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NGU Report 2012.029

Recommended hazard and risk classification system for large unstable rock slopes in Norway

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REPORT

Report no.: 2012.029	ISSN 0800-3416	Gradering: Open

Title:
Recommended hazard and risk classification system for large unstable rock slopes in Norway

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County: Norge	Commune: ---
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000) ---
Deposit name and grid-reference: ---	Number of pages: Price (NOK): 160 Map enclosures:

Field work carried out: ---	Date of report: 19/12/2012	Project no.: 335800	Person responsible: Øystein Nordgulen

Summary: Catastrophic failure of large rock slopes in Norway has several times per century led to rock avalanches or large rock falls, which impacted into settlements directly, but also caused either a displacement wave when impacting a water body or damming of narrow valleys with often fatal consequences. Such events will also occur in the future. Therefore, the Geological Survey of Norway (NGU), following its obligation towards society and the Norwegian Water and Energy Directorate (NVE) carries out systematic geologic mapping of potentially unstable rock slopes that might fail catastrophically. Within the last years mapping in only three of the 17 relevant counties of Norway has revealed more than 300 sites of potential future rock slope failures. This number necessitates a systematic mapping approach that focuses on the relevant geological data for assessing the likelihood of failure. Furthermore, it requires prioritization of follow-up activities, such as periodic or permanent monitoring, early-warning systems, and other mitigation measures. As the likelihood of failure cannot be given quantitatively with today's scientific knowledge, the risk analysis is built on a qualitative hazard analysis and a quantitative consequence analysis.

The classification system is scenario-based as the intensity and rate of displacement, as well as the geological structures activated by the sliding rock mass vary significantly on slopes. In addition, for each scenario the secondary effects, such as generation of displacement waves or landslide damming of valleys with the potential of later outburst floods, have to be evaluated. The hazard analysis is based on two sets of criteria: 1) Structural site investigations including analysis of the development of the back-scarp, lateral limits and basal sliding surface. This includes a kinematic analysis that tests if rock sliding or toppling is kinematically feasible with respect to the slope orientation, the persistence of main structures and the morphologic expression of the sliding surface. 2) The analysis of the activity of the slope is primarily based on the slide velocity, but also includes the change of deformation rates, observation of rockfall activity and historic or prehistoric events. The analysis of consequences focuses on the potential fatalities to the rock slide scenarios and its secondary effects only. Based on the hazard and consequence analysis each scenario is classified into category low, medium or high risk based on a risk matrix. A special document on administrative follow-up and mitigation measures will be presented in due time by NVE. The decisions on mitigation measures will be based on cost-benefit reasoning.

Keywords:	Catastrophic rock slope failure	Rockslide scenario
Displacement wave	Rockslide dam	Hazard analysis
Consequence analysis	Risk matrix	Risk analysis

CONTENTS

1. INTRODUCTION

The Geological Survey of Norway (NGU) carries out systematic geologic mapping of potentially unstable rock slopes in Norway that can undergo a catastrophic failure, financed and supervised by the Norwegian Water Resources and Energy Directorate (NVE).

This classification system will be used by NGU within the mapping projects for unstable rock slopes. Data collection and analyses will be carried out under cost-benefit reasoning using the iterative approach described herein. Classification will follow quality control principles defined within NGU, as well as procedures agreed between NVE and NGU. This includes the communication with municipalities and other stakeholders. A national and international expert team was established first by the Åknes/Tafjord Early-Warning Centre (ÅTB) and then modified by NVE in the past years to assist with decisions on following up of high risk unstable rock slopes. This expert team can be called in to review and support the final classification of any unstable rock slope and contribute with its expertise to the decision on the follow up.

The catastrophic failures described here are limited to those rock slope failures that could involve substantial run-out and fragmentation of the rock mass and could impact an area larger than that of a rockfall (shadow angle of ca. 28-34° for rockfalls, e.g, Evans and Hungr, 1993). This limitation is permissible as there are other mapping products in Norway that characterize the source and invasion areas and its likelihood for small scale rock slope failures (rockfall susceptibility map, detailed hazard maps of landslides on steep slopes). However, this definition also includes smaller rock slope failures that lead to secondary effects, such as displacement waves when impacting a water body or damming of a narrow valley. By systematic mapping in three counties we have so far detected more than 300 rock slopes with significant post-glacial deformation, which might represent sites of future large rock slope failures (Hermanns et al., 2012a). This number will increase with continued mapping. Therefore, clear rules of which geological parameters should be mapped to make sites comparable are set here. These observations will then be used for prioritization of follow-up activities, such as detailed investigations, periodic monitoring, permanent monitoring and early-warning, and other mitigation measures.

In Norway, catastrophic rock slope failures that have resulted in either large rockfalls or rock avalanches occurred repeatedly over the past centuries and caused considerable damage and loss of life (Furseth, 2006; Høst, 2006; Devoli et al. 2011). Of the ten most deadly landslides that occurred in historic time, five have been related to rock slope failures (Table 1; Furseth, 2006; Høst, 2006; Hermanns et al., 2012b). This is mainly, but not only, due to the geomorphological setting of Norway with fjord systems penetrating deep into mountain areas, as well as the presence of mountain lakes. In most cases, rock slope failures are not the direct cause for life loss. The negative consequences to society are the result of displacement waves caused by the impact of the rockslide body hitting either the fjord or lake, that run up the entire shoreline (Harbitz et al., 1993).

The experience in Norway and other countries shows that unstable rock slopes do not fail under aseismic conditions without any pre-failure slope deformation (Table 2) (see also Hermanns and Longva, 2012, Loew et al. 2012). This classification system only focuses on aseismic failures because the timing of earthquakes cannot be predicted up to now, making early-warning of earthquake-triggered rockslides impossible. We have to highlight here that in Norway seismicity rates over the 20th century suggest that the region typically reveals one magnitude (M) 5 earthquake every 10 years and one M 7 earthquake every 1100 years (Bungum et al., 1998, 2000, 2005). However, there are clear regional differences (Standard Norge, 2008) that should be considered in the risk management of rock slope failures. This has to be taken into account when assessing spontaneous (seismically-triggered rockslides) for that a minimum magnitude of M 6 was established by Keefer (1984) based on 40 historical earthquakes. Historic observations over the past 200 years indicate that with the premise of an acceleration phase prior to collapse we could capture the vast amount of rock slope failures in Norway (Furseth, 2006). Said that, triggers (e.g. seismic activity) with a longer recurrence period are not captured in this observational period, highlighting that this classification system cannot be used as a risk management tool alone, but has to be used especially in areas with higher levels of seismic activity in connection with seismic hazard maps as presented by Standard Norge (2008).

Table 1: The ten most adverse mass movement events in Norwegian history (after Hermanns et al., 2012).

Type of landslide	Location	Year	Fatalities
Landslide damming and dam burst	Gauldal	1345	500
Snow avalanche	Ørsta	1679	27
Snow avalanche	Ørsta	1679	28
Rock avalanche and displacement wave	Tjellefonna	1756	32
Snow avalanche	Ørsta	1770	27
Rock avalanche	Arnafjord	1811	45
Snow avalanche	Oppdal	1868	32
Quick clay landslide	Verdal	1893	116
Rock avalanche and displacement wave	Loen	1905	61
Rock avalanche and displacement wave	Tafjord	1934	40
Rock avalanche and displacement wave	Loen	1936	74

After two decades of selected mapping (e.g., Braathen et al. 2004, Blikra et al., 2006) and several years of systematic mapping in three counties of Norway (Møre og Romsdal, Sogn og Fjordane, Troms; e.g. Böhme et al. 2011, Henderson et al., 2011; Saintot et al., 2011, Bunkholt et al., 2011, Hermanns et al., 2011) more than 300 potential unstable rock slopes have been identified (Hermanns et al., 2012a). In the past years, out of those 300 potentially unstable rock slopes, 6 rock slopes at four localities have been classified as high risk objects or were recommended for permanent monitoring and early warning without a risk classification (Blikra et al., 2006; Dahle et al., 2008; Blikra et al., 2009; Dahle et al., 2011). These are today continuously monitored and early-warning practices are in place. 56 other sites are periodically monitored with one to several years interval (Figure 1). These monitoring procedures are established in order to reduce the possibility that a catastrophic rock slope failure will occur unforeseen and result in loss of life.

The decision on monitoring systems has up to now been taken based on expert knowledge without an objective classification system. As continuous monitoring and early-warning are very costly, and periodic monitoring of tens of sites is also costly it became evident that an objective classification system is needed for planning follow-up of the mapping phase. This system has to allow comparing geological conditions at different sites and establishing clear rules based upon those conditions that will help the experts and society to decide on the follow up.

All geological data that are considered (see chapter on hazard classes) will be stored in the national database for unstable slopes (Bunkholt et al., 2012). This recommended classification system should be used in the coming years in order to get an overview of the risk posed by potential catastrophic rock slope failures to the Norwegian society.

The recommended hazard and risk classification system is based on a qualitative hazard analysis and a quantitative consequence analysis to decide on follow-up of unstable rock slope with some type of monitoring, further investigations and/or eventual mitigation measures. It can later be calibrated in certain areas where both the data base on unstable rock slopes and on historic and prehistoric postglacial failures is complete. This would allow transforming the qualitative hazard analyses into a quantitative approach.

This document is based on a first proposal presented in 2010 (Hermanns et al., 2010) and discussed on a meeting of national and international experts in June 2010. The expert group includes Einar Anda (Møre og Romsdal County, Norway), Hallvard Berg (Norwegian Water Resources and Energy Directorate (NVE), Norway), Lars Harald Blikra (Åknes/Tafjord Early Warning Centre, ÅTB, Norway), Martina Böhme (Norwegian Geological Survey, NGU, Norway), Halvor Bunkholt (NGU, Norway), Jordi Corominas (Technical University Catalonia, Spain), Giovanni Crosta (University of Milano-Biccoca, Italy), Halgeir Dahle (Møre og Romsdal County, Norway), Graziella Devoli (NVE, Norway), Olianne Eikenæs (NVE, Norway), Luzia Fischer (NGU, Norway), Corey Froese (Alberta Geological Survey, Canada), Sylfest Glimsdal (Norwegian Geotechnical Institute, NGI, Norway), Carl Harbitz (NGI, Norway), Reginald Hermanns (NGU, Norway), Jarle Hole (ÅTB, Norway), Michel Jaboyedoff (University of Lausanne, Switzerland), Lene Kristensen (ÅTB, Norway), Simon Loew (ETH Zurich, Switzerland), Thierry Oppikofer (NGU, Norway), Aline Saintot (NGU, Norway) and Stine Sæthre (Møre og Romsdal County, Norway). A next version has been elaborated at the Geological Survey of Norway based on the discussions during the meeting and input from Carl Harbitz, Michel Jaboyedoff, and Simon Loew, as well as a further version used for a preliminary risk classification of unstable rock slopes in Møre og Romsdal County (Dahle et al., 2011a). The classification system has finally been presented to the same expert group for final suggestions. Einar Anda, Hallvard Berg, Lars Harald Blikra, Halvor Bunkholt, Giovanni Crosta, Graziella Devoli, Carl Harbitz (in representation of experts at NGI), Michel Jaboyedoff, and Simon Loew provided extensive comments. Due to this large number of reviews all experts naturally did not agree fully in all aspects. Therefore, all comments were evaluated carefully and compiled by Reginald Hermanns and Thierry Oppikofer. In this process it was decided by NGU and NVE to split the document in two parts, this report and a second one that focuses on the administrative follow-up and mitigation measures that will be presented in due time by NVE. In this last step an earlier suggested quantitative hazard analyses was replaced with a qualitative approach.

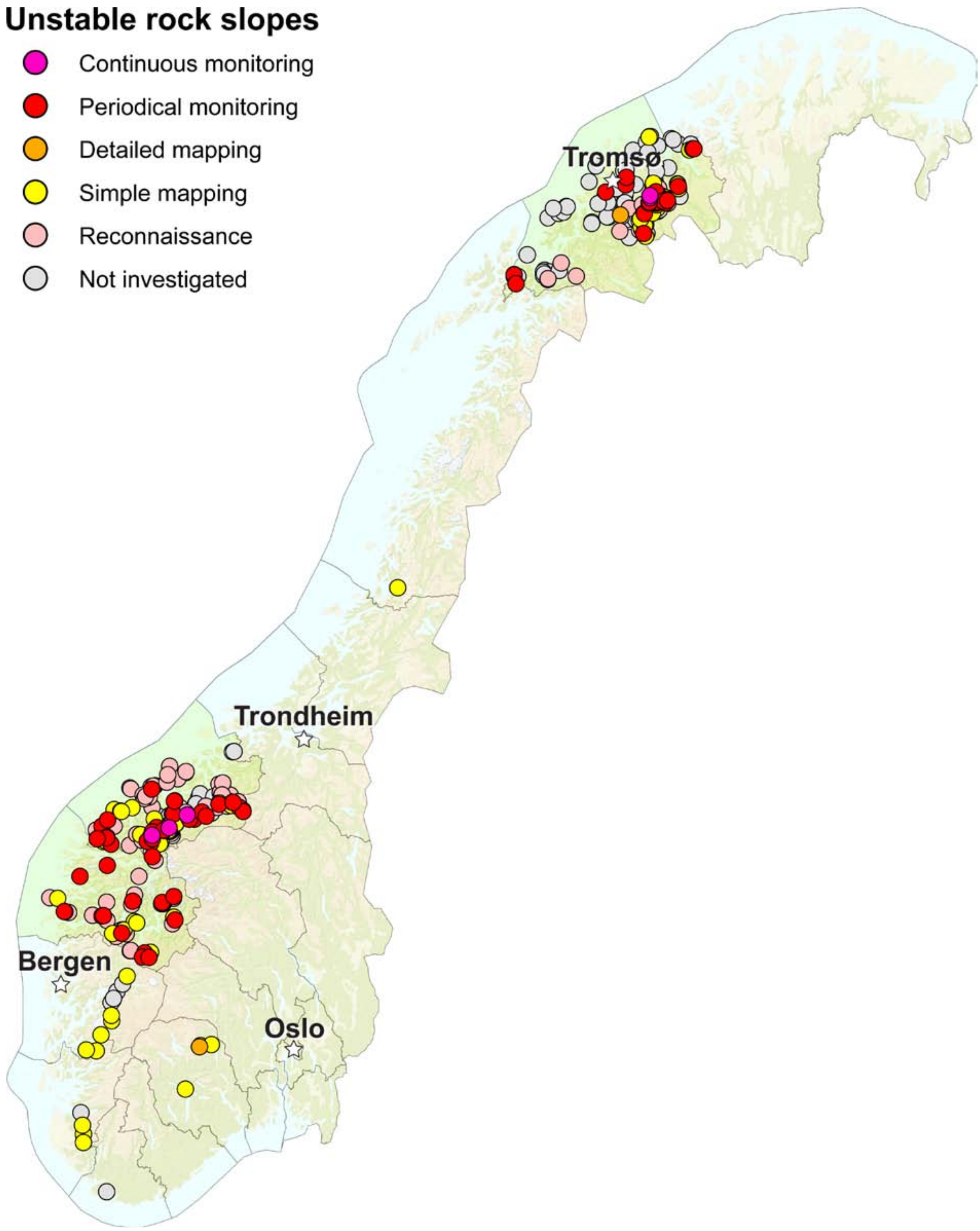

Figure 1: Known unstable rock slopes in Norway classified after degree of information available.

In the past, other classification systems have been proposed for similar purposes. For example Hantz et al. (2002) set focus on a historical analysis in combination with a geomechanical-probabilistic approach. This approach is however only valid for homogenous areas where the past frequency of events is reasonably known. The classification system by Hungr and Evans (2004) is rather on failure mechanisms, and to distinguish between weak rock types where failure does not follow discontinuities and strong rock types. Weak sedimentary rocks do not exist in Norway, and in all known cases, historic failures were controlled by discontinuities. Glastonbury and Fell (2008) used a decision tree combining criteria such as residual strength, friction angle on sliding plane, lateral or toe buttress and external loading to assess the velocity after failure of translational and sheared compound slides. In this classification, they included strain rates of the deforming rock mass similar to Jaboyedoff et al. (2012). The latter authors also suggest adding the temporal and spatial assessment of rock fall activity into the classification of rock slopes. We have taken those earlier classification systems into account, however due to the large number of potentially unstable rock slopes in Norway we focus on those criteria which can be assessed easily by field-geological observations.

By introducing uncertainties in our classification system the system allows to investigate whether and which additional geological information needs to be acquired for the final hazard and risk analyses. This helps to focus costly mapping time and instrumentation only on those sites where necessary. Similarly more detailed consequence analyses could be performed in order to reduce the uncertainty in the risk assessment.

This classification system is built for the special geographic and geological conditions in Norway that is dominated by crystalline rock and does not present large rock slopes with weak sedimentary rocks such as the Alps or the Rocky Mountains. Other observations would have to be included in mountain terrains with thick weakly consolidated sedimentary or volcanic rocks. The classification system was tested against the earlier hazard and risk analyses carried out for Åknes (Blikra et al., 2006b). Results of this classification are corresponding to this earlier analysis (Appendix A1). The classification system should be revised periodically when relevant new scientific understanding becomes available. This will especially be the case after the failure of catastrophic rock slopes that were monitored prior to failure. A first test under such conditions has been carried out by Simon Loew by evaluating the conditions of a rock slope in Preonzo (Switzerland) in January 2012 using this classification system. This slope failed on 14th of May 2012. The analyses of the slope conditions from January 2012 using this classification system suggest a high hazard class (Appendix A2).

The classification system might also be applied in other areas in the world, but needs to be adapted to local geologic, geographic and climatic conditions. The classification system is flexible for such adaptations by giving the possibility to exclude some of the criteria used in Norway and to add new ones. We especially underline that today there is insufficient quantity of information on geological occurrences to support the prediction of large rock slope failures on geological conditions alone and that instrumental monitoring is the appropriate tool for monitoring changes in rock slopes. In general it requires additional geological information to those collected in the classification process in order to set up appropriate continuous monitoring and early warning systems. We suggest developing guidelines that indicate the level of geological knowledge necessary to decide for optimal site-specific monitoring strategies.

Table 2: Precursor rock slope deformation and rock fall activity related to historical catastrophic rock slope failures

Slide	Country	Date	Monitored/Observed Movement	Opening of cracks	Rock fall	Rock Noise	Source
Tjellefonna	Norway	22. 02. 1756	several years	several years	since spring the year earlier	-	Furseth 2006
Loen I	Norway	15. 01. 1905	5 years	-	ca. 1 year enhanced	in 1904	Furseth 2006
Loen II	Norway	12. 09. 1936	throughout 1936	throughout 1936	enhanced 2 days	-	Furseth 2006
Loen IV	Norway	22. 06. 1950	monitoring of slope since 1936 discontinued, 1947 reactivation	in 1936	-	-	Hermanns et al. 2006; Furseth 2006
Tafjord	Norway	07. 04. 1934	-	since 1870	enhanced for years / strongly enhanced for 1 month	-	Blikra et al., 2005; Furseth 2006
Tête Noir	France	21. 02. 1608	-	fractured and semi detached spurs of limestone	likely as people abandoned houses	-	Eisbacher and Clague 1984
Piuro	Italy	04. 09. 1618	10 years of creep	for years	enhanced for 1 week	vibration 1 day	Montandon 1933; Eisbacher and Clague 1984
Preonzo	Switzer-land	22. 06. 1702			Increased for at least 5 years		Loew et al., 2012

Slide	Country	Date	Monitored/Observed Movement	Opening of cracks	Rock fall	Rock Noise	Source
Diablerets	Switzer-land	23. 06. 1714	-	-	3 weeks	3 weeks	Montandon 1933; Eisbacher and Clague 1984
Diablerets	Switzer-land	24. 09. 1749	-	-	precursory noise made people evacuating	Precur-sory	Montandon 1933; Eisbacher and Clague 1984
Lago di Alleghe	Italy	11. 01. 1771	opening of cracks	-	-	-	Montandon 1933; Eisbacher and Clague 1984
Goldau	Switzer-land	02. 09. 1806	at least 30 years	yes	since end of winter	-	Heim 1932; Montandon 1933; Eisbacher and Clague 1984
Elm	Switzer-land	11. 09. 1881	at least 25 years	for 2 years	for 2 years	-	Heim 1932; Montandon 1933; Eisbacher and Clague 1984
Blisadona		09. 07. 1892	-	crack visible 1 year earlier	-	-	Eisbacher and Clague 1984
Arvel	Switzer-land	14.03.1922	opening of cracks	yes, detected 1 day before event	precursory rockfall and "explosions" on day of event	-	Choffat 1929; Jaboyedoff 2003
Motto d´Arbino	Italy	02. 10. 1928	at least 3 years	-	15 years	-	Eisbacher and Clague 1984
Fidaz	Switzer-land	10. 04. 1939	-	-	precursory rockfall	-	Eisbacher and Clague 1984

Slide	Country	Date	Monitored/Observed Movement	Opening of cracks	Rock fall	Rock Noise	Source
Vaiont	Italy	09. 10. 1963	at least 3 years	at least 3 years	3 years before / days before	-	Eisbacher and Clague 1984 / Glastonburry and Fell 2010
Val Pola	Italy	28.07.1987	-	4 weeks of opening, cracks visible years earlier	4 weeks	-	Crosta et al., 2004
Randa I	Switzer-land	18.04.1991	/	probable	more than 20 years, increased in years to days before event	-	Sartori et al. 2003, Willenberg 2004
Randa II	Switzer-land	09.05.1991	monitoring after Randa I (3 weeks before)	3 weeks	Not reported	-	Sartori et al. 2003, Willenberg 2004
Medji St. Niklaus	Switzer-land	22.11.2002	since summer 2002, acceleration before collapse	yes	partially blasted few weeks before failure	-	Rovina 2010
Thurwieser	Italy	18.09.2004	-	4 weeks before	Increase several years before	-	Sosio et al. 2008, G.B. Crosta pers. com.
Eiger	Switzer-land	13.07.2006	several weeks, acceleration before collapse	crack opening on 10/06/2006	since August 2005, acceleration in 2006	Aug 2005	Oppikofer et al. 2008
Prionzo	Switzer-land	16.05.2012	Monitored movement since 1999, acceleration in years before	Since 1989	-	-	Loew et al., 2012

Slide	Country	Date	Monitored/Observed Movement	Opening of cracks	Rock fall	Rock Noise	Source
Nevis Bluff	-	-	-	11 month	-	-	Glastonburry and Fell 2010
Mt. Fletcher	New Zealand	-	-	-	-	3 min	Glastonburry and Fell 2010
Lower Gros Ventre	-	-	-	12 hr	-	hours	Glastonburry and Fell 2010
Nanjiang	-	-	-	-	-	hours	Glastonburry and Fell 2010
Machupicchu	Peru	-	-	years	years	-	Glastonburry and Fell 2010
Frank	Canada	-	-	months	months	months	McConnell and Brock (1904); Glastonburry and Fell 2010
Madison	Canyon	-	-	3 years	-	-	Glastonburry and Fell 2010
Mayunmarca	Peru	-	-	4 years	4 years	-	Glastonburry and Fell 2010

"-" indicates no information available in the data source

2. DEFINING FAILURE SCENARIOS

Deformation of unstable rock slopes can be either uniform over the entire slope or localized. In the latter case, deformation varies strongly between different compartments of an unstable rock slope (also called parts, blocks or similar). This difference in deformation style becomes evident when looking back into geological records indicating that some unstable slopes collapsed repeatedly while others slopes failed in a single event (e.g. Hermanns et al., 2006 and references therein, Longva et al., 2009). These multiple failure sites suggest that parts of a rock slope can get to a critical state at different moments in time. This has been accounted for during the hazard assessment of all sites which became high-risk objects or continuous monitoring sites in Norway so far (Blikra et al., 2006b; Dahle et al., 2008; Blikra et al., 2009) and will therefore be applied in our classification system (see next paragraph). Repeated catastrophic failures in the past century have only occurred on few slopes (Loen in Norway, Cerro Huascarán in Peru, Randa in Switzerland (Hermanns et al., 2006, Evans et al., 2009, Willenberg 2004) and the lack of monitoring and other observations prior to the first failure impedes generally to reconstruct how different compartments of those subsequent failures have deformed prior to the first failure. Therefore we have to base our definition of scenarios on varying geological conditions on the rock slopes and on observations of displacement rates. A slope with a uniform displacement rate and no structural differences is more likely to fail as a single event (one compartment) than a slope deforming with varying rates and/or blocks separated by continuous cracks that might in addition also be controlled by a strong variance of geological structures (various compartments). These compartments may have different failure probabilities, different consequences and pose therefore also different levels of risk. One can define a scenario by a compartment of the unstable rock slope, which might fail in a single event and individually from other compartments. An additional hint to define failure scenarios is the analyses of historic and prehistoric failures along slope sections built by the same lithologies and controlled by the same structures.

Different scenarios are therefore justified and need to be analysed at slopes that show a combination of:

- Different deformation rates
- Varying structural conditions
- Internal scarps, cracks and depression which dissect the unstable rock slope

Based on the combination of those observations the hazard and risk classification for each potential scenario has to be carried out independently.

In order to reduce costs, the development of scenarios has to be an iterative process in which detail of analysis increases stepwise following the principles outlined in Figure 2. The term assessment is here used to describe a semi-quantitative evaluation carried out by the mapping geologist, while the term "analysis" is used here for more thorough, quantitative investigations.

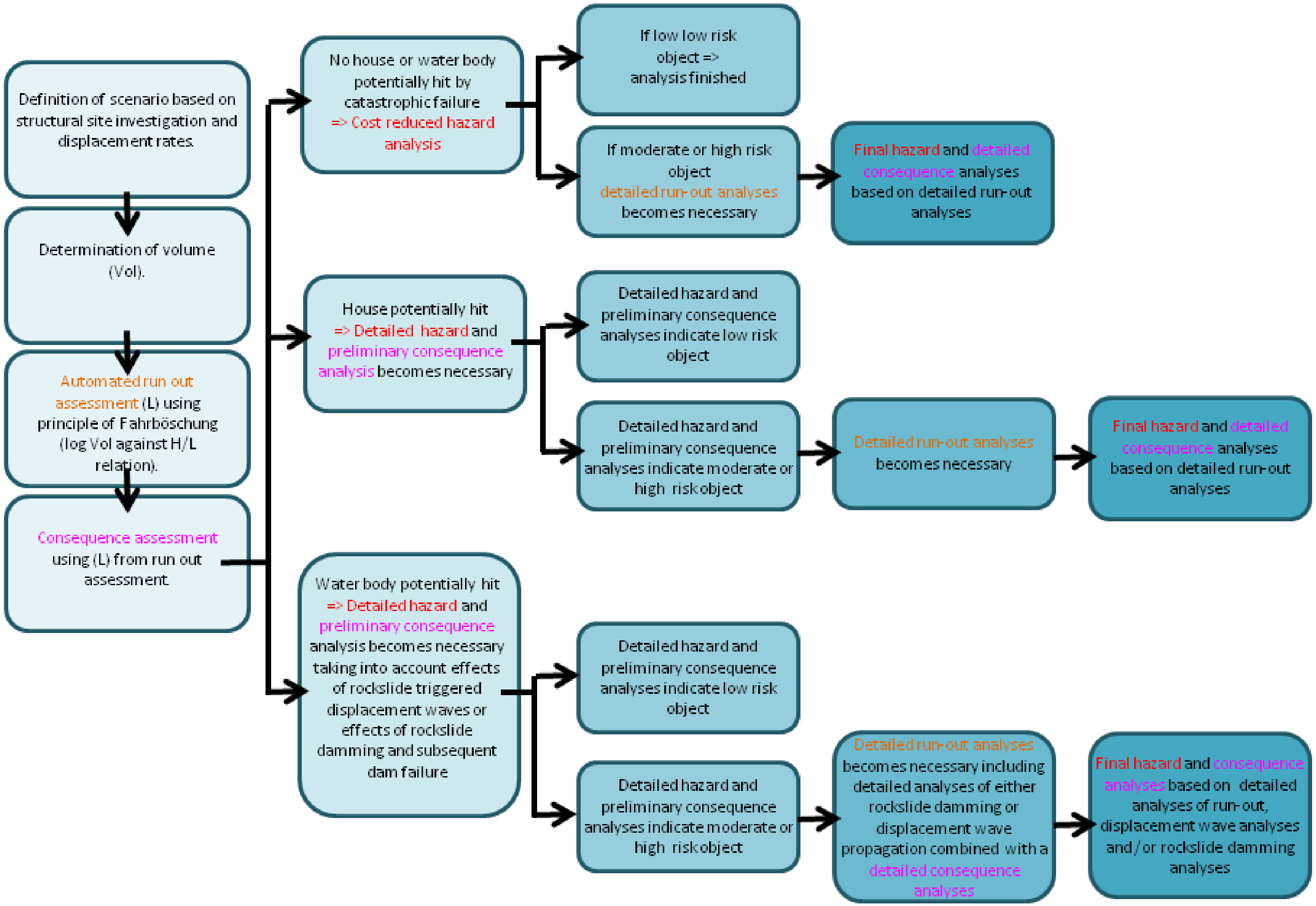

Figure 2: Development of the scenario based hazard and risk assessment by gradually increasing detail (from left to right) of hazard and consequence analyses in an iterative approach. The term assessment is here used for a semi-quantitative evaluation during project development, while analysis is a quantitative evaluation.

Once a scenario has been defined, the volume, V, and potential drop height, H, of this scenario has to be defined for an estimation of run-out distance, L, using simple methods such as V vs. H/L relations (Scheidegger, 1973). Nearly all known historic and prehistoric Norwegian cases plot above Scheidegger's (1973) regression line indicating that this relation is a conservative approach for the Norwegian geographical situation (Figure 3, Table 3). Note that this regression line/approach have been used in a national assessment of lakes and reservoirs in Norway that aimed to test where rock slide triggered displacement waves might be feasible (Romstad et al., 2009). Potential consequences will be assessed based on this preliminary run-out assessment resulting in three cases:

1. No building or water body would be hit by a catastrophic rock slope failure
2. At least one building would be hit by the catastrophic rock slope failure
3. A water body or a water body and at least one building would be hit by the potential catastrophic rock slope failure

1) If the simple run-out assessment indicates that no building or water body can be hit by the rockslide mass, a hazard analysis is only necessary if the hazard assessment indicates a high to very high risk class. For all other hazard classes the simple run-out assessment is presented to prevent from construction in the run-out area.

2) If the simple run-out analysis indicates that buildings may be reached by a catastrophic failure scenario, a detailed hazard analysis becomes necessary in a second step followed by a preliminary consequence analysis using the principles outlined in this document (see section 4). If these combined analyses suggest a low risk object no more detailed analyses are required. If these combined analyses suggest a moderate- to high-risk object a detailed run-out analysis using specialized modelling software (e.g. Dan3D, McDougal, 2006, Sosio et al., 2008) becomes necessary. Results of the modelling will be the base for the detailed consequence analysis and the final risk classification (low, moderate or high risk object).

3) Similarly to consequence 2, if the simple run-out analysis indicates that any water body may be reached by a catastrophic failure scenario, a detailed hazard analysis becomes necessary in a second step followed by a preliminary consequence analysis using the principles outlined in this document (see section 4). If these combined analyses suggest a low risk object, no more detailed analyses are required. If these combined analyses suggest a moderate- to high-risk object, a run-out analysis using specialized modelling software (e.g. Dan3D, McDougal, 2006) becomes necessary to assess either the energy and geometry of the impact into the water body (lake/fjord) or the consequences of rockslide damming (river). In the case that the energy of the rock avalanche impact into a standing water body is high, the assessment of the propagation of the displacement wave becomes necessary. This could be performed in a first step by using empirical data, but down-scaled laboratory physical experiments or numerical modelling (NGI 2001) is recommended for potential high risk sites. Results of those analyses will be the base for the detailed consequence analysis and the final risk classification (low, moderate or high risk object).

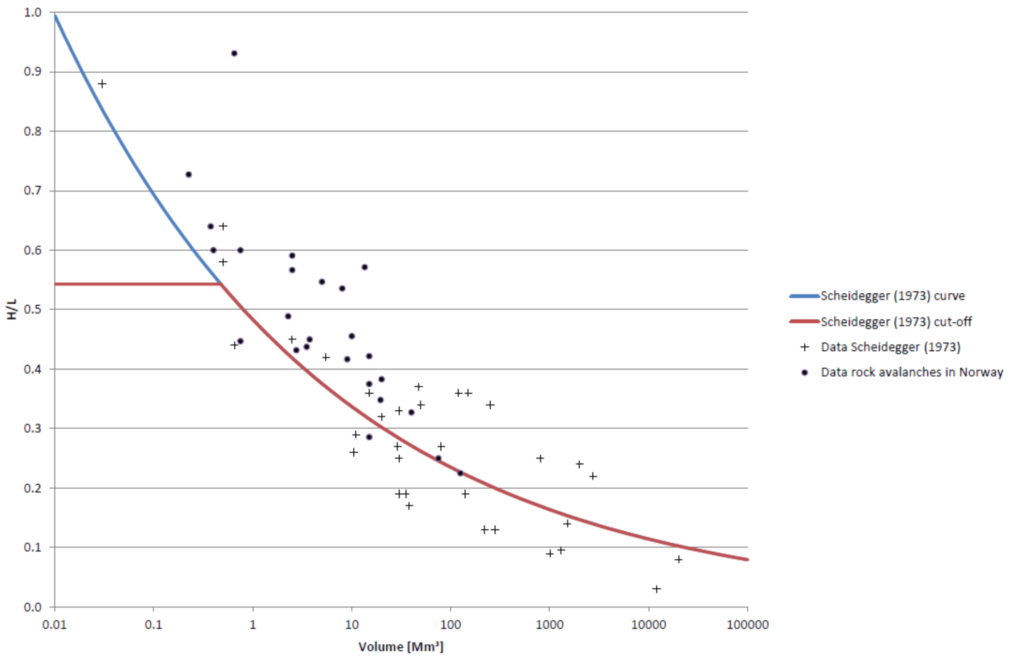

Figure 3: Regression line (red-blue, after Scheidegger, 1973) indicating the logarithmic relation between rockslide volume and run out distance in function of rockslide drop height with cut-off marked at the shadow angle of rockfall (volumes below approximately 0.5 Mm^3 set to be 28.5°). Data are worldwide data from Scheidegger (1973) and observations from historic and prehistoric events in Norway (Table 3).

Table 3: Drop height (H), run out (L), and rockslide volume for historic and prehistoric rock slope failures in Norway

Locality	H [m]	V [Mm^3]	L [m]	H/L
Berrføttene	1000	75	4000	0.25
Bjørkum	400	0.225	550	0.73
Erdalen	460	10	1010	0.46
Frykkjelen	950	2.75	2200	0.43
Furuneset	900	0.75	1500	0.60
Grande	1350	0.65	1450	0.93
Gravem	900	0.4	1500	0.60
Grøtlandsura	500	9	1200	0.42
Gumpedalen	720	40	2200	0.33
Hellaren	900	125	4000	0.23
Hjelle	730	0.5	575	1.27
Hysket	550	2.275	1125	0.49
Kubergan 1	375	8	700	0.54
Kubergan 2	350	5	640	0.55
Langhammaren	850	2.5	1500	0.57
Melkevoll	480	0.375	750	0.64
Nakkevatnet	900	20	2350	0.38
Rørsetura	650	2.5	1100	0.59
Skjærsura	1000	13.5	1750	0.57
Store Urdi	400	15	1400	0.29
Stølaholmen	420	3.5	960	0.44
Sørdalen	675	3.75	1500	0.45
Tjellefonna	750	15	2000	0.38
Urdabøuri	470	19.5	1350	0.35
Venge	760	0.75	1700	0.45
Verkildsdalen	675	15	1600	0.42

3. HAZARD CLASSIFICATION

3.1 Organisation of the hazard classification system

For easier reading examples are given for two different scenarios for catastrophic failures at Åknes in Appendix A1. The classification system uses nine criteria describing the present state of an unstable rock slope. They are described in detail in section 3.4 and can be arranged into two main groups: 1. the structural development of the unstable rock slope; 2. displacement rates and other signs of activity. For each criterion (κ_i) several conditions (χ_{ij}) are possible to choose from and a score (ν_{ij}) is assigned to each condition. The sum of scores for the chosen conditions gives the total score, which is called hazard score, ρ (Equation 1):

$$\rho = \sum_i \nu_{ij} \qquad (1)$$

with j corresponding to the chosen condition χ_{ij} for criterion κ_i.

Using the nine criteria described in section 3.4, the hazard score, ρ, can range from 0 to 12. It is assumed that the likelihood of an unstable rock slope to fail increases with ρ.

3.2 Uncertainties on conditions assessed using a decision tree

Unstable rock slopes are complex landslide phenomena and it may often be difficult to choose only one of the conditions (χ_{ij}) for a given criterion (κ_i). In order to include these uncertainties, probabilities (p_{ij}) for each condition can be given. The average (expected) hazard score, ρ, is obtained by summing all the scores (ν_{ij}) multiplied by the conditions probabilities (Equation 2):

$$\bar{\rho} = \sum_i \sum_j p_{ij} \nu_{ij} \qquad (2)$$

However, this average hazard score does not express the uncertainties on the individual criteria and therefore on the hazard score. In order to compute the entire range of possible outcomes, the criteria are organized in a decision tree. Each criterion, κ_i, represents a node of the decision tree and each condition, χ_{ij}, forms a branch of the tree (Figure 4). For each path of the tree, its hazard score, ρ_{path}, and its probability, φ_{path}, can be calculated using Equations (1) and (3), respectively:

$$\varphi_{path} = \sum_i p_{ij} \qquad (3)$$

with j corresponding to the chosen condition χ_{ij} for criterion κ_i.

Using scores and conditions for the nine criteria as described in section 3.4 leads to 48'600 possible paths and probabilities for individual paths may be very low. However, several paths may lead to the same path hazard score, ρ_{path}. There are for example 2026 paths leading to ρ_{path} = 7.00 (Figure 5a). Therefore, the total probability of having ρ_{path} = 7.00 corresponds to the sum of the 2026 path probabilities, φ_{path}.

The macro developed in Microsoft Visual Basic 6.5 (implemented in Microsoft Excel® 2007) computes all possible paths of the decision tree including ρ_{path} and φ_{path} and creates the sum of all φ_{path} leading to the same ρ_{path}. Using the scores presented in section 3.4, the path hazard score, ρ_{path}, ranges from 0 to 12 with steps of 0.25 interval (0.0; 0.25; 0.5; 0.75; 1.0; 1.25; …; 11.75; 12.0). The final outcome is a probability for each of these 49 different hazard scores, φ_{score} (Figure 5b). The probability distribution of φ_{score} allows obtaining the minimum and maximum hazard scores, ρ, using the chosen probabilities, p_{ij}. The modal value indicates the most probable ρ located at the peak of the probability distribution (Figure 5b), while the mean value is computed using Equation 2 (Figure 5).

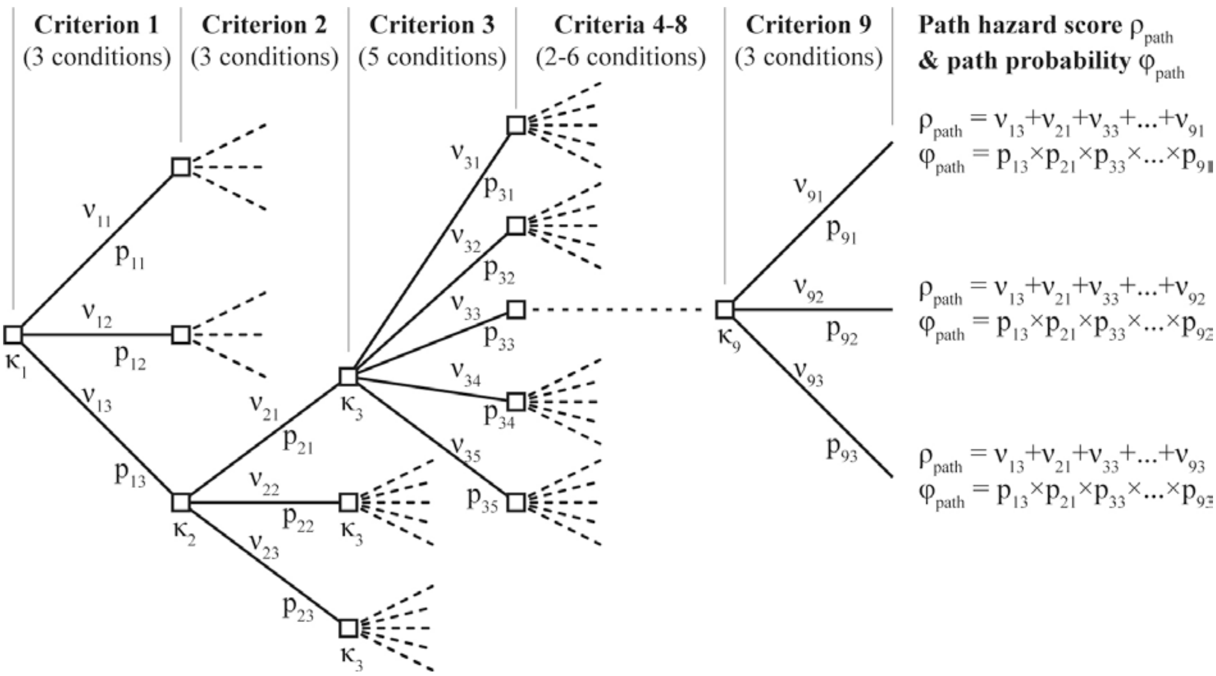

Figure 4: Scheme of the decision tree for assessing uncertainties on the hazard score. The nodes (squares) correspond to a criterion (κ_i) and the branches starting at the node represent the different conditions with the associated scores (v_{ij}) and probabilities (p_{ij}). For each path the resulting hazard score (ρ_{path}) and probability are calculated (φ_{path}).

The cumulative probability distribution of φ_{score} indicates the probability that ρ is smaller or equal to a given value (Figure 5c). This cumulative probability distribution has the shape of a normal distribution, which can thus be used to best-fit the cumulative probability distribution (Figure 5d). This is achieved by a least-squares fitting that minimizes the differences between the observed and modelled distributions by varying the mean value, μ, and the standard deviation, σ, of the normal distribution. Pearson product-moment correlation coefficients were computed and Kolmogorov-Smirnov test with a significance level α of 0.05 were performed to validate the fitting of the normal distribution (Figure 5). See Oppikofer et al. (2011) for relevant equations and an application of such a fitting procedure.

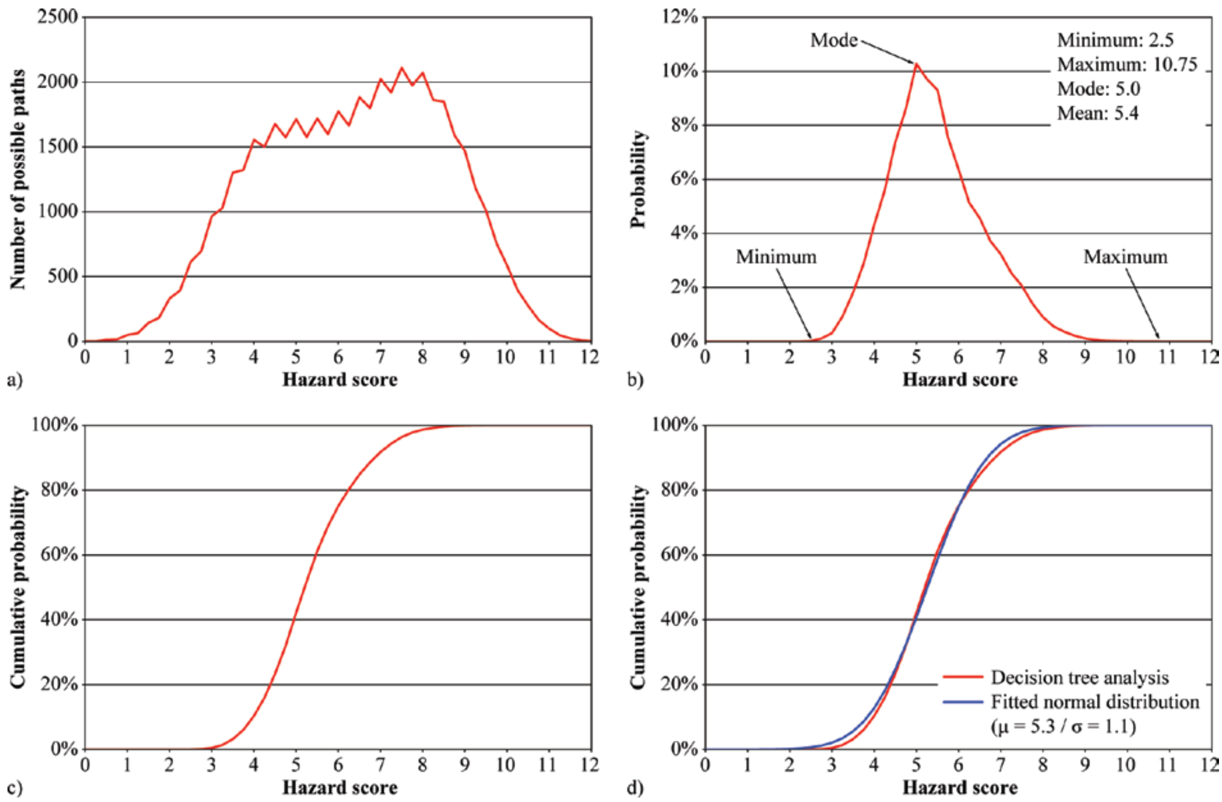

Figure 5: Results from the decision tree analysis: a) number of paths giving the same hazard score; b) Example of a probability distribution with indication of the minimum, maximum, modal and mean hazard scores; c) Cumulative probability distribution using the example from b); d) Fitting of the cumulative probability distribution from c) with a normal distribution (mean μ and standard deviation σ are indicated).

3.3 Hazard classes

Simplified to allow for effective communication, the hazard score is divided into five hazard classes using equal intervals (Table 4, Figure 6). Equal intervals are preferred over expert-knowledge-based class limits, because the latter are more controversial and need to be supported by calibrations of past rock slope failures. For example, one could define the very low hazard class by slopes that move since more than 10,000 years and that did not yet fail catastrophically; hence dating the deformation could solve the problem. However this information from the geological past does not necessarily indicate anything on the performance of the slope in future and continuous fatigue of rock in the past 10,000 years could have led to a critical stability today. Similarly, rock slopes that failed catastrophically could define the very high hazard class, if the slope conditions in the period of months/years prior to the catastrophic failure are used. Unfortunately, there is generally not enough information available on past catastrophic rock slope failures (Table 2), in order to assess their hazard score with satisfying reliability.

The probability of each hazard class is obtained by summing the probabilities of the hazard scores, φ_{score}, falling within the range of the hazard class (Table 4, Figure 6). Alternatively, the probability of each class can be computed using the fitted normal distribution. Figure 6 shows a good fit between probabilities computed with results from the decision tree analysis and from the normal distribution.

The advantage of this decision tree analysis is obvious: instead of giving a single hazard score for an unstable rock slope, the proposed technique with the decision tree analysis gives a range of probable hazard classes. The example data presented in Figure 6 and Table 4 represent a site in the moderate hazard class (about 60% probability), which is in agreement with the mode and mean values from the decision tree analysis (5.0 and 5.4, respectively; Figure 5b). However, there is a probability of about 33% to be in the low hazard class and up to 8% for the high hazard class (Table 4). Similarly, the uncertainty on the hazard score is also expressed by the normal distribution. The hazard of a site can for example be indicated by the normal distribution mean value, μ, and a range of $\pm 2\sigma$ ($\mu = 5.3$; $\mu - 2\sigma = 3.1$; $\mu + 2\sigma = 7.4$ for the example data) (Figure 5).

Table 4: Hazard assessment for an example site: hazard classes based on 5 equal intervals of the hazard score, ρ. Note: "[0.0; 2.4["signifies, for example, the range from 0.0 to 2.4, including 0.0 and excluding the value 2.4; the very high hazard class also includes the maximum hazard score 12.0. The probabilities of each hazard class are shown for the example in Figure 6 based the decision tree analysis and the fitted normal distribution.

Hazard class	Hazard scores	Probability	
	ρ	Decision tree analysis	Normal distribution
Very low	[0.0; 2.4]	0.0 %	0.4 %
Low	[2.4; 4.8]	31.9 %	32.9 %
Moderate	[4.8; 7.2]	59.9 %	62.9 %
High	[7.2; 9.6]	8.2 %	3.8 %
Very high	[9.6; 12.0]	0.0 %	0.0 %

Hazard classes	Class upper limit	Probability	Cumulative probability
Very low	2.4	0.0 %	0.0 %
Low	4.8	31.9 %	31.9 %
Medium	7.2	59.9 %	91.8 %
High	9.6	8.2 %	100.0 %
Very high	12.0	0.0 %	100.0 %

Hazard scores	
Minimum	2.5
Maximum	10.8
Mode	5.0
Mean	5.4
5^{th} percentile	3.7
95^{th} percentile	7.3

Fitted normal distribution	
Mean μ	5.2
St. dev. σ	1.1
Mean - 2σ	3.1
Mean + 2σ	7.4
Corr. coeff.	0.9997
K-S-test (max. diff.)	2.8 %

Figure 6: Screenshot of the Microsoft Excel® 2007 file used for the hazard assessment of an imaginary example of an unstable rock slopes in Norway. The tables show the probability and cumulative probability for each hazard class based on the decision tree analysis (left), the basic statistics of the decision tree analysis (middle) and the parameters of the fitted normal distribution including correlation coefficient and Kolmogorov-Smirnov test results (right). Note: the maximum difference between observed and fitted data must be smaller than 19.4% in order to satisfy the Kolmogorov-Smirnov test with a significance level α of 0.05.

3.4 Criteria describing the present state of an unstable rock slope

In the following we describe each criteria used in the classification system, using examples from unstable slopes in Norway or using scheme drawings. Nature is complex and not ideal, hence, we find few completely ideal geological examples. We have collected these examples, which we think best represent the various conditions possible for each criterion. These examples can also be reviewed and replaced once better examples become available.

Note that due to the use of probabilities in the classification system, it can also be used to determine whether more detailed analyses are necessary. For example, often during early site investigations, no information is available on the velocity of the slide. Hence, this high level of uncertainty should be expressed in the analyses. If the result of the analyses indicates that there is a probability that the sites might be defined as moderate or high risk object, then more investigations become necessary focussing on defining the velocity. If also under the worst case assessment the site remains a low risk object, no further investigations are required.

3.4.1 Development of the back scarp

The back scarp is defined here as the scarp or extensional crack that defines the upper or outermost limit of an unstable mass or of a compartment (block). It is in general the first morphologic expression that helps to recognize an unstable rock slope. However, in Norway care has to be taken when interpreting linear morphological structures along mountain slopes as back scarps. Due to multiple glaciations and missing soil cover, multiple structural lineaments can be mapped along mountain slopes, which are inherited old structures related to the long tectonic history of Scandinavia. Some of these inherited structures may represent zones of weakness which are today influencing gravitational slope deformation; however, such lineaments can also exist along stable slopes.

We divide this criterion into three conditions: 1) back scarp not developed, 2) back scarp partially open over the width of slide body, and 3) back scarp fully open over the entire width of slide body (Figure 7).

1. Back-scarp	Score	Probability
Not developped	0	0.0 %
Partly open over width of slide body (few cm to m)	0.5	40.0 %
Fully open over width of slide body (few cm to m)	1	60.0 %

Figure 7: Conditions used for the criterion 1 "Back-scarp" (screenshot of the Microsoft Excel® 2007 file) filled with example values (similarly as in subsequent figures).

1) A gravitational slope deformation without any back scarp is rare and in general tension cracks appear often with no toe displacement. Nonetheless, a sliding surface might form in the lower part of an unstable rock slope and retrogress towards the upper part. In this scenario, probably no back scarp has developed yet but the gravitational deformation might be visible due to bulging in the lower part of the slope resulting in a convex (lower slope) - concave (upper slope) slope morphology (Figure 8). This situation requires in general strong deformation before failure can occur, thus this condition get the lowest score 0.

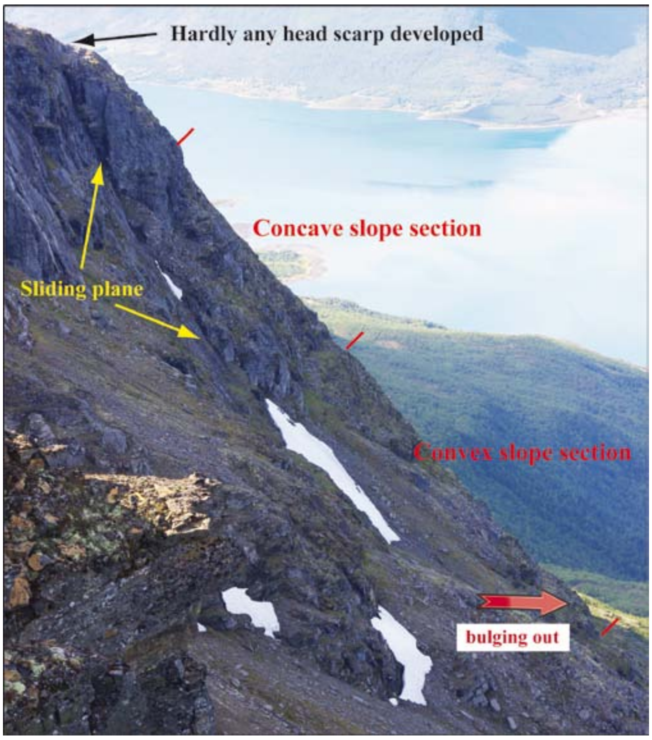

Figure 8: Gravitational slope deformations without a back scarp are either not very common or not very frequently recognized. This example shows a rock slope which is bulging out in its lower part forming a convex lower slope and a concave upper slope suggesting for gravitational deformation along a structural plane here used for sliding (photo: R. Hermanns). (The back scarp score would thus be 0.)

2) Partially open back scarps exist at sites where displacement is juvenile or with a slow rate and the entire rock block has not detached from the stable rock mass or where deformation varied in space (Figure 9). As displacement has to increase to open a back scarp over the full width of the unstable rock slope prior to failure this condition has the score 0.5.

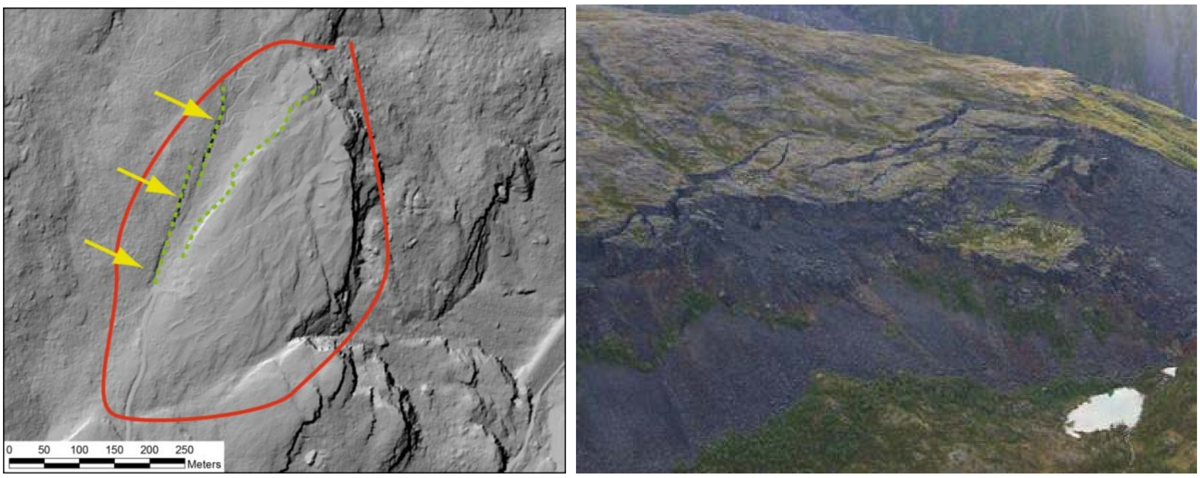

Figure 9: Left: Back scarp (yellow arrows) that is part of an opening graben (green dashed line) in back of large unstable rock slope indicated in red circle is only partly open in two segments. Right: Well developed scarps that do not connect to a singular back scarp (photo: H. Bunkholt). (The back scarp score would thus be 0.5.)

3) Fully open back scarps over the entire width of the slide body occur at those sites where the deformation has been large enough to open the scarp (Figure 10). This can occur both on sites with homogeneous deformation and sliding along a single structure (Figure 10a) or where deformation varies over the entire unstable rock slope (Figure 10b). As no further deformation of the rock mass in the back part is required this condition gets the highest score 1.

Figure 10: a) Unstable block separated from the stable rock mass by a graben that follows an inherited structure (photo: R. Hermanns). b) Although deformation rate and used inherited structures vary over the entire back scarp deformation rate has been high enough to form a continuous back scarp (photo: R. Hermanns). (The back scarp score would thus be 1.)

3.4.2 Potential failure surfaces

One of the most important structural preconditions in a slope is the presence of penetrative structures such as schistosity, bedding planes, faults, or persistent joints. Hence these are different to the criterion 4.4.5 inherited geological structures. These can form sliding planes if they are unfavourably oriented. Unfavourable oriented are those structures parallel to or striking slightly oblique with the slope (up to 30°) and dipping in the same direction as the slope. We distinguish in this criterion three different conditions: 1) no penetrative structures dip out of the slope, 2) penetrative structure dips on average < 20° or steeper than the slope 3) penetrative structure dips on average > 20° and daylights on the slope (20° as conservative value) (Figure 11). In the case that multiple structures exist that are not persistent but closely spaced and rock bridges that would have to fail are therefore small those structures should be evaluated in the same way.

2. Potential sliding structures	Score	Probability
No penetrative structures dip out of the slope	0	0.0 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	0.0 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	100.0 %

Figure 11: Conditions used for the criterion 2 "Potential sliding structures" (screenshot of the Microsoft Excel® 2007 file).

1) If the penetrative structures dip into the slope, no sliding on those structures is possible (Figure 12), therefore this condition has the lowest score 0. However, toppling is still a feasible failure mechanism (Figure 12). With the exception of block toppling that occurs only in minor rock volumes, toppling requires a high degree of internal deformation that requires long periods of pre-failure deformation (e.g. Bedoui et al., 2009).

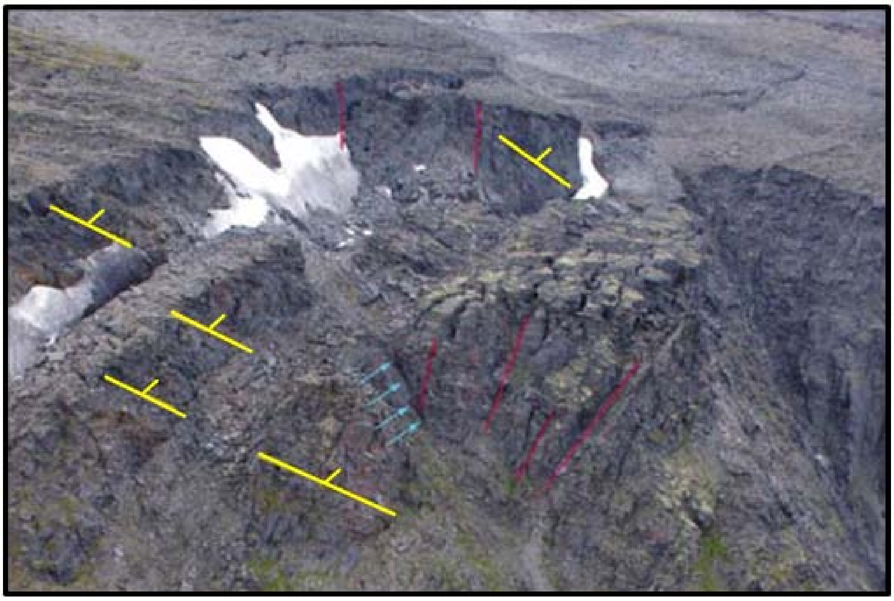

Figure 12: The foliation (yellow) has dip direction perpendicular to the azimuth of the slope hence does not allow for sliding. The joints (red) dip vertically or into the slope and hence allows for toppling. Continuous toppling movement breaks down rock bridges forming sliding surfaces which develop over long time periods (blue arrows) (photo: R. Hermanns). (The potential sliding structure score would thus be 0.)

2) In this condition two possibilities are described: a) Penetrative structure that dip on average < 20° do in general not allow for sliding due to a friction angle higher than the dip angle. However in fault zones clay mineral content can lower the friction angle down to 8° causing sliding to happen (e.g. Wyllie and Mah, 2004) (Figure 13a). b) On slopes with penetrative structures dipping parallel to or steeper than the slope, principally sliding is not possible, however failure of intact rock that restrains block motion through compressive, tensile or flexural cracking can connect the penetrative structure with the slope surfaces, allowing sliding to occur on the penetrative structure (e.g. Hermanns and Strecker, 1999, Goodman and Kieffer, 2000) (Figure 13b). As sliding in such cases depend on additional criteria in order to allow for sliding, this conditions has the score 0.5.

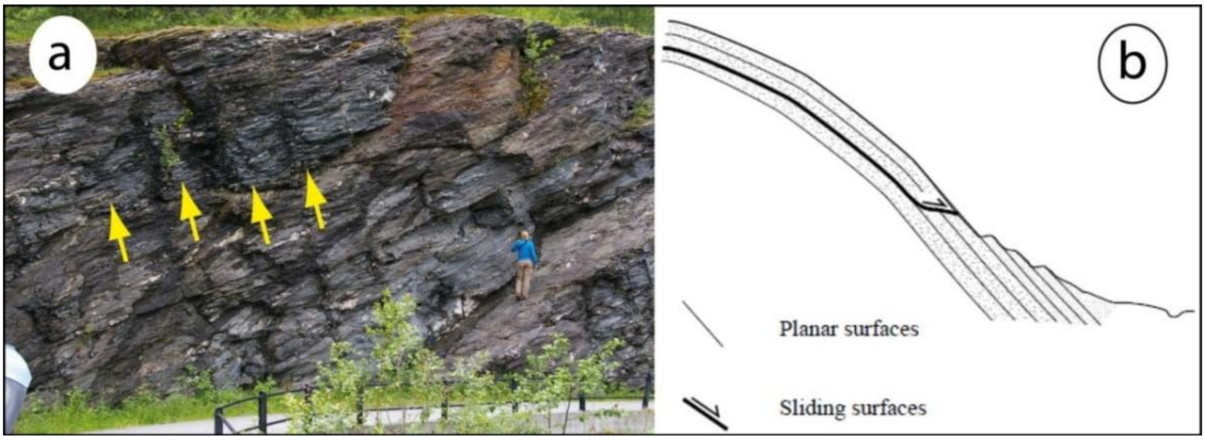

Figure 13: a) Planar penetrative surfaces dipping less than 20° and therefore less than the friction angle of rocks might slide along fracture zones filled with clayey fault gouge which can lower the friction angle down to 8° (photo: R. Hermanns). b) Sliding can occur along penetrative structures which are slope parallel but do not daylight with the slope if other structures exist or form connecting the penetrative structure with the slope (drawing from Hermanns and Strecker, 1999). (The potential sliding structure score would thus be 0.5.)

3) Penetrative structures daylighting on the slope and steeper than the friction angle are the most critical situations as the penetrative structures can form sliding planes (Figure 14). Here we set 20° as the lower value of friction angles in rock (Wyllie and Mah, 2004) as a conservative value. This condition has the highest score 1.

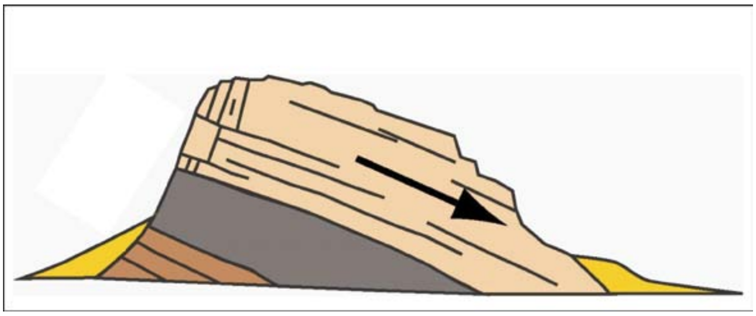

Figure 14: Slopes with daylighting penetrative structures are most critical to generate sliding if the penetrative structure is steeper than the friction angle of the rock mass. (The potential sliding structure score would thus be 1.)

3.4.3 Development of lateral release surfaces

This criterion describes how much displacement has occurred already on the lateral boundaries of the unstable rock slope, and/or how much additional deformation is required prior to failure (Figure 15, Figure 16). Therefore, fully developed lateral release surfaces include here both cases 1) cracks due to rock deformation penetrative and 2) inherited structures (schistosity, faults, joints) that weaken the rock laterally (see also Hungr and Amann, 2011). Furthermore, free faces are weighted in the same way. If fully developed or fully connected they get a score of 0.5 for each side, while partially developed or unconnected release surfaces get a score of 0.25. This leads to five possible conditions indicating the displacement along the lateral boundaries: 1) no lateral surface developed (score 0), 2) lateral surface partly developed on one site (score 0.25), 3) fully developed or free slope on one side or partly developed on two sides (score 0.5), 4) fully developed or free on one side and partly developed on one side (score 0.75), 5) fully developed or free on both sites (score 1) (Figure 15). For wedge failures the more inclined sliding surface should be treated as lateral release surface in this criterion.

3. Lateral release surfaces	Score	Probability
Not developped	0	25.0 %
Partly developped on 1 side	0.25	50.0 %
Fully developped or free slope on 1 side or partly developped on 2 sides	0.5	20.0 %
Fully developped or free slope on 1 side and partly developped on 1 side	0.75	5.0 %
Fully developped or free slope on 2 sides	1	0.0 %

Figure 15: Conditions used for the criterion 3 "Lateral release surfaces" (screenshot of the Microsoft Excel® 2007 file).

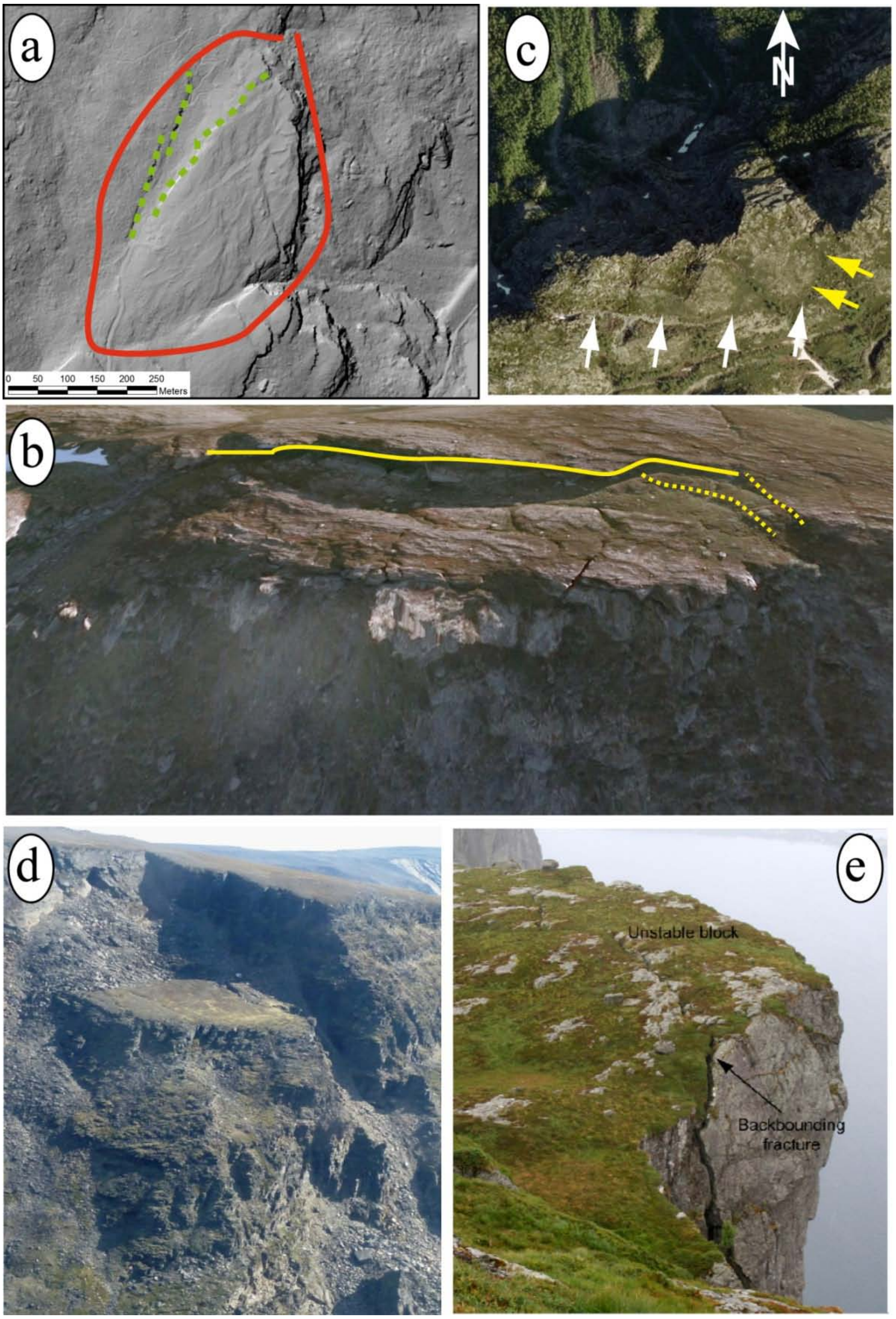

Figure 16: Unstable rock slopes with various types of lateral release surfaces a) No lateral release surface has developed on one side while the other side is a free face. (The lateral release surface score would thus be 0.5.) b) This unstable rock slope has a free face on the left side and a partly developed release surface on the right side (photo: H. Bunkholt). (The lateral release surface score would thus be 0.75.) c) This block has a free face on the west side and poorly developed lateral release surface on the on the east side that is parallel to the joints. However, the length of joints is less than the width of the block (The lateral release surface score would thus be 0.75) d) This block is a wedge in the sense that sliding occurs on two rupture

surfaces although the intersection line does not daylight on the slope. Hence the failure mechanism would be more complex than that of a simple wedge failure. Both failure planes are fully developed (photo: H. Bunkholt). (The lateral release surface score would thus be 1.) e) The back scarp connects two free faces (photo: M. Böhme). (The lateral release surface score would thus be 1.)

3.4.4 Kinematic feasibility test

Discontinuities, such as joints, fractures, faults, bedding or foliation, are anisotropies in the rock mass that have major influences on the slope stability. Kinematic feasibility tests assess the possibilities for different failure mechanisms based on the discontinuity orientations with respect to the slope orientation. Standard criteria from rock mechanics are used and practically assessed in a stereographic projection (Hoek & Bray, 1981; Wyllie & Mah, 2004): For planar sliding, the discontinuity must daylight the topography, i.e. it needs to dip in the same direction as the topography with a tolerance that depends on the slope angle and its dip angle must be smaller than the slope angle, but also steep enough to exceed the friction angle along the discontinuity (20° as conservative value) (Wyllie & Mah, 2004). In a stereographic projection this signifies that the pole of the discontinuity has to fall inside the daylight envelope of the topography and at the same time be outside of the pole friction angle cone (Figure 17a) (Wyllie & Mah, 2004; Rocscience, 2007).

The same criteria apply for wedge sliding mechanisms formed by the intersection of two discontinuities (Markland, 1972; Hoek & Bray, 1981; Wyllie & Mah, 2004). The wedge intersection line must daylight the slope. At the same time the wedge intersection line plunge angle must be steeper than the friction angle (20° as conservative value). Seen in a stereographic projection, the intersection line must fall into the zone delimited by the friction angle cone and the great circle of the slope face (Figure 17b) (Rocscience, 2007).

Compared to planar or wedge sliding mechanisms block toppling occurs only in minor rock volumes. However, flexural toppling can affect large rock masses toppling, but requires a high degree of internal deformation and therefore long periods of pre-failure deformation (e.g. Bedoui et al., 2009). For a toppling failure to occur, the dip direction of the discontinuities dipping into the face must be within a small angle with respect to the dip direction of the face so that a series of slabs can form parallel to the face. Also the dip of the discontinuity must be steep enough for interlayer slip to occur.

For planar sliding, a lateral tolerance of ±20° between the discontinuity dip direction and the slope aspect is generally used in rock slope engineering (Hoek & Bray, 1981; Wyllie & Mah, 2004). In studies on large rock slope failures such a strict limitation of the sliding direction is not suitable due to the generally more complex structures involved in large rock slides and the generally more variable slope orientation. Therefore, conservatively this "Kinematic feasibility test" criterion assumes that planar or wedge sliding is possible (score 0.75) if the difference between sliding direction and slope aspect is smaller than 30° and partly possible (score 0.5) if the difference is larger than 30° (Figure 17, Figure 18).

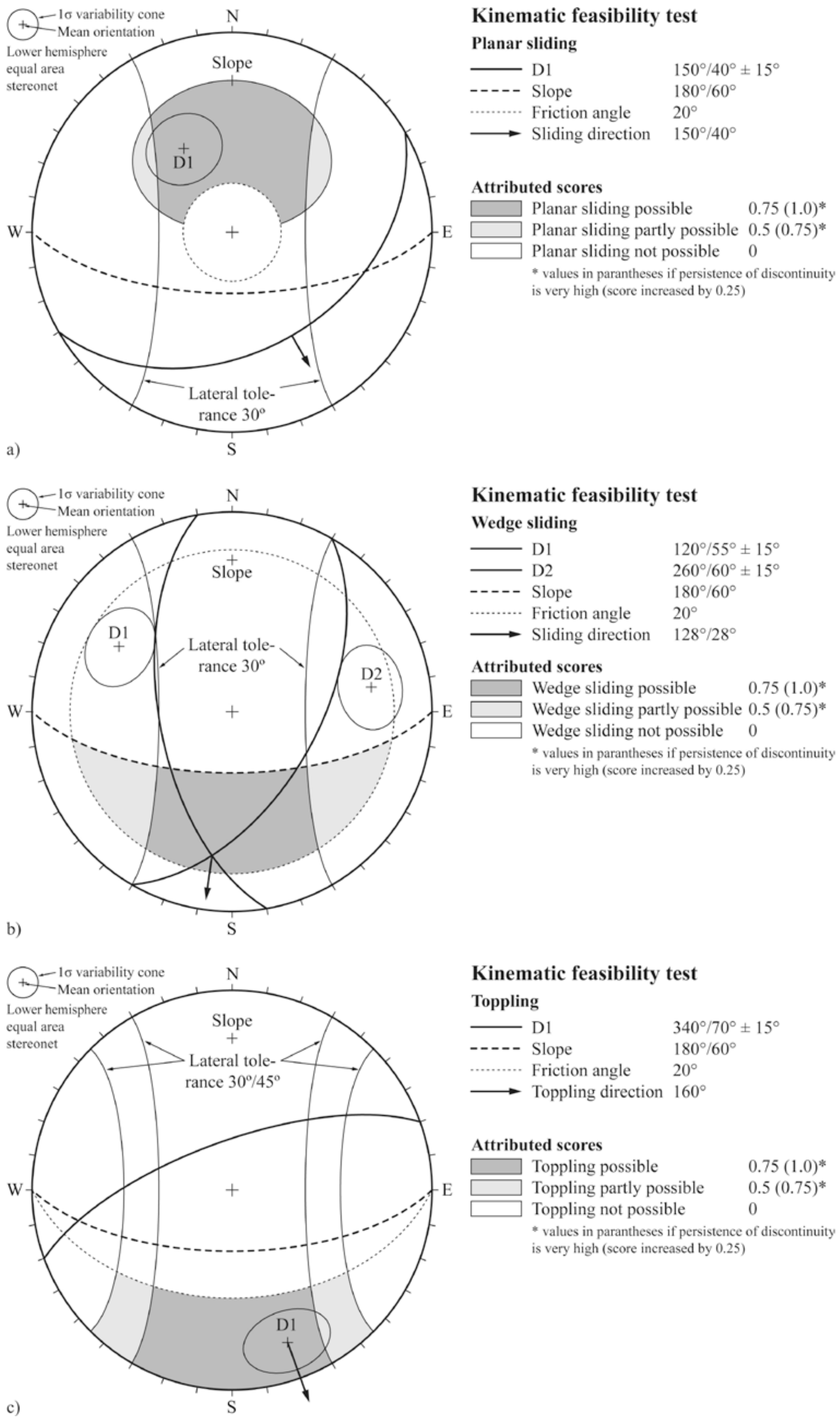

Figure 17: Kinematic feasibility tests for a) planar sliding and b) wedge sliding, and c) toppling failure (modified after Hoek & Bray, 1981; Wyllie & Mah, 2004). A higher score is attributed if the difference between sliding direction and slope aspect is smaller than 30° and if the persistence of discontinuities is very high (>20m according to ISRM, 1978).

Similarly, a lateral tolerance of ±10° between the dip direction of the discontinuities dipping into the face and the dip direction of the slope face is generally used in rock slope engineering (Hoek & Bray, 1981; Wyllie & Mah, 2004). Due to the complexity of large rock slopes, conservatively this "Kinematic feasibility test" criterion assumes that toppling is possible (score 0.75) if the difference between dip direction of the discontinuities and slope aspect is smaller than 30° and partly possible (score 0.5) if the difference is smaller than 45° (Figure 17, Figure 18).

In addition, the criterion takes into account the importance of the persistence of the discontinuity (discontinuities) involved in the planar (wedge) sliding mechanism. As shown in the crystalline rocks in the Matter valley (Switzerland), the persistency has a strong impact on possible size of rock slope failures (Yugsi Molina, 2010). The score of the "Kinematic feasibility test" criterion is increased by 0.25, if the persistence is very high relative to the unstable mass (>20 m according to ISRM is taken as a minimum length for rather smaller unstable masses, 1978) (Figure 17, Figure 18).

4. Kinematic feasibility test	Score	Probability
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	0.0 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	10.0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	50.0 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	10.0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	30.0 %

Figure 18: Conditions used for the criterion 4 "Kinematic feasibility test" (screenshot of the Microsoft Excel® 2007 file).

3.4.5 Morphologic expression of the basal rupture surface

The development and geometry of the basal rupture surface is an important factor controlling slope stability. However, in most cases it is difficult to define both over the entire length without costly geophysical tools or coring. Therefore we base our observations here on the morphologic expression alone that is mappable in the field. However, if the risk analysis suggests that the site is a high risk object, further investigations on the development and geometry might be advisable in order to carry out a more detailed stability assessment and optimize the mitigation measures.

The morphologic expression of the basal rupture surface (sliding surface) gives important information about past deformations of an unstable rock slope. If the basal rupture surface is visible on the slope and can be mapped out (Figure 19a) the slope has already undergone significant deformation and a more or less continuous rupture surface is likely to exist. Fault breccia or fault gouge are clear indications for past displacements along the rupture surface (Figure 19b). In some cases, a continuous rupture surface can also be assumed even if parts of the slope are covered by debris (Figure 19c). Often, the rupture surface is not directly visible, but the slope morphology indicates their location by, for example, a series of springs (Figure 19d) or bulging of the slope (Figure 19e).

It is presumed that past deformation was smaller on slopes with morphologic indications of the rupture surface (score 0.5) compared to those where the rupture surface is visible (score

1), but higher than on slopes without any indications of the rupture surface on the slope morphology (score 0) (Figure 19f, Figure 20).

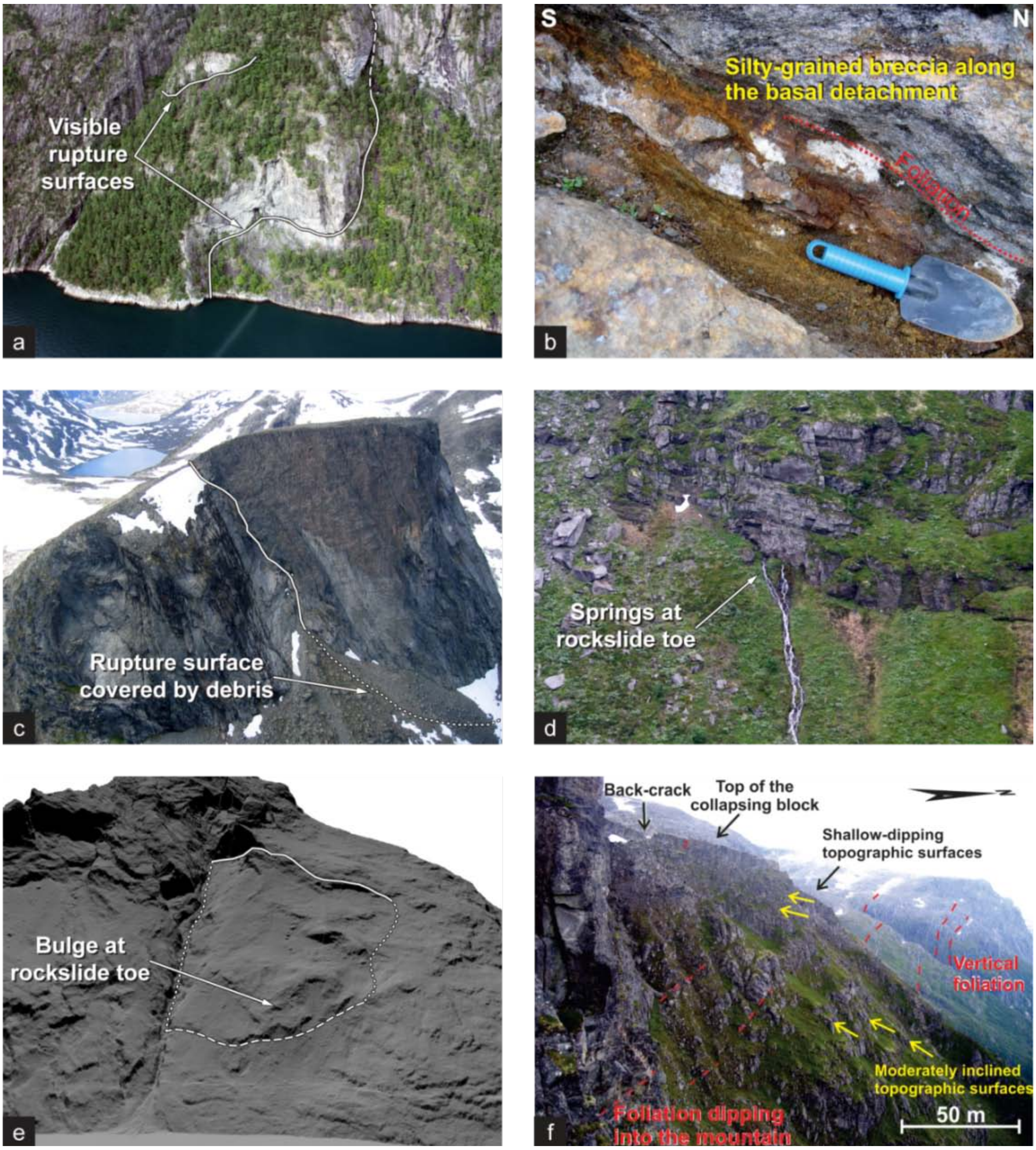

Figure 19: Illustrations of the "Morphologic expression of the rupture surface" criterion: a) The rupture surface is clearly visible on the slope morphology and can be mapped out (photo: T. Oppikofer) (The rupture surface score would thus be 1.); b) Presence of fault breccia along the rupture surface (photo: I. Henderson; from Saintot et al., 2011); c) Continuity of the rupture surface can be assumed, even though parts of the slope are debris covered (photo: I. Henderson); d) Alignment of springs indicating the possible location of the rupture surface (photo: I. Henderson) (The rupture surface score would thus be 0.5.); e) Bulging of the slope expresses the internal deformation in the rock mass and indicates the possible location of the rupture surface (DEM by courtesy of Åknes/Tafjord Beredskap IKS) (The rupture surface score would thus be 0.5.); f) The rupture surface is not clearly visible on the slope morphology, but might correspond to one of the moderately inclined valley-dipping surfaces (from Saintot et al., 2011) (The rupture surface score would thus be 0.).

5. Morphologic expression of the rupture surface	Score	Probability
No indication on slope morphology	0	15.0 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	70.0 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	15.0 %

Figure 20: Conditions used for the criterion 5 "Morphologic expression of the rupture surface" (screenshot of the Microsoft Excel® 2007 file).

3.4.6 Landslide displacement rates

Landslide displacement rates have been defined earlier by Varnes (1978) and by Cruden and Varnes (1996), however those classification systems should classify displacement rates of all landslides types from slow deformations of a few cubic meters of soil to catastrophic failures of entire mountains, and are therefore not detailed enough to describe and distinguish the displacement rates of rock masses prior to failure. Following Varnes (1978) or Cruden and Varnes (1996) all rock slopes continuously or permanently monitored in Norway would fall in the classes "very slow" and "extremely slow". Examples which were used in their classification system had velocities of 20 cm/yr upwards, hence faster than any rockslide displacement measured in Norway. Although limited information exists today on displacement rates prior to catastrophic rockslope failure (Table 2), this information is not detailed enough and observations have not been as precise as technically possible today. Therefore, these cannot be used in order to generate an appropriate classification system. In addition, there is no systematic information linking the kinematics of rock slope deformation and rockslope displacement rates prior to failure.

No significant movement in one year is defined as the lowest class of this condition with a score of 0. Displacement rates of slightly over 10 cm/yr are the highest displacement rates measured up to now in Norway (Kristensen et al., 2010) and therefore set as the upper boundary giving the highest score of 5 (Figure 20). A velocity of 0.2 - 0.5 cm/yr is just above significance limit of monitoring systems we use most frequently (dGPS, satellite- and ground-based InSAR, terrestrial laser scanning) and considered a sign of active displacement (score 1). The condition 0.5 - 1 cm/yr is seen as an advanced displacement rate (score 2). The conditions 1 - 4 cm/yr, and 4 - 10 cm/yr are thought as displacement rates that might lead within the course of a year to failure if structural conditions are very unfavourable or unfavourable (3, 4 respectively) and rock mass volume is relatively small (hundreds of thousands of cubic meters). This classification system of displacement rates has to be revised once detailed monitoring data of slopes that lead to failures become available.

6. Movement	Score	Probability
No significant movement	0	20.0 %
0.2 - 0.5 cm/year	1	50.0 %
0.5 - 1 cm/year	2	20.0 %
1 - 4 cm/year	3	10.0 %
4 - 10 cm/year	4	0.0 %
> 10 cm/year	5	0.0 %

Figure 21: Conditions used for the criterion 6 "Movement" (screenshot of the Microsoft Excel® 2007 file).

3.4.7 Change of displacement rates (acceleration)

Based upon the observations summarized in Table 2 it becomes obvious that acceleration of slope displacement takes place prior to failure. We include this criterion into the assessment of displacement rates to anticipate a possible increase of the score attributed to the landslide displacement rates criterion. Therefore, the change of displacement rates criterion is not assessed if the displacement rate is already >10 cm/yr (highest class in the landslide displacement rates criterion (Figure 22). Acceleration is here defined as a change in displacement rate that is larger than the uncertainty limits of the monitoring system, not connected to seasonal variability and verified not to be a measurement error. This can be done by at least two independent monitoring devices or two repeated measurements separated in time. Therefore, we include this criterion only for sites where the displacement rates exceed 0.5 cm/yr.

7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)	Score	Probability
No acceleration or change in displacement rates	0	90.0 %
Increase in displacement rates	1	10.0 %

Figure 22: Conditions used for the criterion 7 "Acceleration" (screenshot of the Microsoft Excel® 2007 file).

3.4.8 Increase in rock fall activity on the unstable slope

Based upon the observations summarized in Table 2 it becomes clear that increased rock fall activity precedes large rock slope failures. Therefore we include this criterion into the hazard assessment. Here we do not focus on the total number of rock fall per day as different lithologies and diverse structural settings (e.g. dip slope, scarp slope) might naturally lead to a different total amount of rock falls when comparing different rock slopes. The focus here is the increase of rock fall activity compared to the adjacent slopes with similar or identical rock properties (Figure 23). This is often difficult to support with observational accounts but can be assessed by the freshness of rock fall activity in the source area and the foot of the slope as well as damage to the vegetation cover.

8. Increase of rock fall activity	Score	Probability
No increase of rock fall activity	0	90.0 %
Increase of rock fall activity	1	10.0 %

Figure 23: Conditions used for the criterion 8 "Increase of rockfall activity" (screenshot of the Microsoft Excel® 2007 file).

3.4.9 Presence of post-glacial events along the affected slope and its vicinity

This criterion is to include regional geological information into the assessment. Mapping activities in the past decade has indicated that some regions in Norway have a high number of unstable slopes and a high number of rock avalanche deposits, while others have a high number of unstable slopes but a comparable small number of rock avalanche deposits (e.g. Blikra et al., 2006; Longva et al. 2009, Hermanns et al. 2011, Bunkholt et al., 2011). While there are slopes that can deform over thousands of years without failure, slopes with other properties might fail with less deformation. This is related to internal conditions within the slope such as lithological properties, but also to conditions related to climate (e.g. permafrost). As our observation window is restricted to the past 12 ka (after the last deglaciation) and there is not enough data to do a slope specific frequency analysis of past rock slope failures this criterion summarizes conditions along the valley segments with similar conditions. It expresses that valley sections that have frequently failed in the past will likely fail more frequently in future compared to valley sections with a low number of past failures (see also Longva et al., 2009 and Hermanns and Longva, 2012). This is in contradiction to Cruden and Hu (1993) who compiled ages of large landslides in the Canadian Rocky Mountains and proposed an exhaustion model to explain the decrease in activity through the Holocene. The premises of this model are that there are a finite number of potential failure sites that are conditioned by glaciation and that each of these sites can fail only once. Although this model might work in certain regions and for certain rock slope failures, in the general sense their premises have been proven to be wrong because more than one slope failure can occur at a single site and because completely new instabilities can be created through progressive failure (e.g. fatigue of rock masses) (Hermanns et al., 2006 and references therein; Aa et al., 2007, Hermanns and Longva, 2012; Loew et al., 2012). As the largest climatic changes coupled with istostatic adjustment and stress release and the highest temporal density of rock avalanches in Norway occurred after deglaciation and the thousand years thereafter (Longva et al., 2009; Hermanns and Longva, 2012), we divide this criterion into three conditions: 1) no post-glacial events of similar size on slope section with similar properties, 2) one or several events of similar size older than 5000 years, 3) one or several events of similar size younger than 5000 years, (Figure 24).

9. Past events	Score	Probability
No post-glacial events of similar size	0	0.0 %
One or several events older than 5000 years of similar size	0.5	50.0 %
One or several events younger than 5000 years of similar size	1	50.0 %

Figure 24: Conditions used for the criterion 9 "Past events" (screenshot of the Microsoft Excel® 2007 file).

4. CONSEQUENCE AND RISK ANALYSIS AND SUGGESTED SURVEILANCE OF UNSTABLE ROCK SLOPES

4.1 Risk analysis

Fell et al. (2008) define risk as "a measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability of a phenomenon of a given magnitude times the consequences" (p. 86). The risk, R, can be calculated using the widely used risk equation (modified from Leroi, 1996; Fell et al., 2005) (Equation 4):

$$R = P_F \times P_P \times P_E \times V \times E \qquad (4)$$

with P_F = probability of failure; P_P = probability of propagation (probability of the landslide and its secondary effects reaching the element at risk); P_E = probability of presence of the element at risk; V = vulnerability of the element at risk to the landslide event (degree of loss from 0% to 100%); E = element at risk (i.e. exposed population). Several of the factors of

Equation 4 are difficult to quantify within the framework of this hazard and risk classification for unstable rock slopes in Norway, especially the probability of failure, P_F, which cannot be assessed with today's technical understanding of large unstable rock slopes within the timeframe of hundreds to thousands years. For this hazard and risk classification system the hazard score is used as a qualitative measure of the probability of failure, P_F.

4.1.1 Preliminary consequence and risk analysis

The preliminary risk analysis is a first, rough analysis aiming to distinguish between low risk objects and medium to high risk objects that require more detailed risk analyses. Therefore, a worst case scenario is assumed for the preliminary risk assessment and P_P, P_E and V are set to 1 (or 100%) and E is the maximum number of persons living or being present in the affected area (see section 2). This means that the entire area computed in the run-out assessment will be reached by the rock avalanche or displacement wave ($P_P = 1$), all the population and persons that transit are present in the affected area ($P_E = 1$) and their loss of life is certain ($V = 1$). The number of potential life losses is thus equal to E.

4.1.2 Detailed consequence and risk analysis

For potential medium to high risk objects based on the preliminary risk assessment a detailed consquence analysis becomes necessary (see Figure 2). This includes a more detailed quantification of the parameters in Equation 4. Detailed run-out modelling (and displacement wave assessment if relevant) allows the determination of P_P. The parameter P_E is mainly depending on the building type (house, office, shop, school etc.) and can be determined roughly at a national level. Different vulnerabilities can be defined, depending if a building is hit directly by a rock avalanche and loss of life is nearly certain ($V = 1$) or if it is hit by a displacement wave that have an assumed survival rate of 30% ($V = 0.7$) (Blikra et al. 2006). The number of potential life losses is then obtained by multiplying P_P, P_E, V and E for each building and summing over the entire area affected by a rock avalanche and its secondary effects. Areas frequently visited by tourists are assessed in the same manner as buildings.

An exception from the approach outlined above, is up- and downstream flooding related to rockslide dams. In contrast to the direct impact of a rockslide on a building or the impact of a rockslide-triggered displacement wave on a building, people affected by upstream and downstream flooding related to landslide damming and subsequent dam breaching can be evacuated from the building. In these cases the evaluation of hazard and risk related to dam formation and dam failure should be included as outlined in Dahle et al. (2011b) and Hermanns et al. (2012c). However, the final risk classification will mainly be based on the number of people which might lose their life in a potential event.

4.2 Risk matrix & risk classes

This classification system combines the hazard score and the potential life losses in a risk matrix (Figure 25). Isorisk lines are often used in a risk matrix to distinguish between acceptable, tolerable and unacceptable risks as proposed for example for landslides and rockfalls from natural slopes in Hong Kong (Geotechnical Engineering Office, 1998). However, these isorisk lines are not applicable for the present risk classification system, since the hazard score is only a qualitative measure of the probability of failure and the classification focuses on rock slope failures preceded by an acceleration phase only, thus excluding earthquake-triggered rock slope failures. The risk can therefore not be expressed in terms of number of casualties per year, and this is not a risk management tool in its own but a support for risk management.

The purpose of the risk matrix is helping to decide on follow-up of unstable rock slope with some type of monitoring, further investigations and/or possible mitigation measures. For that reason the risk matrix is divided into three risk classes: low (green in Figure 25), medium (yellow) and high (red). The limit between the low and medium risk classes is set along the diagonal going from the high hazard class with very low consequences (0.1 to 1 casualties) down to very low hazard class with high consequences (100 to 1000 casualties). It is expected that most of the sites in Norway fall into the low risk class. Those sites are either considered to have low consequences and further follow up is not economically sustainable, or the site would require dramatic changes in the geological conditions prior to failure. Such changes could be captured with a scanning of geological conditions by means of field visit or remote sensing data interpretation every 10 to 20 years. Medium risk sites are expected to be less common in Norway. However, potential consequences are higher or the probability of failure is higher so that a low-level follow up is recommended to reduce the risk level. The limit between the medium and high risk classes is not precisely defined and is shown as a yellow to red gradient in Figure 25. In this transition zone between medium and high risk, in general further site-specific geological criteria are needed to be studied in order to have a good enough understanding for a final classification. These sites will generally require additional expert judgement that will be used to classify the risk.

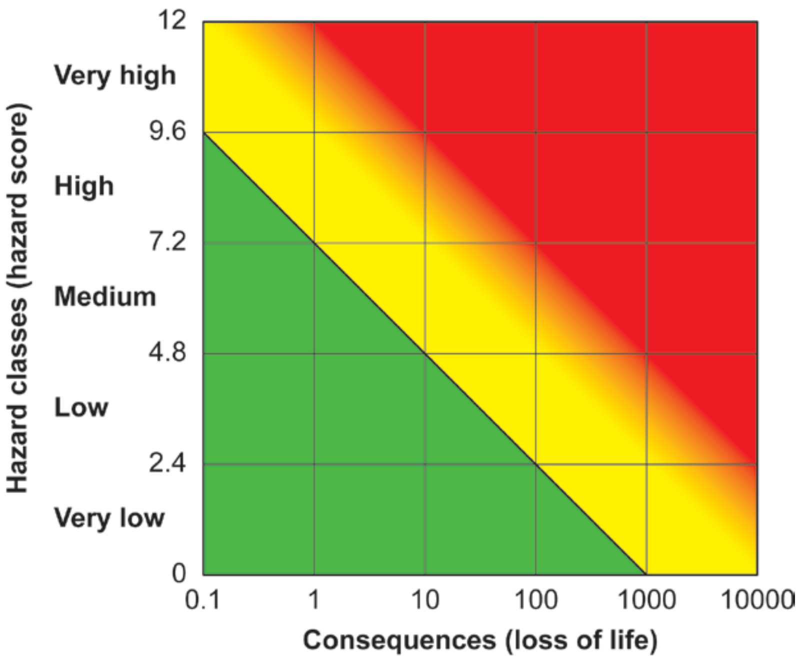

Figure 25: Risk classification matrix for follow up with monitoring and further investigations of unstable rock slopes in Norway: green = low risk; yellow = moderate risk; red = high risk. The transition zone between medium and high risk (yellow to red gradient)

4.3 Representing unstable rock slopes in the risk matrix

An unstable rock slope can be placed in the risk matrix based on the hazard analysis and the consequence analysis. As both factors have uncertainties, the minimum and maximum values for hazard and consequences can also be plotted in addition to the mean value (Figure 26).

The uncertainties on the hazard score and the consequences can have an influence on the risk classification and on the decision on follow-up activities. An unstable rock slope might for example be classified as low risk based on the most likely hazard class, but there might be a certain probability that it ends up as a medium risk. If this probability exceeds 5%, more site investigations should be considered in order to reduce the uncertainties on the assessment of conditions for the different criteria. If this is not feasible, the unstable rock slope might be classified with the higher risk class. The 5% and 95% percentiles of the hazard score are therefore also shown in the risk matrix (Figure 26). Similarly, there is uncertainty related to the consequences and more detailed consequence analyses could be considered in order to reduce the uncertainty. The decision on follow-up activities will be made after a thorough discussion of the uncertainties related to both hazard and consequences.

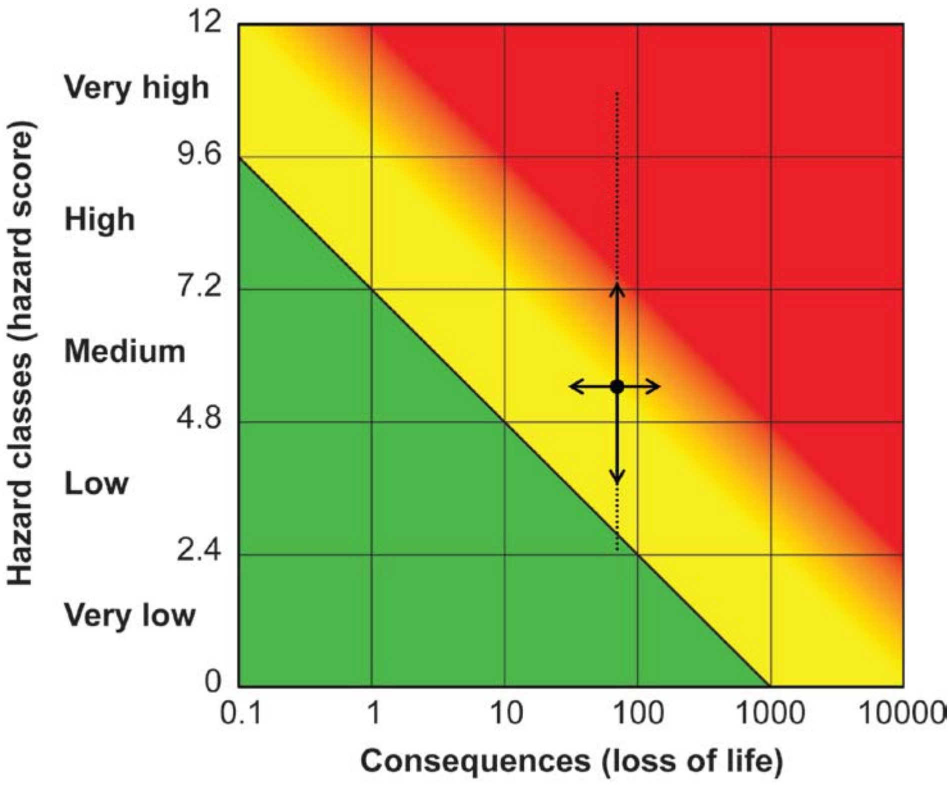

Figure 26: Risk classification matrix for follow-up with monitoring and further investigations of unstable rock slopes in Norway: green = low risk; yellow = moderate risk; red = high risk. The risk of an unstable rock slope is represented by its mean value, the minimum and maximum consequences (horizontal arrows), the 5% and 95% percentiles of the hazard score (vertical arrows) and the minimum and maximum scores of the hazard analysis (dotted line).

4.4 Implications of the risk classification

The risk classification of unstable rock slopes in Norway will be used by the Geological Survey of Norway and the Norwegian Water Resources and Energy Directorate in order to decide on follow-up investigations and mitigation measures. It will also help municipalities and other stakeholders as a basis for land use planning and contingency planning.

A document describing the implications of the risk classification related to the low, medium and high risk classes will be presented in due time by NVE. This will include implications related to land use planning, monitoring and early-warning, contingency planning and structural measures. All decisions on mitigation measures will be based on cost-benefit reasoning.

In general, low risk objects will not be followed up except a routine scanning in the field or based on remote sensing data (air photos, satellite data) every 10 to 20 years. For medium risk objects, periodic monitoring is recommended and the techniques used and the measurement intervals applied will depend on geological conditions on the site, applicability of the various methods under cost-benefit reasoning. For high-risk objects mitigation measures are recommended that have to be discussed among risk owners and geoscientists. The document by NVE will give guidance to follow-up procedures.

The follow-up at any site with every risk level might lead to the detection of significant changes in the state of the unstable rock slope. In that case, a new hazard analysis and risk classification should be carried out with the updated site conditions. This new analysis might lead to a change in the risk classification and the site should then be handled accordingly.

5. Summary

Due to the geomorphologic conditions of Norway with high mountains deeply penetrated by fjords, large rock slope failures occurred repeatedly in the past, often accompanied by secondary effects such as displacement waves. Therefore, in contrast to other mountain belts in the world, these rock slope failures resulted in disasters with a high death toll far from the source area of the rock slope failure. As such events will also occur in the future, systematic mapping of rock slopes has been started in the first decade of the 21st century and today more than 300 unstable rock slopes are known. This high number necessitated a quantitative classification system based on hazard and risk related to the potential failures that should help deciding on follow-up activities. This system was elaborated here in a large effort combining national and international experts from various disciplines in earth sciences.

During the elaboration of this document it became obvious that today there is not enough scientific knowledge to predict the timing of large rock slope failures, and that more research is needed and much can be learned from rock slope failures that have been monitored in the years prior to failure. Therefore, we classified the probability of failure relatively in very high, high, moderate, low and very low. Within the completion time of this document a rock slope failure occurred in Switzerland that has been monitored for more than a decade. The analysis of pre-failure conditions indicated a high hazard for that slope. We take this as a first positive test of our classification system. Furthermore, the probability of the Åknes rock slope in Norway was assessed earlier, and independently of this system, and the results are comparable. As shown in Appendix 1 different scientists might assign slightly different scores for the geological criteria.. In cases that the final risk analysis falls clearly in one field these differences are considered of low importance. However, especially for sites that plot close to the border of the high risk zone, additional independent evaluation has to be considered. NVE's international expert panel is an ideal tool to address these geological uncertainties. In any case we want to highlight that this classification system should be updated once more scientific knowledge becomes available, and that more research is necessary to better understand failure processes of large rock slope failures through time. These efforts will then hopefully allow to replace the qualitative hazard analysis with a quantitative hazard analysis.

Our hazard classification is based on two sets of criteria: 1) Structural site investigations including analysis of the development of the back-scarp, lateral limits and basal sliding surface. This includes a kinematic analysis that tests if rock sliding is kinematically feasible with respect to the slope orientation, the persistence of main structures and the morphologic expression of the sliding surface. 2) The analysis of the activity of the slope is primarily based on the slide velocity, but also includes the change of deformation rates (acceleration), observation of rockfall activity and historic or prehistoric events. For each criterion several observations are possible to choose from. Each observation is associated to a score and the sum of all scores gives the total score for a scenario. The weighting of these scores has changed from the first proposal of the classification system (Hermanns et al., 2010) over a preliminary usage of it (Dahle et al., 2011a) to this final version. For example, in this final version the historic and prehistoric events are weighted much lower than in the first proposal. This seemed necessary as the occurrence of a prehistoric event alone should not raise a site by one hazard class without any signs of present day activity. Furthermore, the displacement rates and morphological expressions/kinematic feasibility of failure are weighted equally. This weighting should be revised once statistically adequate information becomes available.

As all these observations are connected to uncertainties, the classification system is organized in a decision tree where probabilities to each observation can be given. All possibilities in the decision tree are computed and the individual probabilities giving the same total score are summed. Basic statistics show the minimum and maximum total scores of a scenario, as well as the mean and modal value. The final output is a cumulative frequency distribution divided into several classes, which are interpreted as hazard classes.

The consequence analysis is focussed on loss of lives only and we start with a conservative approach by assuming that all people that might be hit by a rock avalanche or a rockslide-triggered displacement wave are likely to lose their lives. For potential high-rsik objects a more detailed analysis is carried out. Here we refer also to the special document on administrative follow-up and mitigation measures that will be presented in due time by NVE.

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7. Appendix

A1. Hazard analysis of Åknes rockslide

The hazard of the Åknes rockslide has been assessed independently by Åknes/Tafjord Early-Warning Center and by the Geological Survey of Norway. The used probabilities for each criterion and the results of the hazard analysis are shown in the following sections.

Scenario 1

Scenario 1 comprises the entire unstable rock slope and has an estimated volume of maximum 54 Mm^3. Active displacements are ascertained for the middle and upper part of the slope, but not the lower part. The annual probability of scenario 1 has been estimated to 1/1000–1/5000 (Hole et al., 2011) and 1/1000–1/3000 (Blikra et al., 2006b). Based on this hazard analysis, scenario 1 falls into the medium hazard class (average score: 6.3–6.4).

Hazard assessment of large unstable rock slopes in Norway

Site name:	Åknes	**Scenario:**	1	**Made by:**	ÅTB & NGU	**Date:**	03.08.2012

Hazard classes	Author 1	Author 2
Very low	0.0 %	0.0 %
Low	6.4 %	2.3 %
Medium	73.6 %	73.8 %
High	20.0 %	23.8 %
Very high	0.0 %	0.0 %

Hazard scores	Author 1	Author 2
Minimum	3.75	4.50
Maximum	8.25	8.50
Mode	6.50	6.50
Mean	6.33	6.44
5^{th} percentile	4.60	4.86
95^{th} percentile	7.67	7.81

1. Back-scarp	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly open over width of slide body (few cm to m)	0.5	0 %	0 %
Fully open over width of slide body (few cm to m)	1	100 %	100 %

2. Potential sliding structures	Score	Author 1	Author 2
No penetrative structures dip out of the slope	0	0 %	0 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	10 %	0 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	90 %	100 %

3. Lateral release surfaces	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly developped on 1 side	0.25	0 %	0 %
Fully developped or free slope on 1 side or partly developped on 2 sides	0.5	50 %	25 %
Fully developped or free slope on 1 side and partly developped on 1 side	0.75	50 %	25 %
Fully developped or free slope on 2 sides	1	0 %	50 %

4. Kinematic feasibility test	Score	Author 1	Author 2
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	0 %	0 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	0 %	0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	30 %	0 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	0 %	0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	70 %	100 %

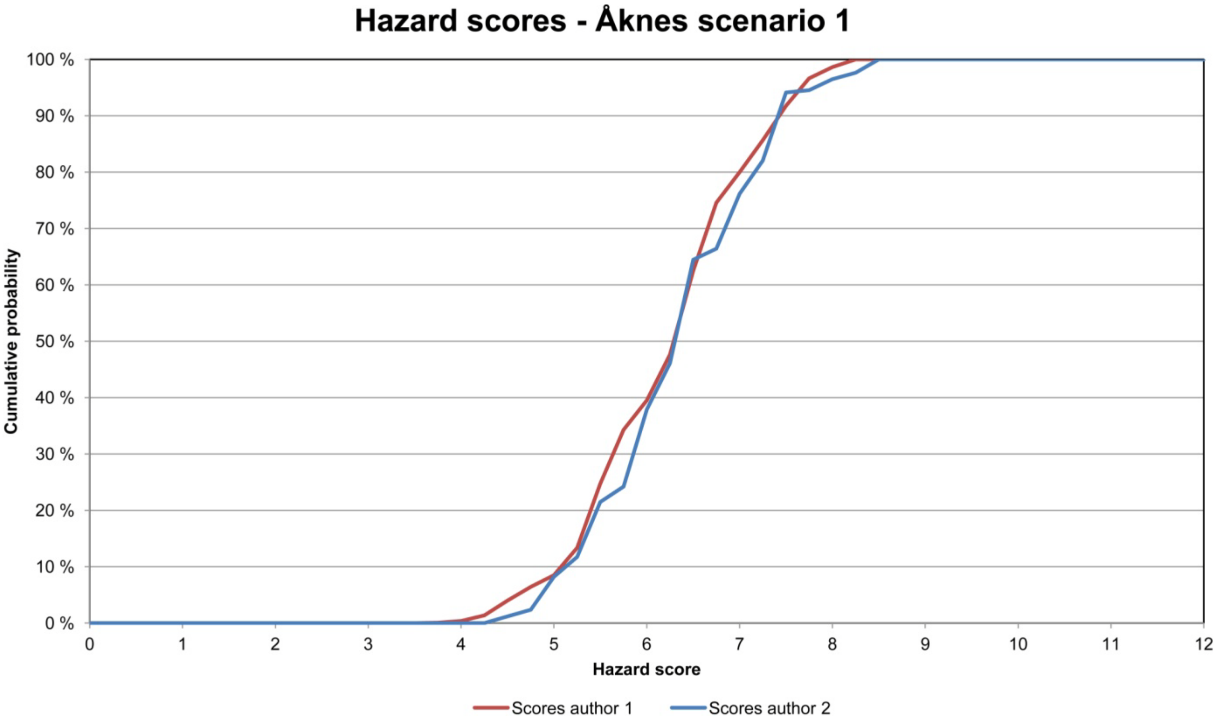
5. Morphologic expression of the rupture surface	Score	Author 1	Author 2
No indication on slope morphology	0	0 %	0 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	75 %	25 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	25 %	75 %

6. Displacement rates	Score	Author 1	Author 2
No significant movement	0	25 %	25 %
0.2 - 0.5 cm/year	1	50 %	50 %
0.5 - 1 cm/year	2	25 %	25 %
1 - 4 cm/year	3	0 %	0 %
4 - 10 cm/year	4	0 %	0 %
> 10 cm/year	5	0 %	0 %

7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)	Score	Author 1	Author 2
No acceleration or change in displacement rates	0	100 %	100 %
Increase in displacement rates	1	0 %	0 %

8. Increase of rock fall activity	Score	Author 1	Author 2
No increase of rock fall activity	0	30 %	75 %
Increase of rock fall activity	1	70 %	25 %

9. Past events	Score	Author 1	Author 2
No post-glacial events of similar size	0	0 %	0 %
One or several events older than 5000 years of similar size	0.5	100 %	100 %
One or several events younger than 5000 years of similar size	1	0 %	0 %


Hazard scores - Åknes scenario 1
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
0 %
Cumulative probability
0
1
2
3
4
5
6
7
8
9
10
11
12
Hazard score
Scores author 1
Scores author 2

Scenario 2

Scenario 2 of the Åknes rockslide encompasses the middle and upper parts of the unstable rock slope, which show active displacements of 1-4 cm/year. The volume is estimated to 18 Mm^3 and the annual probability to >1/1000 (Hole et al., 2012). Based on this hazard analysis, scenario 2 falls into the high hazard class (average score: 8.9–9.4).

Hazard assessment of large unstable rock slopes in Norway

Site name:	Åknes	Scenario:	2	Made by:	ÅTB & NGU	Date:	03.08.2012

Hazard classes	Author 1	Author 2
Very low	0.0 %	0.0 %
Low	0.0 %	0.0 %
Medium	2.8 %	0.2 %
High	77.5 %	69.9 %
Very high	19.7 %	30.0 %

Hazard scores	Author 1	Author 2
Minimum	6.50	6.75
Maximum	11.50	12.00
Mode	8.75	9.50
Mean	8.85	9.44
5^{th} percentile	7.44	8.07
95^{th} percentile	10.10	10.50

1. Back-scarp	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly open over width of slide body (few cm to m)	0.5	0 %	0 %
Fully open over width of slide body (few cm to m)	1	100 %	100 %

2. Potential sliding structures	Score	Author 1	Author 2
No penetrative structures dip out of the slope	0	0 %	0 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	0 %	0 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	100 %	100 %

3. Lateral release surfaces	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly developped on 1 side	0.25	0 %	0 %
Fully developped or free slope on 1 side or partly developped on 2 sides	0.5	0 %	0 %
Fully developped or free slope on 1 side and partly developped on 1 side	0.75	50 %	25 %
Fully developped or free slope on 2 sides	1	50 %	75 %

4. Kinematic feasibility test	Score	Author 1	Author 2
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	0 %	0 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	0 %	0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	20 %	0 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	0 %	0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	80 %	100 %

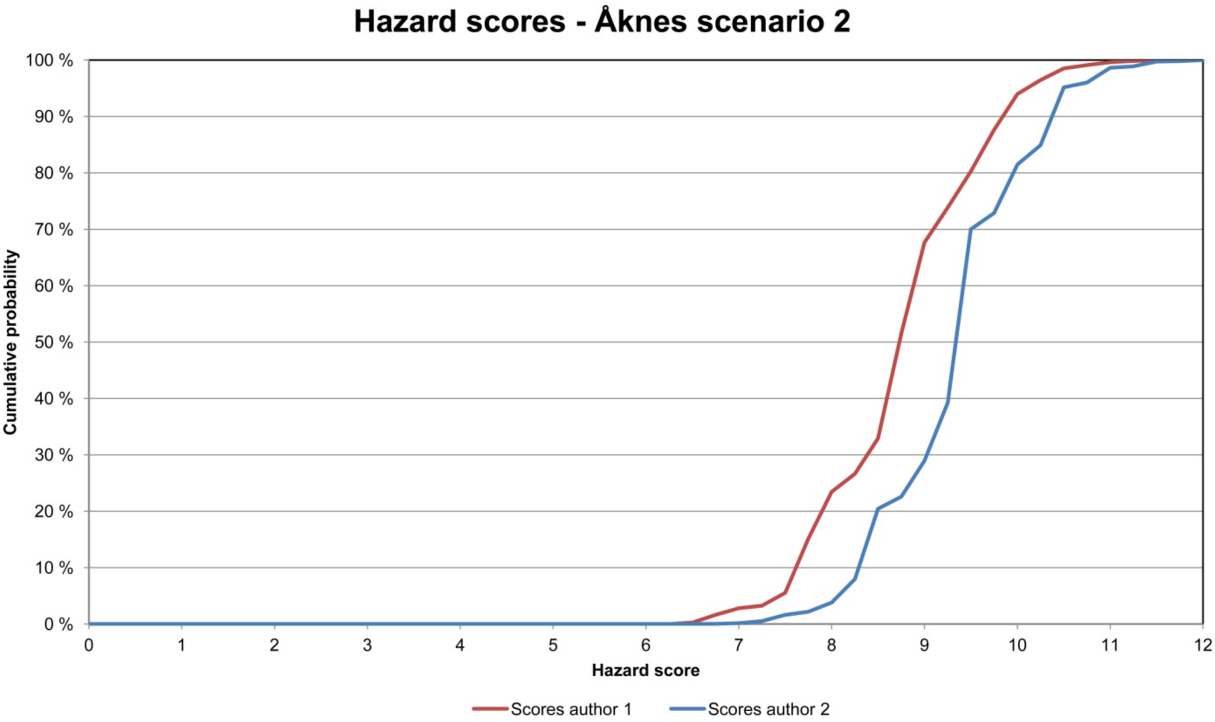
5. Morphologic expression of the rupture surface	Score	Author 1	Author 2
No indication on slope morphology	0	0 %	0 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	75 %	10 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	25 %	90 %

6. Displacement rates	Score	Author 1	Author 2
No significant movement	0	0 %	0 %
0.2 - 0.5 cm/year	1	0 %	0 %
0.5 - 1 cm/year	2	20 %	10 %
1 - 4 cm/year	3	60 %	80 %
4 - 10 cm/year	4	20 %	10 %
> 10 cm/year	5	0 %	0 %

7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)	Score	Author 1	Author 2
No acceleration or change in displacement rates	0	90 %	80 %
Increase in displacement rates	1	10 %	20 %

8. Increase of rock fall activity	Score	Author 1	Author 2
No increase of rock fall activity	0	20 %	25 %
Increase of rock fall activity	1	80 %	75 %

9. Past events	Score	Author 1	Author 2
No post-glacial events of similar size	0	0 %	0 %
One or several events older than 5000 years of similar size	0.5	100 %	80 %
One or several events younger than 5000 years of similar size	1	0 %	20 %


Hazard scores - Åknes scenario 2
Cumulative probability
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
0 %
0
1
2
3
4
5
6
7
8
9
10
11
12
Hazard score
Scores author 1
Scores author 2

Scenario 3

Scenario 3 comprises only the uppermost part of the Åknes rockslide with a volume ranging from 6 to 11 Mm^3. Measured displacement rates are in the range of 4-10 cm/year. Annual probabilities of >1/1000 (Hole et al., 2011) and 1/300–1/100 (Blikra et al., 2006b) have been proposed earlier for scenario 3. Based on this hazard analysis, scenario 3 falls into the very high hazard class (average score: 10.0–11.0).

Hazard assessment of large unstable rock slopes in Norway

Site name:	Åknes	Scenario:	3	Made by:	ÅTB & NGU	Date:	03.08.2012

Hazard classes	Author 1	Author 2
Very low	0.0 %	0.0 %
Low	0.0 %	0.0 %
Medium	0.0 %	0.0 %
High	25.8 %	6.8 %
Very high	74.2 %	93.3 %

Hazard scores	Author 1	Author 2
Minimum	8.50	9.50
Maximum	11.50	12.00
Mode	10.25	10.50
Mean	9.99	11.00
5^{th} percentile	8.66	9.44
95^{th} percentile	11.09	11.94

1. Back-scarp	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly open over width of slide body (few cm to m)	0.5	0 %	0 %
Fully open over width of slide body (few cm to m)	1	100 %	100 %

2. Potential sliding structures	Score	Author 1	Author 2
No penetrative structures dip out of the slope	0	0 %	0 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	0 %	0 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	100 %	100 %

3. Lateral release surfaces	Score	Author 1	Author 2
Not developped	0	0 %	0 %
Partly developped on 1 side	0.25	0 %	0 %
Fully developped or free slope on 1 side or partly developped on 2 sides	0.5	30 %	0 %
Fully developped or free slope on 1 side and partly developped on 1 side	0.75	60 %	0 %
Fully developped or free slope on 2 sides	1	10 %	100 %

4. Kinematic feasibility test	Score	Author 1	Author 2
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	0 %	0 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	0 %	0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	0 %	0 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	0 %	0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	100 %	100 %

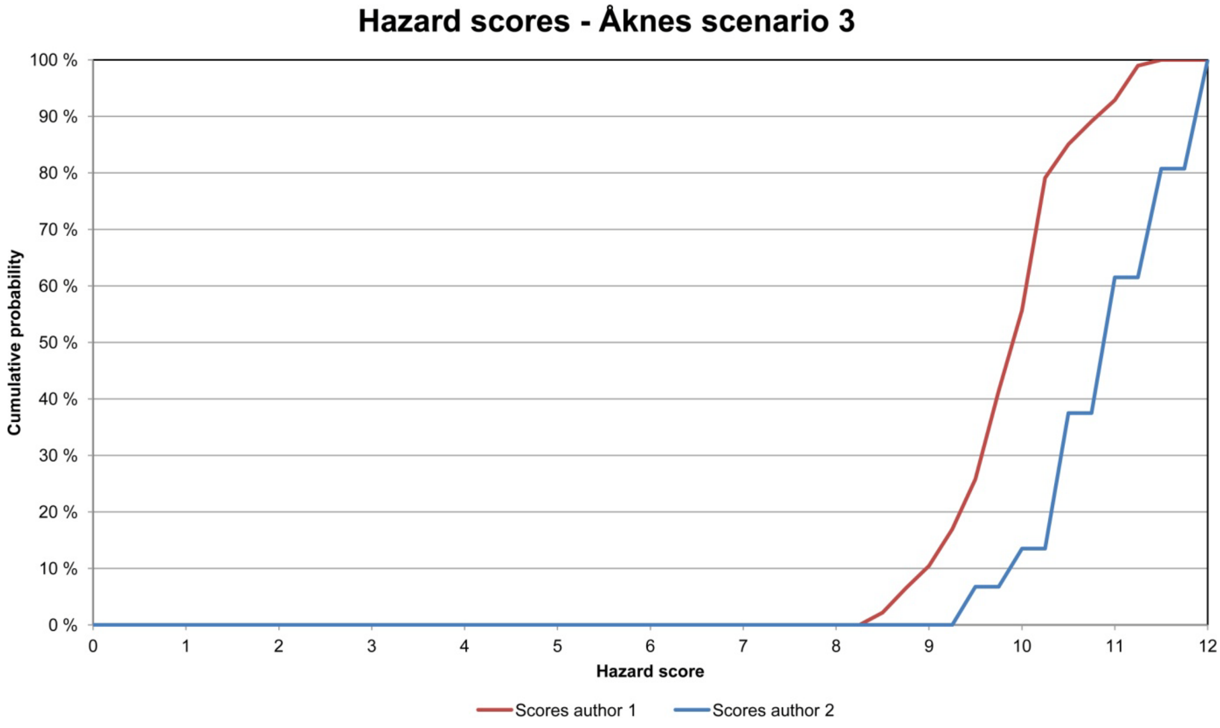
5. Morphologic expression of the rupture surface	Score	Author 1	Author 2
No indication on slope morphology	0	0 %	0 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	40 %	0 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	60 %	100 %

6. Displacement rates	Score	Author 1	Author 2
No significant movement	0	0 %	0 %
0.2 - 0.5 cm/year	1	0 %	0 %
0.5 - 1 cm/year	2	0 %	0 %
1 - 4 cm/year	3	20 %	0 %
4 - 10 cm/year	4	70 %	90 %
> 10 cm/year	5	10 %	10 %

7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)	Score	Author 1	Author 2
No acceleration or change in displacement rates	0	90 %	50 %
Increase in displacement rates	1	10 %	50 %

8. Increase of rock fall activity	Score	Author 1	Author 2
No increase of rock fall activity	0	0 %	30 %
Increase of rock fall activity	1	100 %	70 %

9. Past events	Score	Author 1	Author 2
No post-glacial events of similar size	0	0 %	0 %
One or several events older than 5000 years of similar size	0.5	100 %	50 %
One or several events younger than 5000 years of similar size	1	0 %	50 %



Hazard scores - Åknes scenario 3
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
0 %
Cumulative probability
0
1
2
3
4
5
6
7
8
9
10
11
12
Hazard score
Scores author 1
Scores author 2

A2. Hazard analysis of rock slope failures at Preonzo (Switzerland)

Conditions evaluated are as of January 2012 (this slope failed on May 14th, 2012). Based on this hazard analysis, the Preonzo rock slope failure falls into the high hazard class.

Hazard assessment of large unstable rock slopes in Norway

Site name:	Preonzo	Scenario:		Made by:	Simon Loew	Date:	22.06.2012

Hazard classes	Class upper limit	Probability	Cumulative probability
Very low	2.4	0.0 %	0.0 %
Low	4.8	0.0 %	0.0 %
Medium	7.2	12.0 %	12.0 %
High	9.6	85.2 %	97.2 %
Very high	12.0	2.8 %	100.0 %

Hazard scores	
Minimum	5.8
Maximum	10.8
Mode	8.3
Mean	8.1
5th percentile	6.6
95th percentile	9.3

Fitted normal distribution	
Mean μ	8.0
St. dev. σ	0.8
Mean - 2σ	6.4
Mean + 2σ	9.6
Corr. coeff.	0.9999
K-S-test (max. diff.)	2.4 %

1. Back-scarp	Score	Rel. prob.	Norm. prob.
Not developped	0	0	0.0 %
Partly open over width of slide body (few cm to m)	0.5	50	50.0 %
Fully open over width of slide body (few cm to m)	1	50	50.0 %

2. Potential sliding structures	Score	Rel. prob.	Norm. prob.
No penetrative structures dip out of the slope	0	80	80.0 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	0	0.0 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	20	20.0 %

3. Lateral release surfaces	Score	Rel. prob.	Norm. prob.
Not developped	0	0	0.0 %
Partly developped on 1 side	0.25	80	61.5 %
Fully developped or free slope on 1 side or partly developped on 2 sides	0.5	50	38.5 %
Fully developped or free slope on 1 side and partly developped on 1 side	0.75	0	0.0 %
Fully developped or free slope on 2 sides	1	0	0.0 %

4. Kinematic feasibility test	Score	Rel. prob.	Norm. prob.
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	70	77.8 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	0	0.0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	20	22.2 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	0	0.0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	0	0.0 %

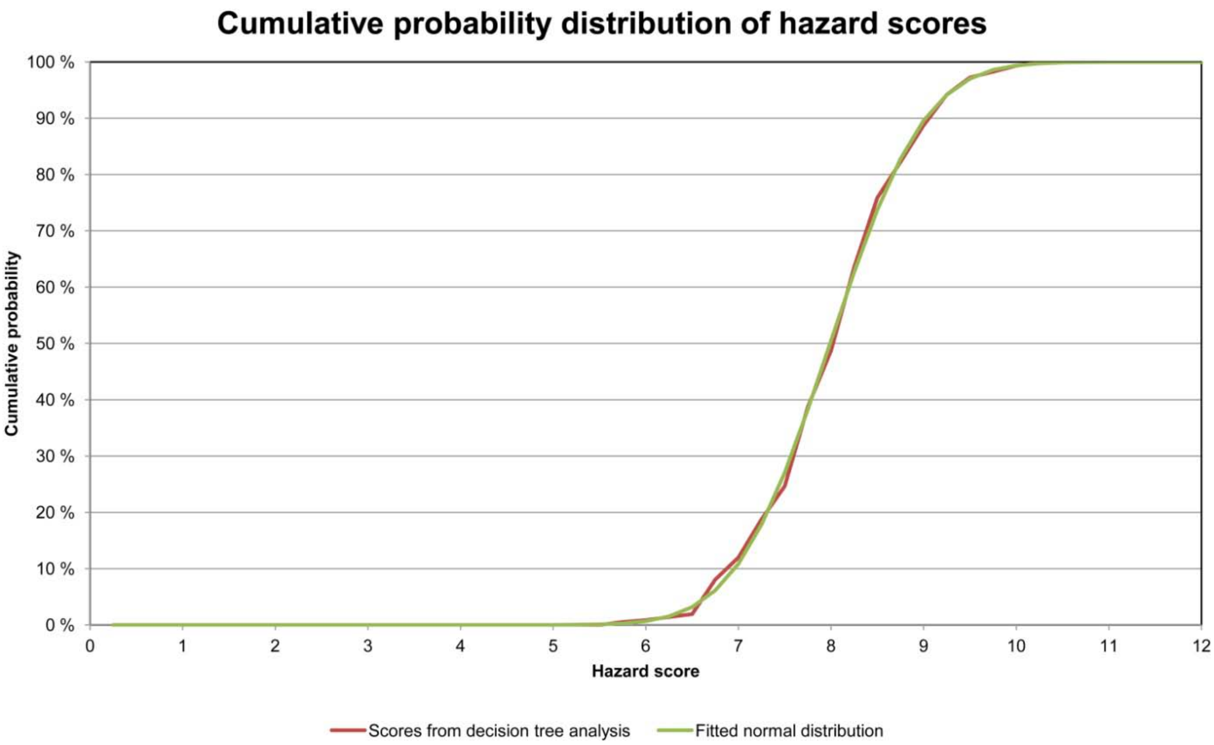
5. Morphologic expression of the rupture surface	Score	Rel. prob.	Norm. prob.
No indication on slope morphology	0	90	90.0 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	10	10.0 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	0	0.0 %

6. Displacement rates	Score	Rel. prob.	Norm. prob.
No significant movement	0	0	0.0 %
0.2 - 0.5 cm/year	1	0	0.0 %
0.5 - 1 cm/year	2	0	0.0 %
1 - 4 cm/year	3	0	0.0 %
4 - 10 cm/year	4	10	10.0 %
> 10 cm/year	5	90	90.0 %

7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)	Score	Rel. prob.	Norm. prob.
No acceleration or change in displacement rates	0	100	100.0 %
Increase in displacement rates	1	0	0.0 %

8. Increase of rock fall activity	Score	Rel. prob.	Norm. prob.
No increase of rock fall activity	0	30	30.0 %
Increase of rock fall activity	1	70	70.0 %

9. Past events	Score	Rel. prob.	Norm. prob.
No post-glacial events of similar size	0	0	0.0 %
One or several events older than 5000 years of similar size	0.5	0	0.0 %
One or several events younger than 5000 years of similar size	1	100	100.0 %


Cumulative probability distribution of hazard scores
Cumulative probability
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
0 %
0
1
2
3
4
5
6
7
8
9
10
11
12
Hazard score
Scores from decision tree analysis
Fitted normal distribution

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Geological Survey of Norway

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