Avalanche forecasting and risk mitigation for specific objects at risk

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ABSTRACT: Objects and individuals can be exposed to different levels of avalanche hazard. For object-specific avalanche forecasting and risk mitigation programs, the general danger scales, such as the European and North American Avalanche Danger Scales, are of limited usefulness because they provide no indication of the actual risk to an object. To ensure that avalanche forecasting is useful at the object level, a quantitative description of the avalanche probabilities of reaching threatened objects with required follow-up actions is proposed. This article discusses the proposed procedure and gives examples of two highway projects in western Norway where local object-specific avalanche forecasting was done.

KEYWORDS: Avalanche forecasting, local forecasting, danger scales, danger levels, probability of occurrence, risk, objects at risk, risk mitigation.

1 INTRODUCTION

Avalanche forecasting is practised with several different spatial and temporal danger scales. Many mountainous countries have public service-like forecasting programs that estimate the general avalanche danger in a given region during a given time period. Avalanche forecasting services in Europe warn of the danger over a region, typically on a mountain range scale with an area of at least of 100 km^2 (Nairz 2010). They predict the hazards for one, or at most, a few days (EAWS 2010). In Europe, the level of danger is stated using The European Danger Scale. In the USA and Canada, the similar North American Danger Scale is used. These danger scales describe qualitatively the danger potential using a five level scale.

To be of use for decision-making at the local level, it is necessary in practice to state not only a qualitative danger level, but also to provide a quantitative probability estimate of the danger. A qualitative description in words is open to subjective interpretation. The quantitative probability estimate requires assigning to the probability of an event in a given period of time, a value between 0 and 1, alternatively stated as a percentage (0 to 100%) or a fraction (0 to 1).

The paper proposes a procedure to associate the probability of an avalanche reaching specific objects at risk within a specified time period, to required mitigation measures (actions). The procedure is explained through two examples of local avalanche forecasting programs in western Norway. In both cases, the warning programs were started before the "National Avalanche Forecasting Program" run by the Norwegian Water Resources and Energy Directorate (NVE) was fully implemented in 2013.

2 AVALANCHE FORECASTING ISSUES

The existing danger scales (WSL 2012 Statham *et al.* 2010) focus on snow stability, release probability, avalanche size and magnitude. There is an on-going discussion on whether the average or the local maximum danger level in the region should be issued for avalanche warnings (Nairz 2010). Another issue is whether the avalanche warnings should provide the users with more specific ad-vice, as now done in the North American Danger Scale (Statham *et al.* 2010). In this respect, a concern is that some of the advice might imply some risk acceptance on the part of the users. However, the level of this implied risk is not quantified.

On the local level, the benefit of a general forecast for specific decision-making can be somewhat limited. The existing avalanche forecasting services do not give any information about the probability of an avalanche reaching specific objects at risk, either for permanent objects such as roads and buildings, or for mobile objects such as cars, trains or skiers. The forecasters usually do not provide information on the susceptibility or vulnerability of the threatened objects. In all objectivity, it is probably not the task of a forecasting service to provide such specific advice to users since the user's risk tolerance may be determined by many factors unknown to the forecaster.

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An object-specific forecasting program able to assess the probability of encountering the objects needs to take into account not only the general avalanche hazard situation but also the susceptibility of the object and the probability of encountering the object under the particular circumstances expected (e.g. local weather, snow drift, slope aspect, elevation, etc.). If a forecast is to be of any real benefit in the decision-making process, the frequency of avalanche occurrence needs to be quantified.

A danger rating in general terms, using the descriptions of the existing danger scales, can often be of little use because of the influence and significance of exposure and terrain, slope aspect, elevation etc., which are specific at the local level.

3 QUANTIFYING PROBABILITIES

The quantification of probabilities is done in many avalanche-related applications, e.g. in the planning of areal use (often specified in building codes), and the planning and management of roads and railways. The probability of an avalanche reaching a given point in the avalanche track is a function of the probability of avalanche occurrence and the distance the avalanche is able to travel downslope. The run-out distance can be modelled to some degree. Estimating frequency-magnitude relationships can also be done where historical records exist. A statistical inference can therefore be used in the forecasting.

The quantitative prediction of avalanche probability based on statistics is not new. Perla (1970) analysed 20 years of weather data from Alta (Utah USA) and found a predictive relationship between hourly precipitation rate and site-specific avalanche occurrence probability. Since then, several papers have been published using multiple meteorological variables to assess the avalanche frequency-magnitude relationship from historical records.

4 CASE 1: HIGHWAY 15 STRYNEFJELLET

In western Norway, Highway 15 is one of the main arteries that connect the west coast regions with the main north-south transport corridor in Norway, Highway E6. Highway 15 is the only ferry-free connection from the western region to the east. Any detours are considerably longer. To reach eastern Norway, Highway 15 crosses

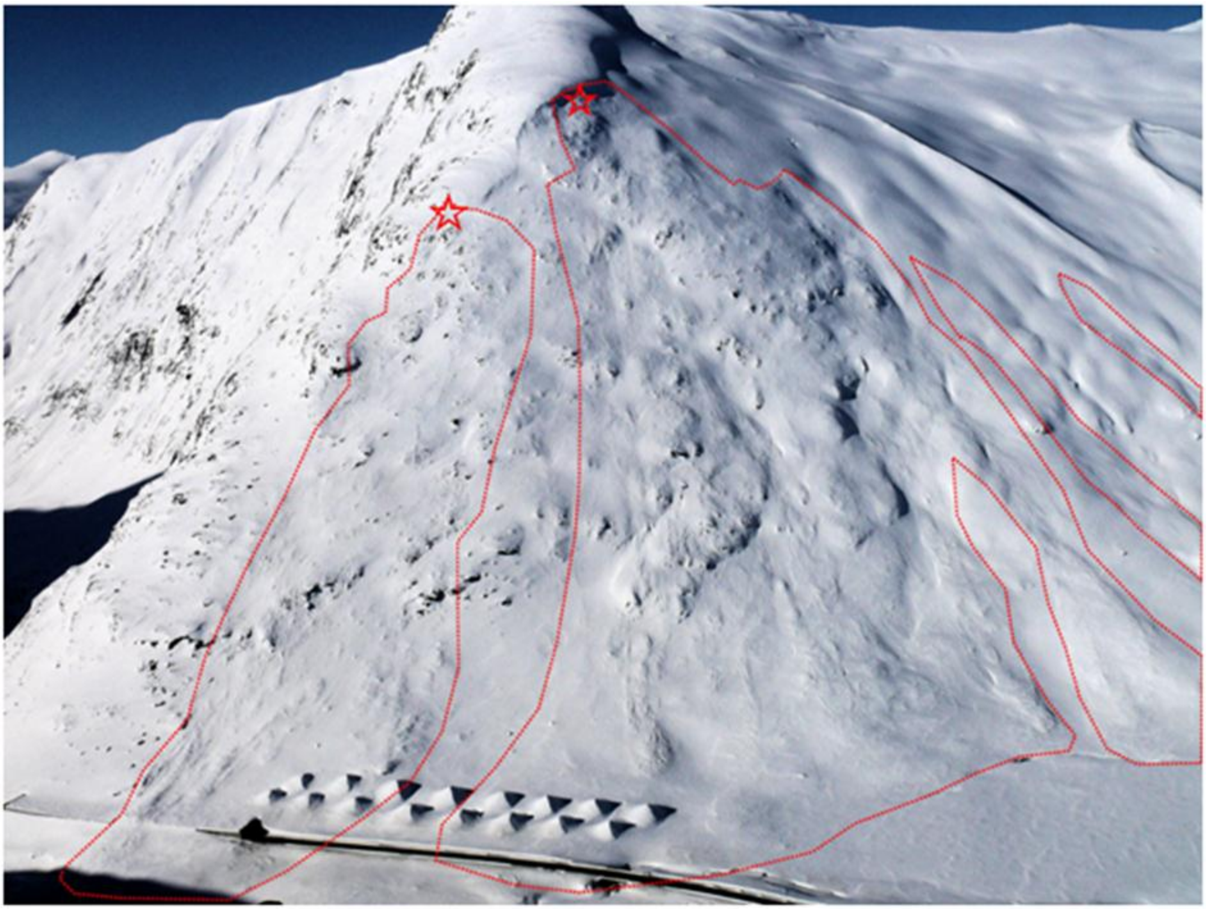

Figure 1. The avalanche path at Sætreskarsfjellet above Highway 15 in Grasdalen [stars indicate location of blasting sites (photo K. Kristensen)].

"Strynefjellet", which is part of the main east-west water divide of the Scandinavian Peninsula. The annual (2010) traffic is around 800 cars per day, with peaks of up to 2500 cars per day in the holiday periods.

The 922-m long unprotected stretch of road in Grasdalen has a high frequency of avalanches reaching the road. The main avalanches come from the NE-facing slope of Sætreskarsfjellet and can reach and impact the road over a length of 650 m (Fig. 1).

A 200-m portion of this stretch is permanently protected by a gallery (also on Fig. 1). Two rows of breaking mounds on the uphill side of the road have also been constructed, but proved to be ineffective for all but the smallest wet snow avalanches. In addition, active protection consists of an avalanche control system using explosive charges in the starting zone. Controlled avalanche release, combined with preventive road closures are estimated to reduce the individual risk for road users to about ¼ of what it would be without these measures (Kristensen 2005).

For Highway 15, NGI developed a multi-winter avalanche forecasting program on contract for the highway maintenance contractor Mesta AS. The forecasting period normally runs from December 1st to April 30th. The forecasting service provides the decision-makers at Mesta and at the National Public Road Administration (NPRA) in Norway with a daily avalanche danger assessment and an estimate of the probability for avalanches reaching the road in the coming 24-hour period. The actions that should follow as a result of the forecast are prescribed in the road maintenance guidelines from NPRA.

To obtain weather and snow data, several automatic weather and snow stations are used. A database of all observed avalanches that have reached the road earlier is also available.

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

Table 1 presents the locally adapted danger scale and the classes of probability for avalanches reaching Highway 15 during the next 24 hours, and the corresponding actions to be taken for the five levels of danger.

The third and fourth columns in Table 1 list the actions that are required in the NPRA guidelines as a result of the forecast. For ease of communication, the terminology of the European Danger Scale was used as the descriptive term in the first column. However, the probabilities of avalanches reaching Highway 15 for the five levels of the danger scale are not in accordance with the conventional use of the European Danger Scale.

The division in the probability classes in the second column and the required actions in the third and fourth columns in Table 1 were worked out in cooperation with the Highway 15 stakeholders (Mesta and NPRA), based on their own experience and risk assessments. As the risk assessment falls outside the scope of the forecasting program, the vulnerabilities of the threatened objects are not included in Table 1.

5 CASE 2: CONSTRUCTION SITE ON HIGHWAY 60 STRANDADALEN

During the winter 2012, the NPRA and their contractors were engaged in the completion of a

Table 1. Probability of avalanche reaching Highway 15 during the next 24 hours, and corresponding required actions for the five danger levels.

Danger Scale	Probability of reaching Highway 15, P (%)	Required actions Traffic	Required actions Road maintenance
1 Low	$P \leq 1$	**No restrictions.**	**No restrictions.**
2 Moderate	$1 < P \leq 5$	**No restrictions.**	**No restrictions.**
3 Considerable	$5 < P \leq 20$	**No restrictions.** Stopping is not allowed.	**Work** in exposed areas **allowed only in daylight**.
4 High	$20 < P \leq 50$	**Conditional closure.** Traffic is continuously monitored, road closing if dark or difficult driving conditions.	**Avalanche control.** Road clearing only in daylight with avalanche watch.
5 Very High	$P > 50$	**Road closed.**	**No activity** in avalanche exposed areas.

large avalanche protection project along Highway 60 in Strandadalen. Three of the work and loading locations were considered exposed to avalanche danger.

As part of the risk management for the safe project realization, an avalanche-forecasting program was implemented, with the possibility of using controlled avalanche release by helicopter with conventional explosives or the MND Daisy-Bell gas detonation system. The action list for each danger level in Table 2 was prepared in a cooperation among all the involved parties. Vulnerabilities, i.e. the probability of fatalities, severe injuries or loss of costly machinery, were not considered in detail, as it was deemed unacceptable that any avalanche should enter the area during active working operation.

Table 2. Avalanche "probability classes" and the required actions for Highway 60 during construction.

Probability class	Probability of reaching object P (%)	Required actions
1 Green	P ≤ 0.1	Permanent presence*.
2 Yellow	0.1 < P ≤ 0.2	Limited presence in daylight and good visibility. Continuous local assessment of any change.
3 Orange	0.2 < P ≤ 2	Few and short, temporary presence allowed only.
4 Red	2 < P ≤ 50	No presence allowed in area. Quick passing through is possible when the visibility is good.
5 Black	P > 50	No presence or passing through allowed in area.

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

From a forecasting point of view, the task was interesting since two of the objects at risk were located in the same path but at different heights relative to the slope. Figure 2 shows the two exposed work locations at the Sledal avalanche site. Avalanche debris are also visible to the right of the two locations. The third object was in a neighbouring avalanche path.

To arrive at a measure of susceptibility for the three sites, a frequency-magnitude relationship was established (in this case the magnitude was mainly considered in terms of run-out distance). Using the statistical/topographic model developed by Lied and Bakkehøi (1980), a simple index of the proximity to the slope was calculated based on the position of each of the three sites relative to the beta point in the path profile (Kristensen *et al.* 2008; Kristensen and Breien, 2012). Meteorological data and avalanche observations were available for about 30 years.

As for Highway 15, five probability classes were suggested. By the time of the Highway 60 Strandadalen forecasting project, the new National Avalanche Forecasting program had been started in Norway, with a pilot site with publicly accessible regional avalanche forecasts. After some discussion and to avoid confusion, the "Danger Scale" (Table 1) was renamed "probability class". The same colour scheme as for the Danger Scale in Table 1 was, however, retained for the five probability classes.

Figure 2. Two of the exposed work locations at the Sledal avalanche site (with avalanche debris visible to the right). The proximity of each site to the avalanche slope differs (photo K. Kristensen).

Figure 3 illustrates the forecast at the three sites of Highway 60 construction between February 1st and April 30th 2012. The daily regional danger ratings (1 to 5) from the National Avalanche Forecasting program are shown at the top, and the local probability classes are shown as colours for the three site forecasts in the lower part of the diagram.

6 DISCUSSION

During a highway or a railroad project, questions often arise on the forecasting of the danger to specific objects at risk. Examples of two local forecasting programs for two highways in Norway were given in the paper.

The relation of local forecasting programs to more general regional forecasting is naturally of interest.

The local programs do supply the National Avalanche Forecasting Program with the local forecasts as a matter of routine. However, the fact that the programs operate at different spatial and temporal resolutions means that there will be differences in the danger assessment (Haegeli and McClung 2000).

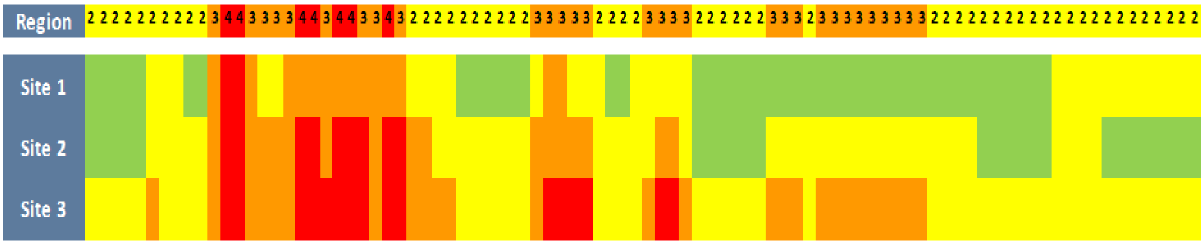

Figure 3. Forecasts at three sites of Highway 60 construction for the period February 1st to April 30th 2012 (chart shows the daily regional danger rating 1 to 5 (top) and the probability class colours for the three forecast sites).

Even if the regional forecast considers areas of minimum 100 km², the assessment of the aspects and elevations of the most susceptible avalanche slopes today are as a rule given in the warnings. This means that local forecasts can, to some degree, benefit from insight from the regional forecast. However, the probability of an avalanche reaching a specific object depends on the exposure of the threatened object. Figure 3 showed that the local and regional forecasts were broadly similar, but in many cases, the regional forecasts cannot contribute significantly to insight into the avalanche probability of reaching specific objects and the actions required at the local level.

One concern is that the use of five probability classes with the same colour and numbering schemes as the Danger Scale used by the national forecasting program may lead to confusion. To avoid this, a different division of classes and colours could be used. Alternatively, single probabilities ("there is a possibility of 50% for an avalanche occurring in the area today"), possibly accompanied by an uncertainty quantification, could be used. This would be similar to weather forecast probabilities from the weather services.

Other concerns relate to the understanding of the concept of probability. Although standard descriptors for probability are used in the examples of local avalanche forecasting, it seems necessary to stress that the probabilities reflect only a best estimate of a likelihood and not a certainty with a high degree of precision. This understanding is often "lost in the transition" from avalanche professionals to the media and to the public.

Such perception may be a consequence of the fact that the probabilistic thinking is somewhat counterintuitive to human cognition (Stanovich 2009). It would be desirable to find new ways to communicate danger concepts and probabilities more efficiently.

7 CONCLUSION

There is a need in Norway for both regional and local avalanche forecasting. The local forecasting should provide decision-makers with quantified probabilities of avalanches reaching specific objects at risk. A list of actions to temporarily mitigate the impact of avalanches on exposed objects, and as part of risk management during, for example, highway or railroad construction, can then be worked out in cooperation with the stakeholders.

Even if local, object-specific avalanche forecasting in many cases needs to be tailored for the specific locations, it would be useful to discuss procedures on how to communicate danger locally and the relationship between regional and local forecast.

The NGI avalanche research group would welcome discussions at upcoming meetings in the working group of the European Avalanche Warning Services (EAWS) and in other fora concerned with avalanche forecasting.

8 ACKNOWLEDGEMENTS

The work presented in this paper was carried out in part through the funding of a NGI research grant from the Norwegian Water Resources and Energy Directorate (NVE). The authors also thank Mesta AS and NPRA Regions Central and East for the opportunity to explore these matters in practice.

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