# International Centre for Geohazards (ICG): Assessment, prevention and mitigation of geohazards

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There is an urgent need to improve the basic understanding of geohazards and our ability to deal with the risks associated with them. The International Centre for Geohazards (ICG) does research on the assessment, prevention and mitigation of geohazards, offshore as well as on land. The main focus is placed on landslides and their effects, such as tsunamis. Activities include hazard and risk assessment for slides and earthquakes, evaluation of soil and rock slopes, instrument design and monitoring, geophysical methods, field studies, application of SAR technology for monitoring of slopes, further development of GIS as a tool in geohazard assessment, tsunami research, and numerical modelling. Education is given high priority, and graduate programmes in geohazards have been established at both the University of Oslo and at NTNU in Trondheim. Over the next few years, emphasis will also be placed on monitoring, early warning systems, and mitigation measures.

## Introduction

Geohazards can be defined as "events caused by geological conditions or processes which represent serious threats to human lives, property and the natural and built environment". Geohazards exist both onshore and offshore. Onshore, the most important are volcanic eruptions, earthquakes, landslides and debris flows, floods and snow avalanches. Offshore, slope instability and earthquakes are the main threats because of their potential for damaging seafloor installations, and for generating devastating tsunamis, such as the 1998 Papua New Guinea event responsible for more than 2000 deaths, and the past Storegga Slide tsunami (Bondevik et al. 1997, in press). Features like shallow gas, gas hydrates and mud diapirism also represent geohazards in the offshore regions.

There is an urgent need to improve the basic understanding of geohazards and the ability to deal with the risks they pose. This need is accentuated by the increasing number of flooding- and sliding events in many regions, increased concern for geohazards in the production and transport of oil and gas, and increased vulnerability to geohazards caused by urbanisation and uncontrolled land use, particularly in developing countries. Geo-related disasters constitute the main obstacles to progress and to the improvement of living conditions in many developing countries. Offshore, several of the largest oil companies define reduction of geohazard-related risks in deep water as one of their top research priorities. The consequences of a geohazard-triggered accident offshore, in terms of loss of life and damage to the environment could be catastrophic.

With this background the International Centre for Geohazards (ICG) was established in 2003, as one of 13 "Centres of Excellence" awarded by The Research Council of Norway. ICG is organised as a consortium of five individual partners: the Norwegian Geotechnical Institute (NGI), the Geological Survey of Norway (NGU), the Norwegian University for Science and Technology (NTNU), the University of Oslo (UiO), and the Norwegian Seismic Array (NORSAR). In these five partner organisations, the necessary expertise in the most relevant research fields, such as geology, geomechanics, geotechnical engineering, geophysics, mathematics, numerical modelling, GIS systems, SAR applications, instrumentation, in-situ measurements, is found. NGI is the host organisation, and the centre is physically located at the NGI building in Oslo, where it has office space for ICG project participants, guest researchers and students. In addition, much research activity is also carried out in the premises of the other four partners.

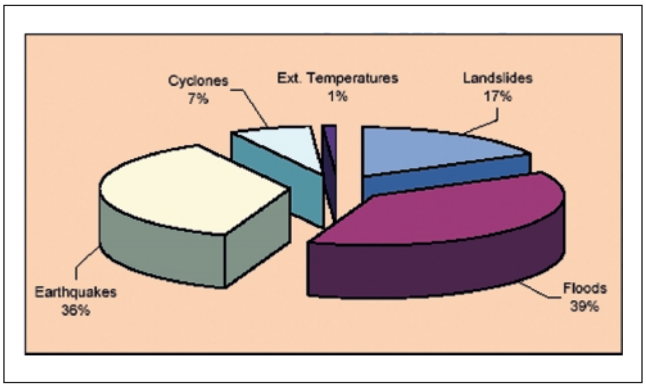


*Fig. 1. Comparison of casualties from different natural hazards in the 20th century (Source: EM-DAT: The OFDA/CRED International Disaster database).*

The main focus of ICG is placed on slides, their triggering factors and effects. Many of the casualties reported after rain storms, large floods and earthquakes (Fig. 1) are actually caused by the slides generated by these events. Developing countries are particularly vulnerable. As an example, extreme rainfall in Venezuela in 1999 triggered flooding and landslides, which alone caused over 20 000 deaths (Fig. 2). Slides of various kinds also form the most important natural hazard in Norway. The number of deaths caused by all types of sliding in Norway over the past 150 years exceeds 2000.

ICG carries out research on the assessment, prevention and mitigation of geohazards, including the risk of landslides due to rainfall, flooding, earthquakes and human intervention, as well the geological risks in deep waters, particularly those related to submarine slides, which can be a threat to seafloor facilities and are also important tsunami generators. Research is presently organised in nine projects:

- Risk and vulnerability analysis for geohazards
- Earthquake hazard, vulnerability and risk
- Rock slope failures, models and risks
- Landslides in saturated and unsaturated soil slopes
- Offshore geohazards
- Geographical information management and analyses for geohazard applications
- SAR applications in geohazard assessment
- Slide dynamics and mechanics of mass disintegration
- Tsunami modelling and prediction

In addition, an academic programme, focusing on education is a prioritised task, and the two university partners of ICG, UiO and NTNU, have established international graduate programmes in geohazard studies. PhD programmes are also being developed, and as of November 2004 15 PhD candidates are working on ICG-related topics. Whereas the programme at UiO addresses geohazards with emphasis on geology and natural sciences, the programme at NTNU focuses on engineering aspects of geohazards. The research work in the MSc and PhD programmes form important parts of several of the ICG projects.

In the near future, increased focus will be placed on early warning systems, risk assessment and mitigation measures. The aim of this paper is to provide a summary of the main activities and achievements of ICG during the first 18 months of its existence.

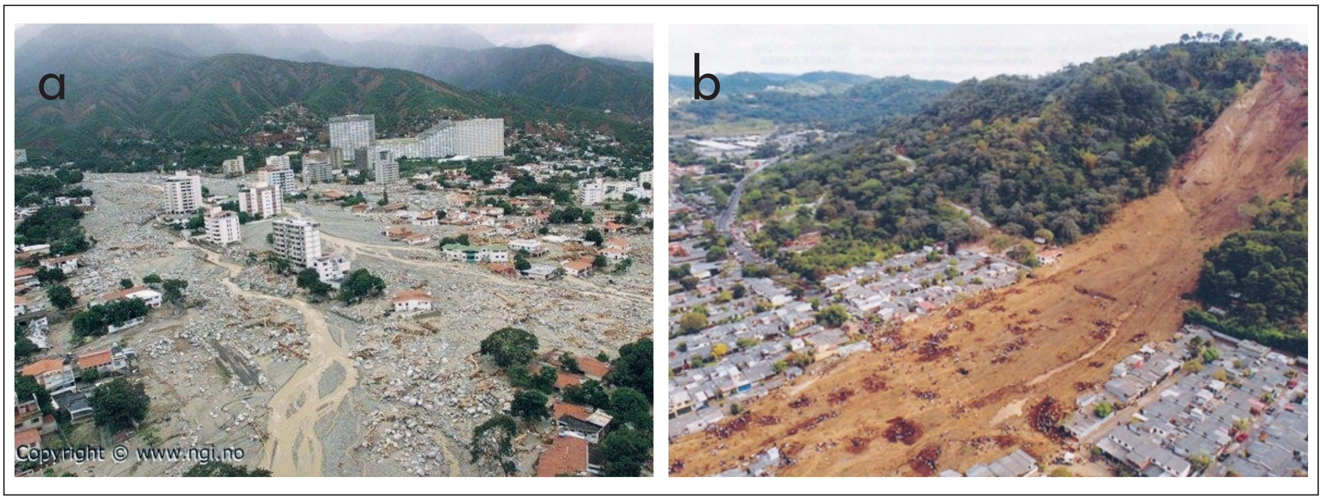


*Fig. 2. A) Flood-triggered mudslides and debris flows caused over 20 000 fatalities in Venezuela, December 1999 (Photo: Scanpix). B) Earthquake-induced landslide at Las Colinas, El Salvador, January 2001, causing over 600 fatalities.*

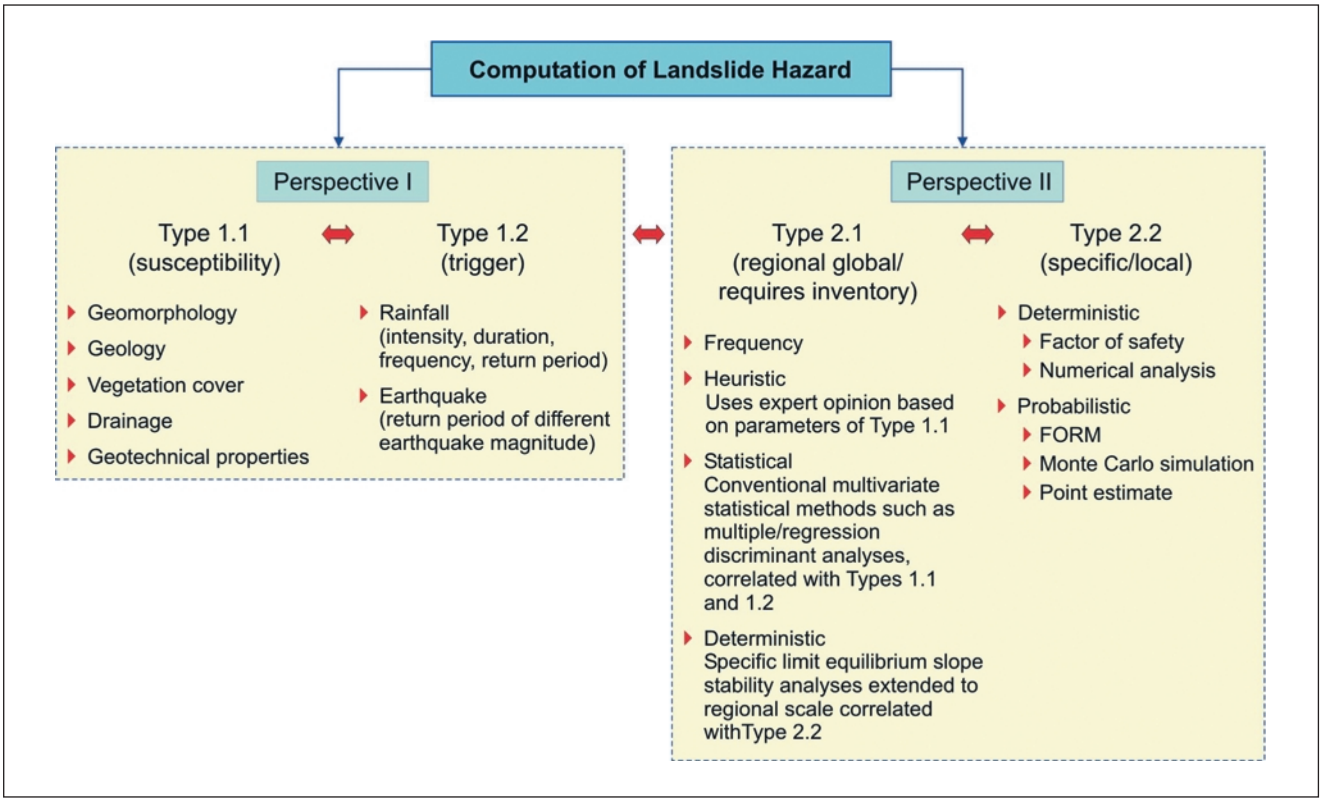


*Fig. 3. Aspects to consider in landslide hazard and risk assessment (S. Duzgun, personal communication, 2004).*

# Risk and vulnerability analysis for geohazards

Society and regulative procedures today require that risks associated with geohazards and civil engineering structures be evaluated. Statistics, reliability analyses and risk assessments are useful tools that assist in the evaluation and the required decision-making. Risk assessment uses probabilistic approaches because they provide a rational framework for taking into account uncertainties. Predicting hazards posed by geological processes, and evaluating the human, environmental and economical consequences of geohazards require an integrated scientific approach involving many disciplines, including also socio-economical aspects.

ICG's project on risk and vulnerability analysis aims at establishing state-of-the-art practice for the analysis of slopes and developing user-friendly tools for applications in the other ICG projects. In 2003-2004, the project concentrated on (1) a review and critique of methods for probabilistic analysis and risk assessment of slopes, (2) the implementation of software for analysis, (3) a review of vulnerability concepts and (4) status on "acceptable/tolerable" probability of failure and risk level. To do this, it was necessary to review concepts from other fields of engineering and from the non-engineering literature. Much work is going on worldwide on the topic of risk and vulnerability, and the project is to continue over a number of years. Many aspects come into the assessment of landslide hazard, whether deterministic or probabilistic. Some of the aspects and methods needing to be considered in the study of the vulnerability and risk associated with landslides are shown in Fig. 3.

## *Analysis models*

Deterministic analytical models should be used when material properties, failure modes (mechanisms and geometries) and forces are known with reasonable accuracy. Safety factor changes may be used to evaluate the significance of parameters or conditions. Probabilistic analyses should be used when the uncertainty in parameters may govern the results of the analysis. The probabilistic analyses quantify the likelihood of failure from geological evidence and uncertainties in input parameters and the analysis model. Realistic models, developed from well designed and executed investigations, should give probabilistic results of real benefit for decision-making and engineering design.

Qualitative estimates of failure likelihood, and any other potential event, can be ranked and assessed using simple matrices (Fig. 4). Upper and lower bound estimates should be included in the ranking to account for uncertainty. The art of the engineer is moving the vector (probability of failure, consequence) to the first quadrant (Fig. 4). Assessing and ranking the risks allow for informed decisions on prioritisation and on accep-

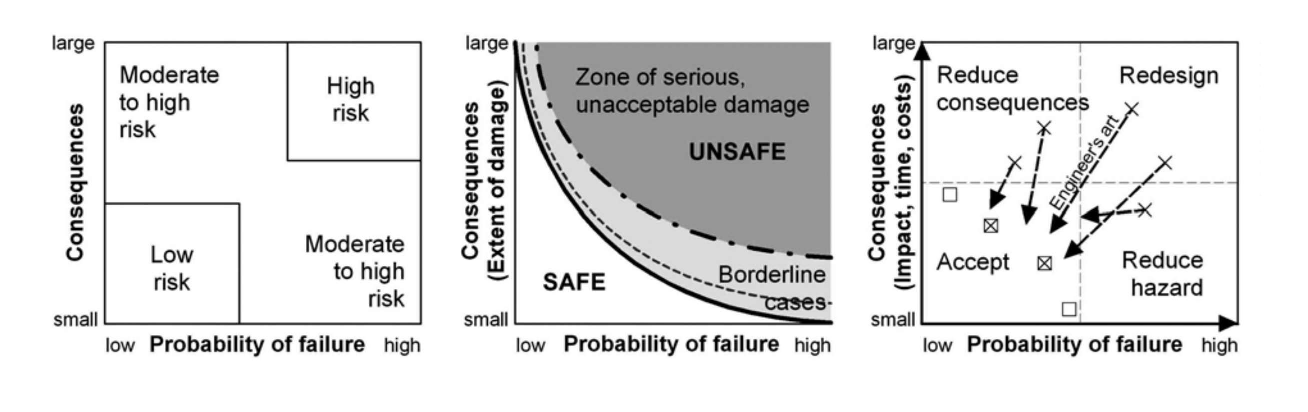


*Fig. 4. Qualitative risk prioritisation matrices.*

ting risk, or treating and control-ling risks so that they are minimised. Dealing with uncertainties is an essential part of design. Evaluation of risk does not need to be quantitative, as a qualitative estimate can also be extremely useful.

Usually it is not feasible to do geotechnical investigations for all slopes to a degree where little uncertainty remains. To identify the most critical slopes, the project looked into a 3-level procedure with increasingly quantifiable results, large-scale mapping, scoring based on engineering judgement and site-specific limiting equilibrium analysis. Probabilistic methods are being developed for each of these approaches. The objective, in the end, is to produce an integrated framework that will allow the evaluation of the probability of landslides.

In addition, the concepts of vulnerability are being reviewed. A 3-D assessment model for vulnerability, considering magnitude and type of event, scale of event, and the element at risk will be developed and implemented. As these factors are correlated, the framework also needs to formulate the correlations among the analysed parameters.

## Earthquake hazard, vulnerability and risk

Through direct and indirect damage earthquakes are the most devastating of natural disasters. Earthquakes are also important triggers of landslides. Therefore, improved procedures for earthquake risk estimation are important tools for the planning of mitigation measures, and for estimating the risk for earthquake induced landslides. The ICG project has developed procedures and software for earthquake risk and loss estimation. The methods have been tested on earthquake scenarios for the city of Oslo, where the local geology is well known (Molina & Lindholm, in press).

The shaking caused by an earthquake is transmitted through the Earth's crust and along the surface until the wave-train arrives at a given site. The site may be an old riverbed or seafloor as for Oslo. The houses may be of varying age and quality, and while some survive the shaking with minor cracks, others might collapse completely. Issues that need to be addressed in the evaluation of seismic hazard and risk include:

- *The earthquake source:* The damage potential depends heavily on the depth to the earthquake source, but also on the source mechanism, its size, stress drop, rupture characteristics, directivity effects and parameters specific to the area.
- *The path of the wave train:* As shaking radiates out from the source it attenuates elastically and inelastically. This frequency-dependent attenuation reflects the characteristics of the crust.
- *Soil amplification:* Local soil amplification of the shaking is related to specific sub-surface conditions, and often contributes significantly to the damage. Other site effects, like topographic amplification may also increase the damage.
- *Earthquake risk and loss estimation:* While some structures are well designed and maintained, others may turn out to be deadly traps. Some infrastructural lifelines and services are very important for a larger population, while others are less important.

Most focus in the project is placed on the two last topics, in addition to the development of methods and procedures.

### *Soil amplification*

Sediment layers may greatly amplify the shaking from earthquakes (Fig. 5). This was dramatically demonstrated in Mexico City in 1985, when an earthquake 400 km distant caused severe damage to the city due to the shaking amplification of the underlying lacustrine sediments. Oslo, which is partly built on thick marine clays, has been investigated for soil amplification using the empirical methods of Nakamura (1989), which are based on the relative amplification of noise-surface-waves of the hori-

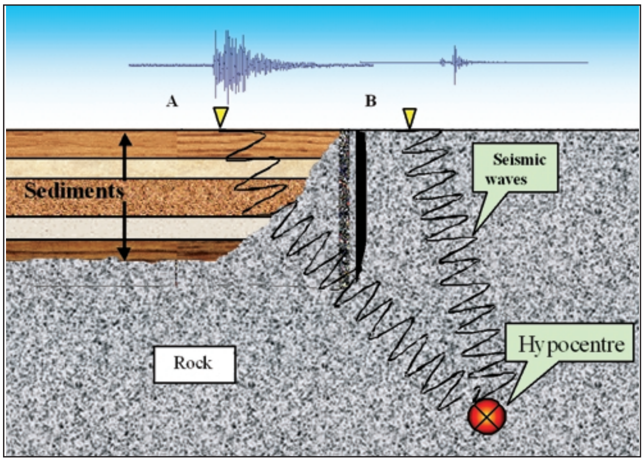


*Fig. 5. Schematic diagram of the amplification of earthquake shaking caused by unlithified sediments.*

zontal to vertical spectral amplitudes. Based on data sampled at night from 35 sites in Oslo, sites underlain by thick marine sediments, showed that a resonance frequency of around 1.5Hz could lead to significant amplification, whereas rock sites showed no amplification.

*Earthquake risk and loss estimation*

Both probabilistic and deterministic earthquake scenarios can be established in the scheme developed for risk and loss estimation (Fig. 6A). The software used has been developed for the United States by FEMA (http://www.fema.gov/hazus). The strategies and methodologies developed are adapted by ICG to a GIS Matlab code and extended to include a logic tree computation taking parameter uncertainty into consideration. Earthquake damage scenarios for Oslo were based on a detailed parameterisation of the vulnerability of each building type in Oslo. The soft sediments were accounted for in terms of amplification factors. The damage pattern (Fig. 6B) illustrates the correlation between damage, shaking and the presence of soft sediments. The procedures established for Oslo will be developed further, and can be used in risk assessments in other areas.

Continuous development is on-going internationally as regards probabilistic seismic hazard estimation, with the main focus on the development and implementation of attenuation models, which are decisive in the hazard modelling. ICG has an active role in these developments.

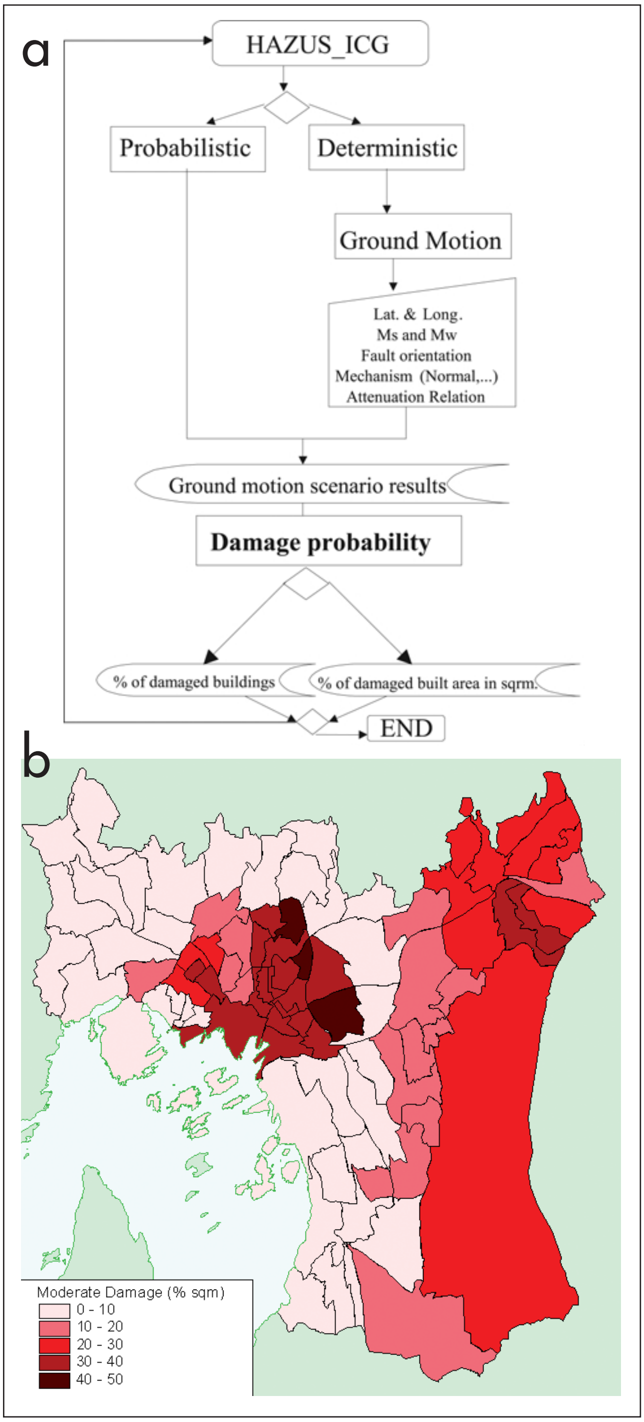


*Fig. 6. A) Flowchart of the computations procedure for seismic hazard assessment (from Molina & Lindholm 2004b). B) Damage scenario for the city of Oslo showing percentage of moderate damage to buildings. The earthquake modelled had its epicenter east of the city, on one of the main Oslo Graben boundary faults, and hence the eastern part of Oslo exhibits severe damage. The city centre, located in an area of thick marine clays, exhibits the maximum damage (from Molina & Lindholm 2004a).*

## Rock slope failures, models and risks

Rockfalls and slides are among the most serious natural hazards in Norway, also because of their tsunamigenic potential, which has taken more than 170 lives in western Norway during the last 100 years. With the increased public attention on these problems in parts of Norway as well as internationally, studies of hazards related to rock slope failures are important ICG activities.

Integration of all geological and geotechnical/geomechanical aspects related to rock-slope failures is important (Blikra et al. in press; Braathen et al. 2004; Bhasin & Kaynia 2004; Bhasin et al. 2004; Dahle 2004; Panthi & Nilsen in press). Hazard and risk zonation need to be performed on both regional and local levels, and all available data from the county of Møre and Romsdal in Norway have been used to evaluate the methods for this (e.g. Blikra et al. in press). The regional hazard zonation was based on the spatial distribution and temporal pattern of events (Fig. 7A), while a more detailed, local and quantitative zonation was performed in a selected fjord area, based on the frequency, age and size of events (Fig. 7B). In addition, tsunami potential and run-out distance will be modelled.

Several uncertainties exist in the quantification of rockslide hazard, one of which is the probability and magnitude of future earthquakes. Although earthquakes above magnitude 6 are uncommon in Norway, the identification of postglacial faults in areas of relatively high seismicity (Anda et al. 2002) suggests that large earthquakes should not be ruled out. Lack of adequate models for slide runout and tsunami run-up are other uncertainties. These are the subjects of other ICG research activities.

*Development of geological and stability models for rock slopes*

Present numerical models for rock-slope stability evaluations are based on shear-fracture characteristics. On-going field studies on collapsing mountain-sides (e.g., Blikra et al. in press; Braathen et al. 2004; Dahle 2004) demonstrate that most rock-slope failure areas contain both shear and tension fractures, as well as a basal shear surface commonly covered with a membrane of crushed rock (fault breccia/gouge) (Fig. 8). The following topics have received particular focus:

- Use of digital elevation models (DEM) to characterise structural patterns of importance for instability (e.g. sliding planes and wedges).
- Detailed studies of slope failures and the use of geophysical methods (2D resistivity, GPR, seismic), as well as sampling and measurements in drill-holes.
- Characterization of weak layers, and particularly the temporal evolution of such layers during creep.
- Utilisation of identified diagnostic structures as geological input to stability models.

ICG research focuses on stability analysis of complex jointed rock slopes using numerical techniques (Bhasin & Kaynia, 2004; Bhasin et al., 2004). The behaviour of a rock slope when subjected to the influence of external loads depends on the characteristics of both the rock material and discontinuities within it.

*Monitoring*

Understanding the 3D kinematics (movement pattern) is of major importance for the evaluation of hazards and for testing the reliability of the numerical modelling. Existing monitoring data, e.g. from the Åkerneset site in Møre & Romsdal, where automatic extensometers have been operating for more than 10 years (NGI 1996), will be used. A potential rock slope failure at Åkerneset might involve a volume of 30-45 mill. m3. Several new monitoring systems will be installed at this site during the next 2 years and will produce a unique

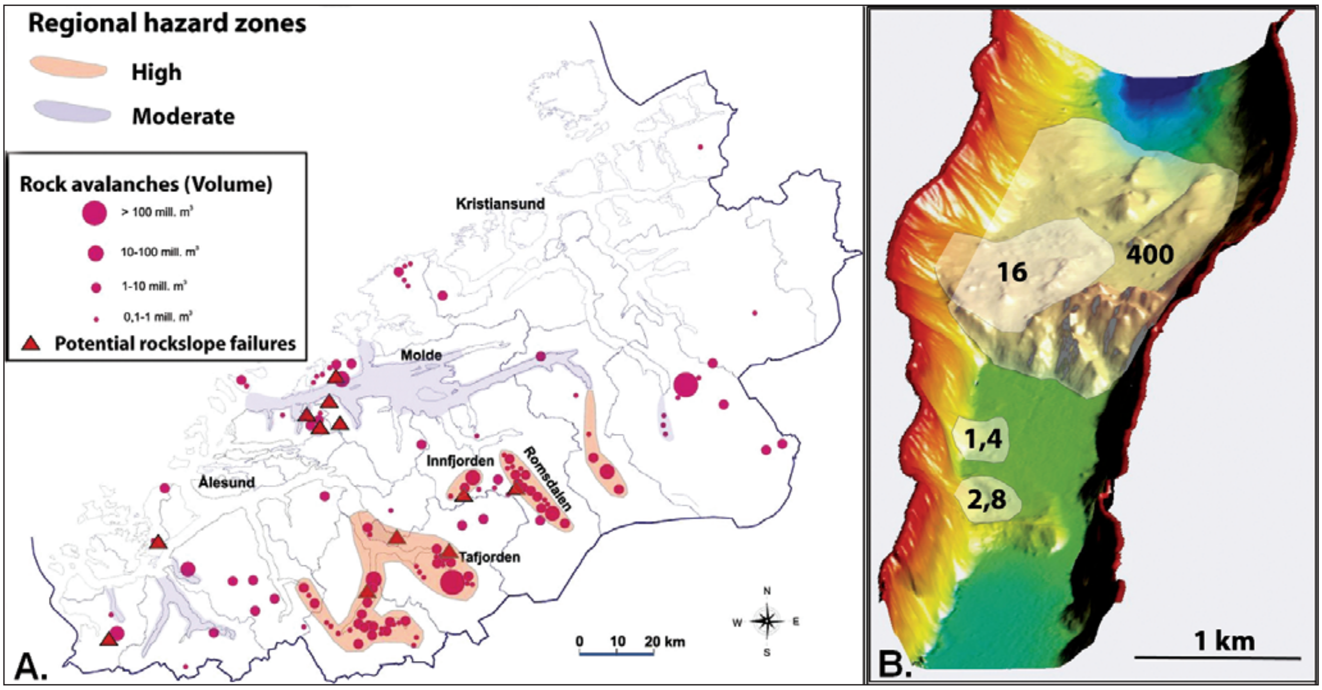


*Fig.7. A) Regional hazard zones in Møre and Romsdal County. B) Rock-avalanche deposits in Sunnylvsfjorden in Møre and Romsdal. Estimated volumes shown are in million $m^3$.*

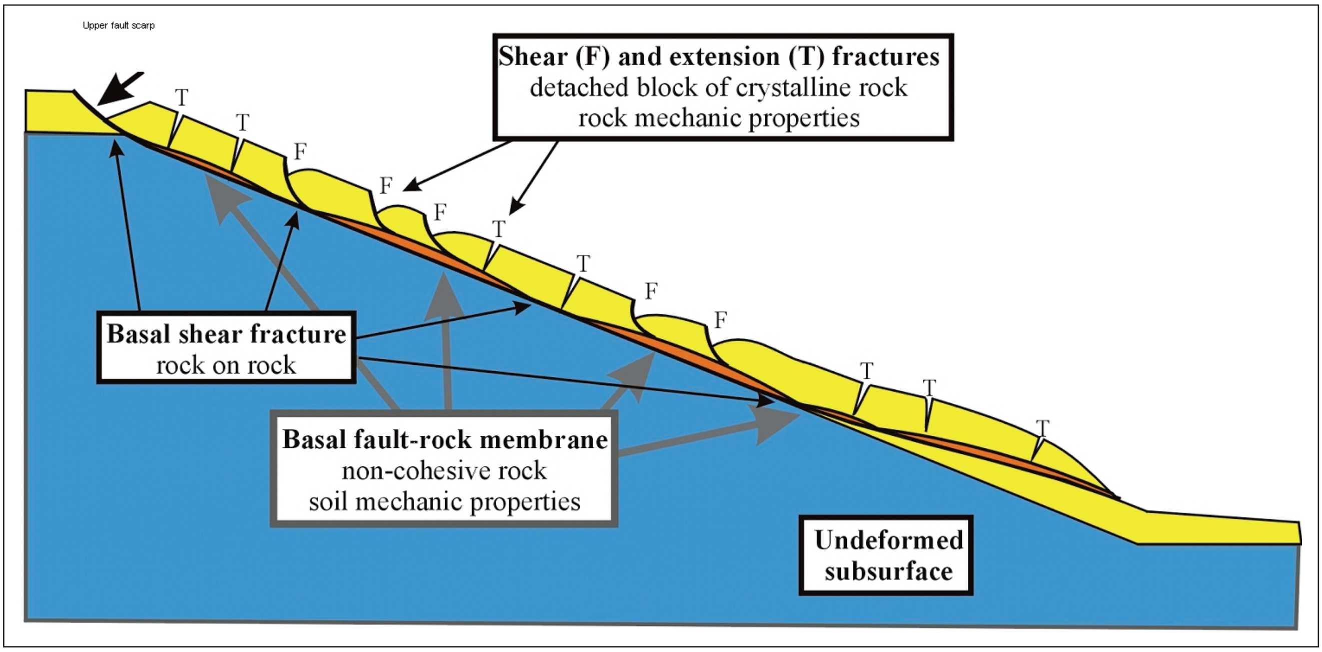


*Fig. 8. Two-layer model for pre-avalanche deformation in a rock-slope failure area. Text boxes describe factors and mechanical properties that have to be evaluated for stability assessments (from Braathen et al. 2004).*

data set. Another important method being explored is micro-seismic monitoring. A small system is already in operation at the topmost part of the Åkerneset slope, where 6 geophones have been installed. The geological and geophysical investigations, drilling, logging, installation of different monitoring systems and modelling at Åkerneset over the next 2-3 years will be an important element in the development of a general approach for analyses of potentially unstable rock slopes.

## Landslides in saturated and unsaturated soil slopes

*Saturated soils (mainly quick clays)*

As a consequence of Late Weichselian deglaciation and subsequent postglacial development, many of the most heavily populated areas of Norway are located in areas where quick clays cause slides, many of which have

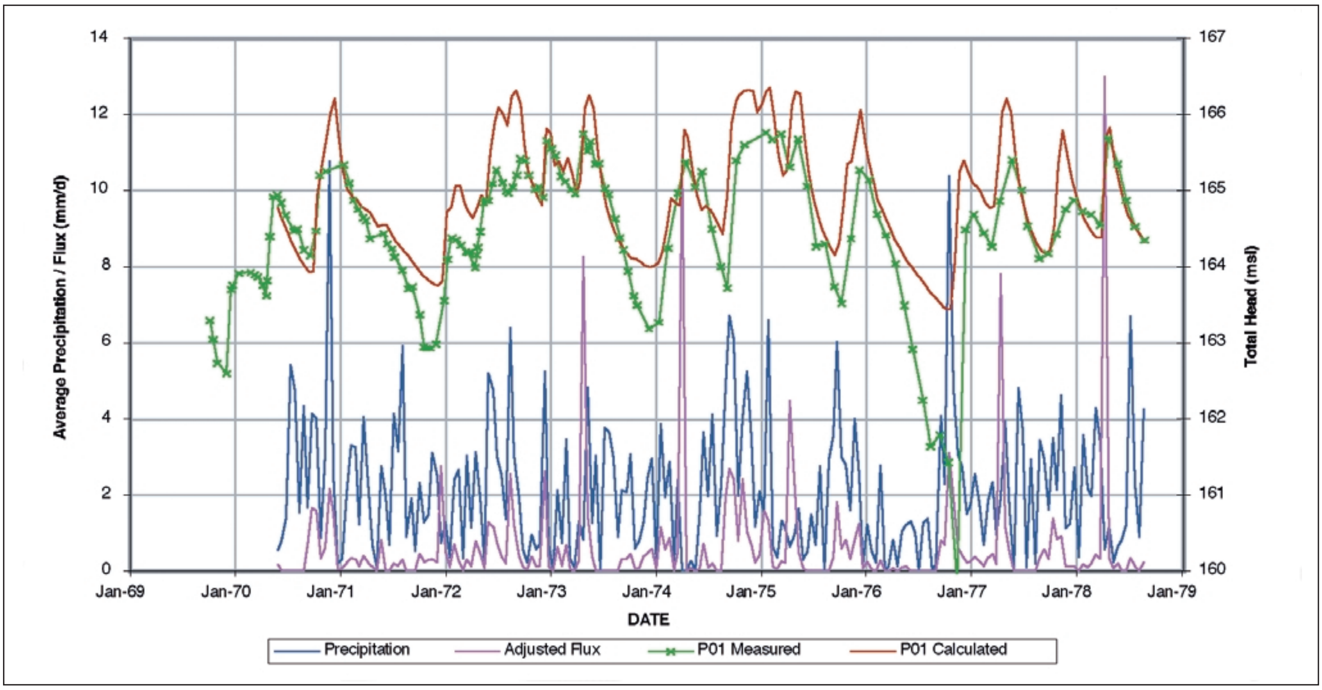


*Fig. 9. Measured versus calculated response for one of 8 piezometers installed in the Romerike area, south-eastern Norway, 15-day average precipitation record, and boundary adjusted flux used for groundwater analysis.*

taken lives. Hazard mapping and research on quick clays are important topics at several of the ICG partner organisations, and new initiatives have been undertaken under ICG. In a recent study in one of the classical quick clay areas, Romerike in central south-eastern Norway, the effects of precipitation on clay slope stability were investigated by re-analysing nine years of data from eight piezometers (Fig. 9). Two-dimensional finite element analyses were performed to evaluate infiltration effects on groundwater flow and piezometer response. Development of the boundary flux record considered the effects of temperature, snow depth, land use practices, and soil hydraulic conductivity. The study showed that the groundwater surface is likely to be at or near the ground surface relatively frequently, but that elevated groundwater conditions alone are not sufficient to trigger local (i.e. shallow) initial slides or slumps in the Romerike area. The importance of soil stratification was also demonstrated. Silt layers in the marine clay significantly affect head losses, piezometer measurements, groundwater flow, and slope stability.

Installing multiple piezometers along important sections and in vertical arrays near the top of slopes is recommended when attempting to model the groundwater regime. These are also useful for interpreting geologic and hydrogeological conditions not readily interpretable through subsurface exploration alone. Piezometers are an important part of any early warning system in quick clay areas, and would provide important data in the planning of mitigation measures.

ICG studies are also ongoing in the Trondheim region and northern Norway, using a combination of geophysical (resistivity, georadar, interferometric sonar) and geological methods, both on land and in the adjacent fjords. The influence of stratigraphic variability, as well as other geological constraints on quick clay slides are, in addition to the development of methods and procedures, important topics of this research, and are expected to produce improved procedures for slide hazard assessment.

### *Unsaturated soil slopes and the effect of increased rainfall*

Heavy rainfall triggers a large number of landslides each year worldwide, many of them causing a high number of casualties and a large impact on society. In many countries, the triggering rainfall occurs during tropical storms and hurricanes, which during recent years, seem to be more frequent. These natural hazards are of particular importance since climate change scenarios suggest more intense precipitation events will occur in the future (IPCC 2001).

Generally, but not exclusively, landslides triggered by heavy rainfall are relatively shallow. The release mechanism for such shallow slides may be described as a loss in soil strength following saturation of the soil. Under normal conditions, the soil close to a slope surface is situated above the phreatic surface (groundwater), which means that the near-surface soil is not saturated. The suction in the soil will be a function of the water content, varying with soil type. However, during prolonged rain, infiltration from the surface will eventually fill up the pores in the soil and the negative pore pressure (i.e. capillary suction) may be reversed to give a positive one. Reduced slope stability follows as an immediate effect of the reduced suction. For many slopes, such loss of suction will lead to landslides.

Parametric studies were performed including factors such as slope geometry, soil types, long -and short-term rainfall and unsaturated flow above the phreatic surface. The focus has so far been on the analysis of pore pressures, as these have a dominant impact on slope stability. One- and two-dimensional flow analyses were run to study the gradual pore pressure change near the slope surface.

Flow analyses, particularly transient analyses, are time-consuming, and it has been an important task to test finite element models to achieve reliable results. The upper soil layers must be modelled in detail, as the changes in pore pressures close to the surface will be large. One-dimensional analyses indicate that as a result of precipitation, the saturation zone increases and progresses downwards until the complete soil profile has been saturated (pore pressure ≈ 0). Then,

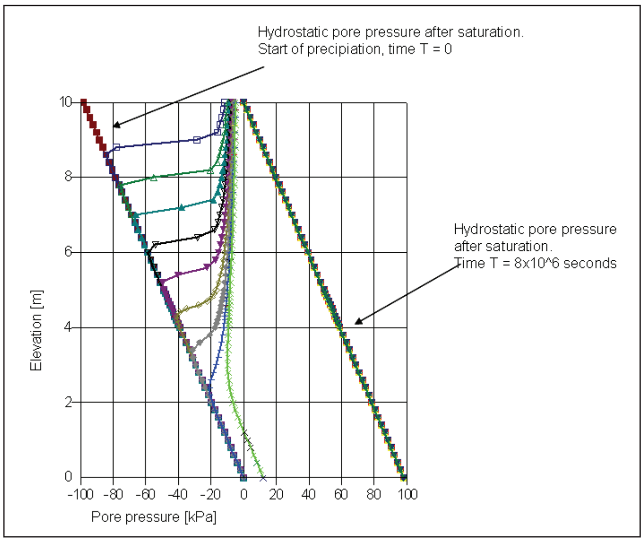


*Fig.10. Advance of the saturated zone with time in a 1-dimensional model of a 10 m high soil column during prolonged rainfall. Continuous rainfall is applied on the surface with intensity equal to the saturated permeability (Ksat) of the soil. The pore pressure distribution in a vertical section is shown for intervals of 50000 seconds, represented by the different curves. Elevation 10 m is at the soil surface (from Edgers 2003).*

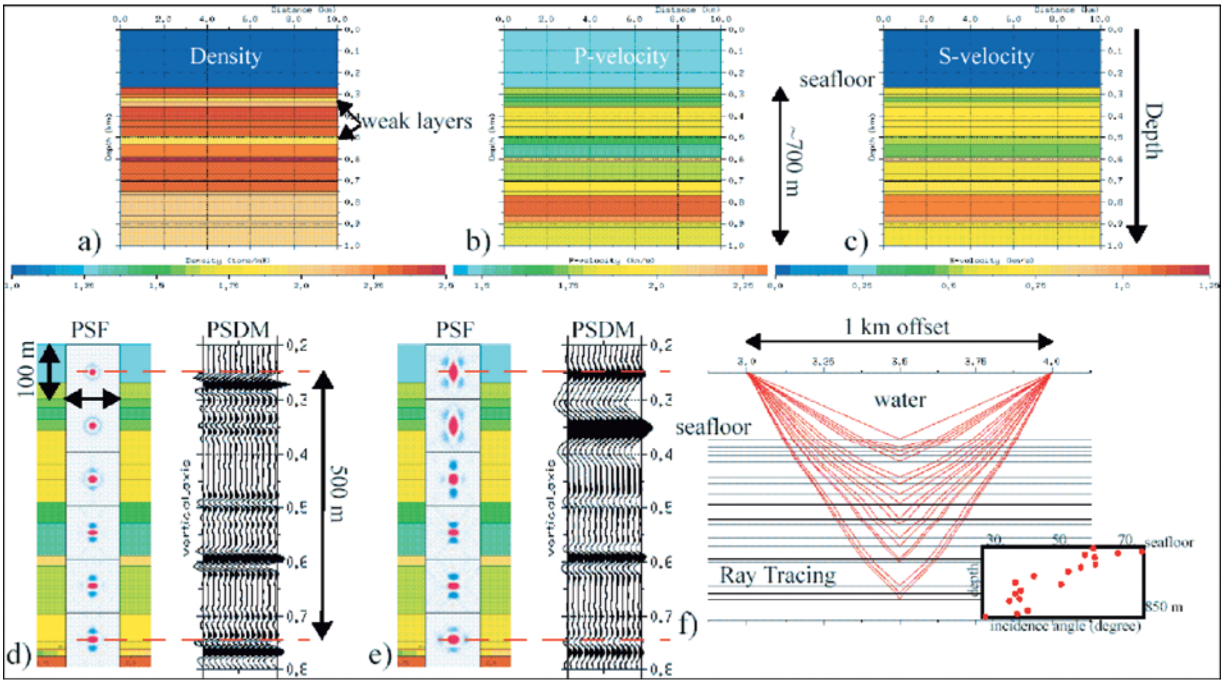


*Fig. 11. 1D synthetic model generated from geophysical well logs. a) Density, with identification of two weak layers, b) P-velocity, and c) estimated S-velocity (rock physics modelling). Corresponding Point-Spread Functions (PSF) and Pre-stack Depth Migrated (PSDM) sections for d) 0 m offset and e) 1000 m offset. f) Ray tracing for the 1000 m offset showing a large variation of incidence angle with depths (from 30 to 70 degrees depending on the layers).*

the pore pressures suddenly "snap" to create a hydrostatic pore pressure distribution (Fig. 10). If this reflects correctly the pore pressure in a slope, rainfall will result in rapid reduction of the slope's safety factor. The numerical flow calculations show that though the changes in the position of the ground water level (phreatic surface) may be small, or even negligible, changes in the suction in the upper soil layers may be very large. Observations of ground water level or pore pressure by traditional methods, such as piezometers or open wells will not give direct information on the actual pore pressures in the unsaturated zone.

## Offshore geohazards

Several ICG projects cover topics relevant for offshore geohazards. However, as a result of the focus on geohazards in deep-water areas by the oil industry, well exemplified through the Ormen Lange Project (Solheim et al. in press), a separate set of activities was defined under the title "Offshore geohazards". Prioritised themes include site surveys, geophysical tools, and the effects of pore pressure. Investigations in the Storegga Slide area offshore mid-Norway for the Ormen Lange gas field development, have generated an enormous amount of data related to offshore geohazards. Recent activities benefit to a large extent from this database, and one of our main goals is to utilise the data to improve the tools and techniques for offshore geohazard investigations. At present, the Ormen Lange investigations can to a large extent be regarded as the state-of-the-art in offshore geohazards.

### *Geophysical studies*

The main focus is placed on processing and techniques to enhance imaging in the upper few hundred meters of the offshore deposits. Submarine slopes often fail along "weak" layers, which can be very thin. The identification of such layers is therefore important. Extraction of quantitative information for geotechnical purposes from the seismic data is also an aim of the geophysical research at ICG.

Seismic wave propagation close to the seafloor and at shallow depths is complex. Understanding wave propagation at shallow depths below the seafloor is a necessity before acquiring and processing data. The project looks into various modelling tools to improve seismic acquisition, processing and imaging for identification of shallow, thin and weak layers. Attenuation, which is more important at shallow depths, decreases the amplitude of the waves and reduces their frequency content, hence degrading the resolution. Most of the standard techniques in seismic processing assume a rather simple earth model. Improved velocity models at shallow depths as well as model-based, amplitude-preserving processing are needed. Inversion techniques to estimate key parameters, such as shear strength, can only be applied if amplitudes have been preserved through the acquisition and processing stages. Only then, are good Amplitude-Versus-Offset (AVO) and Amplitude-Versus-Angle (AVA) analyses possible. A project has been initiated with the aim of improving the results of high resolution acquisition for shallow depths with a model-based processing and imaging approach.

Seismic resolution is a critical issue for interpreters. Point-Spread Functions (PSF), which is the response of a point scatterer after depth imaging, can be an aid in seismic imaging (Fig. 11). With an estimate of the PSF at each location of a heterogeneous structure, the seismic response of that structure can be estimated assuming that reflectors can be represented as a set of point scatterers (exploding reflector concept) (Fig. 11). Based on work conducted by NORSAR and UiO (Lecomte & Gelius 1998; Gelius & Lecomte 1999; Lecomte 2000; Gelius et al. 2002), the results of seismic imaging can be predicted without the need to generate and process synthetic data (Lecomte et al. 2003; Lecomte 2004). A method to compensate for resolution effects in a sort of deconvolution process has been developed and is now ready for ICG applications (Sjøberg et al. 2003; Bulteau 2004).

Other activities in geophysics at ICG are designed to extract more information from the seismic data, applicable for geotechnical engineering and risk assessment. Implementation of NORSAR's rock physics modelling tools for use in unlithified deposits is ongoing. Studies of shear-waves (S-waves) are necessary for the extraction for example of shear strength information from the seismic data. Data acquired by the use of NGI's newly developed S-wave source will be of particular interest for research related to the use of S-waves.The use of electromagnetic seabed logging techniques for geohazard purposes will also be studied.

*A "field laboratory" in Finneidfjord, Northern Norway*

An area of Sørfjorden near the community of Finneid has been a focus for scientific studies following a submarine slide in 1996. This encroached on to land causing loss of life and the disruption of railway and highway traffic. Previous studies focused on the slide event itself (Janbu 1996), as well as on the underlying geological conditions of the location (Longva et al. 1999, 2003; Best et al. 2003). Finneidfjord is an ideal field laboratory, as the conditions represent many of the contributing factors to coastal and offshore slides: submarine slopes, gas-charged soil layers, possible excess pore pressures, high sedimentation rates, etc. The purpose of the ICG project is to extend the database of relevant data for the location via sediment sampling and analysis, as well as long term monitoring of pore pressures, movements and gas seepage.

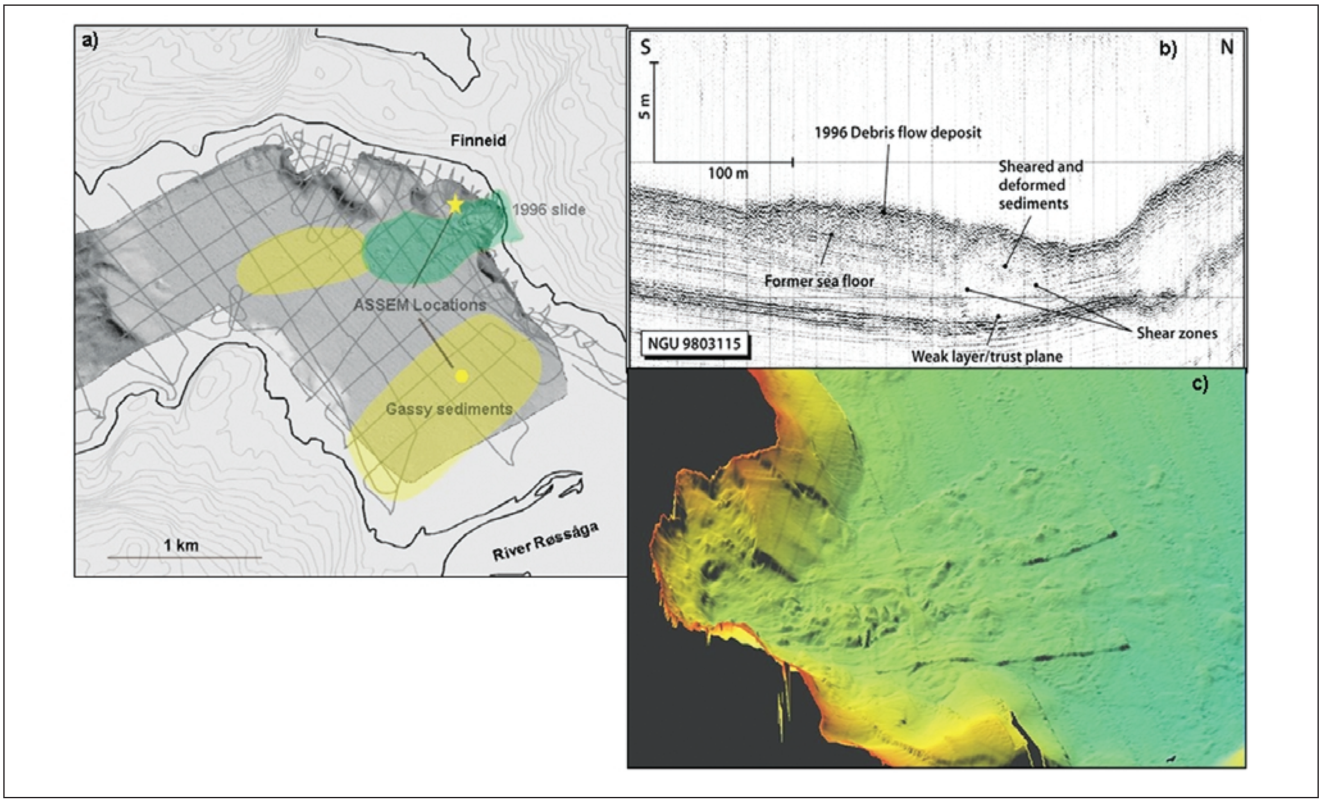


*Fig.12. The "Finneidfjord field laboratory". a) Map of the 1996 slide, areas of gassy sediments, high resolution seismic grid and the two ASSEM locations. Darker grey area shows shadow relief image of multibeam bathymetric data. b) Part of high resolution seismic section across the submarine part of the 1996 slide. c) Interferometric sidescan mosaic showing the 1996 slide*

The field work was conducted in cooperation with the EU project ASSEM (Array of Sensors for SEabed Monitoring for geohazards). The primary goal of ASSEM is the development of monitoring and sensor technology, with verification in pilot experiments. The ASSEM technology deployed includes autonomous benthic stations fitted with sensor strings for monitoring pore pressure in the seabed, methane gas seepage as well as settling and movements of the seabed. The installation of the ASSEM equipment was carried out in May 2004, in intact material adjacent to the 1996 slide, and at a location further out in the fjord basin where geophysical mapping indicated entrapped gas in the sediments (Fig. 12a). The ASSEM equipment was partially recovered in September 2004, but piezometer strings were re-deployed with autonomous loggers so as to continue monitoring until early summer 2005, and thereby obtaining a full year of pore pressure data to allow seasonal variations to be evaluated.

Swath bathymetric mapping using an interferometric sonar system, high resolution seismic acquisition, and sediment coring have been performed at the location (Fig. 12b, c). The bathymetric data were of very high quality and therefore important for delineating the slide lobes and for planning the coring campaign. The failure layer and also areas of potentially gas-charged sediments were mapped using the seismic data. The sediment cores, including samples of the failure layer ("weak layer"), are currently being analysed for a wide range of parameters; physical properties, age determination, mineralogy, geochemistry, texture, etc. Techniques developed in connection with the geophysical activities (above) will be tested to extract quantitive geotechnical information from the seismic data.

The data from the "Finneidfjord field laboratory" will greatly improve the understanding of the mechanisms of submarine sliding. With the extensive and detailed knowledge acquired for this location, it may also form an important test location for other techniques, such as the use of geophysical tools and sampling devices, as well as seismic enhancement and imaging techniques.

## Geographical information management and analyses for geohazard applications

Most modelling tools in Geographical Information Systems (GIS) are designed for the so-called cartographic overlay, meaning boolean, arithmetic, or statistical combination of data layers, and the modelling of static surface or sub-surface flow paths (Tomlin 1990). The rationale for using GIS models in geohazard assessment is to develop physically-based models that require limited input data and yet are simple enough to be applied to large areas (Fig. 13).

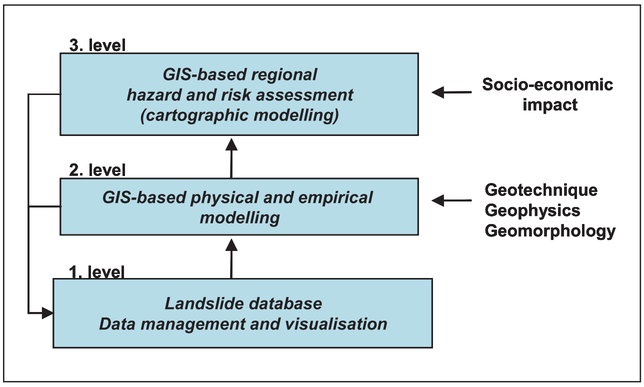


*Fig.13. Principles of GIS-applications within ICG.*

*GIS-based physical and empirical modelling*

ICG research in the field of GIS-based physical and empirical modelling of slope processes concentrates on the calculation of spatially distributed terrain attributes that are physically linked to landslide processes, and the application of these for spatial prediction of landslide hazard. Key tasks are the identification of source areas for landslides and to delineate hazard zones given one or more source areas. The work is based on parameterising and analysing gridded digital elevation models (DEM) within the framework of geomorphometry (e.g. Pike 1995).

A novel approach is the segmentation of the terrain into regions of homogeneous topography and with uniform surface processes. For each region, new attributes can be extracted based on its shape, internal topography and context in the terrain. Grid-based terrain modelling, where the terrain is looked upon as a continuous surface, is combined with an object-based paradigm where the terrain is looked upon as a mosaic of distinct units having characteristics that differ significantly from their neighbours (Fig. 14a). Delineation of regional hazard zones within this framework is based on flow-routing algorithms, typically finding the steepest down-slope route from a given point. Using algorithms that allow multiple flows, probability is distributed down a slope yielding the highest values along the steepest path (Fig. 14b).

*GIS-based regional hazard and risk assessment*

The prediction of areas affected by landslides (hazard) and the estimation of damages (risk) over large areas (regionalisation) require a combination of factors governing the hazard processes (e.g. topography, precipitation, etc) that are not physically comparable. This is done within the framework of cartographic modelling (Tomlin 1990) using regional map layers representing the spatial distribution of an attribute that expresses the degree to which the attribute on various locations contributes to the overall slide susceptibility (index

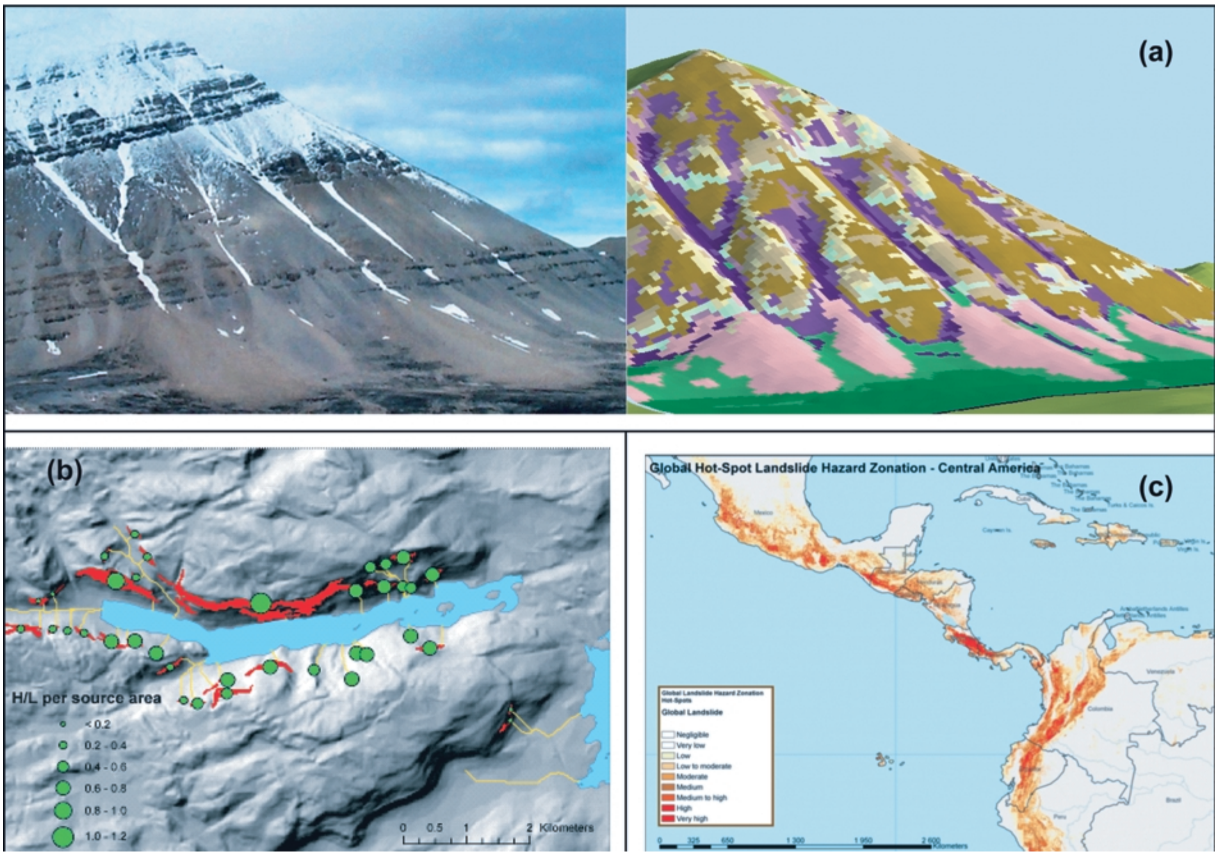


*Fig. 14. a) Example of spatial merging of a DEM for delineation of slope land forms, Sheteligfjellet, Ny-Ålesund, Svalbard (Romstad 2001). Five terrain attributes (slope, three types of curvature and topographic wetness index) have been clustered into nine classes using a combined segmentation-classification algorithm. Purple class corresponds well to source areas, pink class corresponds to areas of accumulation, b) Regional GIS-based analysis, identifying potential source areas (red), potential down-slope fall paths (yellow) and reach angle (green circles), c) Hazard map for central America.*

maps). A weighted overlay then results in a ranking on a susceptibility scale.

In a recent ICG activity, carried out for the ProVention Consortium in the international project "Global Natural Disaster Risk Hotspots", this approach was applied to delineate global hotspots for rapid mass movements, such as landslides and snow avalanches (Nadim et al. 2004). The probability of landslide and avalanche occurrences was estimated by modelling the physical processes and combining the results with statistics from past experiences. The main input data used were topography and slope angles, extreme monthly precipitation, seismic activity, soil type, mean temperature in winter months (for snow avalanches) and hydrological conditions. The risk computations were based on human losses as recorded in natural disaster impact databases. The estimation of expected losses was achieved by first estimating the physical exposure by combining the landslide frequency and the population exposed, and then doing a regression analysis using different sets of uncorrelated socioeconomical parameters. Validation of the global landslide hazard assessment was carried out through a limited number of case studies (Fig. 14c).

A challenge for the future development of such models is to make them less dependent on subjective judgement of input parameters. Implementing results from other ICG projects may make the models more objective, as triggering and run-out patterns can be translated to weighting factors using empirical or physical relationships. This is also necessary to couple GIS-based landslide hazard modelling with future climate change scenarios and to assess the impact of changing temperature and precipitation patterns on landslide occurrences and frequencies.

## SAR applications in geohazard assessment

### *Satellite-based radar interferometry*

Since the early 1990's, satellite-based radar interferometry has been used to identify large ground movements due to earthquakes and volcanic activity.

Differential SAR Interferometry (DInSAR) is a technique that compares the phases of multiple radar images of an area to measure surface change. It first became well known after an image of the Landers Earthquake deformation field was published by Massonnett et al. (1993). Data stacking methods that take advantage of a growing archive of radar images, as well as increasing computing power, have led to a large increase in the precision of the technique. The method has the potential to detect millimetre-scale surface deformation along the sensor – target line-of-sight. Both linear trends and seasonal fluctuations can be identified (Colesanti et al. 2003a, b).

When a pulse of radar energy is reflected back from the Earth to the satellite, two types of information are recorded, amplitude (displayed in typical SAR images), and phase of the wave. The phase of the wave upon return depends primarily on the distance between the satellite and the surface. Atmospheric effects are small. Differences in phase between two images are easily viewed by combining, or interfering, the two phase-images. In the resulting image, the waves will either reinforce or cancel one another, depending upon the relative phases. The resulting image is called an interferogramme and contains concentric bands of colour, or fringes that are related to topography and/or surface deformation. When the effects of topography are removed, the resulting image contains fringes due to surface deformation. Each fringe represents one-half wavelength of surface movement. In the case of the ERS satellites, this is less than 3 cm.

The many small reflective objects contributing to each pixel must remain unchanged or coherent between images, for radar interferometry to work. Decorrelation may occur as a function of the acquisition geometry (geometric decorrelation) and/or time (temporal decorrelation). In addition, atmospheric phase screen, mainly due to the effect of the local water vapour content, can be difficult to discriminate from ground deformation. These problems can be overcome by combining information from a series of radar images to identify stable natural reflectors (called permanent scatterers, PS) that are coherent over a long period of time (Ferretti et al. 2001). This technique (PSInSAR) was developed by the SAR processing group at Politecnico di Milano and is covered by several international patents.

Radar interferometry has been used to investigate fault movements, landslides and subsidence (Dehls et al. 2002; Dehls & Nordgulen 2003a, b). ICG is currently exploiting the PSInSAR technique to identify the slow precursor movements that often characterize both large rock-slope failures and soft-sediment failures. This capability will be tested in Trondheim and Drammen, where there are numerous quick-clay areas and a well-established record of events within the period 1992-2000. The technique is also being tested in western Norway, where large unstable rock masses are a significant threat. The interferometry activities are an integrated part of other ICG activities on both soil and rock slope failures.

### *Ground-based radar interferometry*

In addition to the satellite-based systems, the need for reliable, portable, high resolution measurement systems for monitoring of slope displacement has been recognized. A Ground based INterferometric Synthetic Aperture Radar system (GINSAR) is being developed at ICG. The radar shall be capable of measuring radial displacements down to 1 mm at a typical range of 3 km, and will utilise the synthetic aperture principle in order to achieve very high spatial cross-range resolution.

The use of the GINSAR system will be for a slope identified as a potential area for instability, by monitoring the slope displacements over time. The end product is a map of the slope front with colour codes showing the amount of radial displacement seen from the radar position. The activity includes research in fields such as radio wave propagation and radio wave scattering at the ground surface, radio antenna theory, development of processing routines, and hardware design. ICG expects the GINSAR system to become an important tool for future activities in monitoring both rock –and soil slopes and to be part of early warning systems.

## Slide dynamics and mechanics of mass disintegration

Reliable numerical models for slide initiation and run-out are a pre-requisite for choosing and implementing the right mitigation measures. Despite much research, models for the many different types of slides are still inadequate. In particular, the huge run-out distances on small slope gradients observed for many submarine slides are difficult to model. This is of great importance for the oil industry when designing seafloor facilities at deep-water fields, which are often located in continental slope settings. Consequently, modelling the dynamics of subaqueous slides has been an important activity at ICG since its initiation, as it followed naturally the large Ormen Lange Project, in which both the past Storegga Slide and potential future slides were major issues (Solheim et al. in press).

Run-out distances of several hundred kilometres on slope gradients less than 1° are not unusual for large submarine slides (Hampton et al. 1996; Locat & Lee 2002; Elverhøi et al. 2002). As a debris flow with equivalent material properties would not flow at such low gradients in air, one must conclude that ambient water plays a major role in the subaqueous environment. The mobilising effect of water on the debris flow must be dramatically greater than the resisting effects of increased drag force and reduced gravitational acceleration.

As a function of glacial – interglacial depositional variability, unstable sediment configurations have been built up, and slope failures have occurred periodically along the Norwegian continental margin, to produce glacial debris flows as well as submarine slides with volumes sometimes exceeding 1000 $km^3$, such as the Holocene Storegga Slide (3500 $km^3$) (Bryn et al. 2003, in press). Debris flow deposits of the Storegga Slide have been found at distances as far as 450 km from the escarpment, along sections sloping less than one degree. The recent investigations and mapping of the Storegga area provide a unique opportunity to combine modelling results, laboratory experiments and field data to improve models for the long run-out exhibited by subaqueous landslides.

Recently Mohrig et al. (1998, 1999) found experimentally that clay-rich subaqueous debris flows become naturally lubricated by a thin water layer, a phenomenon termed hydroplaning. Comparison with similar experiments carried out under subaerial conditions revealed a shorter run-out for the same type of material. Furthermore, experiments performed by Mohrig et al. (1999) and subsequent modelling by Huang and Garcia (1999) have showed that for subaqueous debris flows, the initial soil properties are not useful as input parameters for later modelling of the flow behaviour of the disintegrated mass. This means that parameters such as yield strength or a combination of sensitivity and remoulded yield strength (e.g. Locat & Demers 1988) provide too high values for parameter input to realistic submarine flow models.

A clear indication that lubrication or hydroplaning occurs in natural debris flows is the fact that some clay-rich debris flows generate out-runner blocks, which detach from the main front and flow farther (Ilstad et al. in press c). Computer simulations of hydroplaning (De Blasio et al. 2004a, in press), showed that the largest debris flows in Storegga could potentially reach distances as far as the ones observed. Thus, hydroplaning could explain the long run-out of the Storegga landslide, but not the continuity of smaller debris flow deposits along the slope (De Blasio et al. 2003). The laboratory conditions where hydroplaning is observed (only few metres length and a well-remoulded slurry with constant properties) are probably unrealistically favourable to water intrusion and lubrication. In contrast to the long run-out Storegga Slide, the smaller debris flows in the same area (run-out less than 20 km) are well described by a Bingham fluid model. In particular, for the small debris flows the Bingham model explains the empirical observation that the run-out increases as a power law function of the slide volume (Issler at al. 2003). Extending the pure

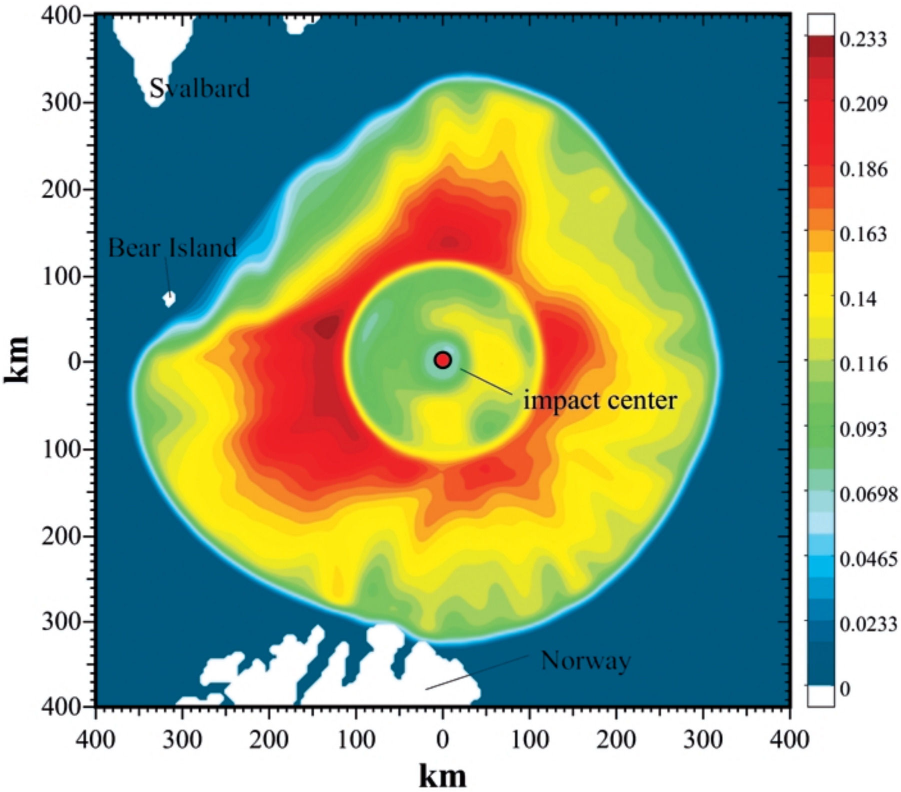


*Fig. 15. Maximum surface elevation of the tsunami generated by the Mjølnir asteroid, 15-60 minutes after the impact.*

Bingham model to larger debris flows from the same area, the simulation points fail to model the long run-out distances. This demonstrates once more that a so-far unexplained mechanism is active in enhancing the mobility of very large debris flows. Much remains to be understood in the disintegration of clay-rich material, particularly when associated with overconsolidated sediments.

Not all submarine debris flows consist primarily of clay. In some cases, silt, sand and gravel are sufficiently abundant to dictate the physical behaviour of the debris flow. These are commonly regarded as granular materials, where Coulomb frictional behaviour and dispersive pressure become much more important than cohesion. Experiments show that sand-rich debris flows are disintegrated by water shear during the flow, resulting in very complex turbulent flow patterns (Ilstad et al. in press a, b). Understanding the dynamics of emplacement of sand bodies will probably require a combination of physical experiments, field observations, theory, and numerical modelling.

## Tsunami modelling and prediction

Tsunamis have caused thousands of deaths and severe destruction worldwide. The three most severe known events in Norway occurred in Loen in 1905 and 1936 and in Tafjord in 1934, with a total of 174 deaths. Earthquakes, slides, and rockfalls are the principal triggers of large tsunamis. Asteroid impacts can also generate destructive tsunamis, but these are rare events. The tsunami research activity at ICG focuses on the development of numerical models for tsunami generation, propagation, and run-up. These numerical tools are applied to improve the understanding of historical tsunamis, and to prevent damage due to potential future tsunamis. The modelling is therefore important for early warning and mitigation planning.

The project "*Tsunamis generated by asteroid impacts, rockslides and landslides*" granted by The Research Council of Norway programme BeMatA, contributes to the tsunami activity at ICG. The model development focused on domain decomposition methods for long wave equations (Glimsdal et al. in press), and the numerical stability of long wave equations applicable to tsunami modelling, the latter having a perticular importance for modelling of tsunamis in fjords. Moreover, the Mjølnir asteroid impact in the Barents Sea 150 million years ago is now well described in the near field of the impact (Shuvalov et al. 2001). The tsunami generated by the Mjølnir impact was probably enormous (Fig. 15). Simulations indicate a maximum surface elevation of the wave front of about 300 m 15 minutes after the impact, and 40 m after 7.5 hours.

Deposits from the tsunami generated by the Holocene Storegga Slide have been found in coastal areas around

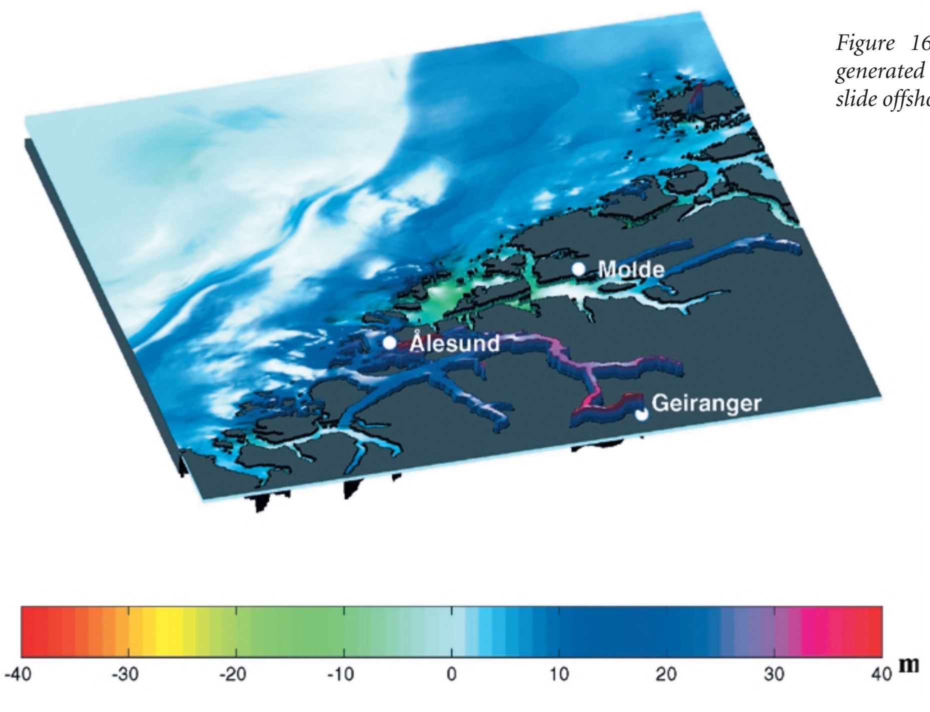


*Figure 16. Snapshot of the wave generated by the Storegga submarine slide offshore Mid-Norway.*

the Norwegian Sea and North Sea, from the east coast of England to beyond the Arctic Circle in northern Norway (Bondevik et al. in press). This prehistoric tsunami (Fig. 16) and potential future tsunamis generated by slides in the Storegga area were analysed with a two-model approach taking the retrogressive behaviour of the slide (Kvalstad et al. in press) into account. The slide volume, maximum slide velocity, initial slide acceleration, and characteristics of the retrogressive motion were shown to be of key importance for the characteristics and the propagation of the generated waves (Løvholt et al. in press; Haugen et al. in press). Simulations of the tsunami generated by the Storegga slide corresponded well with the observed tsunami deposits (Bondevik et al. in press). Back-calculations of tsunamis generated by submarine gravity mass flows in the Trondheim area are also underway.

Tsunamis constitute a serious natural hazard for the populations in exposed areas. ICG has a special focus on the assessment of potential tsunamis generated by rockslides in Norwegian fjords, lakes and hydropower reservoirs (ICG 2004). The potential for tsunamis near Åkerneset in western Norway will be investigated using numerical models, including both model development and assessment of the impact area of potential waves.

One of the future challenges for the tsunami research at ICG is the development of more advanced numerical tsunami models, i.e. Navier Stokes type of models, suitable to handle strong non-linearities, and to couple different long-wave models in a two dimensional domain decomposition framework.

## Concluding remarks

The activities at ICG span the entire "value chain" of geohazard assessment. Field techniques and procedures as well as instruments are being designed. Examples are the land-based portable GINSAR system for high resolution monitoring of deformation, development of satellite-based monitoring, routines for pore pressure measurements (both sub-sea and on land), and acquisition of higher resolution seismic data. Tools and methods for processing and analysis of data form an important part of the development activities. Examples include earthquake risk analysis, geohazards related GIS applications, and various geophysical tools for enhanced seismic resolution and extraction of physical parameters from seismic data. Given a large and expanding amount of data from field investigations and laboratory experiments, numerical modelling becomes increasingly important. ICG includes significant activities related to the development of improved models for actual geohazard problems. Examples include the modelling of slide dynamics and run-out, and the tsunami modelling.

Risk and vulnerability analyses form an integrated part of all practical geohazards work. This is clearly exemplified through ICG's involvement in projects in developing countries, where improved analyses and mitigation measures could save numerous lives and huge costs. In the near future, ICG will also focus on research related to early warning systems and mitigation measures.

As a consortium of five different partners, representative of private research foundations, state organisations and universities and located at different sites, ICG faced a number of organisational challenges. Establishing a central, main office facility was an important success factor. The wide range of research conducted at ICG, only briefly described above, and the international interest shown in it, witness that research on geohazards is timely. This is also clearly demonstrated by the large number of inquiries received from students, post-doctoral fellows and guest researchers interested in doing research at ICG.

Increasing public awareness of geohazards and the establishment of a geohazard-focused programme have been important for recruiting students. The graduate studies in geohazards started at the two university partners, UiO and NTNU, are a success. This is an important aspect of ICG, since recruiting new scientists is a prerequisite for ensuring increased research activity with respect to geohazards. With a potentially changing climate in the future, many of the boundary conditions for geohazards, such as the level and frequency of extreme weather events, may change, making intensified research even more important.

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## References


Anda, E., Blikra, L.H. & Braathen, A. 2002: The Berill fault - first evidence of neotectonic faulting in southern Norway. *Norwegian Journal of Geology 82*, 175-182.

Best, A.I., Clayton, C.R.I., Longva, O. & Szuman, M. 2003: The role of free gas in the activation of submarine slides in Finneidfjord. *In* J. Locat & Mienert, J. (eds.), *Submarine Mass Movements and their Consequences. Proceedings, First International Symposium,* 491-498, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Bhasin, R. & Kaynia, A.M. 2004: Static and Dynamic Simulation of a 700 m High Rock Slope in Western Norway. *International Journal of Engineering Geology 71*, 213-226.

Bhasin, R., Kaynia, A., Blikra, L.H., Braathen, A. & Anda, E. 2004: Insights into the deformation mechanisms of a jointed rock slope subjected to dynamic loading. *International Journal of Rock Mechanics & Mining Sciences 41,* 470-471.

Blikra, L.H., Longva, O., Braathen, A., Anda, E., Dehls, J. & Stalsberg, K. in press: Rock-slope failures in Norwegian fjord areas: examples, spatial distribution and temporal pattern. *In* Evans, S.G., Scarawcia Mugnozza, G., Strom, A.L. & Hermanns, R.L. (eds.), *Massive rock slope failure: new models for hazard assessment.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Bondevik, S., Svendsen, J.I., Johnsen, G., Mangerud, J. & Kaland, P.E. 1997: The Storegga tsunami along the Norwegian coast, its age and run-up. *Boreas 26*, 29-53.

Bondevik, S. Løvholt, F., Harbitz, C.B., Mangerud, J., Dawson, A. & Svendsen, J.I. in press: The Storegga slide tsunami - comparing field observations with numerical simulations. *Marine and Petroleum Geology.*

Braathen, A., Blikra, L.H., Berg, S.S. & Karlsen, F. 2004: Rock-slope failures of Norway; type, geometry, deformation mechanisms and stability. *Norwegian Journal of Geology 84*, 67-88.

Bryn, P., Berg, K., Forsberg, C.F., Solheim, A. & Kvalstad, T.J. in press: Explaining the Storegga Slide. *Marine and Petroleum Geology.*

Bryn, P., Solheim, A., Berg, K., Lien, R., Forsberg, C. F., Haflidason, H., Ottesen, D. & Rise, L. 2003: The Storegga slide complex: repeated large scale sliding in response to climatic cyclicity. *In* Locat, J. & Mienert, J. (eds.), *Submarine Mass Movements and Their Consequences,* 215-222. Kluwer Academic Publishers.

Bulteau, M., 2004: Controlling and correcting resolution effects in marine seismics: application to better assessment of offshore geohazards. Civ. Eng. Thesis, EOST, Louis Pasteur University, Strasbourg, France, ICG report 2004-6-1.

Colesanti, C., Ferretti, A., Novali, F., Prati, C. & Rocca, F. 2003a: SAR monitoring of progressive and seasonal ground deformation using the Permanent Scatterers Technique. *IEEE Transactions on Geoscience and Remote Sensing 41*, 1685-1701.

Colesanti, C., Ferretti, A., Prati, C. & Rocca, F. 2003b: Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. *Engineering Geology 68*, 3-14.

Dahle, H. 2004: Analyse av skråningsstabilitet for Oppstadhornet. Unpublished Master thesis, NTNU.

De Blasio, F. V., Issler, D., Elverhøi, A., Harbitz, C. B., Ilstad, T., Bryn, P., Lien, R., and Løvholt, F. 2003: Dynamics, velocity and run-out of the giant Storegga slide. *In* Locat, J. & Mienert, J. (eds.): *Submarine Mass Movements and Their Consequences. Proceedings, First International Symposium,* 223-230. Kluwer Academic Publishers, Dordrecht, The Netherlands.

De Blasio, F.V., Elverhøi, A., Issler, D., Harbitz, C.B., Bryn, P. & Lien, R. in press: Flow models of natural debris flows originated from overconsolidated clay materials. *Marine Geology.*

De Blasio, F.V., Engvik, L., Harbitz, C.B. & Elverhøi, A. 2004: Hydroplaning and submarine debris flows. *Journal of Geophysical Research, 109, C1*, Paper C01002, 15pp.

Dehls, J.F. & Nordgulen, O. 2003a: Analysis of InSAR data over Romeriksporten. *Geological Survey of Norway Report 2003.076*, 18pp.

Dehls, J.F. & Nordgulen, O. 2003b: Evaluation of the use of PSInSAR for the monitoring of subsidence in Oslo region. *Geological Survey of Norway Report 2003.105*, 45pp

Dehls, J.F., Basilico, M. & Colesanti, C. 2002: Ground deformation monitoring in the Ranafjord area of Norway by means of the Permanent Scatterers technique. *Geoscience and Remote Sensing Symposium IGARSS '02. 2002 IEEE International 1*, 203-207.

Edgers, L. 2003: Unsaturated soils and rain-induced slides. Effects of infiltration on pore pressures and stability. NGI-report no. 20031087-1.

Elverhøi, A., De Blasio, F. V., Butt, F. A., Issler, D., Harbitz, C., Engvik, L., Solheim, A. & Marr, J. 2002: Submarine mass-wasting on glacially influenced continental slopes-processes and dynamics. *In* Dowdeswell, J.A. & Cofaigh, C.Ó (eds.), *Glacier-Influenced Sedimentation on High-Latitude Continental Margins.* Geological Society of London, Special Publication 203, 73–87.

Ferretti, A., Prati, C. & Rocca, F. 2001: Permanent scatterers in SAR interferometry: *IEEE Transactions on Geoscience and Remote Sensing 39*, 8-20.

Gelius, L.-J. & Lecomte, I. 2000: The resolution function in linearized Born and Kirchhoff inversion. *In* Hansen, P.C, Jacobsen, B.H. & Mosegaard, K. (eds.), *Lecture Notes in Earth Sciences: Methods and Applications of Inversion.* 129-141, Springer Verlag.

Gelius, L.-J., Lecomte, I. & Tabti, H. 2002: Analysis of the resolution function in seismic prestack depth imaging. *Geophysical Prospecting 50*, 505-515.

Glimsdal, S., Pedersen, G.K. & Langtangen, H.P. in press: An investigation of overlapping domain decomposition methods for one-dimensional dispersive long wave equations. *Advances in Water Resources.*

Hampton, M. A., Lee, H. J. & Locat, J. 1996: Submarine Slides. *Reviews of Geophysics 34*, 33–59.

Haugen, K.B., Løvholt, F. & Harbitz, C.B. in press: Fundamental mechanisms for tsunami generation by submarine mass flows in idealised geometries. *Marine Petroleum and Geology.*

Huang X. & Garcia, M.H. 1998: A Herschel-Bulkley model for mud flow down a slope. *Journal of Fluid Mechanics 374*, 305-333.

Huang, X. & Garcia, M.H. 1999: Modeling of non-hydroplaning mud flows on continental slopes. *Marine Geology 154*, 132–142.

ICG 2004: Slide-generated waves in reservoirs. ICG Report 10-2004-1.

Ilstad, T., Elverhøi, A., Issler, D., Marr, J. & Parker, G. in press a: Experimental studies of subaqueous debris flow (I) – Measurements of pore-fluid pressure and total stress. *Marine Geology.*

Ilstad, T., Elverhøi, A., Issler, D., Marr, J. & Parker, G. in press b: Experimental studies of subaqueous debris flow (II)– particle tracking. *Marine Geology.*

Ilstad, T., De Blasio, F.V., Engvik, L., Elverhøi, A., Longva, O. & Marr, J. in press c: Submarine outrunner blocks from debris flows: laboratory experiments and field observations in Finneidfjord, Norway. *Marine Geology.*

Intergovernmental Panel on Climate Change (IPCC) 2001. Climate Change 2001: The Science of Climate Change, Cambridge University Press, Cambridge, U.K.

Issler, D., De Blasio, F. V., Elverhøi, A., Ilstad, T., Bryn, P. & Lien, R. 2003: Issues in the assessment of gravity mass flow hazard in the Storegga area off the western Norwegian coast. *In* Locat, J. & Mienert, J. (eds.), *Submarine Mass Movements and Their Consequences,* 231-238. Kluwer Academic Publishers.

Janbu, N. 1996: A comprehensive evaluation of the conditions before, during and after the Finneidfjord slide 20 June 1996. Report 1, revision 1.

Kvalstad, T.J. Andresen, L., Forsberg, C.F., Berg, K., Bryn, P., & Wangen, M. in press: The Storegga slide: Evaluation of triggering sources and slide mechanics. *Marine and Petroleum Geology.*

Lecomte, I. 1999: Local and controlled prestack depth migration in complex areas. *Geophysical Prospecting 47*, 799-818.

Lecomte, I. 2004: Simulating Prestack Depth Migrated Sections. Extended Abstracts, EAGE 66th Conference and Exhibition, Paris, June 2004, P071.

Lecomte, I. & Gelius, L.-J. 1998: Have a look at the resolution of prestack depth migration for any model, survey and wavefields. Extended Abstracts, SEG 68th Annual Meeting, SP 2.3.

Lecomte, I., Gjøystdal, H. & Drottning, Å. 2003: Simulated Prestack Local Imaging: a robust and efficient interpretation tool to control illumination, resolution, and time-lapse properties of reservoirs. Extended Abstracts, SEG 73nd Annual Meeting, Dallas.

Locat, J. & Demers, D. 1988: Viscosity, yield strength, remoulded strength and liquidity index relationships for sensitive clays. *Canadian Geotechnical Journal 25*, 799-806.

Locat, J. & Lee, H. J. 2002: Submarine Landslides: Advances and Challenges. *Canadian Geotechnical Journal 39*, 193–212.

Longva, O., Blikra, L. H., Mauring, E., Thorsnes, T. & Reither, E. 1999: Testprosjekt Finneidfjord; integrert skredfarekartlegging - metodevurdering. Geological Survey of Norway Report 1999.051.

Longva, O., Janbu, N., Blikra, L.H. & Bøe, R. 2003: The 1996 Finneidfjord Slide: seafloor failure and slide dynamics. *In* Locat, J. & Mienert, J. (eds.), *Submarine Mass Movements and their Consequences. Proceedings, First International Symposium*, 531-538, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Løvholt, F., Harbitz, C.B. & Haugen, K.B. in press: A parametric study of tsunamis generated by sybmarine slides in the Ormen Lange/Storegga area off western Norway. *Marine Petroleum and Geology.*

Massonnett, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K. & Rabaute, T. 1993: The displacement field of the Landers earthquake mapped by radar interferometry. *Nature 364*, 138-142.

Mohrig, D., Elverhøi, A. & Parker, G. 1999: Experiments on the relative mobility of muddy subaqueous and subaerial debris flows, and their capacity to remobilize antecedent deposits. *Marine Geology 154*, 117–129.

Mohrig, D., Whipple, K. X., Hondzo, M., Ellis, C. & Parker, G. 1998: Hydroplaning of subaqueous debris flows. *Geological Society of America Bulletin 110*, 387–394.

Molina S. & Lindholm, C. in press: A logic tree extension of the capacity spectrum method developed to estimate seismic risk in Oslo, Norway. *Journal of Earthquake Engineering.*

Molina S. & Lindholm, C. 2004: HAZUS_ICG; Version 1.0. User and Technical Manual.

Nadim, F., Gregoire, A.S., Rodriguez, C.& Peduzzi, P. 2004: Global landslide and avalanche hotspots: First-order identification of global slide and avalanche hotspots. Norwegian Geotechnical Institute (NGI), Report no. 20021613-1.

Nakamura Y. 1989: Method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Railway Technical Research Institute, 30, No. 1

NGI 1996: Åkernes landslide. General description of the Åkernes slide area and control measures. NGI Report 585910-9.

Panthi K. K. & Nilsen B. in press: Numerical Analysis of Stresses and Displacements for the Tafjord Slide, Norway. *Bulletin of Engineering Geology and the Environment.*

Pike, R. J. 1995: "Geomorphometry - process practice and prospect." *Zeitschrift für Geomorphologie, Suppl. 101*, 221-238

Romstad, B. 2001: Improving relief classification with contextual merging. *In*: J. T. Bjørke, J.T. & Tveite, H. (eds.): *Proceedings of the 8th Scandinavian Research Conference on Geographical Information Science.* ScanGIS'2001, 25th-27th June 2001. Ås, Norway, 3-14.

Shuvalov, V., Dypvik, H. & Tsikalas, F. 2002: Numerical simulations of the Mjølnir marine impact crater. *Journal of Geophysical Research 107*, E7 10.1029, 1,1 TO 1-13.

Sjøberg, T., Gelius, L.-J. & Lecomte, I. 2003: 2D deconvolution of seismic image blur, Extended Abstracts, SEG 73nd Annual Meeting.

Solheim, A., Bryn, P., Sejrup, H.P., Mienert, J., & Berg, K., in press: Ormen Lange – an integrated study for the safe development of a deep-water gas field within the Storegga Slide Complex, NE Atlantic continental margin; Executive summary. *Marine and Petroleum Geology.*

Tomlin, C.D. 1990: *Geographic information systems and cartographic modelling.* Englewood Cliffs, N.J., Prentice Hall.