

Combining geomorphological, historical and lichenometrical data for assessment of risk due to present-day slope processes, a case study from the Icelandic Westfjords

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Abstract

Present-day slope processes are the cause of large damage in fjord areas of Iceland. Among all active slope processes, this paper focuses on snow-avalanche and debris-flow impacts in four places located in the north-western part of the island. Spatial distribution of slope processes close to inhabited areas is obtained from geomorphological investigations while dating data are given with the help of historical records and lichenometrical analysis. The combination of the information reveals spatial and temporal patterns of snow avalanches and debris flows in the studied areas. By so doing, slope process runout distances are compared with inhabited spatial extension, which clearly underlines the risk apparition and then its exacerbation during the last century by an increasing superimposition of both phenomenons.

Keywords: Iceland, slopes, inhabited areas, geomorphic and historic study, risk.

1 Introduction

The dramatic increase in losses and casualties due to slope processes during the past four decades in Iceland (Johannesson and Arnalds [1]) has prompted a major scientific initiative. By means of geomorphologic and historic analysis, this study aims to demonstrate the destructive potential of snow avalanches and debris flows in the inhabited areas of north-western part of Iceland, and consequently to assess risk due to these slope processes in the given region through spatial/temporal considerations of both natural and human phenomenon.



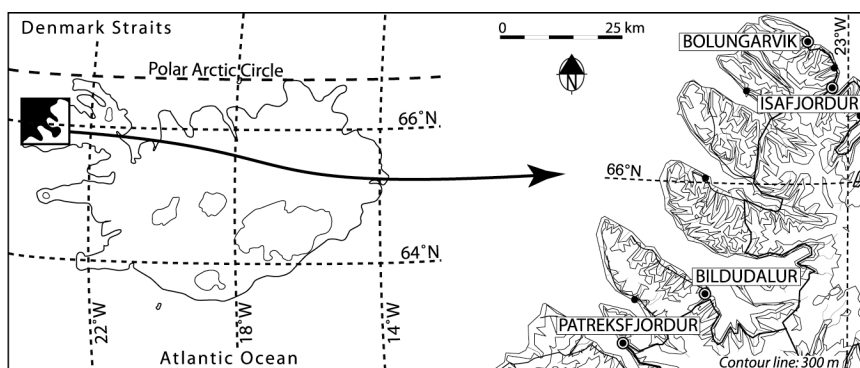


Figure 1: Location of the study area.

The geology of the area consists of superimposed basaltic lava flows and interbasaltic beds dating from Miocene epochs, modified by Pleistocene glaciers, which shaped the fjord landscape. Nowadays, slope profiles are slightly concave, characterised by steep upper part, moderate to steep mid part and low slope angles in lower part; the difference in level varies from 400 to 700 m. Climate is subpolar oceanic, characterised by changing weather and heavy precipitation due to its location at the junction of temperate and arctic zones, and excesses in liquid/solid precipitation and temperature are frequent; annual average temperature is 2,9°C and 960 mm is average yearly rainfall (Decaulne [2]).

Four areas are chosen for this study (fig. 1) because of the recurrence of slope processes:

- Patreksfjörður (800 inhabitants, 0.525 km²) lies on 2.5 km below the southwards mountain which displays a 500 m high slope.
- Bildudalur (290 inhabitants, 0.28 km²) is a 1750 m long village located at the bottom of a 440 m high rockwall oriented to south-east.
- In Bolungarvík (1020 inhabitants, 0.73 km²), the inhabited area is 2 km long below the 600 m high southwards mountainslope.
- The main part of the town Ísafjörður (2800 inhabitants, 1.4 km²) is located down a 700 m high slope facing south-east, interrupted by the Gleidarhjalli bench (470-525 m a.s.l.). To the south, Holtahverfi is a residential area located below a 350 m high slope, facing northwards.

2 Methods

2.1 Geomorphological data: spatial distribution of slope processes

In the vicinity of residential areas, extensive ground surveys and aerial photographs analysis give deterministic data. It involves interpretation of local topography, erosive or accumulative landforms, and vegetal cover. From there, the starting zones of snow avalanches and debris flows, their main active paths, and their maximum extension can be extracted and their spatial distribution is

known (Glade [3]). Probabilistic data, i.e. spatial and temporal probability of triggering factors, have been explained in Saemundsson *et al.* [4] and will only be briefly summarised here.

2.2 Historical data: temporal distribution

Historical data are a relevant complement to geomorphological analysis (Glade *et al.* [5], Calcaterra and Parise [6]) in hazard assessment researches. In Iceland, the first collection of historic slope processes was compiled by Jonsson *et al.* [7, 8], and then by governmental offices [9-32]. Information is primarily derived from announcements made by local populations, authorities, newspapers, broadcast information, and chronicles for oldest events. More than a spatial distribution (sources merely mention the slope concerned but seldom the exact location of the event, i.e. path), a temporal distribution of slope processes is given. Spatiotemporal evolution of settlements is studied through historical data (ancient maps, diachronic photographs). In this study, reports on the construction year of buildings in the upper parts of selected towns and village are used [33-36].

2.3 Lichenometry: a complementary dating tool

Landforms survey on the Isafjordur's slope revealed several fresh debris-flow channels that were not recorded into Annals. In this area of high latitude vegetation, lichens (*Rhizocarpon geographicum* species) are widespread on deposits, and the relative mild climate of the island is auspicious for rapid colonisation on fresh surfaces. Thus, lichenometry has been used as a complementary dating tool: a calculated lichen growth curve was drawn (Decaulne and Saemundsson [37]), calibrated on boulder surfaces of a certain historical age, in order to date debris-flow deposits by measuring the average lichen thalli diameter along well defined geomorphic units such as debris-flow channels, levées or lobes. However, lichenometry is a short time useful tool in Iceland, as a consequence to mild climate: *Rhizocarpon geographicum* is in competition with other fruticose and foliaceous lichens on deposits, and its life expectancy do not exceed 100-150 years at these elevations, close to the sea [2]. Moreover, full-depth snow avalanches are rare, and except for slush and extremely seldom efficient cases, snow avalanches do not leave typical forms that could be used in this way.

3 Results

3.1 Spatiotemporal overview of fjord settlements

During the last century, coastal scattered settlements substantially developed into larger communities along fjords: in 2000, the built surface is a factor of ten bigger than observed in 1900, fig. 2. Radical changes occurred since 1950 in term of space occupation: population/building density evolution shows the progressive extension of land occupation, mainly related to fishing industry



development within the four places. Nevertheless, population growth and building construction are not concomitant. Maximum population density is reached at different periods according to places (fig. 3): Bildudalur has its maximum number of inhabitants within the 1950s, and within the 1960s for Patreksfjordur; during the 1990s Bolungarvik and Isafjordur never had more inhabitants. But in all places, the maximum density of buildings within the investigated areas, located close to the slope, is reached from the 1980s (fig. 4).

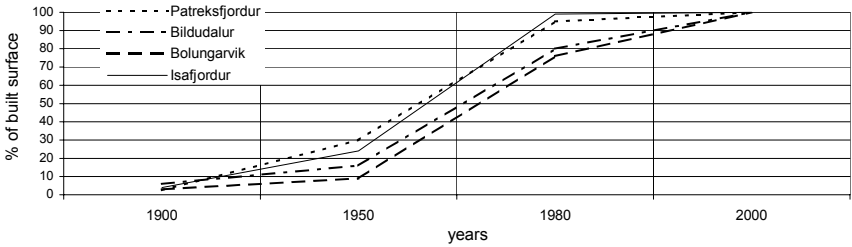


Figure 2: Built surface from 1900 to 2000 in the four places [33-36].

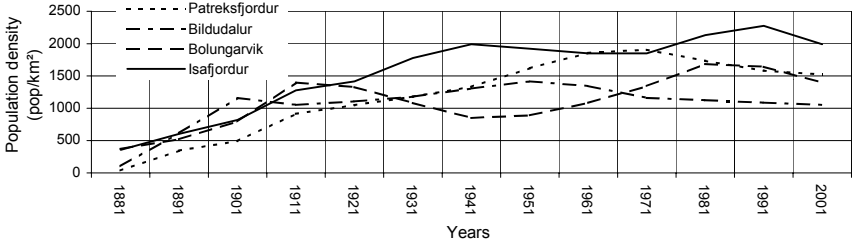


Figure 3: Population density in north-western Iceland from 1900 to 2000 (id.).

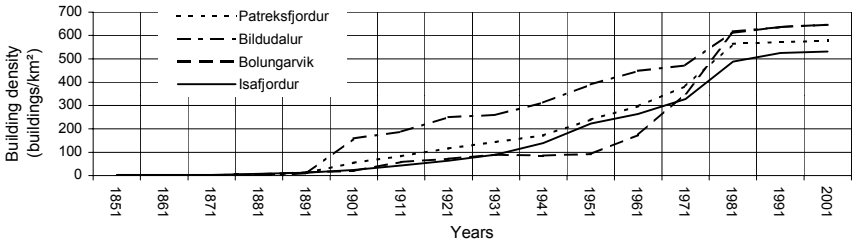


Figure 4: Building density within the four residential investigated areas, 1900-2000 (id.).

3.2 Spatiotemporal characteristics of slope processes

Reported snow-avalanche and debris-flow events were very rare before 1950-1980. It is probably due to lower population number, and moreover to a lower



spatial occupation inside the investigated areas. This is enhanced by increase in event occurrence while residential areas extend. It is particularly true for snow avalanches records (fig. 5). Debris-flow reports (fig. 6) are seldom in Annals, except in favourable places, and do not reflect the widespread fresh landforms they create on slopes. This is the inherent problem of archive sources reliability, as most of these were not collected for geomorphological purposes (Ibsen and Brunsden [38]). Nevertheless, despite the haphazard nature of compiled information, occurrence maps can be drawn for each site (figs. 7-8). The paths of major events, these that caused damages to properties, severe casualties or cut the roads, are highlighted. It must be addressed that this database does not figure the exact slope processes activity, only the recorded one.

Snow avalanches are mainly released further to heavy snowfall and snowdrift, and debris flows are released in equal portions by snowmelt and rainfall [4].

A total of 272 events have been recorded from 1900 to 2003: 67% were registered in Isafjordur, 14% in Bildudalur, 12% in Bolungarvik and only 7% in Patreksfjordur. A combination of length of studied slope/inhabited area and geomorphic facilities for slope processes release explain this variation.

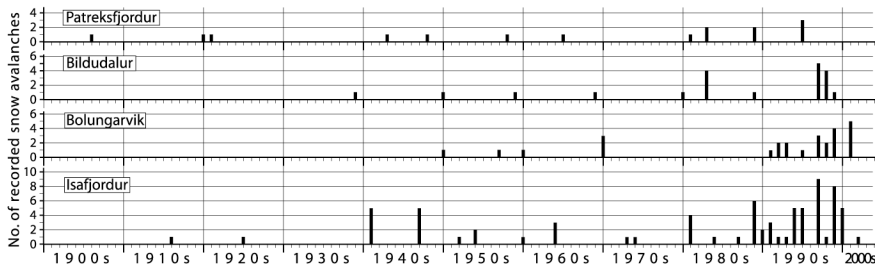


Figure 5: Recorded snow-avalanche occurrence in the four studied places [20-32].

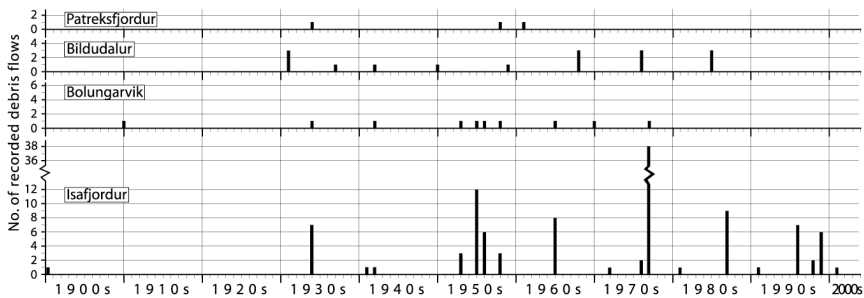


Figure 6: Recorded debris-flows occurrence in the four studied places [id.].

Isafjordur (fig. 7A) is the most extensive place, and consecutively records a greater number of events. The large bench Gleidarrhjalli, located above the main part of the town, is covered by thick unconsolidated debris inherited from glacial periods, and is favourable to debris-flow release [37]. Debris flows are in

Isafjordur more frequent and more numerous (38 debris flows reported for the 1977 event) than in other places, as the debris supply is quasi permanent. In other places, time required for debris replenish by frost-shattering in upper rockwall chutes decreases the event occurrence; snow avalanches are potentially destructive in the western part of the town: the main populated part is endangered by debris flows, that fortunately caused mainly material damages (1965, 1996, 1999), some of them reaching the sea by the past (1934, 1965), while the other is threatened by snow avalanches that caused both material damages and casualties (1941, 1981, 1984, 1994). The use of lichenometry revealed unrecorded activity in few debris-flow channels during the 20th century, while similar activity has been reported on the same slope, confirming and completing historical dating [37]. With about 72 snow avalanches reaching the human infrastructures recorded in 104 years, the snow-avalanche return period is estimated to be 1.44 years, and with 110 debris flows (one single event activating from 1 to 38 channels), the debris-flow return period is lower than 1 year.

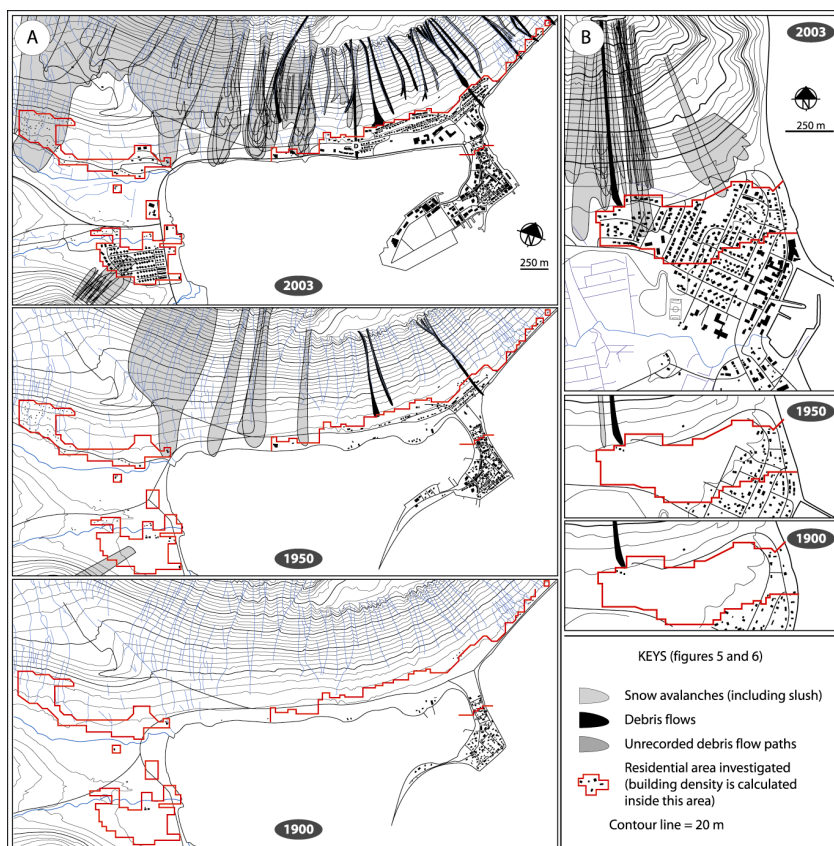


Figure 7: Diachronic maps of registered snow avalanches and debris flows in Isafjordur (A) and Bolungarvik (B) during the 20th century.

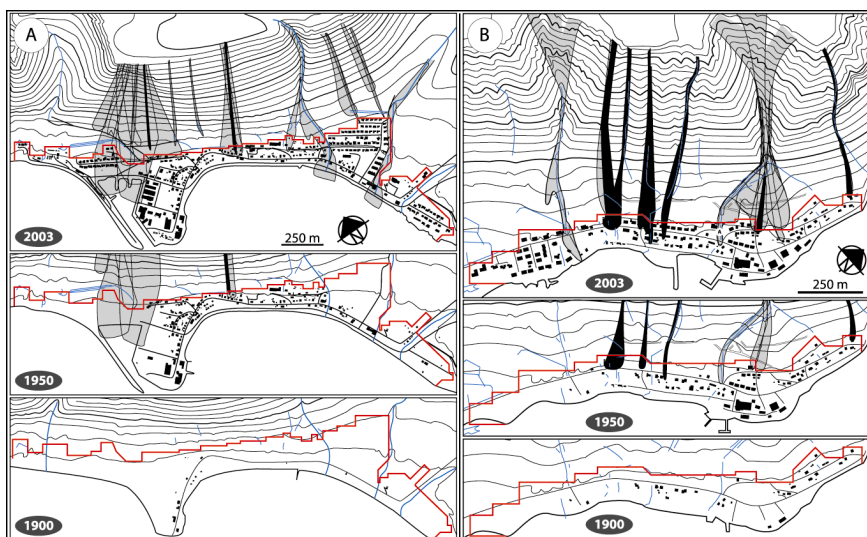


Figure 8: Diachronic maps of registered snow avalanches and debris flows in Patreksfjörður (A) and Bildudalur (B) during the 20th century.

- In Bolungarvík (fig. 7B), snow avalanches are more frequent and have a longer runout distance than debris flows and threaten the uppermost houses: some of them have been built on the path of snow avalanches and were hit several times during the 1990s. Fresh debris-flow landforms are visible above the settlement, and some are said to have often damaged fences and covered fields during the 20th century, without giving dates [31]; nowadays, their paths go through residential areas. 26 snow avalanches have been reported during the period 1900-2003, so its return period is calculated to be 4 years; with about 7 debris flows, the debris-flow return period is about 15 years.
- In Patreksfjörður (fig. 8A), only 15 snow avalanches and 3 debris flows are recorded. Two debris-flow paths have been reported to be active, but several debris-flow landforms were observed on this slope. Two slush avalanches occurred in 1983 along well-defined channels in the north-eastern part of the town, and major snow-avalanche paths are located in the north-western part. Almost all reported event caused damages to properties or casualties. With 15 snow avalanches approaching the houses, the avalanche return period is assessed to be 7 years, while the debris-flow return period is almost 35 years.
- In Bildudalur (fig. 8B), slush flows represent 57% of snow avalanches: 11 slush were released in the two main gullies (10 from 1990), but never caused severe damages; 12 debris flows are reported too, causing property damages. As 23 snow avalanches are registered, the snow-avalanche return period is

4,5 years, and the debris-flow return period is 6,5 years with 16 debris flows recorded from 1900 to 2003.

4 Conclusion

The diachronic analysis of settlements and slope processes through 20th century underlines that risk situation became more problematic with time, as the population density increased within areas that fell to slope processes. In the beginning of last century, no slope processes were reported, i.e. snow avalanches and debris flows did not have catastrophic incidence on people properties and life at that time. Despite the partial data obtained from geomorphological or historical sources, combining the two methods is an approach that could improve risk assessment, by bringing the main tracks and paths into prominence. Nevertheless, a closer analysis of each site is necessary as the activity is not equal overall slope gradients: extreme runout distance events are far most dangerous, but their frequency is low; on the contrary, most frequent events have a shorter extension. The low occurrence frequency of much threatening slope processes in some areas could explain the lack of interest in hazard and risk during the residential spatial expansion period, from 1950 to 1980 in most cases. Moreover, it should be assumed that the most disastrous events have not been all recorded during the last century, as the foot-slope residential area development is not older than 40 years in these fjords: extreme snow-avalanche or debris-flow paths have been observed, but other remain unknown, and the topographic setting is favourable for release above most parts of settlements.

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