THE DIVERSITIES OF LARGE SLUSHFLOWS ILLUSTRATED BY SELECTED CASES

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ABSTRACT: Rapid mass movement of water-saturated snow, usually known as slushflow or slush avalanche, is a major natural hazard in Norway. The destructive forces are larger than those observed from other snow related mass flows of comparable volume. Large slushflows are primarily released in new snow or homogenous coarse-grained snow, often resting on an unstable base and impermeable ground. Most commonly they are triggered by intense rain and/or snowmelt causing water pressure in snowpack in basins and drainages. In some cases large snow avalanches enter into saturated snowfields or impacts ice covered lakes causing abrupt water flow into snow-filled drainages. The flow regime is highly variable, but turbulent and often with saltation layer and airborne part. Erosion, transport and deposition of material is normal along path. A fan with low gradient is characteristic for runout zones. Large flows may also cause floodwaves in fiords and lakes. Slushflow assessment is a major challenge to planning authorities, as well as experts on natural hazards.

Keywords: Natural hazard, large slushflows, triggering mechanisms, flow regimes, human challenges

1. INTRODUCTION

Rapid mass movement of water-saturated snow, usually known as slushflow or slush avalanche, is a major natural hazard in Norway (Fig. 1) (Hestnes 1998, Hestnes and Bakkehøi 2004). The destructive forces of slushflows are larger than those observed from other snow related mass flows of comparable size and velocity.

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Large slushflows primarily occur in terrain with high relief, i.e. in the mountainous parts of Norway. However, an unstable winter snowpack may also favour a considerable spread out down-slope in other areas depending on the topographic conditions in track and runout zones (Hestnes 1985, 1998).

Large slushflows exhibit a greater variety in location, release mechanisms, flow regime, geomorphic processes and consequences than smaller, even though the small ones may account for a greater part of the human and economic losses. These diversities and the challenges that local communities, road authorities, avalanche experts etc. are facing, are illustrated by a selection of well documented large slushflows.

Fig. 1 Slushflows in motion. (Photo A. Ose and T. Prytz)
a) Standalseidet, North-West Norway, 27.11.2008. Release due to pouring rain in new snow, early winter.
b) Skarmodalen, North-Norway, 16.05.2010. Release due to intense snowmelt in late season.

2. DIVERSITIES OF LARGE SLUSHFLOWS

Given favourable conditions slushflows may occur wherever there is snow on ground in potential starting zones. Normally the size and down-slope propagation are governed by local topography, texture and structure of snowpack, as well as the rate and duration of water supply (Hestnes et al. 1994, Hestnes 1998). The documented cases also illustrate that both snow avalanches and floodwater into snow-filled channels, may cause catastrophic slushflows.

Common features and differences of ten cases are briefly described and illustrated by photos and/or maps. The information is based on fieldwork, interviews, photos, meteorological data, historical documentation and newspaper reports. The type of release and comments on flow regime are interpreted from weather data, fieldwork, general experience and a few eyewitness reports. In the following the slushflows are grouped according to their release mechanisms. Some main information and other data are summarized in Table 1 at the end of the paper.

2.1 Release by slab-avalanche

Two slushflows were triggered by large slab-avalanches running into increasingly wetter snow and a water-saturated snowpack in transition zones of uneven topography and varying inclination, 100-250 m above the main valleys. Mixing with the water-soaked snowcover in the valley below one of the slushflows reached far out in the fiord, the other spread out on a wide and flat cultivated floodplain (Fig. 2-3).

A third huge slab-avalanche was probably released in dry new snow approximately 1400 m a.s.l. and became gradually wetter before reaching the valley at 410 m. The completely saturated snowpack in the valley bottom covered a small lake, river and boggy area. The avalanche hit this saturated area, crushing the ice and splashing and pushing a mixture of ice, snow and water along the valley and uphill on the opposite side. Slush and ice closed the main road and almost reached the farmhouses (Fig. 4).

2.2 Liquefaction of wet slab

Wet slab-avalanches on steep slopes may also liquefy immediately into slushflows. This probably occurred in 1994 on the WNW-facing slope of the V-shaped valley on figure 5. The length of the crown (h≤1m) in the wet coarse-grained snowpack was approximately 1000 metres. The slush swept down into the deep and highly saturated snow in the valley bottom. An oscillating flow was set in motion along the 22° steep hanging valley. From the valley-outlet the roaring slushflow cascaded down the steep hillside into the fiord, setting up a

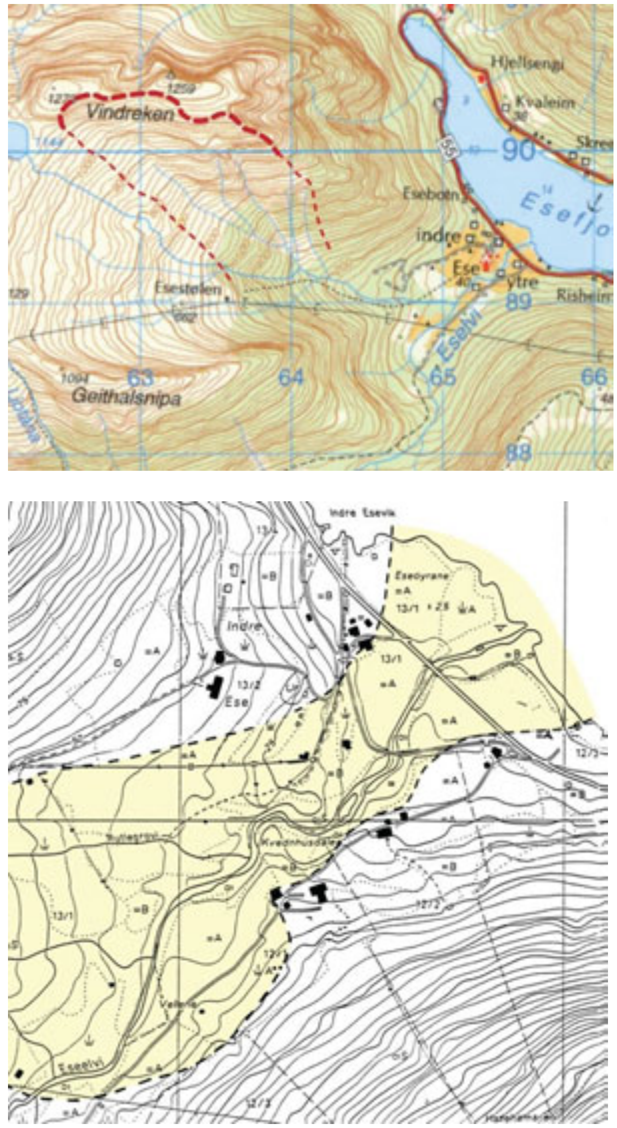

Fig. 2 Ese, Balestrand, West Norway, 09.02.1928
a) Map scale 1: 50 000 show a huge basin with numerous creeks feeding water into an area where slab avalanches can trigger slushflows. Slushflows may also be released in the basin without impact by avalanche.
b) Map scale 1:10 000 with the runout zone of the slushflow in 1928. The annals have information on large slushflows during the 1900th century which also reflects the location of the farms. There is a pressure on building industry as well as recreational homes on the delta by the fiord.

floodwave that destroyed more than 10 boats, 4 boathouses and a cabin along the fiord. The fiord was filled with snow and debris within seconds. A man observing the event from the settlement on the opposite shore 1.5 km away, was caught by a tsunami and dragged 20 m by the wave, but was luckily left on shore almost unharmed when the water retreated.

2.3 Flooding of snow-filled drainage

Sometimes avalanches that enter into lakes may cause critical floods and subsequent slushflows, even during winter. In January 1994 a dry slab having a 1200 m long crown, consisting of 500 000 m^3 of snow entered into a frozen lake close by the NGI research station. The impact and weight of the snow caused a critical rise of water in the snow-filled drainage channel releasing a slushflow that swept through the whole stream-channel to the main river 12 km below. The average gradient of this slushflow was 4.5^o (Fig. 6).

A corresponding event happened when a hydro power company shut down a power plant for renovation. They diverted the winter runoff into the former stream-channel, causing a giant slushflow destroying most of their own temporary camp.

Fig. 3 Fivelstad, Stranda, NW Norway, 05.02.1990. (Photo K. Kristensen, NGI)
The farm buildings were destroyed by a huge slushflow triggered by an avalanche. Soil-profile indicates previous events of comparable size. Protection dam is built.

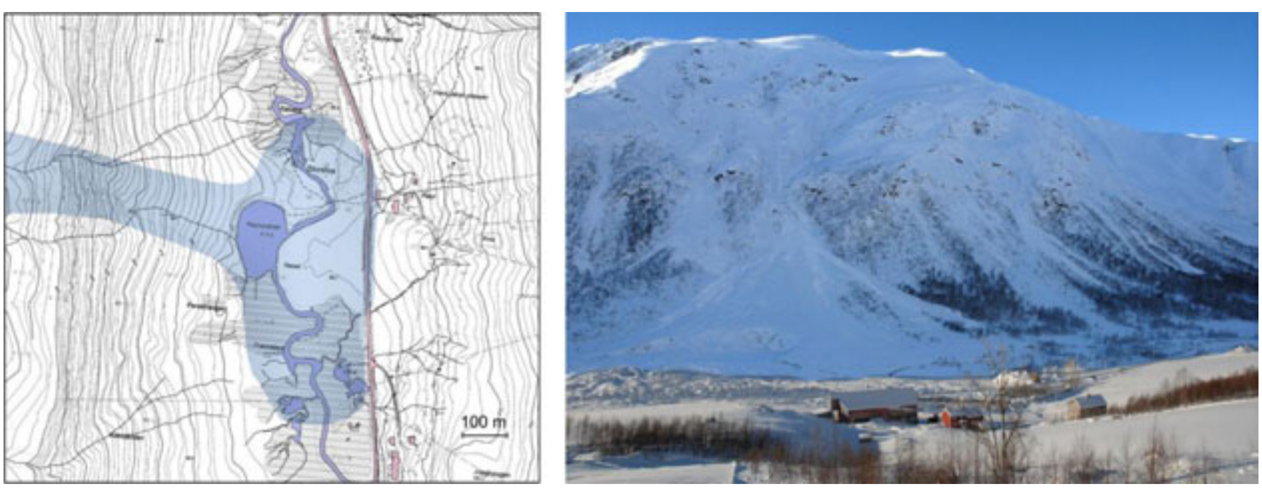

Fig. 4 Røyr, Stranda, NW Norway 29.01.2007. (Photo K. Kristensen, NGI)
The scattering of slush over the valley-floor approximately 300x700 m^2. Total fall of slab-avalanche 1000

m.

2.4 Releases in drainage channels and basins

The remaining five large slushflows presented were released within inclined open basins and drainage channels (Fig. 7-8). They had a prominent crown and scar-like starting zone and liquefaction occurred immediately after release. However, there are noticeable differences in the release mechanism related to local topography, snow conditions and water supply (Hestnes 1985, 1998, Hestnes et al. 1994). The consequences of these slushflows vary not only due to the conditions in the starting zone, but the local topography along track and in runout zone, as well as the possibility to erode and deposit material.

Fig. 5 Moldskreddalen, Balestrand, West Norway, 28.04.1994.
a) Map scale 1: 50 000. The starting zone of the remarkably wide and tin slush-slab is indicated.
b) Air-photo scale 1: 30 000. The oscillating flow along the V-shaped valley can be observed on the vegetation. Frequent slushflows are recorded, but none of comparable size. Neither was such a destructive floodwave. The trees along the flanks in the lower part were destroyed by the air-blast**.**

Fig. 6 Oppljoselva, Stryn, West Norway, 23.01.1994. (Photo K. Kristensen, NGI)
Slushflow during dry snow condition. Fluctuating width of flow 10-100 m, related to grade and cross profile

Fig. 7 Rapbekken, Børgefjell, North Norway, 28.05.1985. (Photo E. Hestnes, NGI)
Crown surface 3-7 m two weeks after release. Rough stream-bed, boulders and debris resting on bedrock.

The flow regime of these slushflows is also characterized as fully turbulent, with a saltation layer and airborne part. Historical records, fragments of rock, soil and organic material in trees, trees cut or uprooted etc. are information and observations documenting such regime.

In four cases the slushflow was released on the steepest part of the drainage just below a change in steepness. This is where the water pressure and tension is supposed to be the highest (Fig. 7-8). Large slushflows along these four paths do erode, transport and deposit mineralogical material on large fans or river plain. These locations, where both landforms and historical records clearly states there are hazardous zones, are also the preferred building areas (Fig. 8-10)

A fifth location has two separate starting zones, where 2-3 releases are reported from each both in 2000 and 2010. The crown of the observed final releases was in shallow basins above the steep mountainside. There is no information on where the other releases occurred, but indications of retrogressive release mechanism in the two basins were observed. The first releases may occur from steeper grade on the upper part of the mountainside (Fig.11).

The slushflows at this location do primarily consist of snow and water due to bedrock in most of the tracks. However, the multiple releases constitute a big problem to the Road Authorities, as the only highway through North Norway is endangered. A 40 m long and 16 m high concrete bridge spanning the track was lost in the fiord 350 m below the highway in 2000. Two slushflows caused floodwaves of limited size in the fiord.

Fig. 9 Sjongsåi, Lesja, Central Norway,06.05.2004 (www.norgeibilder.no)
A mixture of old summer farms and new vacation homes are located in the hazard zone of large slushflows. Two old buildings where partly wrecked and five or six barely escaped ruin this time. Larger flows may occur.

Fig. 8: Vannledningsdalen, Longyearbyen, Svalbard, 11.06.1953 & 14.06.1989.
a) Development of the "staff-town" on the fan started in 1946, neglecting the warning about the hazards. A slushflow hit the topmost building (staff mess), the hospital and 3 out of 6 staff homes in 1953, causing 3 deaths and 12 seriously injured. Consequently, a deflecting dam was built and a routine for removing the snow in the channel by a bulldozer each spring was established. (Photo E. Hestnes 1985)
Windows in a building on this side of the valley was broken by the air-blow from a slushflow in ca.1910.
b) Removing snow from the drainage was neglected in spring 1989, and the municipality got a prompt reminder from the nature. House and infrastructure - road, bridge, water and sewer pipe, and the town heating system, were broken by the flow of dirty snow. (Photo Antonsen, Svalbardposten).

Fig. 10 Sjongsåi, Lesja, Central Norway, 06.05.2004. (Photo U. Domaas, NGI)
A close up view of the deposited material documented on figure 9.

Fig. 11: Herraneselva, Langfjorden, Alta, North Norway, 19.05.2000.
a) The mountainside with the two slushflow paths. Starting zones in the high-lying basins. The bridge is replaced by a fill after the bridge was lost in the fiord in 2000. (www.kart.finn.no)
b) The crossing after the bridge was gone. It is a 800 km detour via Finland from one side to the other.

2.5 Release in perennial snowpack

A case of a full depth release in a several years old snowpack occurred the 21st of June 2005 near the Tystigen summer ski centre in Stryn. Water level in a basin above the starting zone rose rapidly during intense thaw and rain, and saturated the snowpack downslope that mainly rested on impermeable bedrock. A slush-slab that liquefied by release had flank surfaces up to 6 m high (Fig. 12).

3. SUMMARY

The assessment of slushflows hazard is a major challenge to planning authorities and avalanche experts. Their diversity and the lack of models that take such phenomena into account makes hazard zoning a difficult task. The safety of humans and property as well as sustainable development in districts exposed to natural hazards, will depend on the actions local and regional authorities are taking to reduce and avoid future exposure in hazardous zones.

Avalanche experts will have to consider the different modes of release and flow regimes to make the correct decisions concerning hazard potential. A brief summary of these diversities are given in Table 1.

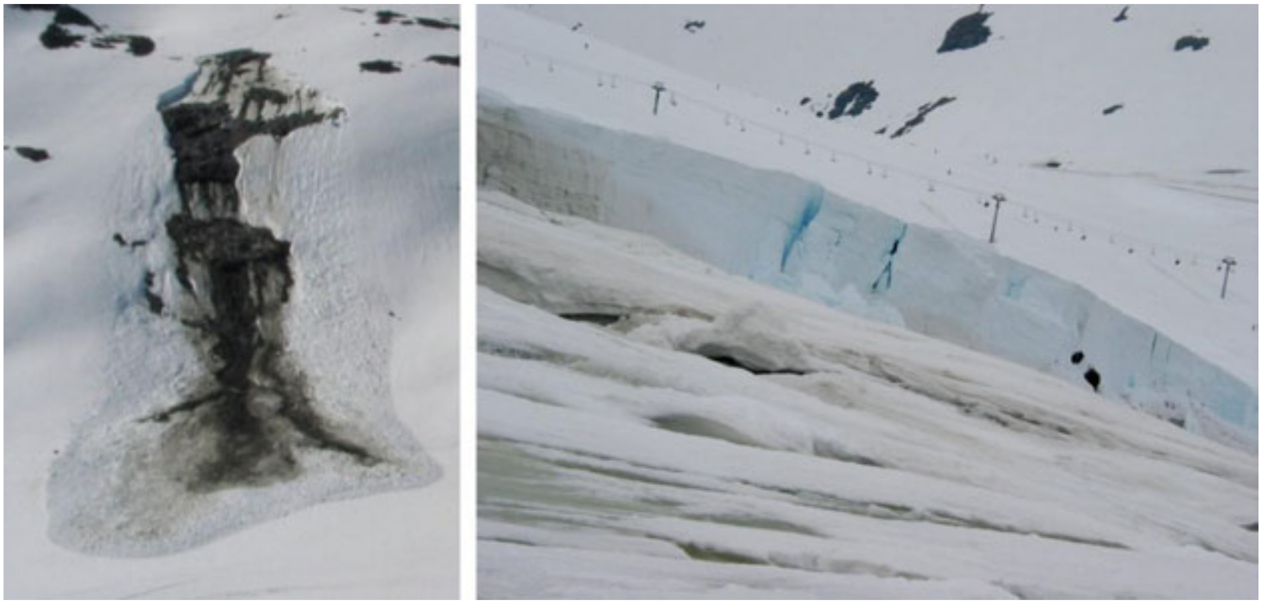

Fig. 12 Tystigen, Stryn, West Norway, 21.06.2005. (Photo K. Kristensen, NGI)
a) The slushflow in perennial snowpack. b) The western flank with the ski-lift in background.

4. ACKNOWLEDGEMENT

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