Avalanche hazard mapping and risk assessment in Iceland

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ABSTRACT: A number of avalanche accidents have occurred in Icelandic towns since urbanization started in the late 19th century. In the year 1995, 34 people were killed in avalanche accidents in two villages in the northwestern part of Iceland. Most of the victims were inside houses that were located outside of hazard zones according to the hazard maps at that time. These accidents led to a complete review of the hazard mapping methods in Iceland, as well as the way to think about acceptable level of avalanche risk in settled areas.
New laws and regulations were conducted where the acceptable level of risk was defined as 0.2 of 10,000 when looking at the annual probability of death for individuals in houses. A new methodology was developed for hazard mapping, based on a combination of physical models and statistical methods. Today, new hazard maps displaying isorisk lines have been made for most urban areas with considerable level of avalanche risk, and avalanche hazard is being evaluated for rural areas and ski operations. The latest development of the methodology focuses on the systematic usage of 2D avalanche models in hazard mapping.

KEYWORDS: Avalanche risk, Hazard mapping, individual risk, Iceland, risk assessment, acceptable risk

1. INTRODUCTION

The Icelandic nation has always lived with natural hazards. Volcanic eruptions, earthquakes and landslides have caused great damage. However, snow avalanches have taken the greatest number of human lives through the centuries, when fatalities due to storms at sea and in wilderness areas are excluded. During the first centuries after the settlement of Iceland, the greatest number of avalanche victims were people travelling in the mountains. After the urbanization began during late 19th century, most avalanche victims in Iceland have been killed in houses or working places.

Two fatal accidents in Icelandic villages caused 34 fatalities in 1995. The catastrophe led to a discussion of what is acceptable in terms of avalanche risk in homes. A new method for risk-based hazard mapping was developed in the following years, and new laws and regulations were enacted.

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In this paper, the background and events leading up to the Icelandic hazard mapping method are reviewed. The idea of using risk as a criterium for hazard zoning is discussed as well as the definition of acceptable risk. The Icelandic hazard zoning procedure is briefly explained as well as the ideas that the hazard mapping methodology is based on.

2. AVALANCHES IN URBAN AREAS AND THE BEGINNING OF HAZARD MAPPING

In the late 19th century and the beginning of the 20th century, many avalanche accidents occurred in settled areas in Iceland. In 1885, an avalanche killed 24 people in *Seyðisfjörður*. It is considered that between 75 and 80 people were caught in the avalanche, which damaged or destroyed around 16 houses. In 1910, 20 people were killed in an avalanche in *Hnífsdalur*. Some houses, fisherman huts and sheds were destroyed. In 1919, an avalanche killed nine people and destroyed a herring factory, two houses and other buildings, in *Siglufjörður*.

During 1965–1980, the population increased in many fishing towns in Iceland. During that period, many settlements expanded towards the mountainsides. Since the towns were reaching into areas where no houses or buildings had stood before, avalanche records were often scarce. However, many houses were built in areas were avalanches were still in the memories of people. During the mid-20th century there were relatively few avalanche accidents in Iceland, probably due to relatively favourable climate conditions.

When two avalanches killed 12 people in *Neskaupstaður* in 1974, it took the inhabitants of the town and the rest of the Icelandic people by a surprise. It seems like nobody had imagined this could happen.

The first avalanche hazard maps were made shortly after the avalanche accidents in Neskaupstaður by local governments. No actions followed the hazard maps in terms of relocating or protecting the settlement, however, the first organised snow observations started at that time.

The first laws on avalanche protection were approved in 1985, after avalanche accidents in *Ólafsvík* and after that, the first hazard maps based on legislation were made.

In 1995, two avalanche disasters in Súðavík and Flateyri, with a total of 34 fatalities, marked a change in the attitude towards avalanche risk in Iceland. Most of the victims were in houses that were outside of the hazard zones according to the hazard maps at that time, which led to the realization that the hazard-zoning procedure had been inadequate (Arnalds and others, 2004). During the next years, the methodology for hazard mapping was revised in Iceland, and new laws and legislation were approved. The Icelandic Meteorological Office (IMO) was made responsible for most aspects of avalanche work, including hazard zoning (Magnússon, 1998).

Figure 1. Destroyed homes in the Súðavík avalanche 1995 (photo: Jón Gunnar Egilsson).

3. ACCEPTABLE LEVEL OF AVALANCHE RISK

Following the 1995 accidents. there was a discussion in Iceland on what is acceptable in terms of avalanche risk in settled areas. Although the economic loss due to avalanches in Iceland has been significant (Jóhannesson and Arnalds, 2001), it was decided that the loss of human lives should be a dominant factor when considering the acceptability of risk for the society. The criterium in the hazard mapping regulation is individual risk, measured as the annual probability of being killed in an avalanche if one lives or works in a building under a hazardous hillside. The building is assumed to be a fairly weak timber or concrete house with relatively large windows facing the mountainside. The reference value of exposure is 75% for living houses but 30% for work places.

One of the advantages of using individual risk as criterium is that the avalanche risk can then be compared to other sources of risk such as traffic or diseases. The traditional way in Europe and North America is to use *return periods* of avalanches as a criterium in hazard mapping. It is, however, not possible to discuss what is acceptable in terms of return periods without thinking in terms of risk. At a first sight, it may seem that a place where the return period of avalanches is on the order of 100 years is acceptable for building a house. However, living in a house in such a place would cause the avalanche risk to be by far the greatest source of risk in life, especially for children and younger people. The annual probability of death due to avalanches would for many people greatly exceed the annual probability of dying in a traffic accident or dying from common diseases such as cancer or cardiovascular diseases.

The Icelandic regulation states that for living houses, a (nominal) risk level of $0.3 \bullet 10^{-4}$ is acceptable assuming 100% exposure and $1 \bullet 10^{-4}$ is acceptable for work places (Icelandic Ministry for the Environment, 2000). Assuming 75% exposure the avalanche hazard on the acceptable risk line will add $\sim 0.2 \bullet 10^{-4}$ or 11% to the death rate of children. Thus, it has been formally decided, politically, that it is not acceptable to have avalanche risk in houses as one of the main sources of risk in people's lives.

According to Wilhelm (1997) it can be assumed that risk due to avalanches is mostly voluntary during activities such as backcountry skiing or ice climbing, and it is mostly involuntary for residential areas. Research indicates that the acceptable risk in society is low for involuntary and uncontrollable risks (Fell, 1994), which supports the decision of a low level of acceptable risk in the Icelandic hazard mapping regulation.

4. HAZARD MAPPING CRITERIA

Three different hazard zones are defined on hazard maps according to the regulation (Icelandic Ministry for the Environment, 2000). Isorisk lines mark the boundary between the zones:

A-ZONE: The local risk assuming 100% exposure is 0.3-1.0 of 10,000. Note that the lower limit is the boundary of acceptable risk, when assuming 75% exposure. Therefore, the risk below the A-zone is considered acceptable, even though it is not zero and should, therefore not be referred to as a “safe zone”. In areas that are previously unsettled, buildings should only be constructed where the risk is acceptable. In already settled areas, single houses and work places can be built in A-zones. Schools, hospitals, apartment buildings and other such buildings should be reinforced.

B-ZONE: The local risk is 1.0-3.0 of 10,000. Working places can be built, but living houses should be reinforced. Schools and such buildings are not allowed.

C-ZONE: The local risk is higher than 3.0 of 10,000. It is only possible to build structures were people are not living or working.

Where existing houses are in C-zones, the local authorities are required to make plans for permanent defense measures with the aim of reducing the avalanche risk to near the acceptable level. During the last 10 years, dams, breaking mounds and supporting structures have been installed above many avalanche prone villages in Iceland. In some areas, houses have been relocated. However, there is still a long way to go to complete the project to protect all settlements in C-Zones.

A national avalanche and landslide fund was established after the 1995 accidents. The fund finances the hazard mapping and 90% of the cost of permanent defense measures for hazard zones.

Hazard maps have been made for all towns and villages where the avalanche risk is substantial. Hazard mapping is now going on for towns and villages with some avalanche hazard in small, specific parts. Also for some rural areas and ski areas.

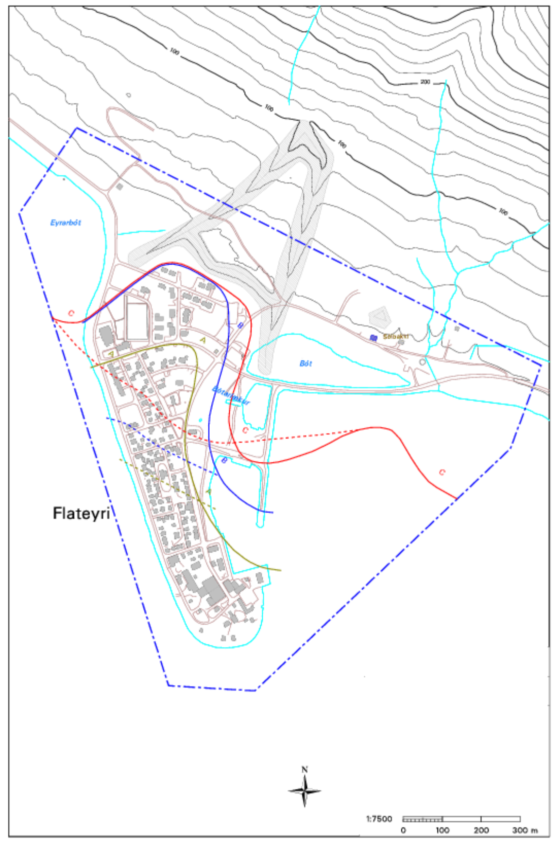

Figure 2. The hazard map for Flateyri before and after the construction of two deflecting dams.

5. THE IDEOLOGY BEHIND THE ICELANDIC RISK METHOD

In order to estimate avalanche risk, both hazard potential and vulnerability should be taken into account as well as the exposure of the individual. In the Icelandic risk model, the frequency of avalanches is estimated as well as the run-out distribution of avalanches. Vulnerability is represented by the probability of being killed if staying in a house that is hit by an avalanche. This was estimated using data from the avalanches of Súðavík and Flateyri, comparing the calculated speed of the avalanche to the survival rate. The exposure is the proportion of the time that a person is expected to spend within the hazard-prone area (Arnalds et al., 2004; Jónasson et al., 1999).

If acceptable risk as defined by Icelandic regulation is to be reached, the return period of avalanches has to be on the order of several thousand years. Since the known avalanche history of each avalanche path does usually not reach far back, it is impossible to base the frequency estimation of long avalanches on local history alone. By combining the avalanche history of many paths with comparable terrain and weather conditions, one may, however, imagine that one path has been observed for a long time rather than many paths for a short time (Jónasson and others, 1999). To make this possible one must be able to tell how far an avalanche that has fallen in a given path would reach in another path. Different models could be used for this purpose, for example topographical models such as the Norwegian alpha-beta model (Lied and Bakkehøi, 1980), as well as the run-out ratio method of McClung and Mears (1991). For hazard mapping in Iceland, physical models have been used for *transferring* avalanches between paths, which is a concept developed in Sigurðsson et al. (1998). By transferring avalanches in a data set to a *standard path* with the PCM model (Perla et al., 1980), the statistical distribution of avalanche run-out has been estimated. Run-out indices have been defined based on the horizontal distance in the standard path. The run-out indices have proven to be a useful tool in hazard mapping. For details regarding the methodology refer to Jónasson et al. (1999), and Arnalds et al. (2004)

The newest development of the Icelandic hazard mapping methods includes the utilization of 2D avalanche models, which have been developed in recent years. The Austrian SamosAT model has been in use at IMO for some years and systematical methods for using it as one of the tools for hazard mapping are being developed. A 2D standard path has been defined and the concept of run-out indices has been expanded to two dimensions (Gíslason, 2008).

6. SUMMARY

Two avalanche catastrophes in 1995 led to a discussion in Iceland about acceptable avalanche risk in residential areas. A total review of the hazard mapping methods followed and a new method based on individual risk was developed. By using individual risk as a criterium it is possible to compare avalanche risk to other sources of risk in society which helps defining an acceptable level of risk.

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