The upgraded full-scale avalanche test-site Ryggfonn, Norway

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ABSTRACT. Measurements of full-scale avalanches are expensive and time consuming, but are indispensable to gain in-depth understanding of the flow behavior of avalanches. They are needed to crosscheck the scaling used in small-scale experiments and also form the basis for developing and calibrating numerical models.

The recent partial upgrade of NGI's Ryggfonn test-site is focused on the processes occurring during interaction between avalanches and a catching dam in the runout zone. These processes are crucial for the efficiency of this type of avalanche mitigation measure, which has been the focus of several small-scale experiments in recent years. But qualitatively and quantitatively good observations from real avalanches for a cross-comparison are rare. Therefore, two new masts were constructed at Ryggfonn. One is located about 10 m upstream of the foot of a catching dam and has a height of 15 m. The other stands on the crown of the dam and is 6 m high. In this way, we also hope to complement the SLF full-scale tests at the Vallée de la Sionne test-site.

Instrumentation on the new masts consists of load-cells and LED-velocity sensors, each type with a vertical spacing of 0.5 m. In addition, flow-height switches are placed with 0.25 m vertical spacing. Thus, the instrumentation is quite similar to the instrumentation used in Vallée de la Sionne, which will hopefully allow better cross-comparison of measurements.

We present the upgraded set-up and show preliminary results from the first measurements.

1 INTRODUCTION

Starting with a quote by Mellor (1968): *"It seems necessary to preface a discussion of avalanche dynamics with a statement of the need for improved observational data, for a sound understanding of the relevant physical phenomena is a vital prerequisite for analysis. If a theoretical study is based upon unrealistic assumptions the results could well be deceiving, no matter how elegant the analytical manipulation may be."* This was in 1968, How far have we come since then?

Definitely, the amount of qualitative and quantitative observations has increased. For example, Schaerer (1975) who provided an analysis of velocity observations from Rogers Pass, British Columbia, Canada, or his and Salway's observations of flow behavior and impact pressures (Schaerer and Salway, 1980). Later, McClung and Schaerer (1985) supplemented those observations. Mears (1980) shared some qualitative and semi quantitative observations on avalanche flow like flow height estimates and granulometry. Also Bartelt and McArdell (2009) contributed with granulometric investigation of avalanche deposits. Sovilla et al. (2001) made studies on the mass balance of avalanches, an important but long time disregarded topic in avalanche dynamics. Kotlyakov et al. (1977) described velocity observations and impact pressure measurements at an avalanche test-site in the Khibins, Kola Peninsula, Russia. Bakkehøi et al. (1983) presented velocity observations from Ryggfonn, Norway. Salm and Gubler (1985) provided then velocity measurements along an entire avalanche descent using a Doppler radar. Recently, Gauer et al. (2007) analyzed pulsed Doppler radar measurements from several avalanches at three different sites. A weakness of those (early) observations and measurements is that they mainly focus on one specific aspect of the avalanche flow or on one specific location and so only provide a limited picture of the avalanche flow. During

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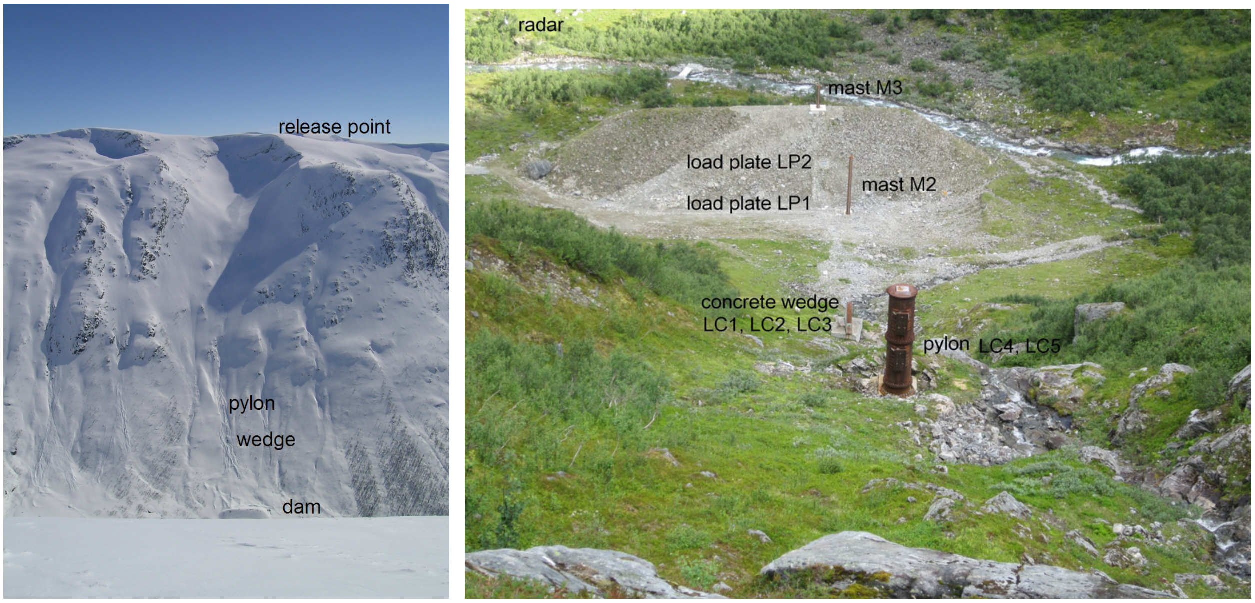


Figure 1: Overview of the Ryggfonn test-site.

the 1980's the Norwegian Geotechnical Institute (NGI) established Ryggfonn as full-scale avalanche test-site building catching dam and various obstacles and measurement devices into the avalanche track (Norem et al., 1985) to obtain a more comprehensive picture of the flowing avalanche. Also in Japan (Nishimura et al., 1989) and France (see Naaim et al., 2001), researcher used full-scale test-sites for their avalanche research. In the 1990's, Switzerland followed with the Vallée de la Sionne test-site (Ammann, 1999; Sovilla et al., 2008; Kern et al., 2009). An overview of the (European) avalanche test-sites can be found in Issler (1999), or an updated version of it in Barbolini and Issler (2006).

At the same time, researchers used small-scale and chute experiments to investigate specific topics of the avalanche motion, for example Lang and Dent (1983), who focused on the basal surface-layer properties in flowing snow. Nishimura and Maeno (1987, 1989) used a small chute in a cold-lab for investigations on mixed-phase snow flows. Beghin et al. (1981), Bozhinskiy and Sukhanov (1998), Turnbull and McElwaine (2008), and Keller (1995) did physical modeling to assay the flow of powder snow avalanches.

More recently, Dent et al. (1998), Kern et al. (2004), and Rognon et al. (2007) investigated the velocity profiles in chute flows. In recent years, small-scale experiments using granular material were used to investigate the interaction between catching-dams or braking mounds and avalanche flow (Hákonardóttir et al., 2003b; Faug et al., 2007; Pudasaini and Kroener, 2008) to test their efficiency.

This is only a brief overview (and by no means complete) of measurements and observations on avalanche dynamics since Mellor made his quote in 1968.

2 INSTRUMENTATION

As mentioned above, NGI has been running full-scale avalanche experiments at the Ryggfonn test-site in western Norway for more than 30 years. In 1981, a 16 m high catching dam was built in the runout area. The crown length of this earth wall is about 75 m and its slope angle is between 35° and 40°. This dam is a unique feature of this test-site.

The upper half of the north-faced track is a small hanging valley with a bowl-shaped main starting zone at the upper end. The total vertical drop height is about 900 m and the horizontal runout distances typically range between 1500 and 1850 m.

Recently, NGI invested in two new measurement masts, one shortly before (M2) and one on top of the catching dam (M3). The aim is to study the interaction of avalanches with those kinds of mitigation measures. The height of the masts are 15 m and 6 m, respectively.

Figure 1 provides an overview of the whole avalanche track and of the sensor area in the lower part of the track.

2.1 Velocity measurements

As all dynamical avalanche models solve the (depth averaged) momentum or velocity equation(s), respectively, velocity measurements along the path and/or at selected locations are most import for validating those models.

2.1.1 Doppler-Radar

Doppler-radar proved to be a valuable device for non-intrusive velocity measurements (Gubler, 1987; Rammer et al., 1998; Gauer et al., 2007). Velocity measurements have been obtained both for selected locations and for stretches along the avalanche track. At Ryggfonn, a 5.8 GHz pulsed Doppler radar are at our disposal during artificial releases, which allows velocity measurements of the dense or fluidized part of the avalanche covering a wide stretch of the track.

2.1.2 Optical velocity sensors

In addition, there are now over 40 LED-optical velocity sensors (Dent et al., 1998; Kern et al., 2009; Nishimura et al., 1993) placed vertically along the two new masts. The vertical distance between the sensors is 0.5 m. The main aim of those sensors is to obtain information on the vertical velocity profile of the avalanche flow. The principle of optical velocity sensors is based on the cross-correlation of the measured light-reflectivity patterns of the passing avalanche flow at two points A and B placed flow-wise at a know distances (Kern et al., 2009; McElwaine and Tiefenbacher, 2003). As far as possible (the main restriction is the data acquisition system) three reflectivity-sensors A, B, and C are used at each location allowing for redundant cross-correlations (see Fig. 2). The sampling rate is planned to be at 45 kHz at the moment.

2.2 Pressure measurements

The instrumentation of the test-site includes five large load cells and new 40 piezo-electric load cells at four locations along the lower part of the track for impact pressure measurements. Each large load cell has an area of 1.2×0.6 m^2 (height×width) and a maximum load capacity of 833 kPa. Three load cells (LC3-LC1) are mounted on a concrete wedge at a distance of 219 m up-slope from the catching dam. Another 101 m uphill, two load cells (LC5, LC4) are mounted on a steel tower. In addition to those load cells, a geophone is placed inside the pylon, whose signal serves as a triggering device for starting all measurements. The width of the concrete wedge equals the width of the load cells (0.6 m) and the load cells are mounted such that vertical heights of the respective midpoint are approximately 0.5 m (LC3), 1.5 m (LC2), and 2.5 m (LC1) above ground.

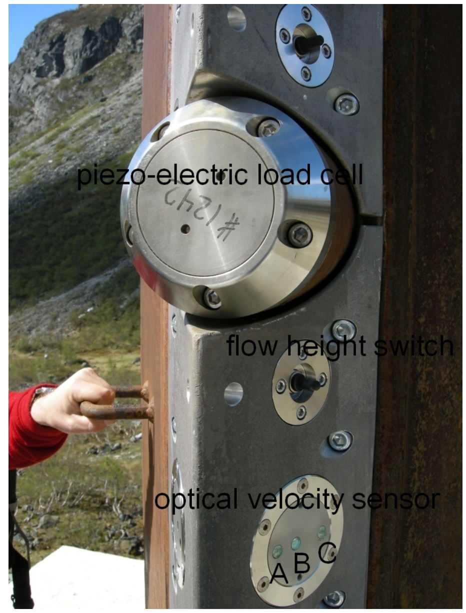


Figure 2: Instrumentation of mast M3 (similar at mast M2).

The 40 piezo-electric load cells are placed vertically with a spacing of 0.5 m at two masts M2 and M3. The sensor area of each sensor is 0.0064 m^{-2} (Ø = 0.09 m). The scope of the piezo-electric sensors is to obtain a vertical pressure distribution and, when combined with the velocity profile, to obtain information on the flow density. Simultaneously, a pressure distribution provides information on the flow height of the avalanche, which is thought to be a major factor in dimensioning of catching dams.

2.3 Flow height

The flow height switches provide redundant measurements for the flow height of the dense part (see Fig. 2). The spacing of these simple switches is 0.25 m and the sampling rate is 1 kHz. Flow height is also an important parameter in depth averaged models.

2.4 Load plates

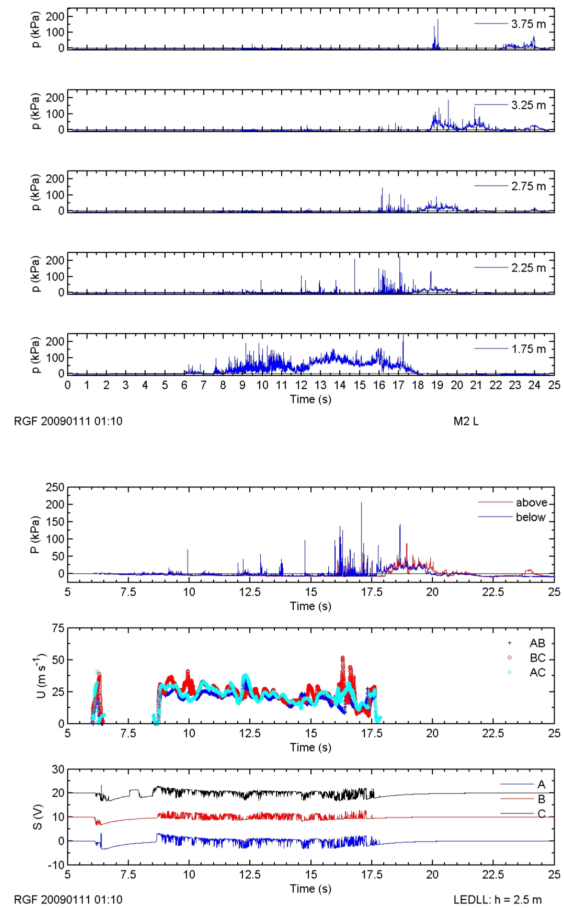
In the uphill side of the dam, two 1×1 m^2 large load plates are placed at vertical distances of 2 and 8 m above the dam base. The plates measure the three stress components: (z) normal to the slope, (x) shear pointing towards the dam crown and (y) shear pointing at a right angle.

2.5 Instrumentation hut

In addition, a new instrument hut was built to house the central computer and to facilitate work at the test-site. There is a connection to the internet across fibre cable enabling remote access to the system. This allows us to download measurement data remotely after a spontaneous avalanche event.

3 OBSERVATIONS AND MEASUREMENTS

The new masts were installed in the period from November 2008 – August 2009. Since then no artificial avalanche release was performed. However, first experience with the system could be gained from two natural releases. The first avalanche occurred January 11, 2009. During this time only a reduced set of sensors was installed at mast M2 and no sensors at M3. The avalanche supposedly overtopped the catching dam by several 10 m; a timely field observation was prevented by enduring bad weather conditions. Timing of the impact pressure measurements suggest that the avalanche velocity was around 40 m s^{-1} as it entered the sensor area below the pylon. The timing between the concrete wedge and mast M2 suggest that the velocity only slightly decreased over this stretch; however, further data evaluation in needed. Figure 3 shows an example of pressure measurements and of raw data from the LED-sensors including a first evaluation of the corresponding velocities at mast M2. In this case it was possible to use cross-correlations of all three LED-elements. The obtained velocities are in accordance with the estimates based on the timing and the observation that the avalanche overtopped the dam by a distance (cf. Gauer et al., 2009). The pressure measurements imply that the dense core of the avalanche was less than 2 m in height (comparing sensors at 1.75 m and 2.25 m). Interesting is the temporal evaluation of the pressure at different heights suggesting that a part of the avalanche started to deposit while it was overflown by following parts. There is a sudden reduction of the LED- signals. The reason for this is not clear; if it was caused by bad reflectivity of the by passing snow or if, as suggested above, the lower part of the avalanche more less stopped ($U \approx 0$). In this case, the continuing considerable pressure measured at h = 1.75 m and 2.25 m might be related to that what Sovilla et al. (2010) calls slow-drag, i.e., a kind of passive "earth pressure". However, we can't be conclusive at this point.



a)

b)

Figure 3: Avalanche 20090111 01:10: a) Measured impact pressure vs time at various heights; b) velocity data at 2.5 m above ground, in addition are the raw data of the pressure measurements at 2.25 m and 2.75 m as well as the raw data of the led-sensors shown.

A second naturally released avalanche was measured mid March 2010. The timing between different sensor implies a velocity of (35–40) m s^{-1} between the pylon and concrete wedge, but a more pronounced velocity decrease between the concrete wedge and mast M2 with a mean of about 20 m s^{-1}.

Figure 4 presents impact pressure measurements from mast M2. As in the first case, the measured pressure values are considerable. There is some noise or slight drift, respectively, obvious at some of the higher sensors. Measurements from mast M3 (not shown here) imply that also this avalanche topped the dam and slight overflowed it. Also in this case the pressure and flow height measurements at mast M2 indicate that the flow height of the denser part was less than 2 m. The evaluation of the velocity and pressure

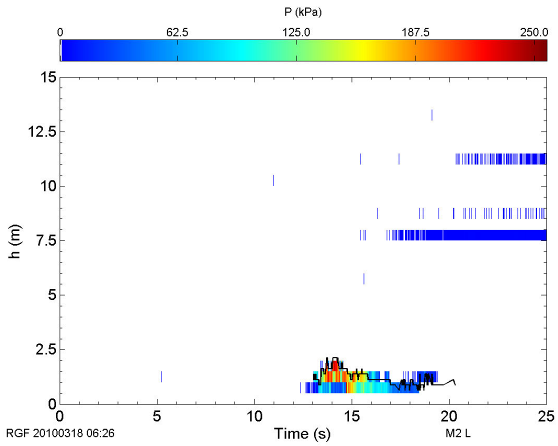


Figure 4: Avalanche 20100318 06:26: a) Measured impact pressure, P (in kPa) vs time and height above ground; black line shows the corresponding measurements of the flow height switches.

measurements are still ongoing.

4 CONCLUSIONS

Full-scale avalanche tests are costly and difficult to perform and not always successful, so why bother? As mentioned above, over the years, small-scale laboratory experiments using granular materials have been carried out to investigate, for example, the dynamics of avalanche dam interactions with respect to the efficiency of dams as a mitigation measure. However, it is still not proven how closely those granular laboratory flows actually resemble full-scale avalanches (Faug et al., 2008). This holds also true for those chute experiments on velocity-profile measurements. Therefore field observation and especially those full-scale tests under “relatively” controlled conditions are necessary for comparison.

Especially the new generation of 2-D dense-flow (Christen et al., 2010; Naaim et al., 2002) and coupled dense-flow/powder snow avalanche models (Sampl and Granig, 2009) require a detailed validation. These models calculated the avalanche flow in a three dimensional terrain and so seemingly relieve the practitioner from defining the way of the avalanche flow. This increases the degree of freedom in those models. Up to now, the experienced practitioner was able to adapt the avalanche profile based on his knowledge and refine the choice of parameters based on expert knowledge (or statistics). Due to the more complex interaction in a three-dimensional terrain this freedom of a practitioner is limited and the numerical models need an improved physically-based basis. For example, underestimation of velocity within the track (to which some of the models seem to tend at present) is critical, as inertia determines the probability that the avalanche flow leaves the common track. The correct assessment of the velocity is also important for the design of mitigation measures along the track and for the separation of hazard zones.

Therefore, full-scale avalanche tests are still required to gain in-depth understanding of the physics of flowing avalanches and to serve as reference for small-scale granular as well as for snow chute experiments. Cross-comparison between different avalanche paths (test-sites) is necessary to uncover scaling relations (e.g. Gauer et al., 2010). Still, the instrumentation at the test-sites is limited and the harsh condition within an avalanche make measurements a difficult task. Hence, the combination of different measurements and observation is desirable to gain a comprehensive and consistent picture the avalanche flow. The complexity and variety of avalanche motion, therefore, requires a combination small-scale experiments (detailed investigations, statistics), large-scale tests (detailed investigation), and field observations (diversity, statistics). We invite the various research groups to participate in this afford.

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