ANALYSIS OF AN ARTIFICIALLY TRIGGERED AVALANCHE AT THE NEPHELINE SYENITE MINE ON STJERNØYA, ALTA, NORTHERN NORWAY

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ABSTRACT: Since 1961, a Nepheline Syenite mine is operated on the island of Stjernøya in the Altafjord, Northern Norway. The facilities are located in Lillebukt, on the southern side of the island. Above the facilities, the Nabbaren mountain is rising to a height of 727 m a.s.l. Rockfall during summer season and snow avalanches during wintertime pose potential hazards from its slopes. Due to this setting, the mining company has long experience with both physical and non-physical hazard mitigation measures. Apart from physical installations against rockfall and snow avalanches, artificial triggering of the Nabbaren avalanche forms part of this mitigation strategy.The winter of 2013/2014 was characterized by an unusual snow scarcity between December 2013 and March 20, 2014. After this date, large amounts of snow fell during a short period. Due to this new snow loading, together with intensive snowdrift, the mining company decided to artificially trigger the Nabbaren avalanche on April 8, 2014. A D4 slab avalanche was released, subsequently evolving into a mixed dry avalanche of impressive scale. In contrast to avalanches triggered in other years, this avalanche overtopped the avalanche deflecting wall at its one end causing slight damages to some of the factory installations. In order to document the avalanche, an on-site study was carried out shortly after the event. In addition, a WorldView-1 panchromatic satellite image was obtained to map the non-accessible parts of the avalanche. Here, we present findings from the field visit, from image analyses and first modellings of the avalanche run-out.

KEYWORDS: Stjernøya, mixed dry avalanche, powder cloud velocity, RAMMS

1. INTRODUCTION

Stjernøya is an island located at 70°19′0.5″N/ 22°39′47.8″E in the Altafiord, Northern Norway. Since 1961, a Nepheline Syenite mine is operated on the island, today owned by the mining company Sibelco Nordic. The mineral Nepheline Syenite is mainly used as an additive in glas-ceramic and porcelain production. The total mineral yield per year is approximately 340,000 tons.

The factory facilities are located in the bay of Lillebukt, on the island's southern side (Fig. 1). The majority of the infrastructure is located between sea level and up to ca. 50 m a.s.l, on a scree deposit accumulated from rock falls, snow avalanches and river flooding on the western shore of Lillebukt (see Fig. 2 for overview). Further

uphill, the terrain rises steeply to the mountain top of Store Nabbaren (727 m a.s.l.).
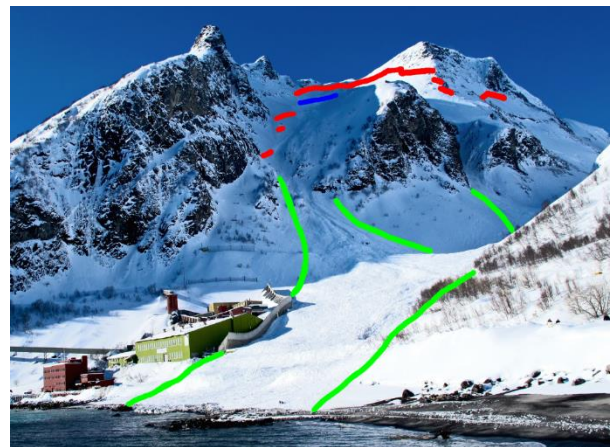

Fig. 1: The Sibelco Nordic mine located below the Nabbaren mountain. Image taken on April 8, 2014, shortly after the avalanche release. Red lines = fracture lines, blue line = stauchwall, green lines = rough outlines of the dense flow. (Image credit: Sibelco Nordic)

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The mine is a combination of underground excavation and an open-pit mine located at about 650 m a.s.l., on top of the Nabbaren mountain.

The outdoor facilities consists of a concentrating factory, a workshop, conveyors, the administration building, living quarters, silos and piers for personnel transport and for the export of the Nepheline Syenite.

2. SITE CHARACTERISTICS

2.1 *Topography*

The mountainous terrain above the factory consists mainly of near vertical rock walls and two major, deeply incised steep gullies, widening uphill to a cirque near the top of the mountain. The cirque acts as the starting zone for major snow avalanches which run downhill through the two gullies. The southern gully leads towards the factory, where avalanches may run all the way to the sea, passing the factory on its way. The northern gully directs part of the avalanche towards the valley floor 400 m uphill from the factory, where the avalanche partly turns downhill in the direction of the factory.
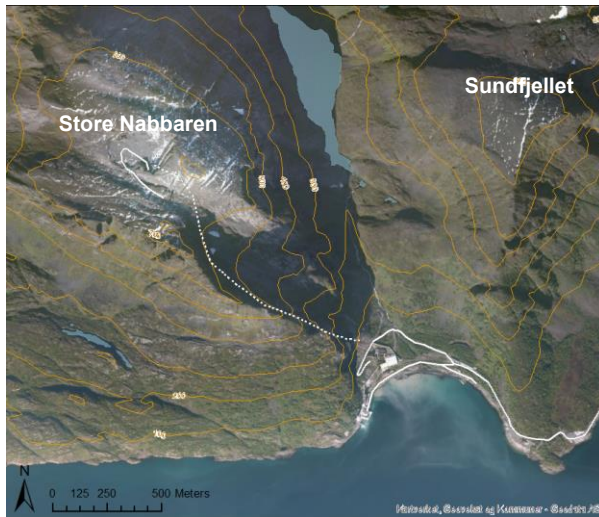

Fig. 2: Arial view of Lillebukt bay with the main factory buildings in the center of the image and the open-pit mine area to the upper left, on the plateau of Nabbaren mountain. The white stippled line markes the tunnel connecting the open-pit mine with the factory facilities at sea shore (Background data: © by Geodata AS)

The width across the cirque is ca. 400 m. The top of the starting zone is located between 600 to 650 m a.s.l. with a length of maximally 800 m. The

inclination of the starting zone is between 27 to 60 deg, with an average of 35 deg for the uppermost vertical 100 m. The average inclination from the seashore to the top of the starting zone is 28 deg with a total length of the avalanche path of 1,300 m. The maximum area of the potential starting zone is estimated at 100,000 m^2. Assuming snow heights of 2-3m, the volume for a major avalanche can, therewith, be estimated to be in the order of 200,000-300,000 m^3.

The living quarters of the mining staff are located on the eastern shore of Lillebukt. Above the quarters the mountain Sundfjellet rises to 640 m a.s.l. Several minor and medium sized avalanche release zones are located on Sundfjellet. Historically, avalanches which have released from these starting zones have hit the living quarters and caused material damage. Following these events, physical protection measures were built to protect the living quarters.

2.2 *Weather and climate*

Stjernøya is characterized by a maritime climate and is exposed to westerly weather and waves from the Atlantic ocean. There is no official meteorological station running on Stjernøya, therefore, we here present meteorological data from the meteorological stations in Loppa municipality (locacted on the mainland, ca. 46 km W of Lillebukt) and at Hasvik airport (located on the island of Sørøya, ca. 25 km NW of Lillebukt).

The yearly average precipitation (measured in Loppa) is 917 mm. Winter precipitation is 515 mm. Average temperature over the year is +3.8 deg C. Maximum recorded precipitation during one, three and five days is 60 mm, 102 mm and 119 mm, respectively.

The main wind direction combined with heavy snowfall is from the northwest (Fig. 3), often caused by intense polar low-pressure systems hitting the coastal areas with strong winds. The east- to southeast-oriented mountain slope of the Nabbaren mountain above the factory lies in a leeward position during such storms, during which the conditions for heavy snow accumulation are favorable.

During high-pressure situations, wind directions from south and southeast are dominating. Little precipitation follows these winds, but snowdrift can be extensive, and cause avalanches on slopes facing towards north and northwest.
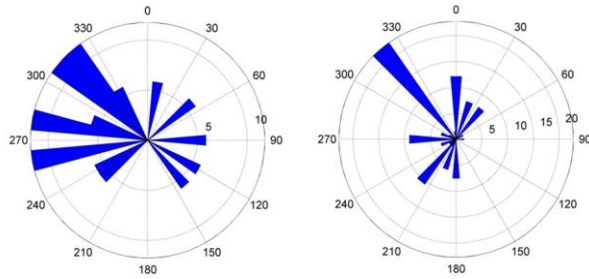
Fig 3. Wind directions in combination with snow-fall (temperature <1 deg C, wind speed >5 m/s, three days precipitation sum >30 mm, snow height >5 cm) for (left) Hasvik Airport from 1984-2012 and (right) Loppa from 1957-1999. (Source: NGI, 2012)

2.3 *The winter of 2013/2014*

The winter of 2013/2014 in the Altafjorden area was characterized by an unusual snow scarcity between December 2013 and March 20, 2014. After this date, large amounts of snow fell during a comparably short period. On April 8, 2014 the mining company decided to artificially trigger the Nabbaren avalanche.

The weather records noted by a staff member of Sibelco reveal the following: "*From December 20, 2013 to March 20, 2014, the total snow height at sea level augmented to 25-30 cm of snow. There was also considerable rainfall during this period, especially during the end of December and again during the onset of March. Predominant wind direction during these months was from southeast, with wind speeds up to fresh gale (Beaufort scale/BFT: 17.2-20.7 m/s). A few days with westerly and northwesterly fresh gale with heavy rain on the westerly wind occurred during late February. On March 8th and 9th, the island was hit by the storm system Jorunn (with wind speeds up to 24.5-28.4 m/s) bringing heavy rain showers. On April 1st rain turned into snow, and snow showers continued to April 2nd resulting in 20 cm new snow at coastal altitude. After calm weather on April 3rd, 15 cm new snow fell during the night, with predominantly moderate breeze (BFT: 5.5-7.9 m/s) from the North. Southwest strong breeze (BFT: 10.8-13.8 m/s) followed during the afternoon of April 4th. During the following night shift to northwesterly strong gale (BFT: 20.8-24.4 m/s) accompanied by snow showers. Snow showers continued over the weekend accompanied by fresh breeze (BFT: 8.0-10.7 m/s). Total snow amount during the weekend augmented to 50 to 60 cm of snow at sea level. An additional 5 cm of snow was measured on April 7th. April 8th, the*

day of the artificial triggering, faced calm sunny weather with temperatures at -4 to -5 deg C in the morning hours."

The records by this local observer are in good congruence with the measurements from the meteorological station at Harvik airport (cf. Fig. 4). They confirm low snow heights throughout most of the winter, as well as distinct rain events by the onset of March, which were followed by intense snowfall in the days prior to the day of the artificial avalanche triggering.
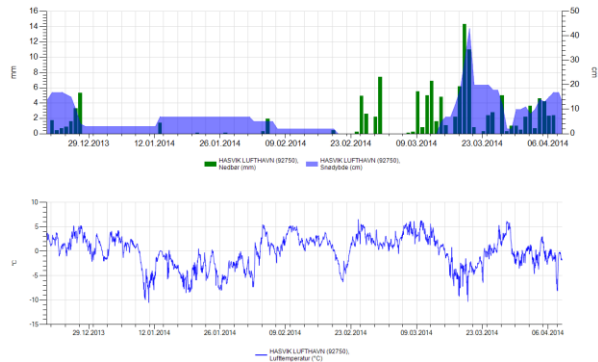

Fig. 4: Snow height in cm (blue shaded areas), precipitation in mm (green columns), and air temperature in deg C (blue line) as measured between December 20, 2013 and April 8, 2014 at Hasvik airport. (Data from http://www.senorge.no)

3. AVALANCHE HISTORY

Avalanche hazard quickly turned out to be a problem for the factory, even before the production started. During the winter of 1960 an avalanche blocked the main entrance to the mine. In 1962 an avalanche from Sundfjellet hit the living quarters, without any human injury, but causing material damage. In 1964 two major avalanches hit the factory. These avalanches caused major damage as several of the main factory installations were destroyed. Several workers were hit, and some were injured, but no lives were lost (SLF, 1964; Monsen, 2011).

When the planning process for the factory started, it became evident that none of the responsible decision makers were aware of the potential avalanche hazard. Among local fishermen, on the other hand, it was well known that the Lillebukt bay was exposed to avalanches from the mountain Nabbaren, as the sea could be covered with avalanche debris (Ramsli, 1970). The average frequency of avalanches that reached the sea was estimated at 1/10 per year (Lied, 1972).

Defence measures to protect the mining facilities from avalanches from the Nabbaren mountain, as well as from Sundfjellet, were established in the mid-1960ies (SLF, 1964) and subsequently extended in line with the further development of infrastructure. Today, there are both snow fences on top of the Nabbaren plateau, as well as snow bridges and snow rakes installed. A 8.5 m high and 168 m long concrete avalanche deflection wall protects the main factory installations. An earth dam and snow bridges protect the living quarters against rock falls and minor avalanches from Sundfjellet, while a concrete wall shields them against avalanches from the Nabbaren mountain. For many years, preplaced explosives implemented near the top of the release zone at Nabbaren were used to artificially release the avalanche as a control measure during hazardous situations. This method proved its efficiency during several occasions. In 2008/2009 the use of such preplaced explosives was, however, stopped due to the following reasons: with the open pit mine established, the placement of the explosives was no longer as effective as before. In addition, access to the area for triggering avalanches became easier. Another advantage was not having to secure the explosives during the summer season with regards to thunderstorms.

4. THE APRIL 8TH, 2014 AVALANCHE

The avalanche was released artificially on April 8, 2014, shortly before noon. It was released through the simultaneous blasting of three explosive charges. The charges, which were not preplaced (see above) were contained in boat fenders which were roped down into the release area on top of the snow surface.

The evolution of the avalanches, as well as certain of its parameters such as its velocity and the height of the powder cloud can be estimated from the abundantly available photography as well as from video footage taken by different Sibelco staff members (cf. http://www.nrk.no/nordnytt/sprengte-los-enormt-snoskred-1.11658148 to see some of the video footage).

4.1 *Volume estimations*

The explosion led to the release of the entire upper part of the release area (cf. Fig. 8), subsequently developing into a large mixed dry avalanche. The fracture line at the blasting site is at an elevation of 650 m a.s.l., but reaches down to 570 m a.s.l. on the ridge on the orographic left side. The total width of the fracture line is ca.

370 m from east to west. The stauchwall in the orographic right part of the cirque is visible on photographs taken by Sibelco staff just after the blasting. The area between the stauchwall and the fracture line is estimated to be ca. 22,000 m² with its width varying between 40-110 m. The area of the orographic left part is ca. 6,000 m², with a width of approximately 120 m.

The height of the fracture line was not measured directly after the release. Observations in the field on April 11th, together with estimation from photographs (Fig. 5) indicates its height to be approximately 2.5 m perpendicular to the surface (or around 3 m vertical) at its highest point. Average fracture line height is estimated to be between 1.5 m and 2.0 m for the part that reaches the southern gully. For the orographic left part the fracture height was difficult to estimate but it is estimated to be somewhat lower, ca. 0.7-1.0 m.

Fig. 5. Orographic right part of the fracture line. (Image credit: Sibelco Nordic)

The height of the stauchwall is estimated to be between 0.3 m and 0.6 m perpendicular to the terrain. The thickness of the snow cover was approximated to be linear from the stauchwall to the fracture line. Based on this assumption, volume calculations yield volumes between 33,000 to 44,000 m³ for the orographic right part and 4,000 to 6,000 m³ for the orographic left part. The total released volume could, thus, have been in the order of 37,000-50,000 m³.

4.2 *Velocity and powder cloud height estimations*

The orographic left part of the avalanche immediately catched great speed, flowing down through the northern gully, overtopping a beak of rock in its path and reaching the valley bottom 27 seconds after the release, ca. 800 m down along its path. The average frontal velocity of the powder cloud can be estimated to be in the order of 30 m/s. The maximal velocity in the lower part of the track is truly higher, but has not been deduced so far.

The orographic right part of the avalanche developed initially slower, due to a flatter area located just below the stauchwall, but gained speed after ca. 400 m where the path steepens again. It reaches the valley bottom 40 seconds after the release, approximately 1200 m downpath, where it conflues with the orographic left part, approximately 150 m from the avalanche deflector wall (Fig. 6). Taking these number, the average frontal velocity of the powder cloud of the orographic right part can also be estimated to ca. 30 m/s.

Fig. 6: Freeze frame taken from video footage of the April 8, 2014 avalanche. (Image credit: Sibelco Nordic)

Using freeze frames from the video footage taken from the western pier we were able to estimate vertical and lateral velocities of the powder cloud by superimposing consecutive imagery on a reference photograph (Fig. 7).

Fig. 7: Outlines (superimposed on photograph of time step 11:44:26) of the lateral front of the powder cloud during a 18 second time interval. The time presented on the photograph is the camera time. The accuracy of the camera time measurement is unknown.

The lateral velocity of the powder cloud along the impacted slope above the creek has been estimated over a period of 10 seconds and over a dis-

tance of 260 m. This yields a velocity of 26 m/s. This is the velocity after a quite sharp turn where the avalanche impacts the slope. The general steepness of the terrain along the valley floor is ca. 15 deg. The slope along the movement of the snow powder cloud front is ca. 10 deg for the first 5 seconds and approximately 15 deg the next 5 seconds.

Using the aforementioned freeze frames we were also able to estimate the height of the powder cloud of the orographic left part of the avalanche by using sight lines within a *Microstation CAD* and using the factory silo as a height reference. That way, maximal height of the powder cloud was estimated to be 120-140 m. Taking this height estimate, together with the freeze frame interpretation, we estimate the average vertical frontal speed of the powder cloud to be ca. 10 m/s over a period of 10 seconds. The steepness of the impacted slope varies between 33-50 deg.

Fig. 8 shows the outlines of the entire avalanche, the release area, an additionally observed fracture zone, and the total impacted area, i.e., including areas with traces of the passing-by of the powder cloud.

During the site visit we surveyed one profile over the avalanche debris with a Differential GPS (cf. brown line in Fig. 8). The surveyed surface was compared to a digital elevation model (DEM) complied from contourlines with 10 m equidistance. The accuracy of the elevation difference between the existing ground and the snow cover/avalanche debris is approximately ±1 m. The height of the snow cover prior to the avalanche is not known but is estimated to be ca. 3 m in the creek bed (snow bridge visible prior to the avalanche) and around 0.7 m uphill from the creek.

If we just consider the main deposition area (blue cross-hatched area in Fig. 8), the area of deposited snow encompasses roughly 80,000 m^2. Assuming an average snow height (remaining after avalanche erosion of unknown order of magnitude) of ca. 1 m, the snow cover volume can by estimated as 80,000 m^3. Note that the snow transported to the sea is not included. It is assumed to be negligible here.

Artificial cross sections drawn within CAD, comparing our GPS survey line with the natural underlying topography, indicate that the surveyed surface lies generally 2-7 m above the existing ground.
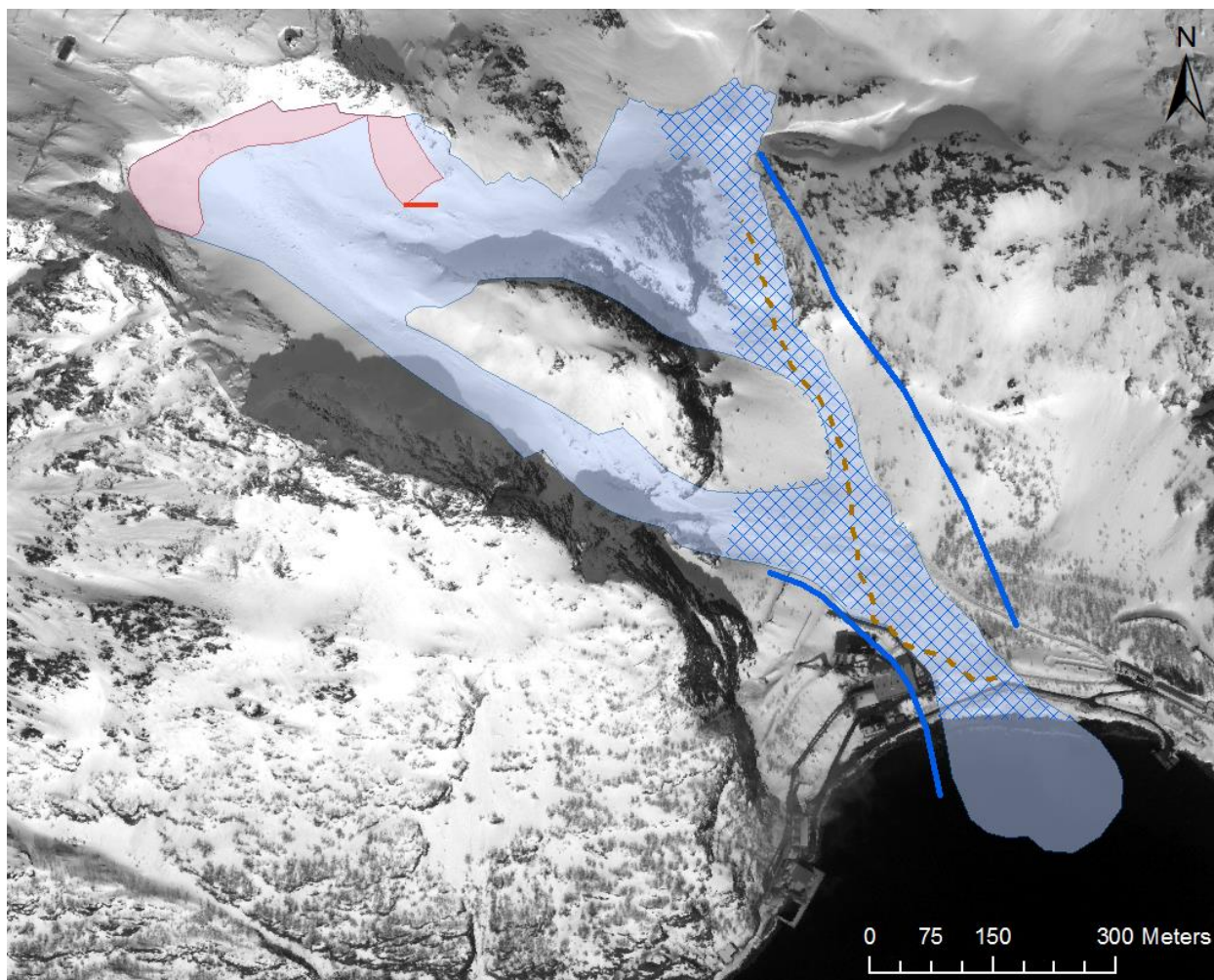
Fig. 8:   Outlines of the Nabbaren avalanche draped on a WorldView-1 image from April 17th, 2014. Pink areas = release area, red line = observed additional fracture line, light blue area = outline of the avalanche (mostly excl. powder cloud impacted areas), blue lines delineate approximate impact area of powder cloud, blue cross-hatched area = area taken for volume estimation of deposited debris, brown stippled line = GPS track. (Satellite image: Copyright © DigitalGlobe/WorldView-1)

Using this information and assuming an average thickness of the avalanche debris of ca. 2 m the total deposited volume would be in the order of 160,000 m^3. This is, of course, a very rough estimate, but more precise estimations are inhibited by the lack of more precise terrain and surveying data.

Based on these numbers, the volume of the avalanche debris is at least four times the estimated release volume, thus indicating considerable entrainment. The site visit, indeed, revealed considerable erosion, for example in the orographic left part of the avalanche.

5. MODELLING WITH RAMMS

The avalanche was simulated with the model RAMMS (Christen et al., 2010) using the above mentioned 10 m resolution DEM and assuming an initial release volume of 33,000 m^3 of snow. A new powder cloud module was applied which is discussed in Bühler et al. (2014).

The model results indicate velocities for both the core and the powder cloud of 30 m/s or more (Fig. 9a, 9b). Note that the absolute maximum velocities are not shown in the figure. Maximum core height is estimated at ca. 3 m with average core heights over larger areas between 1.5 to 2.2 m (Fig. 9c). The height of the powder cloud is estimated to ca. 100 m (Fig. 9d).
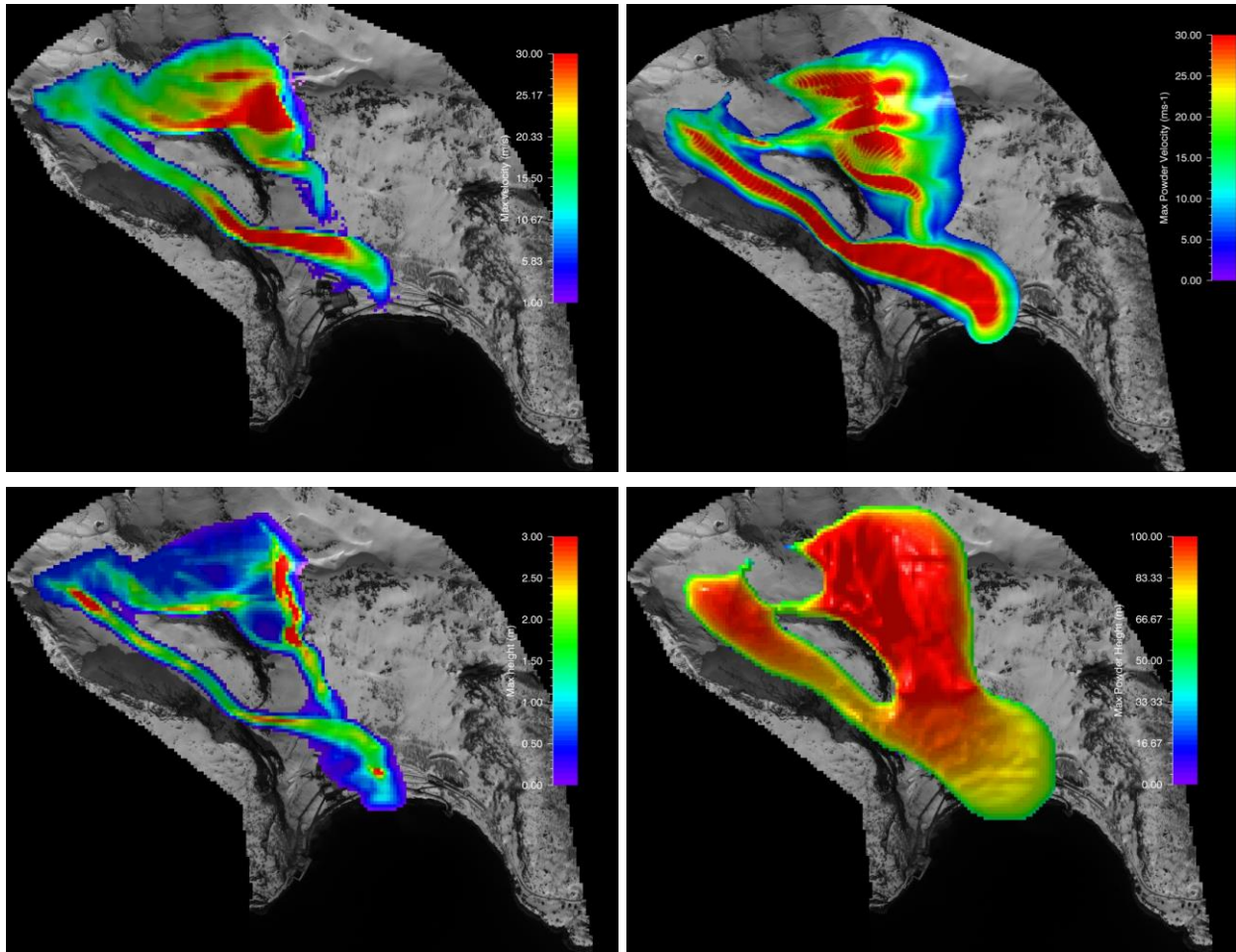
Fig. 9: RAMMS modelling results: Upper left) core velocity (m/s); upper right) powder cloud velocity (m/s); lower left) core height (m); lower right) powder cloud height (m).

According to the model, the core of the orographic right part of the avalanche reaches the valley floor prior to the core of the orographic left part. In the simulation the flow part of this arm is not reaching the sea.

This finding is in contrast to the interpretation of the field observations which seem to imply that the orographic left part of the avalanche reaches the valley floor prior to the orographic right part. However, the findings from the field observations are based on observations of the powder cloud front and not of the core. More detailed analyses of the available imagery and video footage need to be carried out in order to get an even clearer picture of the event. This will be carried out within a next phase of the study.

6. CONCLUSIONS

We presented findings and modelling results from a D4 mixed dry avalanche from Nabbaren mountain, Stjernøya, artificially triggered on April 8, 2014.

The initial release volume is estimated to be in the order of 37,000-50,000 m^3, while the depositonal volume is estimated to ca. 160,000 m^3. This indicates considerable entrainment.

Velocity and powder cloud height estimations based on photographs and video footage yield average frontal powder cloud velocities of 30 m/s and maximal heights of the powder cloud of up to 120-140 m.

Modelling results from RAMMS capture the event reasonably well, with powder cloud velocities in the same range as the numbers given above, however, with differences concerning the timing of

the two frontal parts of the avalanche. In order to further investigate this event, more scenarios with differing release and erosion volumes could be calculated.

ACKNOWLEDGEMENTS

REFERENCES

Bühler, Y., Christen, M., Dreier, L., Feistl, T. and Bartelt, P. (2014): Merging of recent developments in avalanche simulation technology into practice. *International Snow Science Workshop ISSW* 2014. Banff, Canada.

Christen, M., J. Kowalski, and P. Bartelt (2010), RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain, *Cold Regions Science and Technology*, *63*, 1 – 14.

Lied, K. 1972: Report from snow- and avalanche investigations at Norsk Nefelin, Lillebukt, Stjernøy, winter 1971/72; Rapport fra Sne- og skredundersøkelse ved Norsk Nefelin, Lillebukt, Stjernøy, Vinteren 1971/72), 21 pp. (In Norwegian)

Monsen, O. 2011: *Stars over Stjernøy; Stjerner over Stjernøy*. ISBN 978-82-303-1862-1), 92 pp. (In Norwegian)

NGI, 2012: Hazard assessment for property 58/building nr. 13 and 12; Skredfarevurdering for gnr. 58/bnr. 13 og 12. *NGI Report nr. 20120832-01-R.*, 25 pp. (In Norwegian)

SLF 1964: Suggestions for further mitigation measures in the mining area of Stjernøya (Finnmark, Norway); Vorschläge zu weiteren Sicherungsmassnahmen im Bergwerkgebiet von Stjernöy (Finnmark, Norwegen). Eidg. Inst. für Schnee und Lawinenforschung. Report G 64.29, 12 pp. (In German)