Optimizing Mitigation Measures against Slush Flows by Means of Numerical Modelling
- A Case Study Longyearbyen, Svalbard -

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Spitsbergen is usually related to cold climate and harsh weather conditions. In recent years, mild weather in mid-winter has become more frequent, and likewise have slushflows. The latest slushflow incident occurred in Vannledningsdalen January 2012. Longyearbyen Community Council asked NGI for a review of existing mitigation measures, and for a proposal of a revision or extension to fulfill new building regulations. The RAMMS model from SLF/WSL was chosen to simulate the slushflow. The slushflow was first simulated for the existing terrain and input parameters were optimized by comparison with selected known slushflows events. We found the parameters μ=0.05 and ξ=5000 [m/s^2] to give reasonable run-out. These parameters were then used in simulations with a modified terrain including the revised mitigation measures. We consider that the use of RAMMS gives valuable indication on how the slushflow might behave along the path, what flow thickness and speed can be expected as well as to indicate possible deficiencies in the proposed design of the mitigation measures.

Key words: Svalbard, Mitigation measures, Slush flow, RAMMS

1. INTRODUCTION

Svalbard (also named Spitsbergen, located at lat. 78° north) is usually related to cold climate and harsh weather conditions. In recent years, mild weather in mid-winter has become more frequent which also brings the focus to snow related problems such as slushflows that usually occurred only in May in the past.

Late in January 2012, a warm weather spell with precipitation caused a slushflow from Vannledningsdalen (**Fig. 4**) into the canal on the alluvial fan (named "Haugen") and down to the main road to the settlements of "Nybyen". At this time, the flow did not hit or damage any inhabited house on the alluvial fan.

The settlement on the alluvial fan has increased throughout the years, and now the fan area is almost fully developed.

Early on in the settlement history of the alluvial fan, the local authorities realized the need for taking action to protect inhabitants and houses from slushflows. The stream/flow that could spread all over the fan was directed into a small canal. The canal has been modified after several major

Fig. 1 The figure shows the location of Svalbard. Map: Google maps.

slushflow incidents and of today the canal has also a prominent wall on the west side (**Fig. 2**).

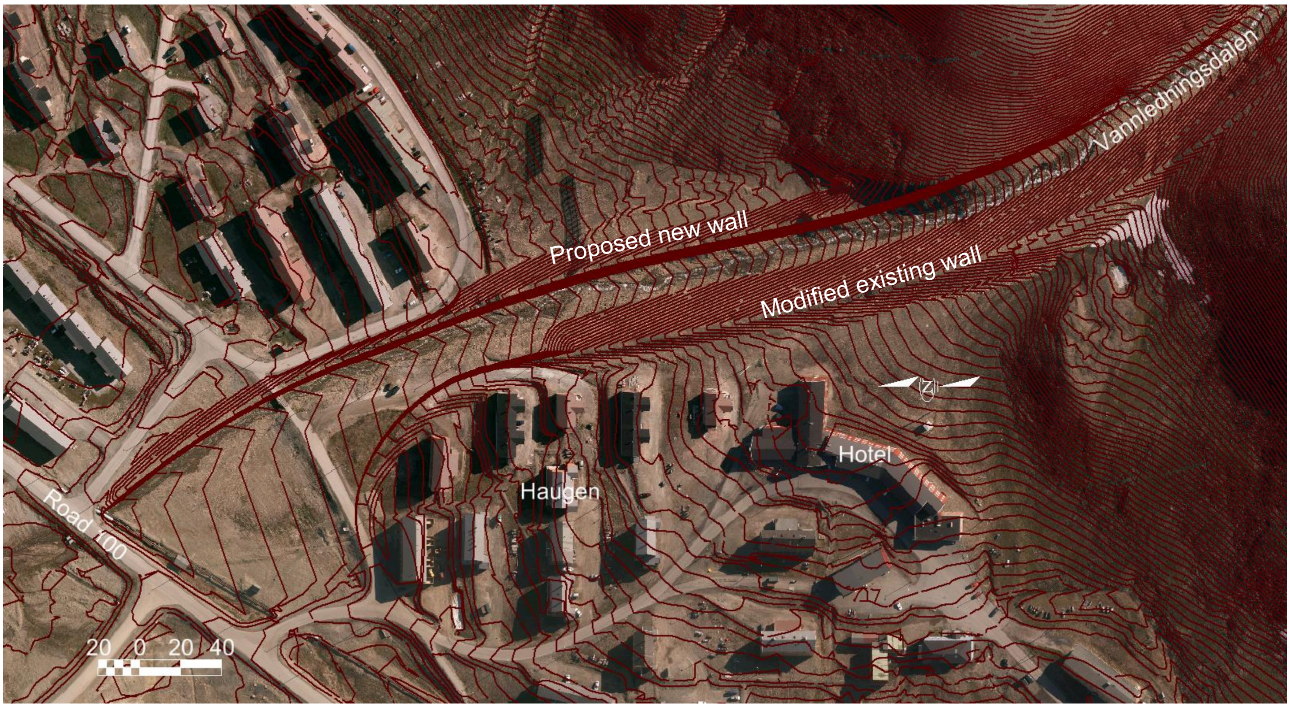

Fig. 2 Overview over the alluvial fan and the settlement. Proposed new mitigation measures, deflecting walls are shown with red contour lines, 5 m equidistance. Background aerialphoto: LL.

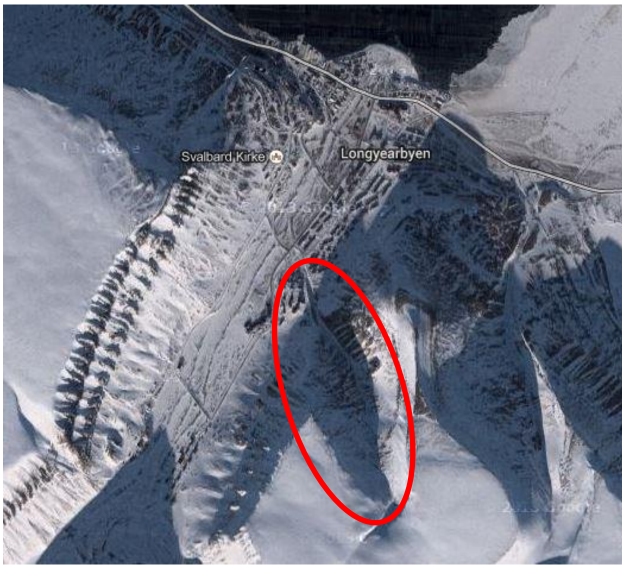

Fig. 3 Aerial view of Longyearbyen. Red ellipse shows Haugen, Vannledningsdalen and the plateau. Aerial photo: Google maps.

After the incident in 2012 the local authorities decided to review the current mitigation measures as the Norwegian parliament had issued new laws and regulations for natural hazard in 2010.

Longyearbyen Community Council (LL) asked NGI to review existing mitigation measures and to propose a revision and/or extension to the existing measures to fulfill the new regulations.

2. THE SITE

Fig. 4 Vannledningsdalen seen from the main road. The slushflow in January 2012 spread out on the open area in the front.

2.1 History of slushflows

The settlement of the alluvial fan, "Haugen" started after the Second World War. At that time, there were a number of persons who pointed out that the area is exposed to slushflows, but their voices were not heard. In 1953, a slushflow from Vann-ledningsdalen killed 3 persons, injured 30 other persons, destroyed the hospital and caused damages of several other buildings on the alluvial fan (UNIS, 2006). Information obtained by G. Ramsli in 1953 indicates that at least 5 larger slushflows occurred in the first half of the 20th century. NGI has also been informed (NGI, 2006) that an air blast from a large slushflow had supposedly smashed windows on buildings on the upside (west side) of Longyearriver (most likely in the year 1910).

Fig. 5 Buildings on Haugen that were hit and destroyed by slushflow in 1953. (UNIS, 2006).

One slushflow hit and damaged few of the houses at the west side of the fan in 1989 without having caused fatalities (NGI, 2012). As mentioned, the most recent slushflow occurred in January 2012. It caused only minor damages to infrastructure.

The NGI report from 1990 states that meteorological- and historical data indicate that larger slushflow events than the ones in 1953 (Fig.5) and 1989 can be expected from Vannledningsdalen.

2.2 Terrain

The bedrock in this area consists mostly of sedimentary rock types like sandstone, siltstone and shale. The landscape is characterized by layered mountains with a plateau on top and U-shaped valleys formed by glaciers. Vannledningsdalen ("water pipe valley") is V-shaped (**Fig. 3** and **Fig. 4**) and it forms a scar in the mountainside. It is mostly shaped by erosion after the last glaciation; the eroded material built up the fan below. There are steep flanks on the orographic right side and more gentle slopes on the left side. The left side has abandoned coal mines at ca. 280 m height above sea level.

Above Vannledningsdalen is the so-called "plateau" at an elevation of about 350 m above sea level. It is relatively open and flat close to Vannledningsdalen but the flat area becomes narrower with steeper hillsides further up. The average inclination of the small stream on the plateau is around 2 to 3 degrees.

At the top of the fan is a fall in the bottom of the stream. The stream is in a right turn (in the direction of the stream) at this location and the existing wall on the west side is low. This point is therefore critical as the slushflow can easily overtop the wall and hit the buildings below.

2.3 The watershed

The watershed above the settlement is divided into two, the area on the plateau and the area along the stream from the plateau to the settlement. The plateau area is around 77.7 ha and the area along the stream is around 98.8 ha, which gives a total area around 176.5 ha.

2.4 The slush flow

There are many factors that can contribute to a release of a slushflow, e.g. temperature, volume of snow, texture and structure of the snowpack, precipitation and snowmelt, to name a few.

No or limited information is available on how much snow were involved in previous slushflows. The estimated critical volume of snow in Vannledningsdalen is around 80000 cubic meters when about 4 m snow height is measured from top to bottom of the stream. The critical snow volume on the plateau is estimated to be around 6000 cubic meters when the average snow height is about 1.0 m, and the width is estimated to be about 30 m and the release length to be about 200 m.

The starting zone of known slushflow events is not well registered but it is known that the slushflows in 1953 and 1989 started below the plateau and the slushflow in 2012 started about 200 m above the alluvial fan.

The form of slushflow release from Vannledningsdalen is not known. Generally, slushflows can start as a "one segment" or a "block" along the valley bottom or it can start as "small segments" which can propagate from the lower part up along the valley bottom. Many scenarios can exist.

Fig. 6 The figure shows how the snowpack in Vannledningsdalen was prepared to minimize the slushflow risk. This method is still used today.

3. MITIGATION MEASURES

3.1 Safety criteria

Svalbard has its own rules and regulations set by the Norwegian government according to The Svalbard Treaty. Until 2013 the safety criteria against natural hazards/forces set by the Norwegian building code did not apply on Svalbard. However, LL decided that the mainland code and safety criteria would apply for Svalbard in this project.

The settlement on the alluvial fan consists mainly of buildings that fall into category S3 (hotels and buildings with many apartments) which means that the nominal yearly frequency of avalanche hitting the area shall be less that 1/5000. This is the highest safety criteria set by the building code.

3.2 Previous mitigation work

Shortly after the incident in 1953 the stream on the alluvial fan was channeled and small walls on both sides were erected past the settlement. A routine for draining the snow with bulldozer from the fan up to the plateau was also established, (**Fig 6**).

NGI (1994) concludes that the smelting season starts on average in the first week of May. The work of draining the snowpack with bulldozer was initiated in this period.

NGI (2006) discusses possible impact from climate changes, and the conclusion is that with warm weather, slushflow can hit any time in the winter (NGI, 2006). As mentioned before, a slushflow was released from Vannledningsdalen in late January 2012.

Since the incident in 1953, the canal on the alluvial fan has been improved step by step, especially on the west side, the last time just after the incident in 1989 (NGI, 2012). The flank on the east side is much lower and a flow could easily overtop it and hit the houses on that side.

3.3 Mitigation plan

3.3.1 The plateau

The estimated release volume of wet or super-saturated snow on the plateau is only around 8% of the estimated snow volume in Vannledningsdalen.

Due to the gentle slope on the plateau, it is thought that some kind of supporting measures might be the best solution to keep the snow in place on the plateau. Two alternatives are considered feasible, a catching dam made of earth material with enough opening or porosity to drain the snow, or supporting structures of steel similar to those used for supporting the snow in steep avalanche starting zones.

Our preliminary conclusion was to propose supporting structures of steel. One of the main reasons for this conclusion is what we consider environmental aspects, which are important in Longyearbyen/Svalbard. It is thought that the relatively limited earthwork during installation weights more than relatively "unnatural" steel constructions. LL will make the final decision when they have considered pros and cons for all alternatives.

3.3.2 Vannledningsdalen

One alternative discussed was to locate supporting structures along the stream at several locations from the alluvial fan to the plateau and drain the snowpack in the same way as was planned on the plateau, however. We face several challenges in Vannledningsdalen that we do not face on the plateau. It is more difficult to estimate the height of the snow cover in a narrow creek as no information is available (measuring work was initiated the winter 2013/2014). A large number of rows is needed to prevent slushflow to be released between the rows. Possible underestimation of the number of rows or height of rows can cause fatal accidents and widespread structural damages to both buildings and supporting structures.

The idea of structures in Vannledningsdalen was therefore put aside and other measures considered.

3.3.3 The alluvial fan

An improvement of the existing mitigation measures, which aim is to divert the slushflow past the settlement, is considered realistic. However, there are several uncertainties that make the work difficult, like unknown volume of snow/slush and unknown velocity. Limited space for earth walls is also a challenge as well as the location of infrastructure, which cannot easily be moved to a new location or excavated deeper into the permafrost.

It is proposed to open up sharp horizontal curves in the stream especially the mouth of Vannledningsdalen and all falls in the vertical profile are planned to be evened out.

Improvements to the height and geometry of the wall on the west side is proposed. The height is set to 12 to 14 m, which is roughly the height of existing wall at the highest point. The lowest row of buildings on the west side has an access road just west of existing canal. It is necessary to move the road to a new location on the top of the earth wall (**Fig. 2).** At this part of the proposed wall height changes from 12 m to almost zero and the wall steepness changes from 1:1.5 to 4:1 due to limited space.

The planned bottom width of the canal is set to ca. 15 m from the mouth of Vannledningsdalen down to the change in wall height were the width is planned to increase so that the snow masses can spread out.

The wall on the east side needs to have the same height as the wall on the west side in the upper part. From the widening of the canal the wall is lowered to 8 m at road 100 (**Fig. 2)**. The impact side of the wall is planned to have a slope of 4:1 partly due to limited space and partly due to run-up height.

4. SLUSHFLOW SIMULATION

Although slushflows constitute a considerable hazard in some regions, especially in Arctic regions, little is known about their dynamics. The combination of snow and water – that is high densities (in the range from 400 to 1000 kg m^{-3}) companied with a high mobility (velocities probably up to 30 m s^{-1}) – can make slushflows a highly destructive force. Only few attempts have been made to simulate slushflows (Bozhinskiy and Nazarov, 1998; Gauer, 2004).

In this study, we choose to use the two-dimensional dynamical model of rapid mass movements RAMMS from the Swiss Snow and Avalanche Research Institute (SLF)/WSL (Christen, et al. 2010) to simulate slushflows. RAMMS originally developed to simulate dense flow avalanches, is also used in a very similar form for debris flow modeling (e.g. Hussin et al. 2012).

RAMMS is based on the so-called Voellmy-fluid, where the frictional resistance can be written as:

$$S = \mu \rho g h \cos\phi + \rho g \frac{U^2}{\xi}, \qquad (1)$$

where ρ is the density, g the gravitational acceleration, ϕ the slope angle, h the flow height, and U the flow velocity. Based on hydrodynamic considerations, Voellmy (1955) introduced the velocity square dependent friction with the turbulent friction parameter, ξ. In addition, he included a frictional resistance in his model, which is proportional to the sliding area and to the normal pressure acting on it, with a frictional coefficient, μ. Considering its origin, the Voellmy-fluid model might be a reasonable choice as a simple slushflow model.

In our simulations we used μ=0.05 and ξ in the range from 3000 to 10000 m/s^2. Such a low μ value can be argued for as it accounts for the reductions of the solid friction due to the pore water pressure, in which case the apparent friction coefficient, μ_a, may be written as

$$\mu_a = \mu_D(1 - r_u), \qquad (2)$$

where r_u is the ratio of pore fluid pressure to total normal stress and μ_D the dry friction coefficient. The values for ξ seem to be rather high in comparison to commonly used ones. However the reason for this choice was twofold: 1) we wanted to obtain reasonable high velocity to be on the conservative side for the planning of the deflection dam; 2) we used the research version of RAMMS which allows to include erosion of snow along the path. We used this option to obtain the observed mass in previous events. However, including mass erosion can lead to

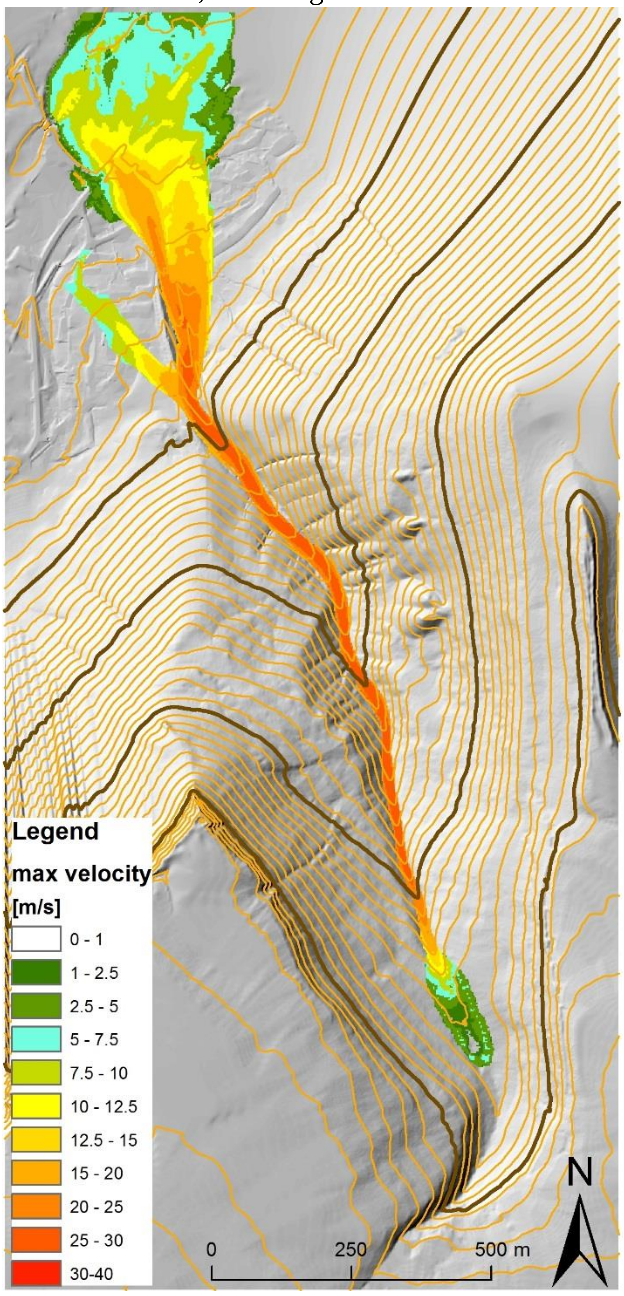

Fig. 2 Example of simulation with RAMMS for existing terrain using μ = 0.05 and ξ = 5000 m s^{-2}. Release height d = 4 m and maximum erosion depth e = 4 m. This type of simulation was used to determine the design criteria for the deflecting walls on the fan.

a momentum loss similar to the velocity-squared term. Therefore, to avoid a double penalty, we used high ξ values.

Fig. 7 shows an example of the simulated maximum velocity. The speed behavior of slushflows is not very well known. Perov (1998) mentions velocities of slushflows depending on the slope angle ranging between 1.5 m s^{-1} on flat ice domes to 4-8 m s^{-1} in mountain valleys with estimated maximum of 15-20 m s^{-1}. Field observations from Kärkerieppe/ Swedish Lapland in 1995 suggests velocity between 10 and 15 m s^{-1} in a 8 to 10° steep gully and 125 m drop height (http://www.mcr.unibas.ch/Projects/ MOSAIC/KV/kv95.en.htm accessed 21.04.2014). In our case, the total drop is about twice that with an averaged slope of 12°. Although the simulated velocities in the range of 25 and 30 m s^{-1} might be at the high end, we consider them still as reasonable for an extraordinary event in this gully. The simulated maximum flow depth in the channel was approx. 3 m. The simulated runout area is consistent with field observations of registered events.

5. FINAL REMARKS

We consider that the use of RAMMS gives valuable indication on how the slushflow might behave in the path, e.g. what speed can be expected and it can indicate possible deficiencies during the design phase of the mitigation measures.

6. EPILOG

The proposed earth walls are considered rather expensive. Therefore LL did later ask for revision of proposed measures and for other alternatives. As of today, all proposed mitigation measures are under consideration by the LL and NVE, the Norwegian Water and Energy Directorate who has the mandate to manage all mitigation work.

7. ACKNOWLEDGEMENT

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