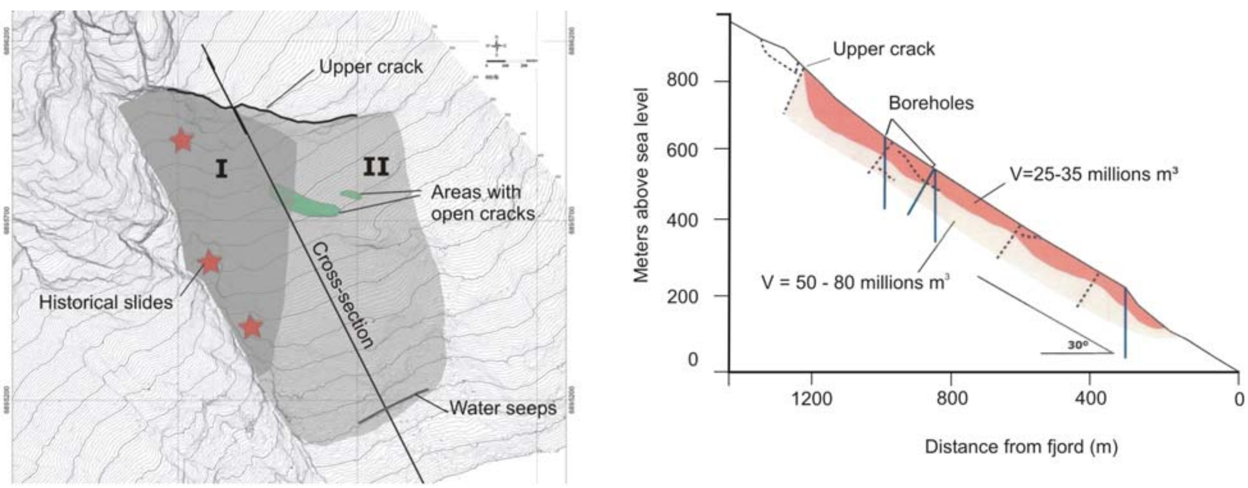

Figure 8 : Sliding volume scenarios. Surficial area (left) and cross-section (right) (modified from Blikra et al. 2007). Area I: Slide volume 10-15 millions m^3, displacement = 6-10 cm/yr, Area II: Slide volume 25-80 millions m^3, displacement = 2-4 cm/yr.

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:

Surface monitoring

- 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.

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 10. 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 as large as 30 million m^3 will pose a serious threat to coastal areas of several communities in the Storfjord region, and may have also serious consequences further out along the fjord.

Table 3 : Estimated run-up heights in the Storfjord region

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

4.5 Event tree analysis (ETA) for the Åknes rock slope

An event tree is a graphical construction that describes the sequence of the occurrence of events in a logical system. The tree identifies the possible outcomes and contains estimates of their probability of occurrence. As the number of events increases, the construction fans out like the branches of a tree. Each path in the event tree represents a specific sequence of events, resulting in a particular consequence. The events are defined such that they are mutually exclusive. ETA is a valuable analysis tool because it is simple and graphic, it provides qualitative insight into a system, and it can be used to assess a system's reliability in a quantitative manner (Hartford and Baecher 2004; Høeg 1996).

In a multi-disciplinary process such as the analysis of hazard and risk associated with natural hazards, a number of "experts", specialists and stakeholders are assembled and need to agree on the numbers set on the branches of the event tree. One needs then to achieve 'consensus'. Consensus derives from Latin, 'cum' meaning 'together with' and 'sentire' meaning to 'think' or 'feel'. Etymologically, 'consensus' therefore means to think or feel together'. In a decision-making process, consensus aims to be:

- inclusive: as many stakeholders as possible should be involved in the consensus decision-making process.
- participatory: the process should actively solicit the input and participation of all decision-makers
- cooperative: participants should strive to reach the best possible decision for the group and all of its members, rather than opt to pursue a majority opinion, potentially to the detriment of a minority.
- egalitarian: all members of a consensus decision-making body should be allowed, as much as possible, equal input into the process; all members have the opportunity to table, amend, veto or "block" proposals.
- solution-oriented: the decision-making body strives to emphasise common agreement rather than differences and use compromise and other techniques to reach decisions and resolve mutually-exclusive positions.

The event trees for Åknes rock slope were constructed by pooling the opinion of engineers, scientists and stakeholders. The objective was to reach consensus on the hazard, vulnerability and risk associated with a rockslide at Åknes and quantify the hazard (probability of a rockslide and tsunami occurring) and the potential losses (human life and material and environmental damage). Different triggers for the rockslide were analysed.

The ETA was carried out over three days, where scientists and stakeholders with relevant competence to grasp the situation as a whole were assembled. The objectives of the analysis were also to examine the required parameters for an effective early warning system and suggest possible mitigation measures, e.g. drainage wells and drainage galleries. Progress is underway on the analysis and the results are only preliminary. The other topics will be the object of future papers.

The participant list for the results shown below included the following representatives:

– manager for Åknes/Tafjord project
– mayor of community
– social scientist from community
– city planner from community
– policeman working on emergency plans and evacuation
– local politician
– representative from community office
– directorate for safety and emergency preparedness

– journalist/media
– officer from ministry of highways
– meteorologist
– physical geographer
– social geographer
– geologist
– engineering geologist
– rock mechanics specialist
– geotechnical engineer
– tsunami specialist
– instrumentation specialist
– earthquake engineer
– seismologist
– mathematician
– statistician
– risk analysis specialist

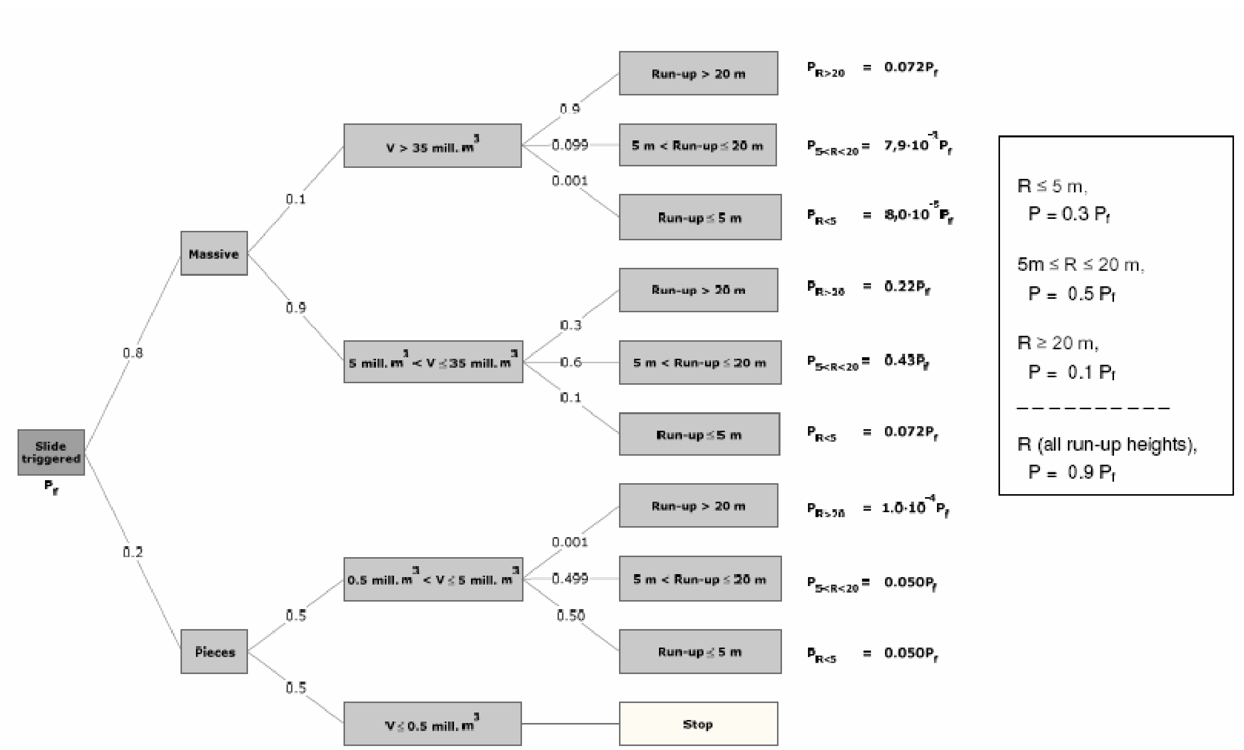

Figure 9 : Event tree for tsunami propagation, given that rock slide has occurred (V= rockslide volume, R=run-up height).

The following event trees were constructed during the three-day meeting:
– event tree, rockslide due to seismic trigger
– event tree, rockslide due to high pore pressure trigger
– event tree, rockslide due to weathering and creep trigger
– event tree, tsunami wave against Hellesylt
– event tree, consequences of tsunami
– event tree, optimum observations for early warning

Event trees were constructed for three triggers of rock slope instability: earthquake, high pore pressure and weathering creep and weakening of sliding plane. The event trees represent the judgment for the "today" (October 2007) situation. The trees set numbers for the probability of a slide within the next year, but the probability changes with time. The event trees should therefore be updated as new information becomes available.

Figure 9 (Lacasse *et al.* 2008) presents an example of the event tree for tsunami propagation, given that the rockslide has occurred. The numbers are given to illustrate the process, and are not to be used as estimates for the rock slope at Åknes. The steps for the tsunami event tree included: 1) rockslide is triggered; 2) slide is in one massive volume or in pieces; 3) volume of rockslide ($V < 5$ millions m^3 to $V > 35$ millions m^3); 4) resulting run-up height on land ($R \leq 5$ m to $R > 20$ m). The failure probability is the summation of the failure probabilities, P_f, in all the branches of the tree.

Table 4 : Estimated probability of run-up heights at Hellesylt, given that a rock slide of larger volume has occurred

Run-up height ≤ 5 m	Run-up height > 5m; ≤ 20 m	Run-up height > 20 m
$P = 3 \times 10^{-4}$/yr	$P = 5 \times 10^{-4}$/yr	$P = 1 \times 10^{-4}$/yr

As part of the evaluation of the consequences of a rockslide and tsunami, the magnitude of the consequences (loss of life and material property and environmental damage) depends on: warning time before the rockslide or tsunami hazard occurs, reliability of emergency preparedness plan, run-up height, local water level, local water flow velocity, availability of escape routes and distance to safe havens, time of the day, time of the year, training of professionals and public, unforeseen concurrent event etc. These factors will form the steps of the event tree on consequences.

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 10 and Table 5 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).

The event tree for the Åknes early warning system involved, among others, the following steps: 1) time needed for warning (t in weeks, days or hours, some triggers give more time than other); 2) technology (working, yes or no); 3) are signals picked up? (yes or no); 4) are signals correctly interpreted? (human element, time available, delegation of authority, etc); 5) warning parameter(s) to follow up before and during warning; 6) choice of threshold values. A number of factors were seen as important to consider:

- 4-5 wks/yr are the most critical because of climatic factors; at that time, one should define an increased alarm level
- life and range of operation of sensors (e.g. extensometers) should be checked continuously
- any presence of large amount of water should be monitored
- careful thought should be given to what is/are the most representative measurements for early warning
- monitoring should be spread out, as failure may occur in other locations than crack; consider additional boreholes and other measurements
- when making decision, look at snow avalanche warning

- statistical evaluation of measured data should be built in system; consider Bayesian updating
- adapt warning curve (Figure 17) as more knowledge is acquired
- consider whether police and other authorities should be on standby earlier than suggested in Table 12 (police needs 72 hours to evacuate entire Storfjord area)
- establish threshold values to decide on when to move back after false alarm, but bake in the possibility of slide developing with time
- be prepared with a new monitoring system to be set in operation quickly after a first slide that has probably destroyed the instrumentation in place

5.0 STRUCTURAL MITIGATION MEASURES

5.1 Physical protection measures

Physical protection measures include, but are not limited to, integrated land use planning, drainage, erosion protection, vegetation and ground improvement techniques, barriers (earth ramparts, artificial elevated land, anchoring systems, retaining structures), and offshore or onshore walls to reduce the energy or the loads induced by landslides.

Table 5 Alarm levels and actions for the warning system at Åknes

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

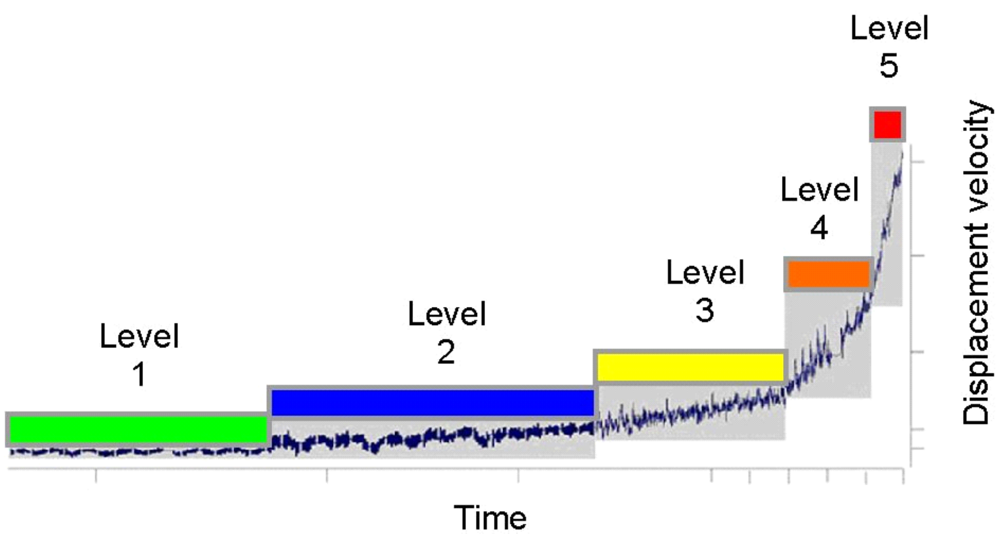

Figure 10 : Illustration of the alarm levels as function of displacement velocities (vertical axis: displacement rate in mm/day; horizontal axis: relative time before failure)

Buildings that are in the path of potential landslides need to be designed to withstand the impact forces of landslides, or built at another location out of the harm's way.

Physical protection barriers may be used to stop or delay the impact of debris flows, reduce the maximum reach of its impact, or dissipate the energy of the landslide. Such barriers may include "soft" structures in the form of dikes or embankments, or "hard" structures like vertical concrete or stone block wall. Any measures need to be part of a community's master plan and subjected to analyses to assess and circumvent any negative environmental impact.

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.

5.1 Example – Hazard and Risk Mitigation in Drammen

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), see Figure 11:

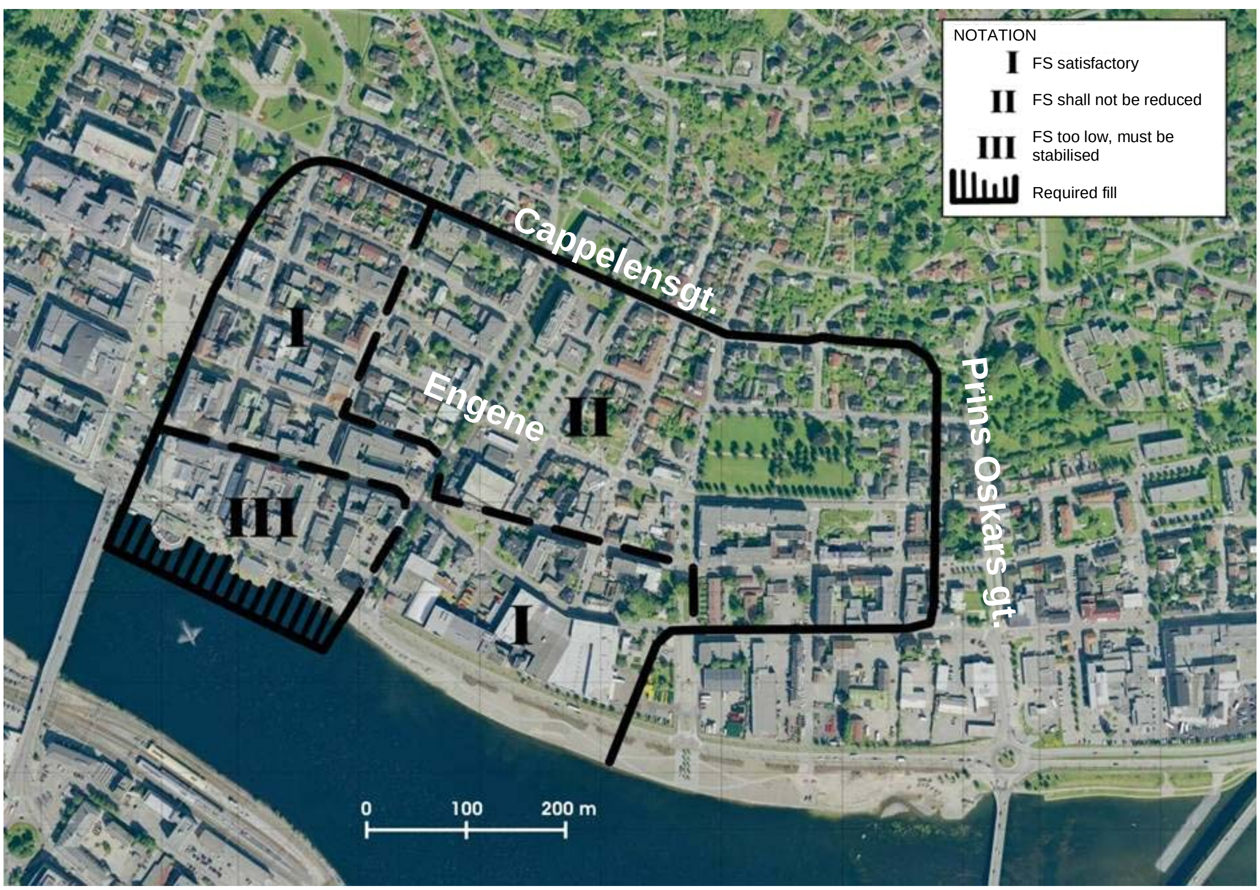

Figure 11 : Classification in hazard zones (Karlsrud 2008; Gregersen 2008)(SF = Safety Factor).

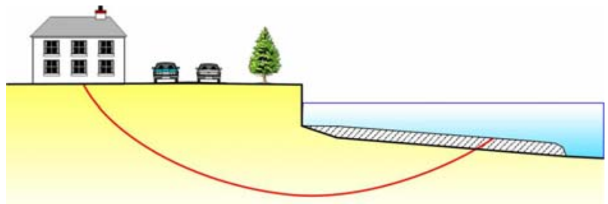

Figure 12 : Mitigation in Zone III in Drammen

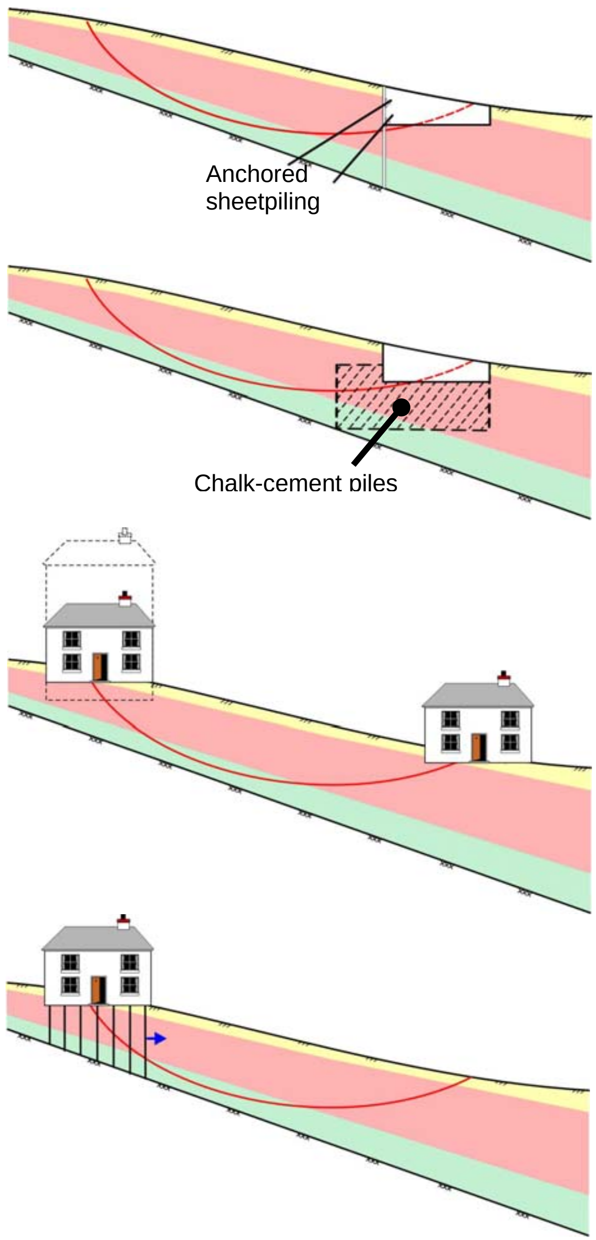

Figure 13 : Hazard, mitigation and preventive measures in Zone II in Drammen

- Zone I FS satisfactory
- Zone II FS shall not be reduced

- Zone III FS too low, area must be stabilised

Figure 12 illustrates the mitigation done 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 structurel and foundation work without first ensuring increased stability. Figure 13 illustrates four cases (Gregersen 2008; Karlsrud 2008): (1) if an excavation is planned, it will have to be stabilised with anchored sheetpiling 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.

5.2 Other examples

Figures 14 and 15 show other examples of physical mitigation measures. Physical intervention is an active countermeasure which very effective when the danger is well identified and limited to a few slopes. The major disadvantage of this strategy is that the costs could be prohibitive. Any physical intervention would require a detailed cost-benefit analysis and, in some situations, an environmental impact study.

Figure 14 : Examples of physical protection measures against debris flows from Austria (left) and France (right).

Figure 15 : Examples of slope stabilisation measures from Switzerland.

6.0 DISCUSSION AND CONCLUSIONS

Landslide risk management typically (but not solely) involves decisions at the local level, and a lack of information about landslide risk and how this risk is changing on account of climate, land-use and other factors, 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 probabilistic 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 landslide 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 has 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 and theorising. 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.

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. 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, geographical, seasonal, warning time or other reasons.

People living in cities are less exposed to the risk posed by landslides than people living in rural areas. The exception is the poorest segment of the population who live in slums that develop at a pace that no urban planner can control.

To attract widespread and effective public support for mitigation and prevention of the risk posed by landslides, more attention should be given on the little-explored interface between technical and natural sciences on one hand, and social and political sciences on the other (Nadim and Lacasse 2008). Such a stance will bring the different professions face to face with the problem of fostering risk reduction measures that have broad appeal to stakeholders as well as victims, researchers and risk management professionals. Geoscientists and engineers can contribute to an improved understanding of risk assessment, mitigation and management.

A proactive approach to risk management is instrumental for reducing significantly loss of lives and material damage associated natural hazards. The major natural disasters that have taken place over the last 5-10 years and received wide media attention, have clearly changed people's mind in terms of acknowledging risk management as an alternative to emergency management.

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.

Kjekstad (2007) suggested an approach based on three pillars for landslide risk management for developing countries:

- Pillar 1 – Hazard and Risk Assessment
- Pillar 2 – Landslide Mitigation Measures
- Pillar 3 – International Cooperation and Support

A milestone in international collaboration 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, which was approved by 165 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.

The Hyogo Framework of Action has increased the awareness and importance of preventive and mitigation measures. It will also contribute to a much better practice for the implementation of risk reduction projects for two reasons: a) by the fact that governments will be in the driving seat, which means that coordination is likely to be improved, and b) the fact that ISDR is given the responsibility for the follow-up of the plan will put pressure for action from countries that are most exposed.

Reducing the impact of landslide with passive and active countermeasures, is both an economical and social necessity. Loss statistics show that number of fatalities is much higher in developing countries than in developed countries. The frequency of landslide disasters is increasing due to more extreme weather than before, increased population and increased vulnerability. The situation calls for intensified focus on and action to provide effective and appropriate preventive measures.

7.0 ACKNOWLEDGMENT

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