Hazard, Reliability and Risk Assessment - Research and Practice for Increased Safety

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ABSTRACT

Society increasingly requires the engineer to quantify and manage the risk which people, property and the environment are exposed to. The role of the geotechnical engineering profession is to reduce exposure to threats, reduce risk and protect people. Hazard, reliability and risk approaches are excellent tools to assist the geotechnical engineer in design, selection of engineering foundation solutions and parameters and decision-making. The significance of factor of safety is discussed, and basic reliability and risk concepts are briefly introduced. The importance of designing with a uniform level of reliability rather than a constant safety factor prescribed in codes and guidelines is illustrated. The paper illustrates the use of the reliability and risk concepts with "real life" case studies, in particular for situations encountered for Nordic environments. The calculation examples are taken from a wide realm of geotechnical problems, including avalanche, railroad safety, mine slopes and soil investigations. The synergy of research and practice and their complementarity for increasing safety and cost-effectiveness is illustrated. With the evolution of reliability and risk approaches in geotechnical engineering, the growing demand for hazard and risk analyses in our profession and the societal awareness of hazard and risk makes that the methods and way of thinking associated with risk need to be included in university engineering curricula and in most of our daily designs.

Keywords: Hazard, risk, risk assessment, uncertainties, factor of safety.

1 INTRODUCTION

More and more, society requires that the engineer quantify the risk to which people, property and the environment can be exposed. The geo-engineering profession should increasingly focus on reducing exposure to threats, reducing risk and protecting people. The paper shows how concepts of hazard, risk and reliability can assist with safer design and in decision-making. After an introduction of reliability concepts, the paper presents "real life" case studies where risk and reliability tools provided insight for informed decision-making. Because factor of safety remains the main indicator of safety in practice, its significance for design is also briefly discussed in terms of reliability. The tolerable and acceptable risk and risk perception are illustrated.

There is a need for increased interaction among disciplines as part of providing a soundly engineered solution. The engineer’s role is not only to provide judgment on safety factor, but also to take an active part in the evaluation of hazard and risk.

Societal awareness and need for documenting the safety margin against 'known' and 'unknown' hazards require that the engineer manage risk.

The calculation examples presented in the paper are taken from a wide realm of geoscientific problems, including avalanches, hazards and risk associated with railroad traffic, mine slopes and soil investigations.

2 EXPOSURE TO GEO-RISKS

Society is exposed to both natural and human-induced risks, and while the risk can never be eliminated, the engineer's goal is to reduce the risk to levels that are acceptable or tolerable. Coordinated, international, multidisciplinary efforts are required to develop effective societal response to geo-risks. The needs in practice are accentuated by recent events with disastrous impact:

- Recent earthquakes in El Salvador (2001), India (2001), Iran (2003), Pakistan (2005), China (2008), Haiti (2010), Japan (2011), Christchurch (2011) and Nepal (2015) caused high fatalities and made many homeless. In 2010, earthquakes ravaged Chile, China, Sumatra and Iran. Earthquakes often lead to cascading events such as landslides, avalanches, lake outburst floods and debris flows.
- Tsunamis (e.g. Indian Ocean 2004; Tōhoku 2011) cause enormous personal and societal tragedies. The Japan disaster showed the vulnerability of a strong prosperous society, and how cascading events paralyzed an entire nation, with worldwide repercussions. Since 2004, at least eight tsunamis have caused fatalities. In Norway, tsunamigenic rock slides caused the loss of 174 lives in the past 110 years.
- The Baia Mare tailings dam breach for a gold mine in Romania (2000) released cyanide fluid, killing tons of fish and poisoning the drinking water of 2 million people in Hungary. The Aznalcóllar tailings dam failure in Spain (1998) released 68 million m^3 of contaminated material into the environment. The Mount Polley tailings dam breach (2014) was Canada's largest environmental disaster ever.
- The collapse of Skjeggestad bridge in Norway and of a viaduct at Scillato in Italy, both due to landslides in early 2015, as well as unexpected failures in tunnels, cost millions of dollars for repairs. Roads and railways in Norway are increasingly exposed to landslide and avalanche hazards. Often, the fact that no lives were lost in these four examples is only due to coincidental sets of lucky circumstances.

Many lives could have been saved if more had been known about the risks associated with the hazards and if risk mitigation measures had been implemented. A proactive approach to risk management is required to reduce the loss of lives and material damage. A milestone in recognition of the need for disaster risk reduction was the approval by 164 United Nations (UN) countries of the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters" (ISDR 2005).

Since the 80's, hazard and risk assessment of the geo-component of a system has gained increased attention. The offshore oil and gas, hydropower and mining sectors were the pioneers in applying the tools of statistics, probability and risk assessment in geotechnical engineering. Environmental concerns and natural hazards soon adopted hazard and vulnerability assessment.

Whitman (1996) offered examples of probabilistic analysis in geo-engineering. He concluded then that probabilistic methods are tools that can effectively supplement traditional methods for geotechnical engineering projects, provide better insight into the uncertainties and their effects and an improved basis for interaction between engineers and decision-makers. Nowadays, the notion of hazard and risk is a natural question in the design of most constructions

3 IMPORTANCE OF UNCERTAINTIES IN GEOTECHNICAL ENGINEERING

3.1 Uncertainty-based analyses

Accounting for the uncertainties in foundation analysis has now become a frequent requirement. Statistics, reliability and risk estimates are useful decision-making tools for geotechnical problems that can account for the uncertainties. Uncertainty-based analyses are needed because geotechnical design is not an exact science. Uncertainty in foundation performance, due to soil spatial variability, limited site exploration, limited calculation models and limited soil parameter evaluation, is unavoidable.

Uncertainty-based analysis can be done with the statistical and reliability theory tools available today (Lacasse 1999; Ang and Tang 2007; Baecher and Christian 2003).

It is important to adopt approaches that inform of and account for the uncertainties. Only by accounting for the uncertainties, can the designer get insight in the risk level.

Risk considers the probability of an event occurring and the consequences of the event should it occur. The purpose of risk analysis is to support the decision-making process, given plausible scenarios. The probabilities are the quantification of one's uncertainty.

3.2 Factor of safety and uncertainties

The factor of safety gives only a partial representation of the true margin of safety that is available. Through regulation or tradition, the same value of factor of safety is applied to conditions that involve widely varying degrees of uncertainty. That is not logical.

The factor of safety against instability is a measure of how far one may be from failure. Factors of safety are applied to compensate for uncertainties in the calculation. If there were no uncertainties, the factor of safety could be very close to 1.

There is therefore always be a finite probability that the foundation slope. Defining the level of the finite probability that is tolerable is the challenge. The geotechnical engineer should provide insight in this discussion. To select a suitable factor of safety, one therefore needs to estimate the uncertainties involved. There exists no relationship between safety factor based on limit equilibrium analysis and annual probability of failure. Any relationship would be site-specific and depends on the uncertainties in the analysis.

3.3 Factors of safety for a piled installation

As example of deterministic (conventional) and probabilistic analyses of the axial capacity of an offshore piled foundation were done. First, before pile driving (1975), with limited information and limited methods of interpretation of the soil data, and second, 20 years later, when more information had become available and a reinterpretation of the data was done with the new knowledge accumulated over the 20 years. The soil profile consisted of mainly stiff to hard clay layers, with thinner layers of dense sand in between. The profiles selected originally showed wide variability in the soil strength, with considerably higher shear strength below 20 m. No laboratory tests, other than strength index tests, were run for the 1975 analyses to quantify the soil parameters, and sampling disturbance added to the scatter in the results.

During pile installation, records were made of the blow count during driving. These records were used 20 years later to adjust the soil profile, especially the depth of the stronger bearing sand layers. New samples were also taken and triaxial tests were run. The new evaluation indicated less variability in the strength than before.

The requirement was a factor of safety of 1.50 under extreme loading and 2.0 under operation loading. The analyses used the first-order reliability method (FORM). Each of the parameters in the calculation and the calculation model were taken as random variables, with a mean and a standard deviation and a probability density function.

Figure 1 presents the results of the analyses. The newer deterministic analysis gave a safety factor (FS) of 1.4, which was below the requirement of 1.50. However, the newer information reduced the uncertainty in both soil and load parameters. The pile with a safety factor of 1.4 has significantly lower failure probability (P_f) that the pile which had a safety factor of 1.79 twenty years earlier. Taking into account the uncertainties showed that the pile, although with lower safety factor, had higher safety margin than the pile with a much higher safety factor calculated at the time of pile driving.

The implications of Figure 1 are very important. A foundation with a central factor of safety of 1.4 was safer than a foundation with a higher central factor of safety 1.8 and had a much lower annual probability of failure. Factor of safety alone is not a sufficient measure of the actual safety.

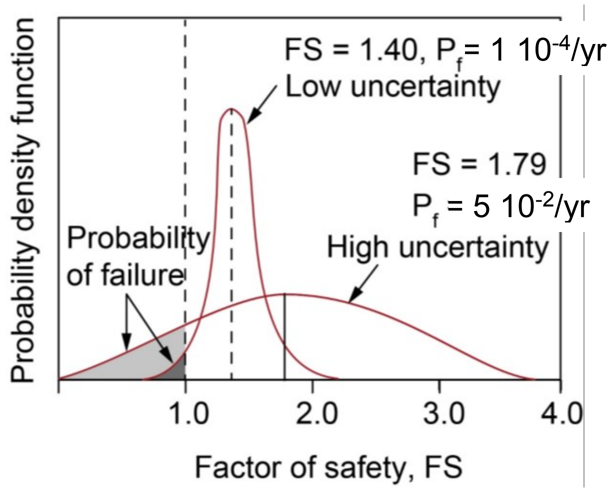

Figure 1 Factor of safety and probability of failure.

One also needs to be aware that the factor of safety is never zero. Factor of safety is not a sufficient indicator of safety margin because the uncertainties in the analysis parameters affect probability of failure. The uncertainties do not intervene in the conventional calculation of safety factor.

Figure 1 illustrates with probability density functions the notion that the factor of safety alone is not a sufficient measure of the margin of safety. In addition, the safety factor should not be a constant deterministic value, but should be adjusted according to the level of uncertainty. Ideally, one could calibrate the required safety factor that would ensure a target annual probability of failure of for example 10^{-3} or 10^{-4}.

The essential component of the estimate of an annual probability of failure estimate is geotechnical expertise. A clear understanding of the physical aspects of the geotechnical behavior to model is needed. The experience and engineering judgement that enter into all decisions for parameter selection, choice of most realistic model and reasonableness of the results, are also absolutely essential components. The most important contribution of uncertainty-based concepts to geotechnical engineering is increasing awareness of the uncertainties and of their consequences. The methods used to evaluate uncertainties, annual probability of failure are tools, just like any other calculation model or computer program.

3.4 Comparison of two analysis approaches

Stability analyses were done with the effective stress (ESA) and the total stress (TSA) approaches. The first approach uses friction angle (ϕ'), cohesion and pore pressures (or the effective stress path), the second uses undrained shear strength and in situ effective stresses (total stress path). Factor of safety was defined as the ratio between the tangent of the friction angle at failure and the tangent of the friction angle mobilized at equilibrium for the ESA approach. For the TSA approach, the factor of safety was defined as the ratio between the undrained shear strength and the shear stress mobilized at equilibrium.

A shallow foundation on a contractive and on a dilative soil was analyzed (Nadim *et al* 1994; Lacasse 1999). The effective stress paths for each soil type are illustrated in Figure 2. The "true" safety margin for the foundation (or probability of failure, P_f) is independent of the method of analysis.

Table 1 presents the results of the calculations. Depending on soil type, the computed annual probability of failure differed significantly for the two approaches.

The results of the analyses, both deterministic (in terms of factor of safety, *FS*) and probabilistic (in terms of annual probability of failure, P_f) showed significant differences for the dilatant soil as the uncertainties in the soil parameters influenced differently the failure probability.

For the effective stress approach, the uncertainties in the cohesion and pore pressure close to failure had the most significant effect on the probability of failure. For the total stress approach, the uncertainties in undrained shear strength had the most significant effect on the probability of failure. To have the two analysis methods give consistent results at a safety factor of 1.0, a model uncertainty would have to be included. Again factor of safety gives an erroneous impression of the actual safety margin.

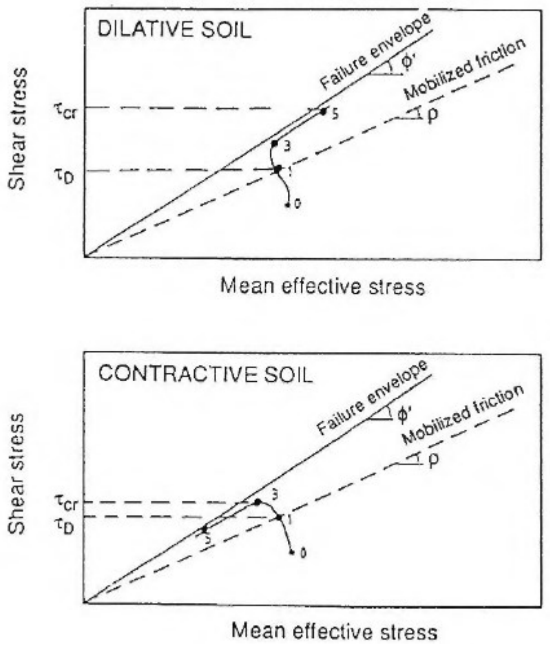

Figure 2. Mobilized friction angle and available shear strength approaches for contractive and dilative soils[1]*.*

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[1] Notation: ρ is the mobilized friction angle; numbers on stress path indicate shear strain in percent; τ_{cr} is the critical shear stress at yield; τ_D is the mobilized shear stress in design; in the ESA analysis, the material coefficient is $\tan\phi'/\tan\rho$; in the TSA analysis, the material coefficient is τ_{cr}/τ_D.

Table 1. Stability analyses with two approaches.

Analysis	Soil type	*FS*	Annual P_f
ESA	Contractive	1.9	1.7×10^{-5}
TSA	Contractive	1.4	2.5×10^{-3}
ESA	Dilative	1.4	6.7×10^{-3}
TSA	Dilative	1.5	2.3×10^{-6}

Notation		
	ESA	Effective stress analysis
	TSA	Total stress analysis
	FS	Factor of safety
	P_f	Probability of failure

4 BASIC RELIABLITY CONCEPTS

4.1 Terminology

The terminology used in this paper is consistent with the recommendations of ISSMGE TC32 (2004) Glossary of Risk Assessment Terms:

Danger (Threat): Phenomenon that could lead to damage, described by geometry, mechanical and other characteristics, involving no forecasting.

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

Exposure: The circumstances of being exposed to a threat.

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

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

Figure 3 illustrates how hazard, exposure and vulnerability contribute to risk with the so-called "risk rose".

4.2 Risk assessment and management

Risk management refers to coordinated activities to assess, direct and control the risk posed by hazards to society. Its purpose is to reduce the risk. The management process is a systematic application of management policies, procedures and practices. Risk management integrates the recognition and assessment of risk with the development of appropriate treatment strategies. Understanding the risk posed by natural events and man-made activities requires an understanding of its constituent components, namely characteristics of the danger or threat, its temporal frequency, exposure and vulnerability of the elements at risk, and the value of the elements and assets at risk. The assessment systemizes the knowledge and uncertainties, i.e. the possible hazards and threats, their causes and consequences. This knowledge provides the basis for evaluating the significance of risk and for comparing options.

Figure 3. Figure 1. Components in the "risk rose" (after IPCC 2012).

Risk assessment is specifically valuable for detecting deficiencies in complex technical systems and in improving the safety performance, e.g. of storage facilities.

Risk communication means the exchange of risk-related knowledge and information among stakeholders. Despite the maturity of many of the methods, broad consensus has not been established on fundamental concepts and principles of risk management.

The ISO 31000 (2009) risk management process (Fig. 4) is an integrated process, with risk assessment, and risk treatment (or mitigation) in continuous communication and consultation, and under continuous monitoring and review. ISO correctly defines risk as "the effect of uncertainties on objectives".

Higher uncertainty results in higher risk. With the aleatory (inherent) and epistemic (lack of knowledge) uncertainties in hazard, vulnerability and exposure, risk management is effectively decision-making under uncertainty. The risk assessment systemizes the knowledge and uncertainties, i.e. the possible hazards and threats, their causes and consequences (vulnerability, exposure and value). This knowledge provides the basis for comparing risk reduction options.

Today's risk assessment addresses the uncertainties and uses tools to evaluate losses with probabilistic metrics, often in terms of expected annual loss and probable maximum loss, costs and benefits of risk-reduction measures and use this knowledge for selecting the appropriate risk treatment strategies.

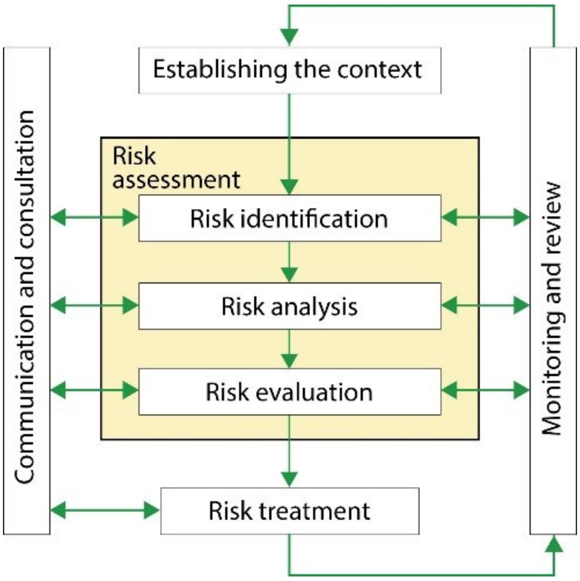


Figure 4 Risk management process (after ISO 2009).

Many factors complicate the risk picture. Urbanization and changes in demography are increasing the exposure of vulnerable population. The impact of climate change is altering the geographic distribution, frequency and intensity of hydro-meteorological hazards. the impact of climate change also threatens to undermine the resilience of poorer countries and their citizens to absorb loss and recover from disaster impacts.

4.3 Acceptable and tolerable risk

A difficult task in risk management is establishing risk acceptance criteria. There are no universally established individual or societal risk acceptance criteria for loss of life due to landslides.

For individual risk to life, AGS (2000) suggested, based on criteria adopted for Potentially Hazardous Industries, Australian National Committee on Large Dams (ANCOLD 1994; ANCOLD 2003), that the tolerable individual risk criteria shown in Table 2 "might reasonably be concluded to apply to engineered slopes". They also suggested that acceptable risks can be considered to be one order of magnitude lower than the tolerable risks.

Table 2. Suggested tolerable risk (AGS 2000).

Slope types	**Tolerable risk for loss of life**
Existing engineered slopes	10^{-4}/year for person most at risk 10^{-5}/year for average person at risk
New engineered slopes	10^{-5}/year for person most at risk 10^{-6}/year for average person at risk

With respect to societal risk to life, the application of life criteria reflects that society is less tolerant of events in which a large number of lives are lost in a single event, than of the same number of lives are lost in several separate events. Examples are public concern to the loss of large numbers of lives in an airline crash, compared to the many more lives lost in traffic accidents.

As guidance to what risk level a society is apparently willing to accept, one can use '*F-N* curves'. The *F-N* curves relate the annual (or any temporal) probability (*F*) of causing *N* or more fatalities to the number of fatalities. The term "*N*" can be replaced by other measures of consequences, such as costs. *F-N* curves give a good illustration for comparing calculated probabilities with, for example observed frequencies of failure of comparable facilities. The curves express societal risk and the safety levels of particular facilities.

Figures 5 and 6 present families of *F-N*-curves. GEO (2008 compared societal risks in a number of national codes and standards Figure 5 presents the comparison. Although there are differences, the risk level centers around 10^{-4}/year for ten fatalities. Figure 6 illustrates the risk for different types of structures. Man-made risks tend to be represented by a steeper curve than natural hazards in the *F-N* diagram (Proske 2004). On the *F-N* diagram in Figure 7, lines with slope equal to 1 are curves of equirisk, where the risk is the same for all points along the line. The *F-N* curves can be expressed by the equation:

$$F \cdot N^{\alpha} = k \qquad (1)$$

For a *k*-value of 0.001, α becomes unity (1). An *F-N* slope greater than 1 reflects the aforementioned risk aversion The ALARP zone represents the risk considered to be "As Low As Reasonably Practicable". Figure 7 also contains an illustration of ALARP: risk is to be mitigated to a level as low as reasonable practical. The residual risk is marginally acceptable and any additional risk reduction requires a disproportionate mitigation cost/effort, or is impractical to implement.

Acceptable risk is the level of risk society desires to achieve. Tolerable risk refers to the risk level reached by compromise in order to gain certain benefits. A construction with a tolerable risk level requires no action nor expenditure for risk reduction, but it is desirable to control and reduce the risk if the economic and/or technological means for doing so are available.

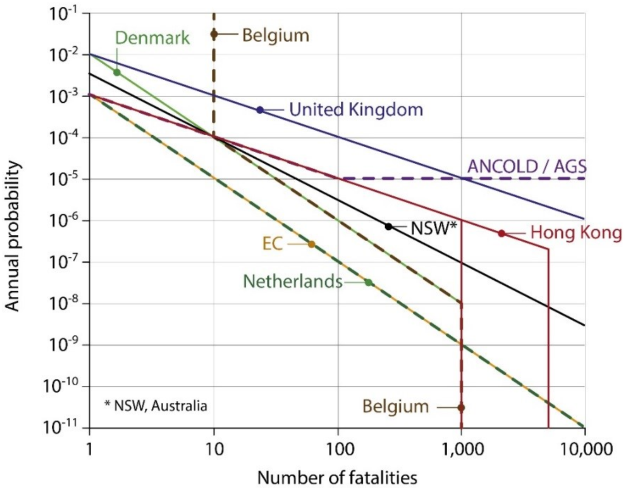


Figure 5. Comparison of risk guidelines in different countries (after GEO 2008).

Risk acceptance and tolerability have different perspectives: the individual's point of view (individual risk) and the society's point of view (societal risk). Figure 8 presents an example of accepted individual risks for different life or recreation activities. The value of 10^{-4}/year is associated with the risk of a child 5 to 9 years old dying from all causes.

The *F-N* diagrams have proven to be useful tools for describing the meaning of probabilities and risks in the context of other risks with which society is familiar.

Risk acceptability depends on factors such as voluntary vs. involuntary exposure, control or not, familiarity vs. unfamiliarity, short vs long-term effects, existence of alternatives, consequences and benefits, media coverage, personal involvement, memory, and trust in regulatory bodies. Voluntary risk tends to be higher than involuntary risk (driving a car).

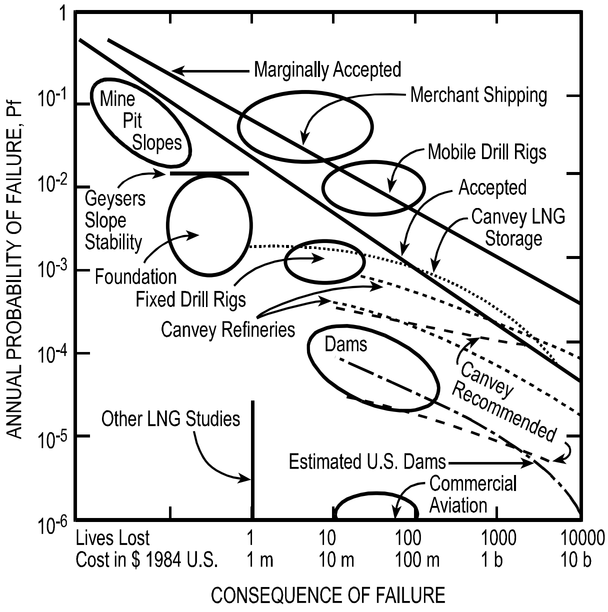
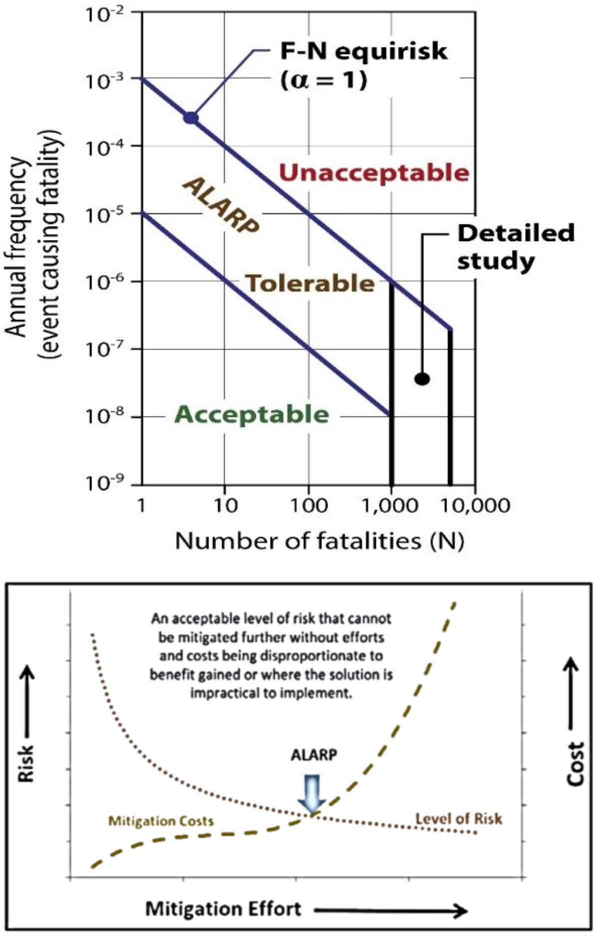


Figure 6. Examples of risk levels for different construction and activities (Whitman 1984).



An acceptable level of risk that cannot be mitigated further without efforts and costs being disproportionate to benefit gained or where the solution is impractical to implement.

Figure 7. F-N curves, lines of equirisk and significance of ALARP (lower diagram, CAA 2016).

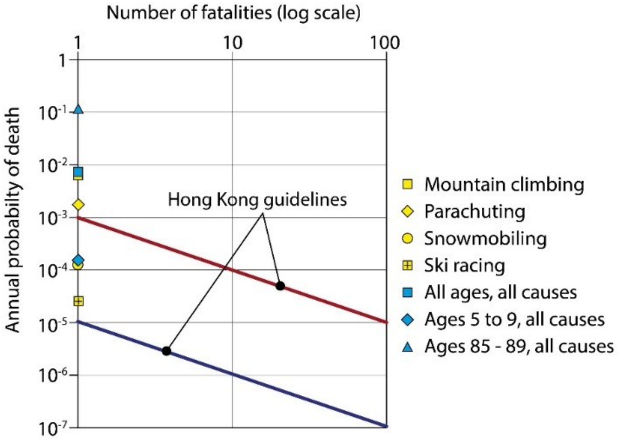


Figure 8. Accepted individual risks (Thomas and Hrudey 1997; Hutchinson2011 Personal comm..)

Figure 9 illustrates how "perceived" and "objective" risk can differ. Whereas the risk associated with flooding, food safety, fire and traffic accidents are perceived in reasonable agreement with the "objective" risk, the situation is very different with issues such as nuclear energy and sport activities.

4.4 Risk treatment (risk mitigation)

To reduce risk, one can reduce the hazard (or P_f, the probability of failure, reduce the consequence(s), or reduce both. Figure 10 illustrates this risk reduction concept on the *F-N* diagram. The United States Bureau of Reclamation 2003 guideline for dams is also shown. A mitigation strategy involves: 1) identification of possible disaster 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 of the danger, 4) recommendation of specific remedial measures and, if relevant, reconstruction and rehabilitation plans, and 5) transfer of knowledge and communication with authorities and society.

The strategies for risk mitigation can be classified in six categories: 1) activation of land use plans, 2) enforcement of building codes and good construction practice, 3) use of early warning systems, 4) community preparedness and public awareness campaigns, 5) measures to pool and transfer the risks and 6) physical measures and engineering works. The first five categories are "non-structural" measures, which aim to reduce the consequences. The sixth includes active interventions such as construction of physical protection barriers, which aim to reduce the frequency and severity of the threat.

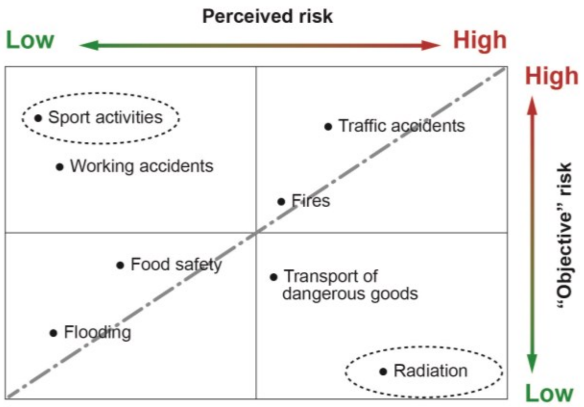


Figure 9. Perceived vs. "objective" risk (Max Geldens Stichting 2002).

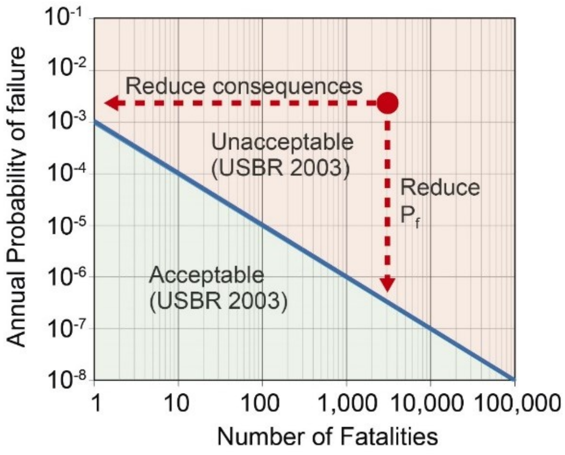


Figure 10. F-N curves and reducing risk.

In many situations, an effective risk mitigation measure can be an early warning system that gives sufficient time to move the elements at risk out of harm's way.

Early warning systems are more than just the implementation of technological solutions. The human factors, social elements, communication and decision-making authorities, the form, content and perception of warnings issued, the population response, emergency plans and their implementation and the plans for reconstruction or recovery are essential parts of the system. An early warning system without consideration of the social aspects could create a new type of emergency (e.g. evacuating a village because sensors indicate an imminent landslide, but without giving the village population any place to go, shelter or means to live). Challenges in designing an early warning system include the reliable and effective specification of threshold values and the avoidance of false alarms. The children's story about the little shepherd boy who cried "wolf" is the classic example of how false alarms can destroy credibility in a system.

The earthquake-tsunami-nuclear contamination chain of events in Japan is a telling example of cascading hazards and multi-risk: the best solution for earthquake-resistant design (low/soft buildings) may be a less preferable solution for tsunamis (high/rigid buildings). The sea walls at Fukushima gave a false sense of security. The population would have been better prepared if told to run to evacuation routes as soon as the shaking started.

5 CASE STUDIES

5.1 Slide in mine waste dump

The risk to persons living in the houses and travelling on the road below a mine waste dump, and an assessment of whether or not the risks are acceptable was evaluated. Figure 11 presents schematically the slope layout and the elements at risk (persons, houses, road, and the damage to the mining property and facilities).

Danger (landslide) characterization
The mine waste is silty sandy gravel and gravelly silty sand coarse reject from a coal wash deposited over 50 years by end tipping. Geotechnical site investigations, hydrological and engineering analyses showed that the waste is loose, and that the lower part is saturated, and that the waste is likely to liquefy and flow liquefaction occurs for earthquakes loadings larger than 10^{-3} annual exceedance probability (AEP) or once in a 1,000 years. The culvert through the waste dump exceeds its capacity and runs full for floods greater than 0.1 AEP (once in 10 years). For larger floods, water flows over the sides of the waste dump and leaks onto the waste material through cracks in the culvert, thus increasing the pore pressures in the waste.

The factor of safety of the waste dump slope under static loading was 1.2 for the annual water table levels. If the dump slides under static loading, it is likely to flow because of its loose, saturated granular nature.

Given that a slide has occurred, the annual probability of a debris flow reaching the houses is 0.5 based on post-liquefaction shear strengths obtained in the laboratory, and empirical methods for estimating travel distance (Fell *et al* 2005). The volume of the likely landslide and resulting debris flow is about 100,000 m^3 and the debris are likely to be travelling with high velocity when they reach the road and houses.

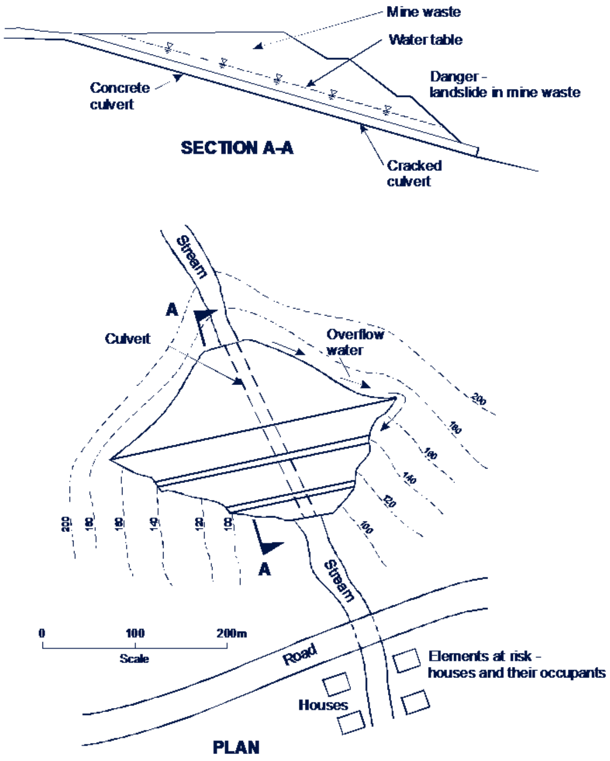


Figure 11. Slide in mine waste dump area: slope hazard and elements at risk (Fell et al 2005).

Hazard (frequency) analysis
The potential failure modes are:

- The culvert runs full, water leak, saturates the downstream toe and causes a slide.
- As above, but a smaller slide blocks or shears the culvert and causes a slide.
- The culvert collapses, flow saturates the downstream toe and causes a slide.
- A larger flood causes the culvert overflow, saturates the fill and causes a slide.
- As flood above, but the scour by the flowing water at the toe of fill initiates a slide.
- Rainfall infiltration mobilizes earlier slide.
- An earthquake causes liquefaction.

Based on the catchment hydrology, the culvert hydraulics, the stability analyses and engineering judgement, the sliding frequency of the waste for the seven potential modes of failure was estimated as 0.01/yr (or $1\cdot10^{-2}$/yr). An analysis of the liquefaction potential (Youd *et al* 2001) and of the post-liquefaction stability suggested that the frequency of sliding was 0.005 per yr (or $5\cdot10^{-3}$/yr). Hence the total annual probability of a slide, P_{slide}, was 0.015 or ($1.5\cdot10^{-2}$/yr). The probability of the slide reaching the elements at risk (P_{reach}) was uncertain, and was taken as at a value of 0.5 (i.e. completely uncertain, therefore 50% uncertain/certain, or "as likely as not"[2] to reach the road and houses).

Consequence analysis

The temporal spatial probability of the persons in the houses, and travelling on the road was estimated as follows. A survey of occupancy of the houses showed that the person most at risk in the houses spent on an average 18 hours/day, 365 days per year, or an annual proportion of time of 0.75. Each house was occupied by four persons for an average 10 hours/day and 325 days/year. Assuming that the persons were in the houses at the same time, the annual occupancy for the 16 persons is [10/24 · 325/365] or 0.36. Vehicles susceptible to be affected by the debris flow were assumed to travel with average velocity of 30 km/hr on the 100-m long stretch of road. For each vehicle on the road, the annual exposure was [(100/30,000) × 1/(365 × 24)], or $3.8\cdot10^{-7}$. If a vehicle travels 250 times a year (such as a school bus), the annual exposure probability became 9.5×10^{-5}.

To estimate the vulnerability (V), the velocity and the volume of the slide were considered. With the likely slide high velocity and large volume, the vulnerability of persons in the houses was estimated as 0.9, and the vulnerability of persons on a bus as 0.8.

Risk estimation

The annual probability of loss of life for the person most at risk (P_{LoL}) was obtained as follows (Eq. 2):

$$P_{LoL} = P_{slide} \times P_{reach} \times P_{most\ vulnerable\ person} \times V$$

$$P_{LOL} = 0.015\times0.5\times0.75\times0.9 = 5\cdot10^{-3}/\text{yr} \quad (3)$$

If all four houses are hit by the slide, 0.9 × 16 persons lose their lives (14 fatalities). The annual probability for 14 fatalities in houses is:

$$0.015 \times 0.5 \times 0.36 = 2.7\cdot10^{-7}/\text{yr} \quad (4)$$

If a 40-passenger bus is taken, 0.8 × 40 persons lose their lives (32 fatalities) The annual probability for 32 fatalities in a passing bus is:

$$0.015 \times 0.5\times0.5\times95\cdot10^{-5} = 7.1\cdot10^{-7}/\text{yr} \quad (5)$$

Ignoring loss of life in other vehicles on the road, the cumulative probabilities are (Table 3):

Table 3. Risk of fatalities, slide in mine waste dump.

Consequence	Annual frequency
≥ One fatality	$5\cdot10^{-3} + 2.7\cdot10^{-3} + 7.1\cdot10^{-7} = 7.7\cdot10^{-3}$/yr
≥ 15 fatalities	$2.7\cdot10^{-3} + 7.1\cdot10^{-7} = 2.7\cdot10^{-3}$/yr
≥ 33 fatalities	$7.1\cdot10^{-7}$/yr

Risk assessment and management

Individual risk: The risk for the person most at risk is 5×10^{-3}/year, which is in excess of the acceptable individual risks Shown in Table 1 and Figures 5 to 7.

Societal risk: Compared to the *F-N* charts in Figures 3 to 7, the three points in table 3 have risks that are in excess of the tolerable risk for the loss of 1 and 15 lives, but fall within in the *ALARP* range for the loss of 33 lives.

Mitigation

Risk mitigation options should be adopted and the risks recalculated. Mitigation options include reducing the probability of sliding by repairing the cracks in the culvert, controlling water overflow when the culvert capacity is exceeded, removing and replacing the outer waste well compacted so it will not flow if it fails, adding a stabilizing berm, or installing a warning system so persons in the houses can be evacuated and the road blocked to traffic when movement are detected in the waste.

5.2 Avalanches risk management

Avalanche forecasting

Avalanche forecasting uses several different spatial and temporal danger scales. Many

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[2] "As likely or not" is IPCC language in extreme event report (IPCC 2012).

mountainous countries have public service forecasting programs that estimate the avalanche danger in a given region during a given time period. Avalanche forecasting services in Europe warn of the danger over a region, typically on a mountain range scale with an area of minimum 100 km^2 (Nairz 2010). They predict the hazards for one or a few days (EAWS 2010). In Europe, the level of danger uses The European Danger Scale. In the USA and Canada, the similar North American Danger Scale is used. These danger scales describe qualitatively the danger potential using a five level scale. On the local level, the benefit of a general forecast can be somewhat limited.

To help decision-making locally, one needs to state not only a qualitative danger level, but also to provide a quantitative estimate of the danger. The quantitative estimate is obtained by calculating the probability of an event in a given period of time.

Kristensen *et al* (2013) proposed a procedure to associate the probability of an avalanche reaching objects at risk within a specified time period to specific mitigation measures. The procedure is illustrated with two examples of local avalanche forecasting programs in western Norway.

Quantifying the probabilities

An object-specific forecasting program able to assess the probability of encountering the objects needs to take into account not only the general avalanche hazard but also the susceptibility of the object, the probability of encountering the object should the avalanche occur and the local conditions (weather, snow drift, slope, elevation, etc.). The probability of an avalanche reaching a given point is a function of the probability of avalanche occurrence and the distance the avalanche is able to travel downslope. Estimating frequency-magnitude relationships can also be done where historical records exist. A statistical inference can therefore be used in the forecasting. Examples of probabilistic techniques are given after the two examples.

Highway 15, Strynefjellet

Highway 15 in western Norway is one of the main arteries that connect the west coast to Highway 6, the main north-south transport corridor in Norway. Highway 15 crosses "Strynefjellet. The annual (2010) traffic is around 800 cars per day, with peaks of up to 2500 cars per day in the holiday periods.

The 922-m long unprotected stretch of road in Grasdalen on Highway 15 has a history of frequent avalanches reaching the road. The main avalanches come from the NE-facing slope of Sætreskarsfjellet and can reach and impact the road over a length of 650 m. A 200-m portion of this stretch is permanently protected by a gallery. Two rows of breaking mounds on the uphill side of the road have also been constructed, but proved to be ineffective for all but the smallest wet snow avalanches. Pro-active protection, including an avalanche control system using explosive charges in the release zone and controlled avalanche release combined with preventive road closures, were estimated to reduce the individual risk for road users by about one-fourth (Kristensen 2005).

For Highway 15, an avalanche forecasting program was developed for the period between December 1st and April 30th. The forecasting service would then provide a daily avalanche danger assessment and an estimate of the probability of an avalanche reaching the road in the next 24-hour period.

To obtain weather and snow data, several automatic weather and snow stations were used. A database of all observed avalanches having reached the road earlier was also used (database over more than 50).

The forecasting procedure relied on both traditional and statistical methods. The relationship between the three- and five-day accumulated precipitation and wind conditions and the probability of an avalanche reaching the road were estimated for one particular avalanche path (Bakkehøi, 1985).

Table 4 presents the danger scale classes and local probabilities (P) for avalanches reaching Highway 15 in the next 24 hours and the corresponding actions to be taken for each level, for both traffic and road maintenance. For ease of communication, the European "Danger Scale" terminology and colours was used. However, the probabilities of avalanches reaching Highway 15 are not in accordance with the conventional use of the European Danger Scale. In Class 4 (red), the exposed area is under avalanche control. F0r Class 5, the road is closed.

Table 4. Probability of avalanche reaching Highway 15 in the next 24 hours, and required actions (after Kristensen et al 2013).

Danger Scale	$P_{(Hwy\ 15\ reached)}$ (%)	Required actions, Traffic	Required actions, Hwy maint'ce
1 Low	P≤1	No restrictions.	No restrictions.
2 Moderate	1<P≤5	No restrictions.	No restrictions.
3 Considerable	5<P≤20	No restrictions; Stopping not allowed	Work in area allowed during daylight only.
4 High	20<P≤50	Traffic monitoring cont'ly Road closing if dark or difficult driving cond.	Road clearing only in daylight under avalanche watch.
5 Very high	P>50	Road closed.	No activity in exposed areas.

Cont'ly: continuously
Maint'ce: maintenance

Construction site, Highway 60, Strandadalen

During the completion of a large avalanche protection along Highway 60 in Strandadalen winter 2012, three of the work and loading locations were considered exposed to avalanche danger. As part of the risk management for the safe project completion, an avalanche-forecasting program was implemented, with the possibility of using controlled avalanche release by helicopter with conventional explosives or a gas detonation system. Table 2 was prepared through a dialogue and cooperation among all involved parties in the project. The guiding criterion was that it was unacceptable that any avalanche should reach the area during active working operation.

Two of the three elements at risk were located in the same path but at different location on the slope. To arrive at a measure of susceptibility for the three sites, a frequency-magnitude relationship was established. Using the statistical/topographic model developed by Lied and Bakkehøi (1980), an index of the proximity to the slope was calculated based on the position of each of the three elements at risk relative to the Beta point (where slope angle is 10 degrees) in the avalanche path (Kristensen *et al.* 2008; Kristensen and Breien, 2012). Meteorological data and avalanche observations were available for about 30 years.

The probabilities (*P*) are presented in Table 5 together with the required actions. The probability classes have boundaries different from those for Highway 15. In this case (developed after the previous case study), the Danger Scale had been renamed Probability Classes.

Table 5. Probability of avalanche reaching elements at risk on Highway 60 under construction in the next 24 hours, and required actions (after Kristensen et al 2013).

Probability Scale	*P* (%)	Required actions, Presence in work areas
1 Low	P≤0.1	Permanent presence allowed*.
2 Moderate	0.1<P≤0.2	Limited presence under daylight & good visibility; Continuous local assessment of any change.
3 Considerable	0.2<P≤2	Only few and short, temporary presence allowed.
4 High	2<P≤50	No presence allowed; Quick passing-through allowed if good visibility.
5 Very high	P>50	No presence or passing-through allowed.

* Presence of the work force in exposed areas during normal working hours (8 hours a day).

Figure 12 illustrates the forecast for the three elements at risk (Sites 1, 2 and 3) during the Highway 60 construction between February 1st and April 30th 2012. The regional danger ratings (1 to 5) from the National Avalanche Forecasting program are shown at the top.

Observations from the two examples

Since the local and regional forecasting programs operate at different spatial and temporal resolutions, there will be differences in the danger assessment. The local forecasting was very useful and enabled a significantly increased number of hours.

Local forecasts can benefit from insight from the regional forecast. However, the probability of an avalanche reaching a specific object depends on the exposure of the object to the threat. Figure 12 showed that the regional forecasts can provide only limited insight into the avalanche probability of reaching specific objects and the actions required at the local level. The regional and

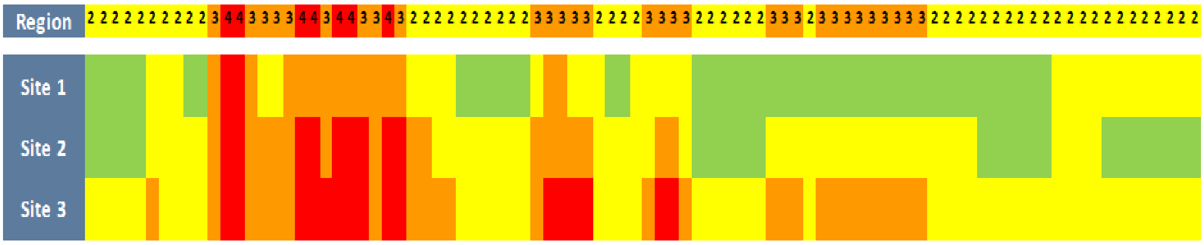


Figure 12. Forecasts for three elements at risk during Highway 60 construction (February 1st to April 30th 2012). Chart shows the daily regional danger rating 1 to 5 (top) and the probability classes for Sites 1, 2 and 3 (see Table 5 for colour codes) (Kristensen et al 2013).

local forecasts agree well in the cases of high probability of avalanche.

The probabilities reflect only a best estimate of a likelihood and not a precise value. This understanding can be "lost in the transition" from avalanche experts to the media and to the public concerned.

The local forecasting should provide decision-makers with quantified probabilities of avalanches reaching specific elements at risk. A list of actions to temporarily mitigate the impact of avalanches on exposed objects can be made, and the persons concerned can be prepared for a potential avalanche occurring.

Reliability methods for snow avalanches Harbitz *et al* (2001) discussed several aspects of probabilistic analyses for avalanche zoning. In particular, the first order reliability method (FORM) and Monte-Carlo simulations were used to evaluate the probability of occurrence associated with avalanches. Two of the models used are described herein: a mechanistic probabilistic model and a model based on observations of avalanches.

Mechanical probabilistic model

For the standard snow slab avalanche model, the safety factor (FS) is defined as the ratio of the total resisting forces in the downslope direction to the driving shear force:

$$FS = (F_S + F_T + F_C + F_F)/T \qquad (6)$$

where

F_S is the shear force along the shear surface,
F_T is the tension force at the crown,
F_c is the compression force at the wall,
F_F is the flank force,
T is the total weight driving component,
W, of the release slab
$W= \rho gBLD + W_{ext}$ (W_{ext} external load on slab),
$T= W \sin \psi$ (ψ is the slope inclination),
$F_F=2LDc$
$F_C=BD\sigma_c = 2BDc(1+\rho gD/c)$,
$F_T=BD\sigma_t$,
$F_s= BL\tau_s$,
ρ density of snow,
g gravity acceleration
B, L, D width, length and thickness of slab,
c shear strength of the slab,
σ_c compressive strength of the wall,
σ_c compressive strength of the wall,
σ_t tensile strength of the snow,
τ_s shear strength on the shear surface.

Equation 6 was used for both the Monte-Carlo and the FORM analyses. Details on the approaches can be found in Harbitz *et al* (2001) and many other sources quoted in this paper. A standard slab avalanche was used. Nine basic variables were defined with mean, standard deviation and the probability distributions given in Table 6.

Table 6. Probability distribution of basic random variables in the mechanical probabilistic model (after Harbitz et al 2001).

Random variable	PDF	Mean	SD
Thickness of slab, D (m)	LN	0.7	0.1
Slope angle, ψ (degree)	LN	38°	3
Cohesion-snow, c (kPa)	LN	6	1.5
Tensile strength-snow, σ_t (kPa)	LN	9	2.4
Shear strength on sliding plane, τ_s (kPa)	LN	1.05	0.32
Width of slide, W (m)	LN	50	25
Length of slide, L (m)	LN	50	25
Density of snow, ρ (kg/m^3)	N	220	20
External load, W_{ext} (kN)	LN	10	2

PDF: Probability density function
N, LN: Normal, Lognormal
SD: Standard deviation

With 100,000 simulations, the Monte-Carlo analyses gave an annual probability of failure P_f of 0.051 (or $5 \cdot 10^{-2}$/yr). The FORM analyses gave an annual probability of failure of

0.063 (or $6 \cdot 10^{-2}$/yr). The difference is negligible. Both approaches gave the same "design point" (i.e. the most probable combination of parameters leading to an avalanche).

In the FORM analysis, the directional cosines of the vector of random variables are called the sensitivity factors, because they indicate the relative influence of each basic variable on the reliability index and probability of avalanche occurrence.

Figure 13 illustrates the sensitivity factors for a representative analysis. The data demonstrate that the uncertainties in the shear resistance on the sliding surface and in the snow-slab dimensions (length and width) are the most significant influencing the probability of the occurrence of an avalanche.

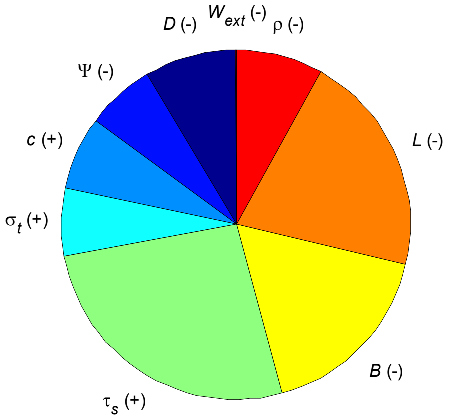


Figure 13. Sensitivity factors from the FORM analyses indicating the relative influence of each random variable on the probability of an avalanche occurring (Harbitz el al 2001).

Model based on observed events.

It is difficult to quantify the annual probability of an avalanche occurrence on the basis of mechanical models. In areas where general climatic conditions and topography are prone for avalanche activity, local wind conditions may prevent the accumulation of snow and an avalanche would rarely occur. As an alternative, Harbitz *et al* (2001) presented two easily applicable statistical approaches.

The P_f is defined as the probability of an extreme avalanche occurring in a specific path during one year, which is assumed to be small (e.g. $P_f < 0.1$). It is assumed that the probability of more than one (extreme) avalanche in one year is negligible, and that the probability in a future year is independent of avalanche activity in previous years.

The number of avalanches, r, occurring during a period of n years, conditional on P_f is then binomially distributed. The return period, $\Delta t_r \approx 1/P_f$ is the mean time period between successive avalanches. If denotes a random period between two successive avalanches, it can be approximately exponentially distributed with mean ΔT_r :

$$f(\Delta T_r) \approx (1/\Delta T_r)e^{-\Delta T_r/\Delta t_r} \quad \text{for } \Delta T_r \geq 0 \qquad (7)$$

The number of avalanches occurring during any time period, Δt, can be approximated by a Poisson distribution with mean $m = \Delta t/\Delta t_r$. Two methods can be used to estimate the probability of avalanche release:

Within a "classical" statistical framework P_f is considered a constant, and the term probability has a strict frequentist interpretation. This is equivalent to saying that P_f is close to the ratio R/n for large n. For example, if $r = 1$, i.e. one avalanche has occurred during an observation period of $n = 200$ years, the estimate of P_f is 1/200. If one tries to estimate a conservative upper value, with "95% certainty" for P_f not to be exceeded, one can construct a 95% confidence interval for P_f. The upper interval limit is then found from the cumulative binomial distribution function.

In the Bayesian approach, contrary to the classical approach, the P_f is treated as a stochastic variable with an a priori probability density function called the prior. The prior can be based on subjective knowledge, historical observations or both, before (new) observations are made. Once new observations are available, the so-called posterior probability density function for P_f conditional on r can be found. The Bayesian approach is particularly useful if a good a priori knowledge exists (e.g. observations from similar paths. It can also be implemented if no a priori knowledge is available, by applying so-called non-informative, or "vague", priors. As an illustrative example, let a prior be applied before the first year of observations, which will give one or zero avalanches. The posterior, $f_n(p_f \mid r)$, after n years of observations with totally r avalanches observed, is then:

$$f_n(p_f \mid r) = \mathrm{Beta}(r + 1, n + 1) \qquad (8)$$

with Bayes estimate of:

$$p_f = (r + 1) / (r + n + 2) \qquad (9)$$

Figure 14 presents examples of the updating procedure for one to eight years of no observations of avalanches in one location. Analogous to the classical confidence intervals, a credibility interval for P_f, can be constructed.

Figure 15 compares the "classical" and the Bayesian approaches in terms of P_f and confidence level.

Canadian guidelines on avalanche risk

The Canadian Avalanche Association (2016) recently published a useful guide on the technical aspects of snow avalanche risk management. The handbook, published online, is a detailed resource and guidelines for avalanche practitioners. The publication provides operational guidelines for:

1) Municipal, residential, commercial and industrial areas.
2) Transportation corridors.
3) Ski areas and resorts.
4) Backcountry travel and commercial activities.
5) Worksites, exploration, survey, resource roads, energy corridors and utilities, managed forest land and other resources.

The handbook describes element(s) at risk, their vulnerability, and their potential for exposure, along with tables that summarize both planning and operational risk management guidelines for specific activities or industry sectors. The helpful guideline tables include:

- Element at risk.
- Avalanche size or impact pressure.
- Return period (years).
- Risk management guidelines for planning.
- Risk management guideline for operation.

CAA (2016) illustrates the effect on uncertainty on probabilities (Fig. 16). Vulnerability in Figure 16 is defined as the probability of loss of life, for the case of snow avalanches.

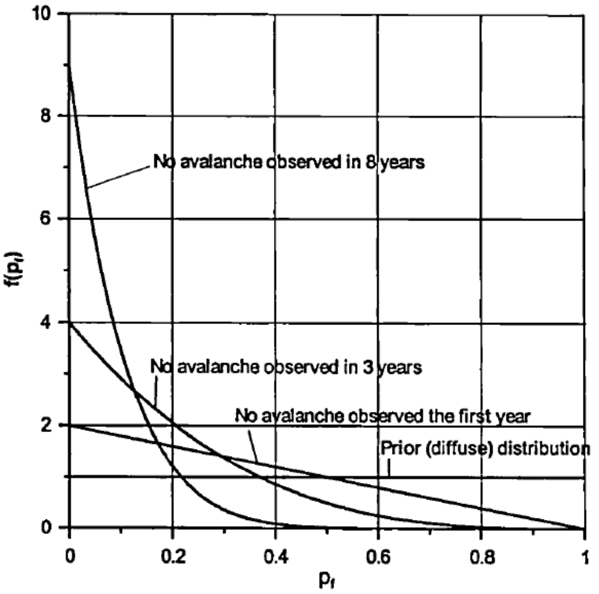


Figure 14. Probability distribution of annual avalanche cibsuderubg 0, 1, 3 and 8 years of observations of no avalanche (Harbitz et al 2001).

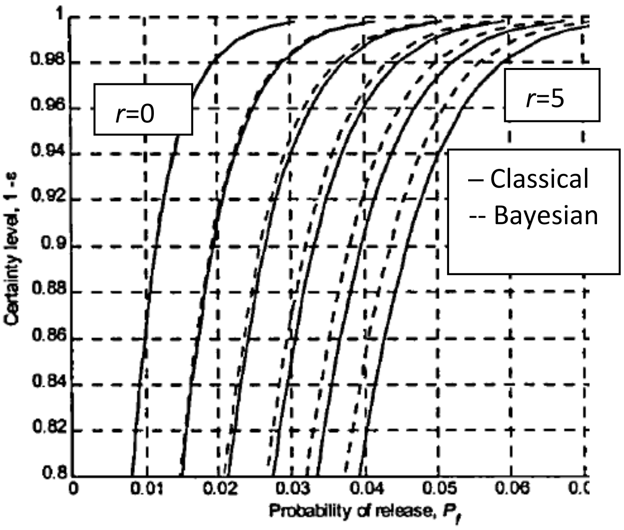


Figure 15. Annual probability of failure with confidence P_f from classical and Bayesian approaches; 0 to 5 avalanche observations (*r*) over *200 years (n) (Harbitz et al 2001).*

Statham *et al* (in prep.) suggests a model of avalanche hazards. For each avalanche type at a location, the hazard is determined by evaluating the relationship between likelihood of triggering and avalanche size. The likelihood of triggering an avalanche depends on the triggers and spatial distribution of the weaknesses in the snow mass.

5.3 Risk assessment for railways

A GIS-based methodology for regional scale assessment of hazard and risk along railway corridors was developed for the Norwegian

National Rail Administration (Hefre *et al* 2016).

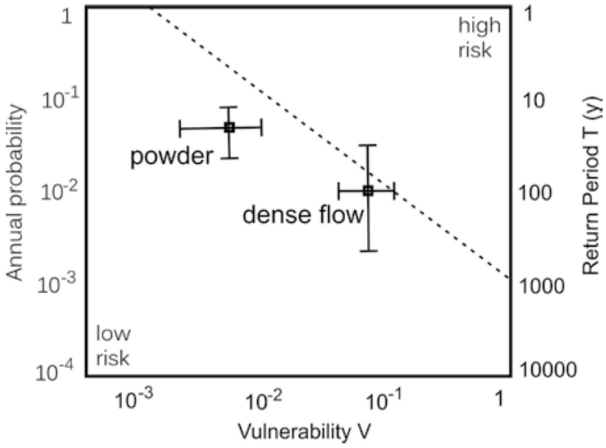


Figure 16. Risk graph showing the annual probability of occurrence and vulnerability for two hypothetical scenarios (CAA 2016).

Field investigation of hundreds of kilometres of railway would be time-consuming and expensive to conduct. The assessment of the risk along railway corridors was aided with a Geographical Information System (GIS), combining detailed Digital Elevation Models (DEM) and railway data. The GIS analyses identified risk hotspots.

A relative quantification of the hazards and consequences was done over the complete network of railway and combined to identify zones of low, medium and high-risk. The results were presented in a series of detailed maps showing the most critical areas along the railway, thus providing the stakeholders the background to make decisions on the need for further investigations and/or mitigation measures. The GIS-based methodology proved to be a time- and cost-efficient approach to conduct risk assessment over wide areas such as railway corridors.

The hazard analysis considered the average slope angle within the exposed slope, slope direction relative to railway, soil type, area of exposed slope, earlier sliding evidence, drainage capacity (expected discharge, culvert capacity and upstream slope angle) and potential erosion (distance between toe of railway and river and height difference between embankment and river).

The consequence analysis included elements at risk, accessibility for rescue, terrain conditions at time of potential derailment and impact speed.

Figure 17 presents an example of the resulting risk map. The map covers one km of railway. Such map is produced for each one km of railway analysed. On Figure 17, the hazard class, consequence class and risk class are shown graphically (with colours). The resulting risk is in the middle. A short section, close to an earlier landslide, was identified as high risk, and mitigation measures should be implemented in this area.

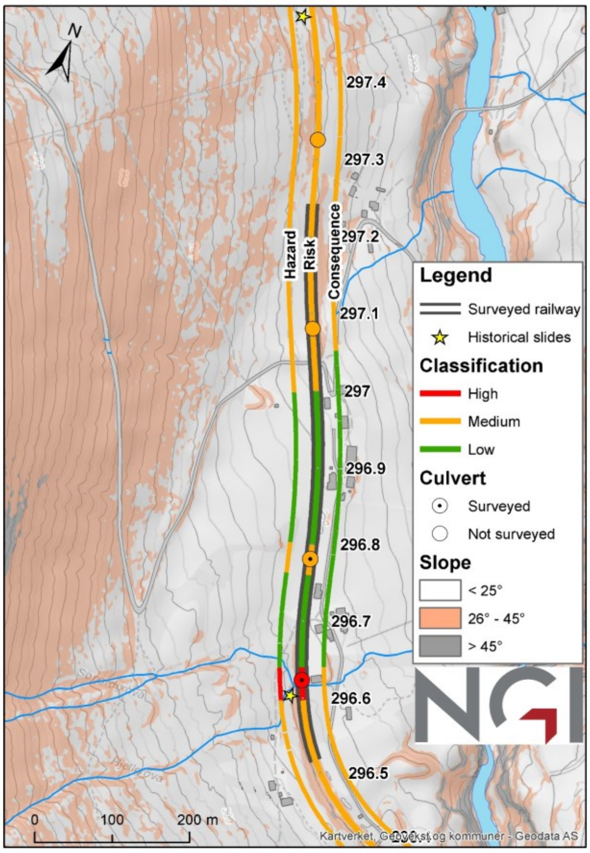
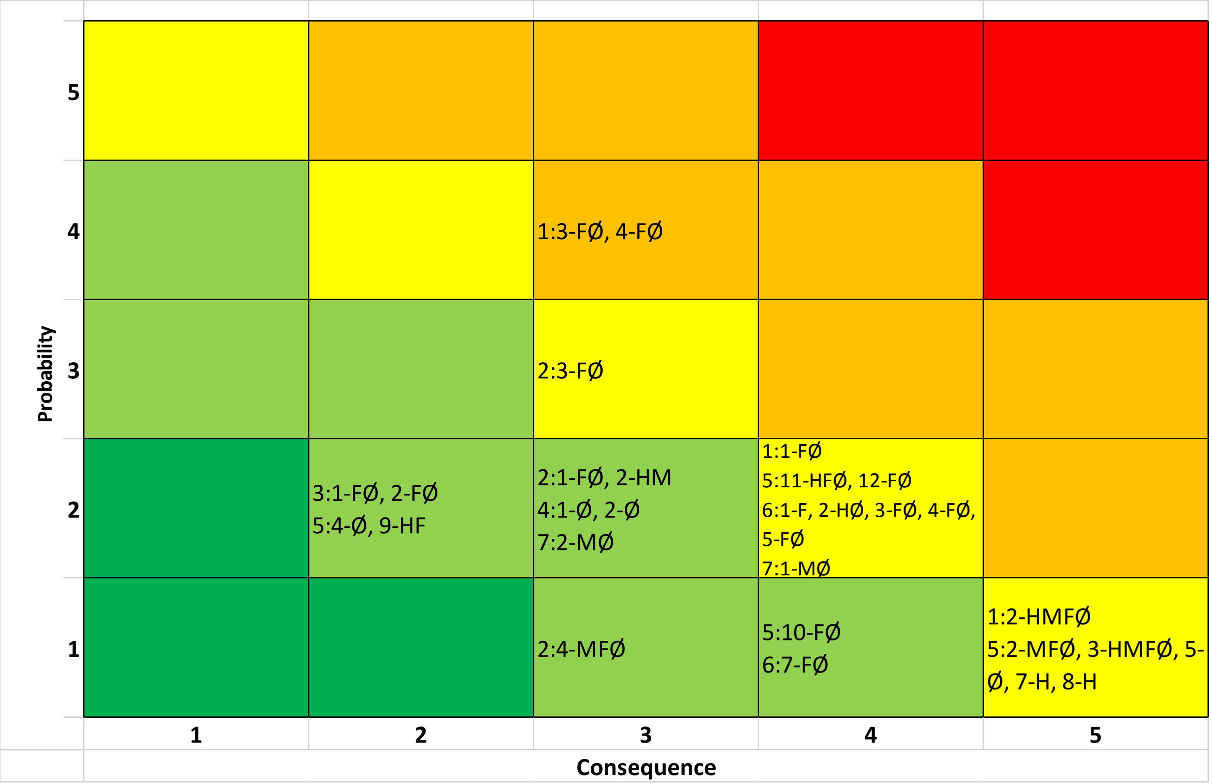


Figure 17. Risk map for I km of railway. The hazard, consequence and risk classes along the railway are shown continuously, in addition to risk level of culverts and location of historical slides (Hefre et al 2016).

5.4 Excavation and foundation works

Kalsnes et al (2016, this conference) present the concepts and an example of the application of risk analysis to excavation and foundation works. The proposed method is based on ISO's framework, with five stages: 1-Establish basis; 2-Risk identification; 3-Semi-quantitative risk analysis; 4-Risk Assessment; 5-Risk reduction measures. The method has been implemented in a spreadsheet. The analysis can best be completed by a team. As the project progresses and new information becomes available, the spreadsheet can be reviewed and revised.



Probability	1	2	3	4	5
5					
4			1:3-FØ, 4-FØ		
3			2:3-FØ		
2		3:1-FØ, 2-FØ 5:4-Ø, 9-HF	2:1-FØ, 2-HM 4:1-Ø, 2-Ø 7:2-MØ	1:1-FØ 5:11-HFØ, 12-FØ 6:1-F, 2-HØ, 3-FØ, 4-FØ, 5-FØ 7:1-MØ	
1			2:4-MFØ	5:10-FØ 6:7-FØ	1:2-HMFØ 5:2-MFØ, 3-HMFØ, 5-Ø, 7-H, 8-H

Figure 18. Risk assessment example for sheetpiling (after Kalsnes et al 2016; Vangeslten et al 2015).

Notation in each risk matrix cell: n:m-consequence = project phase:source of uncertainty-consequence

Project phases:	*1*	*Design and planning*
	2	*Preparation work*
	3	*Pre-excavation for sheetpiling*
	4	*Sheetpiling*
	5	*Excavation, construction pit*
	6	*Shoring and stiffeners*
	7	*Local conditions, environment*
Sources of uncertainty	*1*	*Material*
	2	*Design*
	3	*Execution*
	4	*Environmental loads (natural sources)*
	5	*External loads*
	6	*Extreme rainfall*
	10	*High groundwater*
	11	*Fallout on excavated slopes*
Consequences	*H*	*Health damage or fatality*
	M	*Environment*
	F	*Progress in execution*
	Ø	*Economy*

Figure 18 gives an example of the resulting risk matrix for an excavation. Kalsnes et al (2016) suggested designations for the hazard and consequence classes. Each project selects its project phases, sources of uncertainty and consequences.

For probabilities, S1 corresponds to "Extremely unlikely", S2 to "Very unlikely", S3 to "Unlikely", S4 to "Somewhat likely", and S5 to "Likely". The probabilities may range from less than 0.1%/year for Class S1 to more than 10%/year for Class S5.

For consequences, C1 would correspond to "Hazardous", C2 to "Harmful", C3 to "Critical", C4 to "Very critical" and C5 to "Catastrophic". Such classes and their meaning are to be established for each project.

The approach allows to vary the model for risk evaluation process by changing the shapes of the coloured regions in the risk matrix in Figure 18. In Figure 18, a standard staircase colour distribution is used. In a risk aversion case, the orange and res zones in the matrix would be made much larger.

The aspects requiring actions are found in the orange and red zones in the risk matrix. In the example, the uncertainties associated with the execution of the sheetpiles and the environmental loads should be examined in more detail to establish mitigation measures. Examples are given in Kalsnes *et al* (2016).

5.5 Cost-effective soil investigations

Soil investigations represent a subconscious risk-based decision. Soil investigations, in the way they are planned, represent a risk-based decision. The complexity of a soil characterization is based on the level of risk of a project. Lacasse and Nadim (1998; 1999) illustrated this graphically (Fig. 19).

A low risk project involves few hazards and has limited consequences. Simple *in situ* and laboratory testing and empirical correlations would be selected to document geotechnical feasibility. In a moderate risk project, there are concerns for hazards, and the consequences of non-performance are more serious than in the former case. Specific *in situ* tests and good quality soil samples are generally planned. For a high-risk project involving frequent hazards and potentially risk to life or substantial material or environmental damage, high quality *in situ* and laboratory tests are required, and higher costs are involved. The decision-making process for selecting soil investigation methods, although subconscious, is risk-based. It involves consideration of requirements, consequences and costs.

In general, more extensive site investigations and laboratory testing programs reduce the uncertainties in the soil characteristics and design parameters. At a certain point however, as Wilson Tang (1987) pointed out, the benefit obtained from further site investigations and testing may not yield sufficient added value (read: increase in the reliability of the performance) to the geotechnical system, and hence may not justify the additional cost (e.g. Folayan *et al* 1970).Probabilistic concepts can also help optimize site investigations.

The uncertainty in a geotechnical calculation is often related to the possible presence of an anomaly, e.g. boulders, soft clay pockets or drainage layer. Probability approaches can be used to establish the cost-effectiveness of additional site investigations to detect anomalies. Figure 20 presents an example where the presence of a drainage layer was determinant on the resulting post-construction building settlements. A settlement of less than 50 cm would mean an important reduction in costs. With drainage layer detectability for each boring of 50% or 80% (Fig. 20), and assuming a given drainage layer extent, 3 to 6 borings were required in this case to establish whether the drainage layer was present or not.

6 THE OBSERVATIONAL METHOD AND BAYESIAN UPDATING

One recurring factor in geo-failures is that the construction does not follow the original script, or changes occur underway which effects were not checked (Lacasse 2016). Examples include the pillar collapse on Skjeggestad bridge in Norway in 2015 due to as slide in quick clay and the Aznalcóllar tailings dam failure in Spain in 1998 and the Mount Polley tailings dam failure in Canada in 2012 where the downstream slopes were steeper than originally intended. Such events reinforce the importance of and the need for the "observational method", a seminal deterministic method in geotechnics (Peck 1969). The observational method consists of:

(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
(b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
(c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

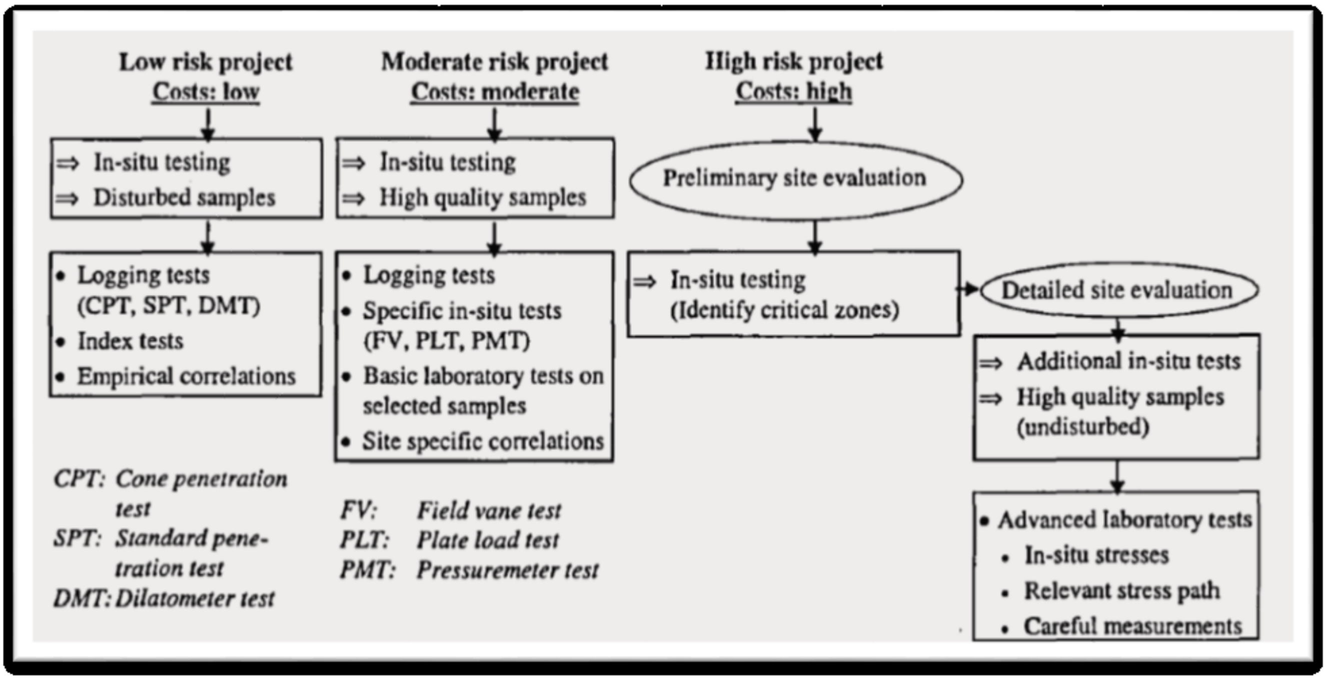


Figure 19. Site investiagtions: a subconscious risk-based decision (Lacasse and Nadim 1998).

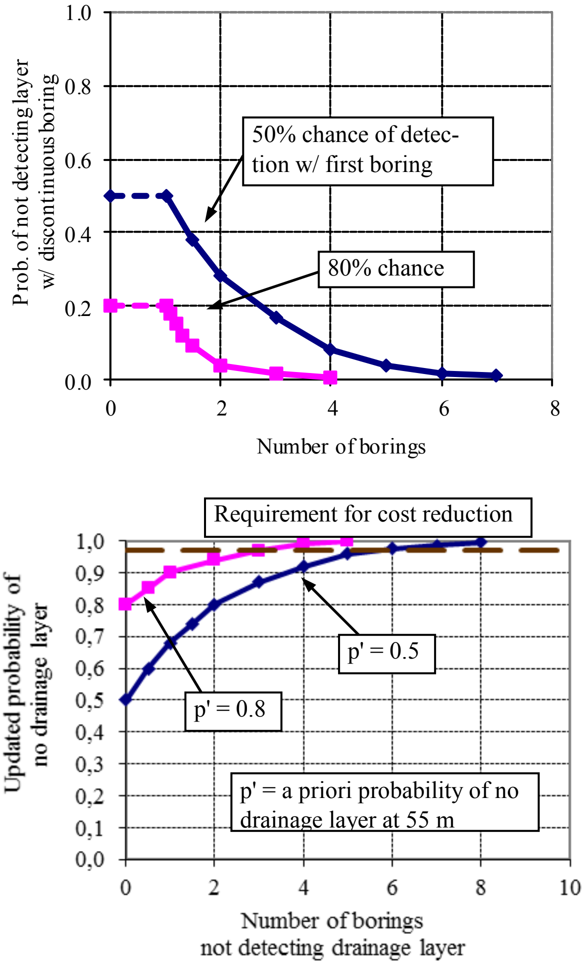


Figure 20. Cost reduction with increased number of borings (Tang 1987; Lacasse and Nadim 1998); p' is the prior probability.

(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
(e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
(f) Selection in advance of a course of action or modification of design for each foreseeable significant deviation of the observational findings from those predicted with the working hypothesis.
(g) Measurement of quantities to be observed and evaluation of actual conditions. (h) Modification of design to suit actual conditions.

The "observational method" is closely related to the techniques of Bayesian updating (Lacasse 2015). Bayes' theorem provides a probabilistic framework to allow updating of prior estimates with new information. Bayesian updating can be in fact a mathematical continuation of the observational method.

It would be very useful to couple the observational method to risk management, with focus on dynamic updating of the risk picture on the basis of observations and prepared scenarios. The contribution of the quantitative assessment of hazard and consequences (risk) is to reveal (quantitatively) the riskcreating factors and the need for remedial changes. It therefore encourages foresight rather than hindsight. Risk management combining the observational method and Bayesian updating will provide the preparedness with risk mitigation options selected and evaluated in advance.

7 RISK MANAGEMENT AND FORWARD STRATEGIES

7.1 Current directions and lessons

Risk management encompasses several necessary steps, including:

- Quantifying the uncertainties, and not the least, the modelling uncertainty(ies).
- Doing scenario-based risk assessments, including scenarios with future expected and climate impact.
- Applying improved technology and methods.
- Addressing national policies.
- Improving national and international cooperation and coordination.
- Enhancing communication.

Emphasis should be placed on improving warning systems, enhancing emergency preparedness and response, community resilience and recovery. For enhanced preparedness and resilience to take root, effective public education and strong government support are essential.

7.2 Extreme events

Occurrence

The U.S. National Science Foundation defines an extreme event as "a physical occurrence that with respect to some class of related occurrences, is either notable, rare, unique, profound, or otherwise significant in terms of its impacts, effects, or outcomes." The Intergovernmental Panel on Climate Change (IPCC) has the following, more quantitative definition for an extreme events "... An event that is rare at a particular place and time of year. Definitions of “rare” vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function…" (IPCC, 2012).

An example of an extreme event is the Great East Japan earthquake (Tōhoku earthquake) and tsunami of 11th March 2011. This magnitude 9.0 (Mw) earthquake was the most powerful earthquake ever recorded to have hit Japan, and the fourth most powerful earthquake in the world since modern record-keeping began in 1900. One of the catastrophic consequences of this event was the Fukushima Dai-ichi nuclear power plant accident.

Another example of a "usual" natural hazard event leading to extreme consequences was the 2010 eruptions of Eyjafjallajökull volcano in Iceland (Gudmunsson et al. 2012). These relatively small volcanic eruptions caused enormous disruption to air travel across western and northern Europe over a period of six days in April 2010. During the period 14–20 April, ash covered large areas of northern Europe when the volcano erupted. About 20 countries closed their airspace for commercial jet traffic and it affected about 10 million travellers (WENRA 2011).

The impact of extreme weather events (near-‘black swans’ events), which may be exacerbated by climate change, is considered as a major risk concern. An extreme weather event can also be a natural aleatory phenomenon within the natural and intrinsic variability of the weather system.

Stress testing

Conventional strategies for managing the risk posed by natural and/or man-made hazards rely increasingly on quantitative risk assessment. One of the challenges in the management of risk associated with extreme events is that the mechanism triggering an extreme event may be different from those triggering the more frequent events. Climate change has introduced substantial non-stationarity into risk management decisions. Non-stationarity is the realization that past experiences may no longer be a reliable predictor of the future character and frequency of events; it applies both to hazards and to the corresponding response of the systems.

The conventional design approach implicitly accepts that there is a "residual" risk, which could be "neglected" because the probability of that risk being realized is extremely small. This residual or neglected risk can be due to "extreme events", which have a longer return period than the return period for the design load (denoted with blue stars in Fig. 21), or they could be due to the uncertainty in the prediction models and lack of knowledge of the mechanisms at work (denoted with red stars in Fig. 21).

Both types of events pose a risk. This risk which is implicitly accepted and knowingly neglected in conventional engineering design. Nevertheless, these events can occur, and when they do, they are referred to as extreme events. Therefore, the conventional engineering design is not suitable for dealing with the risks posed by extreme events.

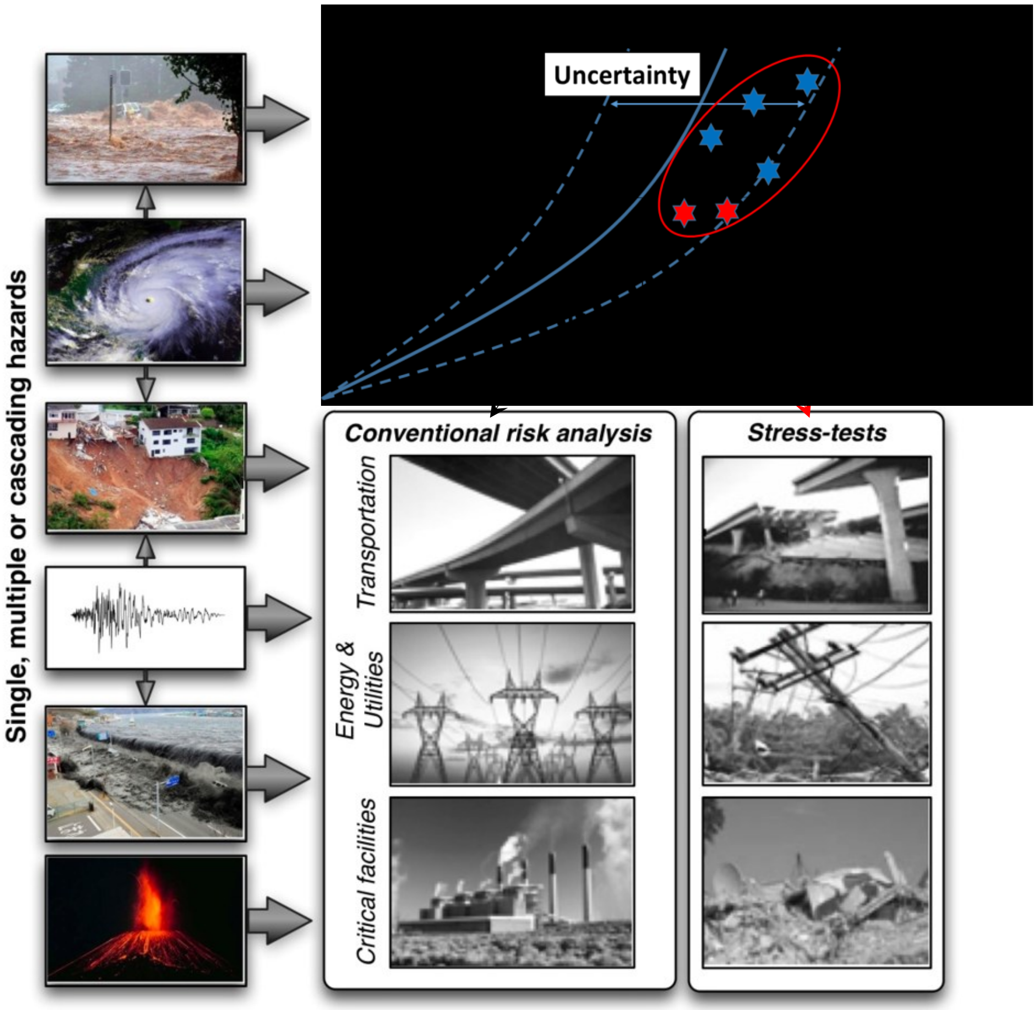


Figure 21. Residual (or neglected) risks in conventional reliability-based design approach (Nadim, 2016).

Stress testing is a procedure used to determine the stability and robustness of a system or entity. It involves testing the specific system or entity to beyond its normal operational capacity, often to a breaking point, in order to observe its performance/reaction to a pre-defined internal or external pressure or force. Stress tests have been used for many years in air traffic safety, in particular for airplanes and helicopters. In recent years, stress testing has often been associated with methodologies to assess the vulnerability of a financial system or specific components of it, such as banks. A number of analytical tools have been developed in this area and have been frequently used since the late 1990's (e.g. Borio et al. 2012).

Stress testing has been applied to the comprehensive safety and risk assessment of Nuclear Power Plants, in particular in the aftermath of the 2011 Fukushima Dai-ichi accident. In particular, the accident highlighted three areas of potential weakness in present safety approaches: (1) inadequacy of safety margins in the case of extreme external events (especially natural hazards); (2) lack of robustness with respect to events that exceed the design basis; and (3) ineffectiveness of current emergency management under highly unfavorable conditions. These issues were the focus of the stress tests imposed on all nuclear power plants in Europe in 2011 and 2012 (WENRA, 2011).

Nadim (2016) proposed stress testing as a complement to traditional risk assessment for managing the risk posed by extreme events, focusing on the challenges faced by civil engineers in general, and geotechnical engineers in particular, in managing the risk posed to critical infrastructure by extreme natural hazard events. Most risk evaluations are based on probability estimates using historical data and consequence models that try to estimate the impact of unwanted future hazard situations. For natural hazards, historical data may in some cases be sparse or highly uncertain. Similarly, simplified models of highly complex situations may yield forecasts containing significant uncertainty. Both of these situations may therefore neglect risks that should be introduced into the evaluations.

7.3 Interaction and communication

There is much room for cross-fertilization of ideas and insights, as well as joint development of strategies and best practice within the area of risk assessment and management.

Within risk, communicating the message effectively is of paramount importance, at least at three levels: (i) on the cross-disciplinary scientific level, (ii) with the stakeholders and (iii) with the general public. Good communication is imperative to provide the insights required to shape a resilient environment prepared for future challenges.

Enhanced interaction and communication among the geo-disciplines and outside the geo-arena can be achieved through multidisciplinary gatherings on geotechnical hazard and risk management. The discussions should preferably involve also government officials who are responsible for formulating policies.

7.4 Risk management strategy

In the context of protecting the community from the adverse consequences of geo-related disasters, the following strategies are pertinent in the management of hazards and risk (after Ho *et al* 2016):

a) Avoidance, with use of planning, warning or alert systems, and public education.
b) Prevention, such as enforcing slope investigation, design, construction, supervision and maintenance standards.
c) Mitigation, with the implementation of engineering measures to reduce the impact of hazards, e.g. retrofitting of substandard slopes or adding mitigation measures.
d) Preparedness, focusing on procedures, human resource management, emergency systems, training of the vulnerable community for a prompt response etc.
e) Response, involving search and rescue, evacuation and provision of basic humanitarian needs, relief measures, inspections for identification of any imminent danger, settlement of evacuated people etc.
f) Recovery, starting after the immediate threat to life has been dealt with, to bring the affected area back to the normal and carry out repair or mitigation works.

Items (a) to (c) are broad risk reduction or control strategies whereas items (d) to (f) relate mainly to emergency management. Items (b) to (e) reflect the ability of a system to withstand shocks and stresses whilst maintaining its essential functions (defined as resilience). Resilient systems are also more amenable to recovery.

8 RECENT RESEARCH

In terms of improved technology and methods mentioned in Section 7.1, recent work is aiming to bridge some of the knowledge gaps. Two recently completed European collaborative research studies, namely the CHANGES *(www.itc.nl/changes*) and SafeLand projects *(esdac.jrc.ec.europa.-eu/projects/safeland)*.

8.1 SafeLand Project

The need to protect people and property in view of the changing pattern of landslide hazard and risk caused by climate change, human activity and changes in demography, and the need for societies in Europe to live with the risk associated with natural hazards, formed the basis for the 2009-2012 European SafeLand project “Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies”. The project involved 27 partners from 12 European countries, and had international collaborators and advisers from mainland China, Hong Kong, India, Japan and USA. SafeLand also involved 25 End-Users from 11 countries. SafeLand was coordinated by the Norwegian Geotechnical Institute's (NGI) Centre of Excellence “International Centre for Geohazards (ICG)” (http://safeland-fp7.eu/; Nadim and Kalsnes 2014).

The SafeLand conclusion was that climate change, human activity and change in land use and demography all need to be considered in the assessment of landslide risk, and that climate impact on slope safety need to be given high priority. The SafeLand project provides, among other results:

- Guidelines on landslide triggering processes and run-out modelling.
- Methods for predicting the characteristics of threshold rainfall events for triggering of precipitation-induced landslides, and for assessing the changes in landslide frequency as a function of changes in the demography and population density.
- Guidelines for landslide susceptibility, hazard and risk assessment and zoning.
- Methodologies for the assessment of physical and societal vulnerability.
- Identification of landslide hazard and risk hotspots in Europe.
- Simulation of regional and local climate change at spatial resolutions of 10 x 10 km and 2.8 x 2.8 km.
- Guidelines for the use of remote sensing, monitoring and early warning.
- Prototype web-based "toolbox” of mitigation measures, with over 60 structural and non-structural risk mitigation options.
- Case histories and "hotspots" of European landslides covering almost all types of landslide in Europe.
- Stakeholder workshops and participatory processes involving population exposed to landslide risk in the selection of the most appropriate risk mitigation measure(s).

8.2 CHANGES Project

The CHANGES Marie Curie Training Network education network (Changing Hydro-meteorological Risks – as Analyzed by a New Generation of European Scientists) aimed at developing an advanced understanding of how global changes (environmental and climate changes and socio-economical change) affect the temporal and spatial patterns of hydro-meteorological hazards and associated risks in Europe. The project focused on the assessment and modelling of the changes, and incorporating them in sustainable risk management strategies, including spatial planning, emergency preparedness and risk communication. The work was interdisciplinary and inter-sectoral, with stakeholder participation. The main objectives of the project were to:

- Provide high-level training, teaching and research in the field of hazard and risk management in a changing environmental context to European young scientists;
- Reduce the fragmentation of research on natural processes; and
- Develop a methodological framework combined with modelling tools for probabilistic multi-hazard risk assessment taking into account changes in hazard scenarios (related to climate change) and exposed elements at risk.

The network consisted of 11 full partners from seven European countries. The network was run by ITC, Faculty of Geo-Information, Science and Earth Observation of the University of Twente in The Netherlands, and employed 17 Early Stage Researchers from all over the world.

A "Risk Change Spatial Decision Support system for the Analysis of Changing Hydro-meteorological Risk" was developed. The Spatial Decision Support System analyses the effect of risk reduction planning alternatives on reducing the risk now and in the future, and support decision makers in selecting the best alternatives. The decision support system is composed of a number of integrated modules. It is available online, and can be accessed through the URL:http://changes.itc.utwente.nl/RiskChanges.

8.3 Other EU initiatives

Following the Great East Japan earthquake and tsunami of March 2011, leading to the Fukushima Dai-ichi nuclear accident, the European Commission initiated collaborative research projects to develop methods for stress testing of critical infrastructure and management of the risk posed by rare, extreme events and by cascading hazards or events. Key European research projects on stress testing of critical infrastructure and management of the risk posed by rare, extreme events and by cascading hazards include (see Ho et al 2016, Nadim 2016 and websites for further details):

- STREST: Harmonized approach to stress tests for critical infrastructures against natural hazards (coordinator: ETHZ, Switzerland.
- MATRIX: New Multi-Hazard and Multi-Risk Assessment Methods for Europe (Coordinator: GFZ, Germany.
- INFRARISK: Novel Indicators for Identifying Critical Infrastructure (CI) at Risk from Natural Hazards (Coordinator: Roughan & O'Donovan Limited, Ireland.
- INTACT: Impact of Extreme Weather on Critical Infrastructures (Coordinator: TNO, The Netherlands.

9 SUMMARY AND CONCLUSION

Risk and reliability in geotechnical engineering represent a shift in practice. The concepts of probabilistic risk analyses for dams, mining and offshore structures have been around for a long time.

With increasing frequency, society demands that some form of risk analysis be carried out for activities involving risks imposed on the public. At the same time, society accepts or tolerates risks in terms of human life loss, damage to the environment and financial losses in a trade-off between extra safety and enhanced quality of life.

The most effective applications of risk approaches are those involving relative probabilities of failure or illuminating the effects of uncertainties in the parameters on the risks. The continued challenge is to recognize problems where probabilistic thinking can contribute effectively to the engineering solution, while at the same time not trying to force these new approaches into problems best engineering with traditional approaches.

The tools of statistics, probability and risk can be intermixed, to obtain the most realistic and representative estimate of hazard and risk. It is possible to do reliability and risk analyses with simple tools, recognizing that the numbers obtained are relative and not absolute. It is also important to recognize that the hazard and risk numbers change with time, and as events occur or incidents are observed at a facility.

For the purpose of communication with stakeholders, the profession needs to focus on reducing the complexity of the technical explanations. The geo-engineer's role is not only to provide judgment on safety factor, but also to take an active part in the evaluation of hazard and risk. The hazard and risk models should be easy to perceive and use, without reducing the reliability, suitability and value of the models required for the assessment.

There should be increased attention on hazard- and risk-informed decision-making. Integrating deterministic and probabilistic analyses in a complementary manner will enable the user (with or without scientific background) to concentrate on the analysis results rather than the more complex underlying information.

Conventional risk assessment methodologies are not well suited for dealing with the risk posed by low probability – high impact (extreme) events.

Stress testing provides a complementary approach to conventional risk or safety assessments. The approach is used for managing the risk posed by extreme events to constructed facilities and critical infrastructure. In stress tests, the focus is on the performance of the system under consideration subject to extreme event scenarios. This is a rapidly evolving field and the new research initiatives in Europe and elsewhere. Stress testing provides valuable additional insight for extreme situations.

It is imperative to remain vigilant of geotechnical hazards under a changing climate and to be prepared to deal with extreme events. The engineering approach needs to be supplemented by other measures involving enhanced emergency preparedness, response and recovery.

Disasters can manifest themselves as fast events, but the vulnerability for disasters is built up slowly, and can be the result of neglecting to be adequately prepared. Focus needs to shift from prevention-mitigation to building resilience and reducing risks.

Focus needs to remain on "safety". Faced with natural and man-made hazards, society's only resource is to learn to live and cope with them. One can live with a threat provided the risk associated with it is acceptable or is reduced to a tolerable level. It is important to understand that:

- Risk estimates are only approximate, and should not be taken as absolute values.
- Tolerable risk criteria are themselves not absolute boundaries. Society can show a wide range of tolerance to risk.
- One should use several measures of tolerable risk, e.g. *F-N* pairs, individual and societal risk, and costs vs and maximum justifiable cost for risk mitigation.
- The risk will change with time because of natural processes and development.
- Extreme events (Taleb's (2007) "black swans)" should be considered as part of possible triggers of a cascade of events.
- Often, it can be the smaller, more frequent, events that contribute most to risk.

With the evolution of reliability and risk approaches in geotechnical engineering, the growing demand for hazard and risk analyses in our profession and the societal awareness of hazard and risk makes that the methods and way of thinking associated with risk need to be included in university engineering curricula and in most of our daily designs.

There is a need to adopt a risk awareness and risk reduction culture

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REFERENCES

ANCOLD 1994. *Guidelines on risk assessment.* Australian Committee on Large Dams.

ANCOLD 2003. *Guidelines on risk assessment.* Australian National Committee on Large Dams.

Australian Geomechanics Society (AGS) (2000). "*Landslide risk management concepts and guidelines".* Australian Geomechanics Society, Sub-Committee on Landslide Risk Management, Australian Geomechanics, 35: 49-92.

Ang, A, H-S. and Tang, W.H.(2007). *Probability concepts in engineering. Emphasis on applications to civil & environmental engineering.* 2nd Ed., Wiley. 406 pp.

Baecher, G.B. and Christian, J.T. (2003). *Reliability and statistics in geotechnical engineering*. Wiley. 605 pp.

Bakkehøi, S. (1985). Oppdatering av skredkriterier for Rv. 15 på strekningen Grotli-Skåre. NGI Report 81403-2, Statens Vegvesen, Vegsjefen i Oppland.

Borio C., Drehmann M. and Tsatsaronis K. (2012). Stress-testing macro stress testing: Does it live up to expectations? BIS Working Papers, No 369, January.

Canadian Avalanche Association (CAA) (2016). Technical Aspects of Snow Avalanche Risk Management and Resources and Guidelines for Avalanche Practitioners in Canada. (C. Campbell, S. Conger, B. Gould, P. Haegeli, B. Jamieson, & G. Statham Eds.). Revelstoke, BC, Canada: Canadian Avalanche Association.

(http://c.ymcdn.com/sites/www.avalancheassociation.ca/resource/resmgr/Standards_Docs/TASARM_English.pdf.

EAWS (Europe Avalanche Warning Services). (2010)

Fell, R., Ho, K.K.S., Lacasse, S., Leroi, E. (2005). A framework for landslide risk assessment and management. State-of-the-art paper." International Conference on Landslide Risk Management. Vancouver 2005. Proc. pp. 3-25.

Folayan, J.I., Høeg, K. and Benjamin, J.R. (1970). Decision theory applied to settlement prediction," ASCE .J. *of the Soil Mechanics and foundation Division.* 96 (SM4) 1127-1141.

GEO (Geotechnical Engineering Office) (1998). "Landslides and Boulder Falls from Natural Terrain: Interim Risk Guidelines." *GEO Report 75*, Gov. of Hong Kong.

GEO (Geotechnical Engineering Office) (2008). Ken HO (personal communication).

Gudmunsson, M.T., Thordarson, T., Höskuldsson, Á., Larsen, G., Björnsson, H., Prata, F.J., Magnússon, E., Högnadóttir, T., Petersen, G.N., Hayward, C.L., Stevenson, J.A. and Jónsdóttir, I. (2012). Ash generation and distribution from the April-May 2010 eruption of Eyjafalljökull, Iceland, Scientific Reports, 2, 572, doi: 10.1038/srep00572.

Haegeli, P. and McClung, D.M. (2000). A new perspective on computer-aided avalanche forecasting:

Scale and scale issues. International Snow Science Workshop - Big Sky. Montana. Oct. 2-6, 2000: 66-73.

Harbitz, C., Harbitz, A. and Nadim, F. (2001). On probability analysis in snow avalanche hazard zoning. *Annals of Glaciology*. **32** 290-198.

Hefre, H., Sverdrup-Thygeson, K., Eidsvig, U. and Høydal, Ø.A. (2015). Efficient risk assessment of Norwegian railways combining GIS and field studies. Interpraevent 2016. Lucerne. CZ, June 2016.

Ho. K.K.S., Lacasse. S. and Picarelli, L. (2016). Preparedness for Climate Change Impact on Slope Safety. Overview paper in *Slope Safety Preparedness or Climate Change Effects*. Taylor & Francis (in prep).

IPCC (2012). Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). http://ipccwg2.-gov/SREX/report/.

ISDR (Intern. Strategy for Disaster Reduction) (2005). *Hyogo Framework for Action 2005-2015*, 21 pp.

ISO 31000:2009(E) International Standard on Risk management - Principles and guidelines, 2009-11-15. ISO/IEC 31010 (2009) Ed. 1.0, 2009-11. Risk Management-Risk Assessment Techniques.

ISSMGE TC32 (Technical Committee on Risk Assessment and Management) (2004). Technical Glossary of Risk Assessment Terms. http://140.112.12.21/issmge/2004Glossary_Draft1.pdf

Kalsnes, B, Vangelsten, B.V. and Eidsvig, U. (2016). Risk analysis in excavation and foundation work. NGM 2016 (this conference).

Kristensen, K. (2005).

Kristensen, K. (2005). Rv. 15 i Grasdalen. Skredforhold ved Riksveg 15 gjennom Grasdalen, Strynefjellet. NGI Report 20051040-1.

Kristensen, K., Breien, H. and Lacasse, S. (2013). Avalanche forecasting and risk mitigation for specific objects at risk, Proc. International Snow Science Workshop. Grenoble – Chamonix Mont-Blanc.

Kristensen, K. and Breien, H. (2012). Fv. 60 Røyr-Herdal Snøskredvarsling, Strandadalen anlegg. Grunnlagsrapport. NGI Report 20111019-00-2-R 25.

Kristensen, K., Kronholm K. and Bjørdal, N.H. (2008). Avalanche Characterization for Regional Road Forecasting. Proc. ISSW'08. Whistler, Canada.

Lacasse, S. (1999). The importance of dealing with uncertainties in foundation analysis. 15th ECSMGE. Amsterdam. Proc. Balkema (Rotterdam). ISBN 90 5809 047 7. pp. 385-392.

Lacasse, S. (2016). The 55th Rankine Lecture (2015). Manuscript for Geotechnique (in preparation).

Lacasse, S. and Nadim, F. (1998). Risk and Reliability in Geotechnical Engineering. State-of-the-Art paper. Fourth International Conference on Case Histories in Geotechnical Engineering, St-Louis, MO, USA.

Lied, K. and Bakkehøi, S. (1980). Empirical Calculations of Snow-Avalanche Run-Out Distance Based on Topographic Parametres. *Journal of Glaciology*. 26 (94).

Nairz, P. (2010). Results. Meeting of the Working Group of the European Avalanche Warning Services (WG EAWS) Innsbruck, June 11th 2010.

Max Geldens Stichting (2002). "Als je leven je lief is".

Nadim, F. (2016). Challenges in managing the risk posed by extreme events. Keynote Paper. 6th Asian-Pacific Symposium on Structural Reliability and its Applications (APSSRA6). Shanghai. Huang *et al* (eds).

Nadim F. and Kalsnes B.G. (2014). Progress of Living with landslide risk in Europe. Plenary Lecture. World Landslide Forum 3 Beijing. Ch. in "*Landslide Science for a Safer Geoenvironment*". (IPL), ISBN 978-3-319-04999-1, 3-20.

Nadim, F, Lacasse, S, and Guttormsen, T.R. (1993). Probabilistic foundation stability analysis: Mobilized friction angle vs available shear strength approach. International Conference on Structural Safety and Reliability, 6. ICOSSAR'93. Innsbruck 1993. Proc. 3, pp. 2001-2008.

Peck, R.B. (1969). Advantages and Limitations of the Observational Method in Applied Soil Mechanics. Géotechnique. 19(1)171-187.

Proske, D. 2004. *Katalog der Risiken.* Eigenverlag Dresden. 372 p.

Statham, G., Haegeli, P., Birkeland, K., Greene, E., Israelson, C., Tremper, B., . . . Kelly, J. (In prep.). The Conceptual Model of Avalanche Hazard. In preparation for *Natural Hazards*.

Taleb, N.N. (2007). *The Black Swan: The Impact of the Highly Improbable*. Random House (USA), ISBN 978-1400063512.

Tang, W.H. (1987). Updating anomaly statistics – single anomaly case. *Structural Safety*. 4 151-163.

Thomas, S.P. and Hrudey, S. (1997). "Risk of Death in Canada: What We Know and How We Know It". University of Alberta Press, 1997. ISBN: 0888642997, 280 pp.

Vangelsten, B.V., Haugen, T. and Kalsnes, B. (2015). DP5 Verktøy for risikovurdering – Risikoveiledning. BegrensSkade Report (c/o NGI. Oslo). 31 March 2015.

WENRA (West European Nuclear Regulators Association) (2011). "Stress tests" specifications – Proposal by the WENRA Task Force, 21 April 2011. http://www.-oecd-nea.org/nsd/fukushima/documents/WENRA-20110421StressTestsSpecifications2011-04-21.pdf.

Whitman, R.V. (1984). "Evaluating calculated risk in geotechnical engineering". *Journal of Geotechnical Engineering,* ASCE, Vol. 110, No. 2; 1984.

Whitman, R.V. (1996). Organizing and Evaluation Uncertainty in Geotechnical Engineering. Uncertainty 1996. ASCE STP 58 Uncertainty in the Geologic Environment. Madison, WI, **1** (1-28).

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian J.T., Dobry, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, MS., Robertson, P.K., Seed, R.B. and Stokoe, K.H. (2001). Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF Workshops on evaluation of liquefaction resistance of soils. J. Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 127, No. 10, 817-834.