

HAZARD AND RISK CLASSIFICATION FOR LARGE UNSTABLE ROCK SLOPES IN NORWAY

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ABSTRACT

We present a classification system for hazard and risk that is posed by unstable rock slopes in Norway that might undergo catastrophic failure in future and can cause loss of life. The 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 the 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, are evaluated. The hazard analysis is based on two types of criteria: 1) Structural site investigations including analysis of the development of a back-scarp, lateral boundaries and basal sliding surface. This includes a kinematic analysis for sliding and toppling based on slope orientation, persistence of main structures and morphologic expressions of the sliding surface. 2) Analysis of slope activity primarily based on slide velocity, 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 secondary effects. Based on the hazard and consequence analysis each scenario is classified in a risk matrix into category low, medium or high risk.

KEY WORDS: *catastrophic rock slope failure, secondary effects, hazard analysis, consequence analysis, risk matrix*

INTRODUCTION

Catastrophic failure of large rock slopes in Norway has several times per century led to rock avalanches or large rock falls, which directly affected settlements, but also caused either a displacement wave when impacting a water body with often fatal consequences or damming of narrow valleys with a high loss of property (BLIKRA *et alii*, 2006a; FURSETH, 2006). Such events will also occur in the future. For catastrophic failure we follow here the definition given by HERMANN & LONGVA (2012) as rock slope failures that could involve substantial run-out and fragmentation of the rock mass and could impact with high velocity an area larger than that of a rockfall with typical shadow angles of ca. 28-34° (e.g. EVANS & 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) (e.g. HØST *et alii*, 2013).

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 (HERMANN *et alii*, 2013a). 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. A first guideline on the mapping approach and a hazard and risk classification is given in a geological report (HERMANN *et alii*, 2012) and is summarized in this publication. Mapping as well as hazard and risk classification will follow in Norway in the upcoming years these guidelines until a large number of sites are classified and related geological data and data on potential consequences stored in a related database (BUNKHOLT *et alii*, 2013). Then the classification system can be reviewed based on real data. As the likelihood of failure cannot be given quantitatively in hundreds or thousands of years with today's scientific knowledge, the risk analysis is built on a qualitative hazard analysis and a quantitative consequence analysis. The goal is to assemble enough data on historic and pre-historic rock slope failures in Norway that will allow for a calibration of the qualitative hazard analyses.

The working approach for the elaboration of this classification system was to combine a broad national and international experience on large rock slope failures and a group of 18 Norwegian and 5 international experts had participated in the discussion preceding this classification system (see summary in HERMANN *et alii*, 2012). Furthermore, earlier proposed classification systems that focus on long term slope stability of large rock slopes have been taken as guide (HANTZ *et alii*, 2002; HUNGR & EVANS, 2004; GLASTONBURY & FELL, 2008; JABOYEDOFF *et alii*, 2012).

Examples of 32 historic catastrophic rock slope failures from Norway and around the world show that unstable rock slopes do not fail under aseismic conditions without any pre-failure slope deformation (HERMANN *et alii*, 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 alii*, 1998, 2000, 2005). However, there are clear regional differences with most of the seismic activity concentrated in small areas located in the near-shore or off shore area (STANDARD NORGE, 2008) that should be considered in the risk management of rock slope fail-

ures. 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).

Hence the hazard analysis focuses on capturing unfavorable geological conditions, morphological features expressing slope deformations and changes within the slope that can give a hint of the stability state of the slope as well as on the area that will be impacted by the direct impact of the rockslide or a related secondary effect. The risk classification focuses on the potential loss of life only.

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, Apennine 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 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 slope.

DEFINING FAILURE SCENARIOS

Deformation of unstable rock slopes can be either uniform over the entire slope or spatially distributed. In the latter case, deformation varies between different compartments of an unstable rock slope (also called parts, blocks or similar). This difference in deforma-

tion style also 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. HERMANN *et alii*, 2001; WILLENBERG, 2004; HERMANN *et alii*, 2006 and references there in, AA *et alii*, 2007). These multiple failure sites suggest that at some rock slopes parts of the rock mass can get to a critical state at different moments in time. 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 analyzed 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 Fig. 1. 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.

HAZARD CLASSIFICATION ORGANIZATION OF THE HAZARD CLASSIFICATION SYSTEM

The classification system uses nine criteria describing the present state of an unstable rock slope (Fig. 2). They 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 (v_{ij}) is assigned to each condition. The sum of scores for the chosen conditions gives the total score, which is called hazard

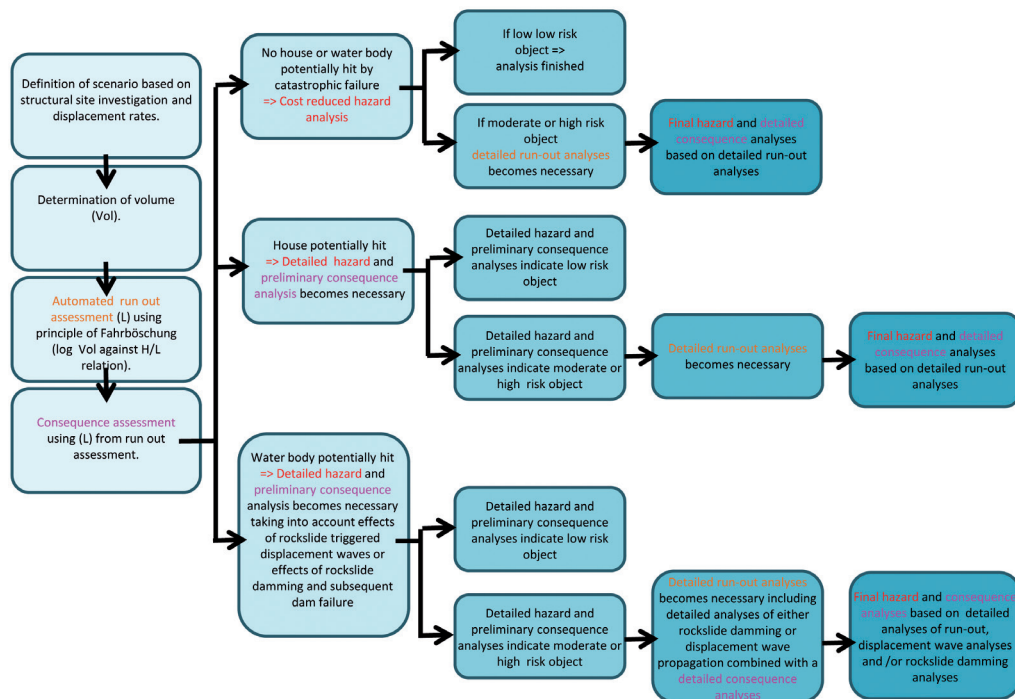


Fig. 1 - Development of the scenario based hazard and risk assessment by gradually increasing detail (from left to right) of hazard and consequence analyses in an iterative approach. The term assessment is here used for a semi-quantitative evaluation during project development, while analysis is a quantitative evaluation

score, ρ (Equation 1):

$$\rho = \sum_i v_{ij} \quad (1)$$

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

Using the nine criteria, 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 .

CONDITION UNCERTAINTIES

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, $\bar{\rho}$, is obtained by summing all the scores (v_{ij}) multiplied by the conditions probabilities (Equation 2):

$$\bar{\rho} = \sum_i \sum_j p_{ij} v_{ij} \quad (2)$$

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. 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:

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

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

Using scores and conditions for the nine criteria shown in Fig. 2 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} . Therefore, the total probability of having a given hazard score corresponds to the sum of

	Score	Rel. prob.	Norm. prob.
1. Back-scarp			
Not developed	0	0	33.3 %
Partly open over width of slide body (few cm to m)	0.5	0	33.3 %
Fully open over width of slide body (few cm to m)	1	0	33.3 %
2. Potential sliding structures			
No penetrative structures dip out of the slope	0	0	33.3 %
Penetrative structures dip on average < 20 degree or steeper than the slope	0.5	0	33.3 %
Penetrative structures dip on average > 20 degree and daylight with the slope	1	0	33.3 %
3. Lateral release surfaces			
Not developed	0	0	20.0 %
Partly developed on 1 side	0.25	0	20.0 %
Fully developed or free slope on 1 side or partly developed on 2 sides	0.5	0	20.0 %
Fully developed or free slope on 1 side and partly developed on 1 side	0.75	0	20.0 %
Fully developed or free slope on 2 sides	1	0	20.0 %
4. Kinematic feasibility test			
Kinematic feasibility test does not allow for planar sliding, wedge sliding or toppling	0	0	20.0 %
Failure is partly kinematically possible (movement direction is more than ±30° to slope orientation)	0.5	0	20.0 %
Failure is kinematically possible (movement direction is less than ±30° to slope orientation)	0.75	0	20.0 %
Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ±30° to slope orientation)	0.75	0	20.0 %
Failure is kinematically possible on persistent discontinuities (movement direction is less than ±30° to slope orientation)	1	0	20.0 %
5. Morphologic expression of the rupture surface			
No indication on slope morphology	0	0	33.3 %
Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)	0.5	0	33.3 %
Continuous rupture surface is suggested by slope morphology and can be mapped out	1	0	33.3 %
6. Displacement rates			
No significant movement	0	0	16.7 %
0.2 - 0.5 cm/year	1	0	16.7 %
0.5 - 1 cm/year	2	0	16.7 %
1 - 4 cm/year	3	0	16.7 %
4 - 10 cm/year	4	0	16.7 %
> 10 cm/year	5	0	16.7 %
7. Acceleration (if velocity is >0.5 cm/yr and <10 cm/yr)			
No acceleration or change in displacement rates	0	0	50.0 %
Increase in displacement rates	1	0	50.0 %
8. Increase of rock fall activity			
No increase of rock fall activity	0	0	50.0 %
Increase of rock fall activity	1	0	50.0 %
9. Past events			
No post-glacial events of similar size	0	0	33.3 %
One or several events older than 5000 years of similar size	0.5	0	33.3 %
One or several events younger than 5000 years of similar size	1	0	33.3 %

Fig. 2 - Nine criteria describing the present state of the slope: For each criterion several conditions are possible to choose from and a score is assigned to each condition

all ϕ path with the same p path.

We have developed a macro in Microsoft Visual Basic 6.5 (implemented in Microsoft Excel® 2007) that is downloadable at the same website as the report (see HERMANN *et alii*, 2012 in the references). It computes all possible paths of the decision tree including p path and ϕ path and creates the sum of all ϕ path leading to the same p path. Using the scores presented in Figure 2, the path hazard score, p path, ranges from 0 to 12 with steps of 0.25. The final outcome is a probability for each of these 49 different hazard scores, ϕ score. 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, while the mean value is computed using Equation 2.

HAZARD CLASSES

Simplified to allow for effective communication, the hazard score is divided into five hazard classes using equal intervals (Fig. 3). 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

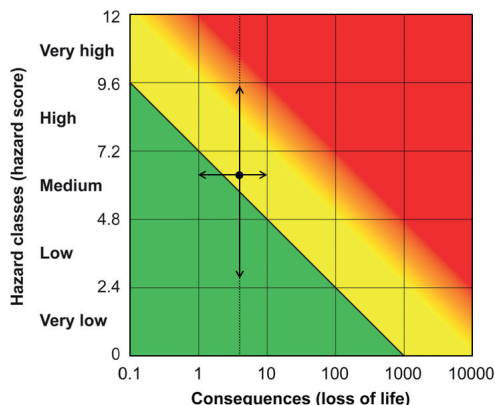


Fig. 3 - Risk classification matrix for follow-up with monitoring and further investigations of unstable rock slopes in Norway: green = low risk; yellow = moderate risk; red = high risk. The risk of an unstable rock slope is represented by its mean value, the minimum and maximum consequences (horizontal arrows), the 5% and 95% percentiles of the hazard score (vertical arrows) and the minimum and maximum scores of the hazard analysis (dotted line)

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, in order to assess their hazard score with satisfying reliability.

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.

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 displacement rate 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 to be of moderate or high risk, then more investigations become necessary focusing on defining the velocity. If also under the worst case assessment the site remains a low risk object, no further investigations are required.

CONSEQUENCE AND RISK ANALYSIS AND SUGGESTED SURVEILANCE OF UNSTABLE ROCK SLOPES

FELL *et alii* (2008) define risk as "a measure of the probability and severity of an adverse effect to health, property or the environment". We focus in our consequence/risk analyses on loss of life only. "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 alii*, 2005) (Equation 4):

$$R = P_F \times P_p \times P_E \times V \times E \quad (4)$$

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_p , 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 P_p .

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 and E is the maximum number of persons living and being present or transit in the affected area.

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 .

DETAILED CONSEQUENCE AND RISK ANALYSIS

For potential medium to high risk objects based on the preliminary risk assessment a detailed consequence analysis becomes necessary (Fig. 1). This includes a more detailed quantification of the parameters in Equation 4. Detailed run-out modeling (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 alii*, 2006b). 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 and all infrastructure with persons in transit are assessed in the same manner as buildings (e.g., BLIKRA *et alii*, 2013).

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. Hence this secondary effect is treated as a flood hazard and in these cases the evaluation of hazard and risk related to dam formation and dam failure should be included as outlined in DAHLE *et alii* (2011a) and HERMANN *et alii* (2013b). However, the final risk classification will mainly be based on the number of people which might lose their life in a potential event.

RISK MATRIX AND RISK CLASSES

This classification system combines the hazard score and the potential life losses in a risk matrix (Fig. 3). Isorisk lines are often used in a risk matrix to distinguish between acceptable, tolerable and unacceptable risks as proposed for example for landslides and rock falls from natural slopes in Hong Kong (GEO-TECHNICAL 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 actions for unstable rock slopes including monitoring, further field investigations, and/or possible mitigation measures. For that reason the risk matrix is divided into three risk classes: low (green), 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 cas-

ualties). 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 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.

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 (Fig 3).

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 (Fig. 3). 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.

IMPLICATION OF THE RISK CLASSIFICATION

The risk classification of unstable rock slopes in Norway will be used by the NGU and the NVE 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 that will be explained in more detail in the NVE document.

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 will often be coupled monitoring and early warning techniques. This has to be discussed among risk owners and geoscientists.

SUMMARY AND DISCUSSION

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 in a large effort combining national and international experts from various disciplines in earth sciences. During the elaboration of this system 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 qualitatively classified the probability of failure in very high, high, moderate, low and very low.

Our hazard classification is based on two sets of criteria: 1) Structural site investigations including analysis of the development of a back-scarp, lateral boundaries 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 (acceleration), observation of rock-fall 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 (HERMANN *et alii*, 2010) over a preliminary usage of it (DAHLE *et alii*, 2011b) 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.

Within the completion time of this document a rock slope failure occurred in Switzerland that has been monitored for more than a decade (LOEW *et alii*,

2012). The analysis of pre-failure conditions indicated a high hazard for that slope (in HERMANN *et alii*, 2012). 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 (BLIKRA *et alii*, 2005; HERMANN *et alii*, 2012). Nevertheless 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 replace the qualitative hazard analysis with a quantitative hazard analysis.

The consequence analysis is focused on number of 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-risk objects a more detailed analysis is carried out that includes the probability of surviving the rockslide triggered displacement wave. Both the qualitative hazard analysis and the quantitative consequence analyses are combined in a risk matrix for a risk analysis. Three different risk classes are defined. Low risk where no further follow up is needed, medium risk where periodic monitoring of the rock slope is suggested and high risk that suggest for further follow up. Follow up for high risk objects has to be discussed with the risk owners and could be resettlement, periodic monitoring, continuous monitoring coupled with early warning or any other mitigation measure that has to be decided after cost-benefit reasoning. Often additional geological information to those summarized in this classification has to be assembled for optimal monitoring practices and a thorough slope stability analysis. This might include subsurface information obtained from core logging, geophysics and hydrological investigations.

Finally we want to stress again that the hazard and risk classification system is not a risk management tool in itself as it does not include seismically triggered rock slope failures. It is thus a support tool for risk management that will help to decide on follow up (e.g. no follow up necessary, periodic monitoring is recommended to reduce the risk, more studies are required and/or risk mitigation measures should be taken). This is also not a guideline for early warning practices as these are regulated in Norway by the

building code TEK 10 § 7.4 (Byggeteknisk forskrift, 2010) and we thus do not include a discussion on triggering mechanism here.

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