SIGNIFICANCE OF HISTORICAL RECORDS FOR AVALANCHE HAZARD ZONING IN NORWAY

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ABSTRACT: In avalanche hazard zoning, it is common practice to investigate the previous avalanche history for the area considered. Historical observations of avalanches serve as an aid in the classification of the terrain, and may also serve as verification of estimates of avalanche runout. Conditions influencing the avalanche occurrences may change significantly over time and it is important to take these changes into account when using historical avalanche observations in hazard zoning today. A number of the most extensive avalanches recorded in Norway, are found during the eigthteenth and nineteenth century. The catastrophes may be linked to weather as well as to socio-economic conditions, in particular deforestation of mountain slopes. The implications of using or disregarding historical avalanche observation are shown in an example of statistical estimation of avalanche runout.

KEYWORDS: Snow avalanche, run-out distance, probability, extreme value statistics, Western Norway

1. INTRODUCTION

According to the Norwegian Building Regulations, the "safe" areas for habitations in the snow-avalanche prone regions of Norway are defined as areas where the nominal annual probability of a house being hit by an avalanche should be less than 10^{-3}. This means that not only the obvious paths with recurring avalanches have to be considered, but also areas where avalanches are known to have occurred very rarely, or not at all.

Land use planning in avalanche prone areas is usually an interdisciplinary task. It includes avalanche dynamics calculation, geomorphologic interpretation, meteorology, climatology and historical research. The historical records of avalanches often serve as an indication of what may be potential starting zones and as a verification of estimates of avalanche runout.

The existence of a historical observation is often seen as proof of an existing hazard today. Given enough time, nature will again provide the conditions that caused the avalanche in the past. Assuming that the avalanches were mainly related to the weather conditions, the avalanche probability can be related to the probability of such weather conditions.

One problem with this approach is that it may often not be possible to reconstruct the snow conditions and the weather sequences with enough detail. Another problem, which will be discussed in this paper, is that there may be other, non-weather related, factors influencing the avalanche activity. This makes it important to have a fairly broad historical perspective when using historical avalanche observations. It may also be that some of these factors are not present today, and this may have implications on the estimates of avalanche probabilities.

2. USE OF HISTORICAL DATA

Historical data of avalanche occurrences in Western Norway vary in quality and availability. In many cases the interpretation of them demand use of historical research methods, particularly the procedures of source validation. The sources include farm and family histories, newspaper reports, official reports of damage appraisals, personal letters, etc. Problems with the sources include lack of coherent terminology: e.g. they may not distinguish between snow and slush avalanches. It may also be that the messenger has underlying motives, such as pleas for tax reduction or financial support that could lead to overstatements of the magnitude of the avalanche.

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Unless photos or maps exist, reconstructing the spatial distribution of an avalanche in the past at a given site, will often include rather subjective interpretation. If it is possible to identify ruins or obtain old maps of building sites, this can provide data on certain points, e.g. which buildings were destroyed and which were not. But often the determination of the avalanche's area of influence is left to interpretation and avalanche dynamics calculations and this is clearly a source of error. A claim about what a snow avalanche debris looked like 100-200 years ago, is unlikely to be verified nor disproved even by detailed sedimentology or archeological methods.

Western Norway is fortunate to have a good record of avalanche events since the "land rent", a measure of taxability, was assessed for individual farms on the grounds of, among other things, their vulnerability to avalanche hazard (Grove and Battagel, 1983). Claims of tax reduction could be made after avalanche damages to a farm, and all such claims were assessed by official tax commissions and thus recorded for the aftertime. A voluminous and fairly accurate record of avalanche damage from around 1650 to 1815 of exists. After 1815 the tax assessment system changed, but similar data can be extracted from other sources. The records available show several major avalanche winters during the latter part of the nineteenth century

3. THE AVALANCHES IN 1868

The most disastrous avalanche winter in terms of loss of lives occurred in the winter of 1867/68 when a total of 161 people were killed. This winter, avalanches started running down into the inhabited areas of the north region of Western Norway (figure 1) on February the 6th, with several disasters following the next twenty days until the 26th. The communities that suffered the greatest losses were Stryn with 35 and Oppdal with 32 fatalities. All of the victims were caught inside houses that were destroyed by the avalanches (Kristensen, 1998).

The avalanches of 1868 in Stryn have been examined closer (Kristensen, 1999). Avalanches struck clusters of farms that both had, and did not have a previous history of avalanche damage. One of the settlements affected (13 victims) had been struck by an avalanche in 1718, 150 years before. However neither of the other two settlements, Gjørven, where four farms were destroyed and 11 people lost their lives, nor Tenden, where the destruction of two farms also claimed 11 victims, had any history of avalanche damage. Both settlements are known to have been permanently settled before 1600 AD. Furthermore, Gjørven and Tenden are still occupied today, more or less at the same sites as in 1868 and none have suffered any avalanche damage since then.

It may be of interest to look at the conditions that led to this unusual avalanche activity in 1868. Was it only the unusual combination of weather sequences or were other factors also important?

4. CONDITIONS THAT LED TO AVALANCHES IN 1868

4.1 Weather conditions

The disasters of 1868 have been linked to a unique combination of a cold early winter with prevailing storms from the Norwegian Sea following in February. The weather data available, although limited, support this (Kristensen, 1999). It is likely that a widespread instability in the mountain snow cover developed during the early winter because of a shallow snow cover and low temperatures. In this period a snow cover was present also in the lowland. From around mid-January, the low-pressure activity over Western Norway increased markedly with Northwest winds and large amounts of snow. The extraordinary snowfall is mentioned in many eyewitness accounts from the time.

Since local weather data from Stryn are not available, it is difficult to estimate the return period for similar weather situations. Preliminary analyses of data from nearby stations indicate that there is hardly any reason to conclude that the conditions were sufficiently unique to not have occurred several times during the preceding 200 years with known settlement or during the time after 1868 (Kristensen, 1999). In an analysis of major avalanche winters by Fitzharris and Bakkehøi (1986) several winters with similar synoptic characteristics as the 1867/68 winter are reported.

4.2 Other factors

The socio-economic conditions in Norway in the 1860-ies were very different from today's. The 1860-ies were generally hard times in the West-Norwegian countryside. The size of the population had reached a level where the food production could hardly keep up. This led to an intensification of the agricultural practices that involved large-scale use of the mountain slopes for forest cutting and for grazing livestock on summer pastures above the timberline. A large portion of a farm's production was actually moved from the valley floor up into the mountains. Since the production of the summer dairy farms near the timberline increased, so did the demand for firewood for heating and making brown whey cheese. There are several contemporary accounts of the lack of forest, which sometimes led to abandonment of the summer dairy farms.

An increasing number of cotters (landrenters usually farming the outskirts of a regular farm) sometimes led to settlements in marginal areas, no doubt also leading to increased exposure to avalanche danger.

The forester A. T. Gløersen (1868) comments that although the winter conditions were special, they were not all that unusual. Similar snow and weather conditions had been experienced before without the same dire consequences. A new and unique factor must therefore have been added, he argues.

Gløersen leaves no doubt about what he thinks this is: "I have come to the conclusion that a large number of the avalanches last winter is to blame on the thoughtless, fast spreading destruction of the birch forest in the upper mountain meadows" (translation by the authors).

The seriousness of situation was can only be inferred by indirect data, since quantified forest data before 1900 are not available. Photographs from the late nineteenth century show many slopes almost without trees, that are covered with dense forest today. Forest inventories done in the twentieth century show a dramatic increase in the growing stock in the four West-Norwegian counties of Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal during the last century; from 18 mill. m^3 in 1930 to 81 million m^3 in 1998 (Tomter ed., 2000). In the 1930-ies however, the pressure on the countryside had already been greatly reduced compared to sixty years earlier, because of a large-scale emigration to the USA and the generally increasing industrialization of Norway. Statistics of grazing domestic animals (cattle, sheep and goats) also point in the same direction. In the Stryn parish the number was reduced by almost 50% from 1865 to 1907 (Timberlid, 1988). Also the peak in the number of cotters around 1870 (Timberlid, 1981) supports that the population pressure on the countryside was especially high during this period.

Thus it seems clear that around the 1860-ies there had been an unprecedented exploitation and deforestation of the mountain slopes in the populated valleys of Western Norway. The question is if and how this influenced the avalanche activity.

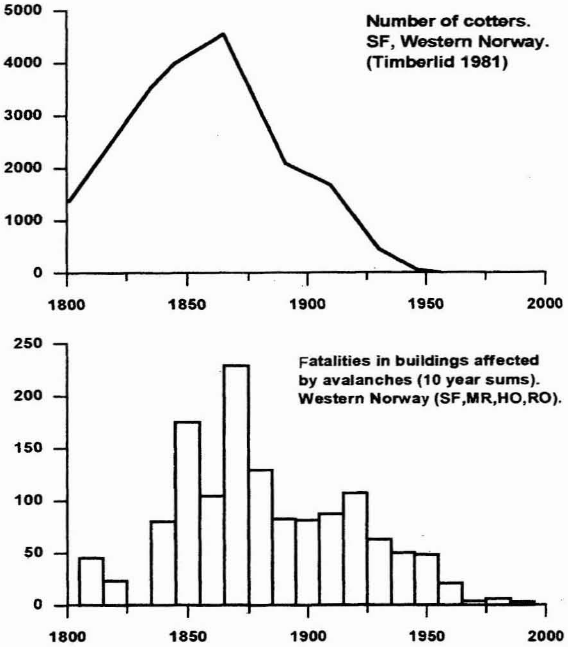

Figure 1. Graph showing the number of cotters in Sogn og Fjordane (SF) and the number of avalanche fatalities (in the four West-Norwegian counties of Rogaland, Hordaland, Sogn og Fjordane and Møre og Romsdal).

4.3 Effect on avalanches by forest

The paths of the 1868 avalanches in Stryn are now covered by dense forest for up to 2/3 of their elevation. It is well known that forest in the starting zone, when dense and strong enough, can prevent slab avalanche formation. Gløersen was of the opinion that lack of forest in the starting zones was the main cause of the avalanches in 1868. However, the avalanches in Stryn may well have started above the natural timberline and it is less clear what the effect is on an avalanche that enters a forested slope from above. Two effects may be possible. First, there may be a small braking effect on the flowing part of the avalanche. Salm (1979) estimates that there will be an efficient reduction for high tree densities only, e.g. more than 1000 trees per hectare. The avalanche forces acting on the stem of a tree depend on the velocity and density of the flowing snow, and the drag coefficient around the tree. According to Salm (1979), the energy loss is relatively small.

Second, a forest will influence the stratification of the snow cover as the canopy of the forest intercept the falling snow. The snow in a forest is also less subject to wind transportation and the microclimate near the snow surface will be different from an open slope because of the forest's effect on in- and outgoing radiation. The result is an overall rise in the snow stability that may reduce the avalanche's entrainment and volume increase when it travels through a forest, compared to over an open slope. It seems likely that this will also be reflected in the runout distance, although more research is needed to verify this.

The implications for hazard zoning of using or disregarding a historical avalanche observation because of radically changed conditions, is possible to analyze by statistical means.

5. SIGNIFICANCE OF HISTORICAL AVALANCHE OBSERVATIONS IN HAZARD ZONING TODAY

The unconditional annual probability of extreme runout can be seen as the annual probability of avalanche release at a given area times the probability of run-out exceedance for a released avalanche. Both factors can be calculated by mechanical/dynamical probabilistic models involving probability distribution functions for the physical parameters, by statistical models based on observations and terrain parameters, or by combinations of these. Because we in this paper focus on historical observations with limited information on the physical parameter values, i.e. the contemporary snow conditions, a purely statistical approach is shown.

5.1 The probability of release

The annual probability of avalanche release, p_f, in a specific path will be estimated based on the number of avalanches, r, that are observed during the relevant observation period of n years. We assume that p_f is small (< ca. 0.1), and that r is binomially distributed with known parameter n and unknown parameter p_f. Because the traditional point estimator r/n for p_f is very uncertain due to few, if any observations (r small), we construct a 95% confidence interval $[0, U_{p,0.95}]$ for p_f and use the upper limit, $p_{f,0.95} = U_{p,0.95}$, as a conservative estimator for p_f that with "95% certainty" is not exceeded. $U_{p,0.95}$ is found by solving the equation

$$F(r_{\mathrm{obs}};\, n, p_f) = 0.05 \qquad (1)$$

(Harbitz et. al, in press) with respect to p_f, where F denotes the cumulative binomial distribution with parameters n and p_f, and where the argument r_{obs} is the actual number of observed avalanches. The equation above must be solved numerically.

5.2 The probability of extreme runout

The annual probability of extreme run-out can be estimated by using the statistical/topographical α/β -model (Lied and Bakkehøi, 1980; Bakkehøi et al., 1983). Here the run-out distance equation is found by regression analysis correlating the longest observed run-out distances in 206 Norwegian avalanche paths to a selection of topographic parameters. According to Harbitz et al. (in press) it is assumed that α, the average inclination of the total avalanche path, observed in each path is the most extreme of N avalanches. It is further assumed that α follows a Gumbel extreme value distribution (McClung, 2000). It is also assumed that N does not vary substantially between the paths in the database on which the α/β regression line is based, and that the variance of α for a specific path is independent of β (homoskedasticity, i.e. uniform variance). The "terrain parameter" β is the average inclination of the avalanche path between the starting point and the point of 10° inclination along the path profile. Under the assumptions above, the α/β-model can be expressed as:

$$\alpha(m_s) = 0.96\,\beta - 1.4^\circ + b(m_s) + W \qquad (2)$$

where W is Gumbel distributed with zero mean and standard deviation $\sigma = 2.3^\circ$.

Let $m_s = \Delta t_s/\Delta t_r = \Delta t_s \cdot p_f$ denote the ratio between the required mean recurrence interval, Δt_s (e.g. 1000 years according to the Norwegian Building Regulations), and the return period, $\Delta t_r = 1/p_f$. Based on the properties of the Gumbel distribution, the dynamics of the regression line is now reflected through the parameter $b(m_s)$:

$$b(m_s) = -\,6^{1/2} \cdot 2.3^\circ \cdot \ln(m_s)/\pi \qquad (3)$$

If the climatic and meteorological conditions have been more or less the same over the years with avalanche observations, so has the probability of release above the timberline. However, the increased altitude of the timberline and the densification of the forest may have reduced the extent of the release area and may also affect the run-out distances.

5.3 Example calculations

The path to be analyzed below is from Gjørven, Stryn, where observations have been made for 350 years (figure 2). In 1868, with other forest conditions than today, an extreme event with an observed α-angle α_{obs} = 29.4° occurred. Except for this observation, there are only few observations of avalanches with run-out angles higher (i.e. shorter runout) than the β -angle of 31.5°. These observations are not considered important, except for the fact that they indicate a significantly lower probability of extreme runout in other periods. They should be neglected when probability of release are discussed in combination with the α/β -model that is based on a database that excludes avalanches with short run-out distances.

It is now of interest to analyze how the 1868 event may influence potential hazard zones in the area. Three different cases can be analyzed:

1) the observation is considered relevant also under current conditions, i.e. **one** avalanche has occurred over the last **350 years** (since 1650);
2) the observation is not relevant today, i.e. **no** avalanches with runout past the β-point have occurred during the last **350 years**;
3) the observational period is reduced to cover only the period with today's conditions, i.e. **no** avalanches have occurred over the last **100 years**.

Case 1 probably represents the most common way of using a historical observation. For case 1 the p_f-estimate from Eq. (1) is $p_{f,0.95}$ = 1.35%, corresponding to a return period Δt_r = 74 years, i.e. considerably less than 350 years. In this case $m_s = 1000 \cdot 0.0135 = 13.5$, from Eq. (3) $b = -4.7^\circ$, and finally from Eq. (2) $\alpha_{s1} = 0.96\beta - 6.1^\circ = 24.3^\circ$ is a possible estimate for a "safe area". This estimate corresponds to the mean 1000-year avalanche. In practical terms, we are "95% certain" that the unconditional avalanche frequency is at the most 10^{-3}/year at $\alpha = 0.96\beta - 6.1^\circ$ when one avalanche is observed in 350 years.

For cases 2 and 3 (no avalanche observations) the p_f estimates become 0.95% and 2.95%, respectively. This corresponds to $b = -4.0^\circ$, $\alpha_{s2} = 25.0^\circ$ for case 2, and $b = -6.1^\circ$, $\alpha_{s3} = 22.9$ for case 3, i.e. considerably different from the first case.

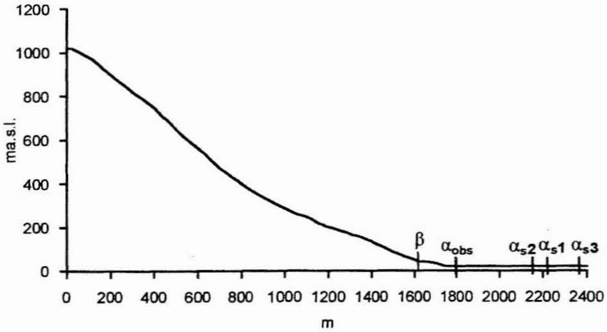

Figure 2. Terrain profile with observed and estimated runout.

It should be emphasized that considerable conservatism is built into the above calculation examples. The choice of an upper limit of a 95% confidence interval as an estimator for p_f is rather strict, and an alternative is to choose e.g. a 50% confidence interval instead. This would be more in agreement with common hazard zoning practice, but may not be considered conservative enough when so few observations are available. In addition, appropriate alternatives to the mean in the Gumbel distribution are the less conservative mode and median. As an example, the mode of the extreme value distribution is the parameter chosen in the 100-year wave concept related to ocean wave dynamics. In our case, the choice of mode would give approximately 1° higher α-values in the above calculations.

It should be noted that in these example applications, the statistical uncertainty associated with the statistical/topographical α/β -model is neglected. This is justified by the relatively large amount of observations and the fact that the β – value in our calculation example is relatively close to the mean of the observed β-values.

6. ACKNOWLEDGEMENTS

This paper is a contribution to the research project "SIP6 20001018.820 -Risk analysis", funded by the Research Council of Norway, and the EU- program "Catastrophic Avalanches, Defense Structures and Zoning in Europe", partly funded by the European Union under the contract no. EVG1-CT-1999-0009.

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