There is uncertainty if the occurrence of slush flows will increase due to warmer climate and increased precipitation, or if it will reduce since temperature increase will result in increased altitude for precipitation as snow. Regardless of this, Norway is in need of improved expertise related to more precise prediction of slush flow warnings, the run-out distance under given conditions, and the resulting forces exerted by a slush flow on structures.

The work package has three aspects:

1. Snow cover modelling to predict more precisely where and when water will come into the snow mass and thereby increase the probability for a slush flow.
2. Thorough analysis of observed slush flows to estimate the speed, flow height and pressure, which will be valuable for mapping and selection of type and design of mitigation measures.
3. Understanding of the slush flow process and mathematical modelling of slush flow run-out distance to be used in mapping projects.

Status

NGI’s earlier research in this field, including long term meteorological measurements in known...
slush flow areas in Mo i Rana, showed the following:

- Depressions and areas where water can be trapped are most prone to initiate a slush flow.
- The pore water pressure relative to the snow height is the most dominant indicator of the snow cover stability against slush flow.
- The speed of increase in water level, and the texture and structure of the snow are key factors related to release of a slush flow.
- The pore water pressure may increase quickly not only due to rain, but also due to snow melting. The required energy for melting can be supplied through warm rain, strong, warm and humid wind, and to a lesser degree from radiation from the sun.

This implies that the installation of pore water pressure sensors which measure the fluctuation in water level in areas prone to be release areas for slush flows is important. Both for R&D purposes and for slush flow warning in exposed areas. Forecasting of slush flows on a local (1-10 km²) and regional level (up to 10 000 km²) may be based on indexes which can be calculated from automatic meteorological measurement stations hooked up to pore pressure sensors.

NGI has developed an index for forecasting of slush flows (1996). In Switzerland they have developed an index which is used to forecast wet snow avalanches. A study will be made to investigate if the Swiss index can be applied to improve NGI’s index for slush flow forecasting.

Earlier research at NGI has led to a model which calculates the melting rate from an interpolation of air temperature, air moisture and wind velocity measured at a meteorological station to potential release areas hight above sea level. The model remains to be thoroughly tested and to optimize the operational procedures for slush flow forecasting.

Over the last years the development of snow cover models have provided the possibility to study in detail the snow cover texture, structure and water content based on meteorological data. The progress and development in computer science and information technology makes it possible to run simultaneous simulations and analyses for several areas. An important question is if the physical snow cover models can provide substantially more accurate melting rates than NGI’s more empirical model, and if they also can be expanded to predict the water level when the snow starts to become completely saturated.

**Visual documentation**

Only very few examples of slush flows in motion exists. The hope is that the use of present digital cameras over time will provide access to more documentation of real events. Such Picture series may be used to estimate the front speed of the slush flows in retrospect, both by field inspection and by aid of detailed topographic models and image processing software.
Dynamic run-out models for slush flows is not available. Analysis models such as the Voellmy-type RAMMS or MoT-Voellmy may possibly be applied for slush flows because these type of avalanche models were formulated by hydraulic concepts. On the other hand both the water content and snow cover texture and structure will have a significance for how the snow cover will rupture and for the run-out distance of the slush flows.

It is therefore relevant to study and backcalculate well documented slush flows with selected existing models, to see if they may be adapted to slush flows. If the results are not satisfactory, a New model concept should be worked out and developed. New research in granular materials with pore fluids, such as flood slides, will most likely be of great use.

The research efforts in slush flow should be intensified. A goal within WP3 is therefore to establish a research network within slush flows, initially based within the Scandinavian countries, Russia and Alaska. We hope that such a network may work out and conduct a comprehensive international research project. Such cooperation will enable coordinated efforts and funding of costly and resource demanding full scale tests to investigate the dynamics of slush flows.

**Deliverables**

- Analysis and calculation of front end velocity from existing Pictures of slush flow incidents in 2014.
- Establishment of snow cover model for the Fonnbu station 2014/2015.
- Memorandum of Understanding agreement between cooperation partners for slush flow research in 2015.

**Results 2014**

NGI has produced front end velocity measurements of slush flows from pictures. Work has been done to make the SNOWPACK model (developed by SLF in Switzerland) able to simulate the Development in the snow cover from meteorological measurements at the Fonnbu station.

The first step is simulation of the snow cover adhjacent to the measurement station, where the simulations can be compared with periodic manual snow cover inspections. Subsequently, the development of the snow cover will be simulated in potential release areas for slush flows, close to the research station.

See Annual report 2014 for WP3.

**Resultater 2015**

A script has been developed to automatically run SNOWPACK every hour with the latest updated data from Fonnbu. It turned out, however, that several sensors at Fonnbu can be
unreliable, leading to useless simulations. Repair of the sensors and a critical review of the data series from earlier years are required before SNOWPACK can be tested with different boundary conditions and assumptions on the atmospheric stability.

A MSc-thesis at the University of Oslo, which was started in 2015 and submitted in 2016, investigates geo-meteorological criteria for predicting the release of slushflows with data from some recent slushflows in Norway. NGI provided professional guidance for this thesis. The results are described here (Norwegian text only).

A network of slush flow researchers from around the world, Circum-Arctic Slushflow Network, with around 50 members from Norway, Sweden, Finland, Iceland, Russia, Germany, Greenland, Czech Republic, Kazakhstan, North America, and Japan, has been established at the initiative of the NGI.

Front speed measurements from the slushflow in Skarmodalen in 2010 was used to calibrate a dynamic model for snow avalanches (RAMMS:: AVALANCHE) to see whether it can be used for simulation of slushflows. The value of the parameter $\beta$ could not be determined directly because the landslide did not stop before it reached the river, but had to be less than 0.1. With $\beta = 0.05$, a value of $\gamma = 2000 \text{ m s}^{-2}$ led to the best correspondence between simulated and observed front speeds (with the highest values of around 25 m s$^{-1}$). These values are also considered physically realistic.

See Annual report 2015 for WP3.

Results 2016

In 2015, simulations of the snow cover at Fonnbu with SNOWPACK indicated problems with several sensors over the years. Therefore, data from eight winters were checked thoroughly and erratic data were removed. For more details see the report "Review of meteorological data from Fonnbu 2009–2016".

The topic of a MSc-thesis at the University of Oslo was to examine how well the development of the snow cover in the Norwegian mountains can be simulated with the SNOWPACK software, by comparing simulations with data from Fonnbu and Finse, with snow profiles taken right next to these two measurement locations. The main findings are that a usable simulation is possible at these two sites if (i) there are reliable input data (in particular of precipitation or snow height) and (ii), the Monin–Obukhov formula for atmospherical stability is used. The model predicts, however, too rapid melting in the last phase of the snow season.

Can a snow pack model such as SNOWPACK, be used operationally for daily avalanche and slush flow forecasts at the local and regional levels? Such models require reliable input data of more variables than what most meteorological stations in Norway can supply. The following
parameters should be measured and supplied at least once per hour:

- air temperature
- relative humidity
- wind speed
- precipitation or snow depth
- incoming or reflected short-wave radiation
- incoming long-wave radiation or temperature of the snow surface
- if available, SNOWPACK can also use the ground temperature.

The report "Weather stations in Norway suitable for SNOWPACK modelling in Norway in 2016" evaluates more than 3500 meteorological stations in Norway with data available to the public. Only 11 stations on mainland Norway and two on Jan Mayen and Svalbard meet the requirements. Moreover, some of the stations are no longer in operation. This means that, at present, one can use an advanced snowpack model for operational avalanche forecasting in Norway only at the local level and if a measurement station with the required sensors is set up in the vicinity of the area of interest.

Under the International Snow Science Workshop 2016 in Breckenridge, Colorado, a first meeting of the Circum-Arctic Slushow Network (CASN) was held with about 20 participants. The main purpose of the successful meeting was that the participants were to introduce their slushow-related projects to each other. In the course of 2016 the CASN-website was established.

See Annual report 2016 for WP3.

/ CONTACTS

Christian Jaedicke
Position | Technical Lead Avalanches
Avalanches and Rockslides
E | christian.jaedicke@ngi.no
M | +47 959 92 282