NGI

Ryggfonn - Options for Reconstruction of the Test Site

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Summary

Options for reconstructing NGI's full-scale avalanche test site at Ryggfonn are discussed for different assumed levels of funding. If full funding can be obtained, it is recommended that the proposal for the equipment of a European avalanche test site as elaborated by the SAME project be realized. For lower funding levels, the optimum equipment depends strongly on the specific avalanche-dynamics problems that the experiments shall address. The choice of those questions depends in turn on the practical problems for which tools are to be developed. A pressure-sensor based, inexpensive method for measuring density and velocity inside a powder-snow avalanche is suggested, and the quantities to be measured for investigating avalanche impact on the dam are derived. Only general concepts are presented at this stage, and substantially more detailed feasibility studies will be needed before decisions are made.

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APPENDICES

Review and reference document

1 SCOPE OF REPORT

NGI's full-scale avalanche test site at Ryggfonn (Kvisterøy, 1983; Lied, 1984) has been in operation since 1982. Since then, it has produced a wealth of data on avalanche velocities and pressures (Kristensen, 1996, 1997, 2001; Rammer et al. 1998) that were of immediate practical use, e.g., in the dimensioning of masts for power lines or of catching dams. Furthermore, the measurements were used for testing the dynamical models of avalanche movement available or under development in the 1980s (see, e.g., (Norem et al., 1987, 1989)).

Due to avalanches that exceeded the design assumptions, the tubular steel mast in the avalanche track and the mast on the catching dam had to be rebuilt several times. An extraordinarily large avalanche in February 2000 again destroyed these instrument supports and, in addition, the concrete pressure-plate support somewhat below the tubular mast. In the fall of 2000, the concrete pressure-plate support could be reconstructed and equipped in its original form. Thus at present, only a limited number of sensors are operational.

It is widely felt, within NGI and outside, that the Ryggfonn site is still vital for solving pressing practical problems of avalanche dynamics in a scientific way. This situation raises the question whether the former equipment should simply be rebuilt, or upgraded and modernized, or new instrumentation better matched to modelers' needs in the foreseeable future should be devised and installed. The present report outlines reconstruction options differing in their costs and in their focus. Much of this report is based on the author's experience gained in the planning of the Vallée de la Sionne test site in Switzerland and the first measurement campaigns there. A general set-up of an avalanche test site is schematically represented in Figure 1.

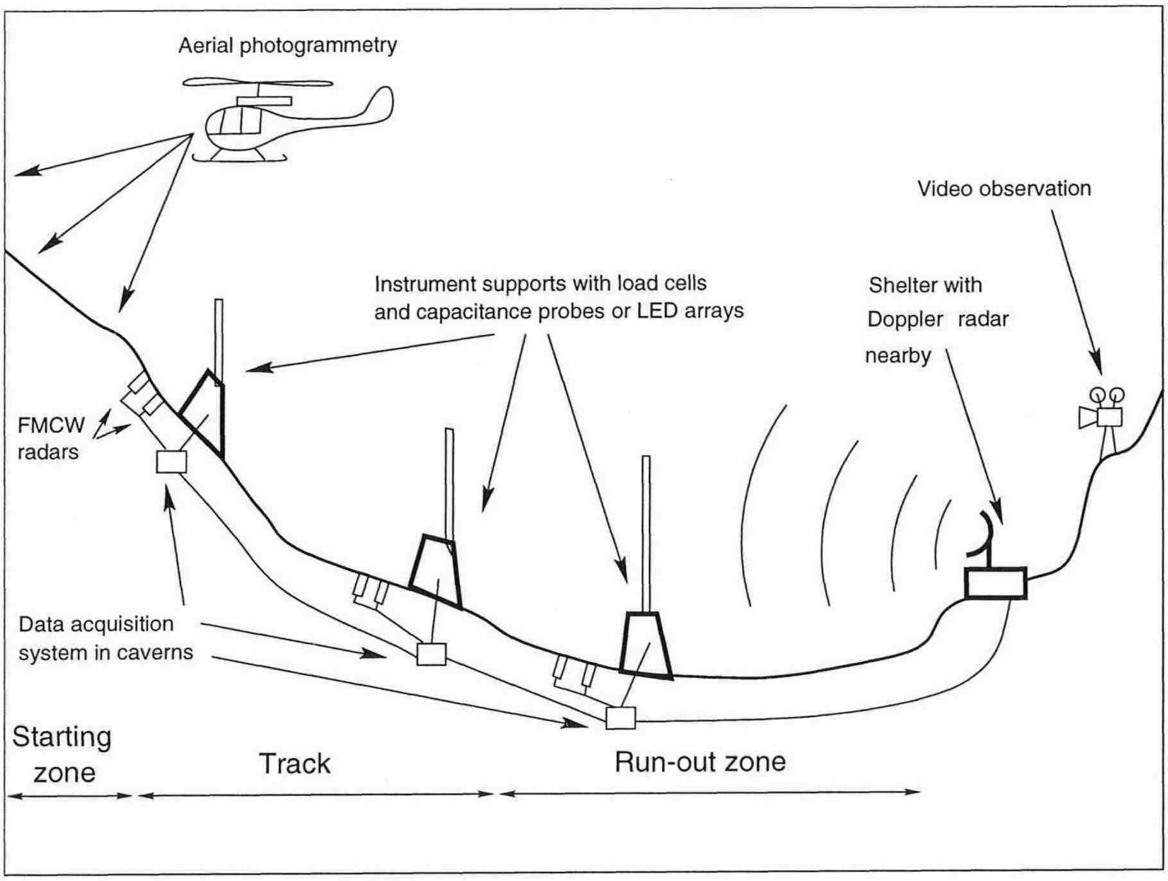

Figure 1. Schematic view of the set-up of a large experimental site with 3 instrument support structures in different sectors of the path and a shelter at the foot of the opposite slope. From Harbitz and Issler (1998)

2 DATA THAT CAN BE OBTAINED WITHOUT FURTHER INVESTMENTS

Reconstruction of the Ryggfonn test site beyond the concrete structure with its three load plates is not likely to be completed before the fall of 2001. The question therefore arises whether it is it worth conducting measurement campaigns at Ryggfonn as long as the site is only partially reconstructed. The following data can be obtained from available equipment or procedures:

- *Release statistics*
  Some information on the probability of artificial release that can possibly be used to improve estimation methods for recurrence periods.
- *Video tapings of artificial avalanche releases*
  - Front velocity

  - Trajectory (sidewise spreading of powder-snow cloud, etc.)
  - Height and shape of powder-snow cloud (requires multiple video cameras and an observation point to the side of the avalanche track, if at all possible)
  - Extent of deposits, run-out distance

- *Impact loads on three load plates in the track*

- *Doppler radar measurements* by the AIATR group
  - Front/characteristic velocities in lower track and run-out
  - Velocity spectra
  - Differential velocity of dense-flow and powder-snow parts

- *Manual surveys* after avalanche release (if the slope is safe!)
  - Fracture depths along fracture line, maybe release area
  - Deposit distribution near dam
  - Depth and density of deposits, approximate global mass balance
  - Local mass balance at several places under favorable conditions (eroded new snow, deposited snow masses)

Main difficulties and drawbacks:

- Effort for measurement campaigns is substantial.
- Large survey area restricts possibility of complete observations.
- The AIATR radar group must arrive in time. Finding an optimal yet safe observation point for the radar team is extremely difficult.
- Video taping requires good weather.

Such measurement campaigns do not add any new type of data beyond what has already been collected at Ryggfonn or other test sites. Due to the limited number of variables measured, it is very unlikely that significant new insight into the dynamics of avalanches is gained, but the measurements would add to the database available for model testing. It is important, however, that the dense-flow avalanche velocity be measured along the path; due to the usually forming powder-snow cloud, this can in practice only be done by using radar. Full testing of the presently available models like Voellmy-Salm or NIS would require that the flow depth be also measured. This is not possible without additional sensors, however.

Assessment: If the weather is good and the Austrian radar is available, some information useful for the calibration of simple models (1D, 2D, few parameters) can be obtained. *Under these conditions, a measurement campaign is recommended.*

3 MEASUREMENT OPPORTUNITIES AFTER SMALL INVESTMENTS (200-300 KNOK)

Recent cost estimates have shown that reconstructing the tubular tower will be very expensive, exceeding the funding level assumed in this section. The steel mast on the dam is bent but still functional and needs to be instrumented. As better knowledge of the initial conditions by means of aerial photogrammetry is essential for model validation, installation of permanent marker plates at the periphery of the path is proposed at this funding level.

- *Marker posts for photogrammetry* (approx. 50 kNOK)
  - ➢ Global mass balance from photogrammetry and field survey. (Beware of the high costs per campaign for helicopter and photogrammetric analysis!)
- *Equipping instrument tower on dam* with several absolute-pressure and stagnation-pressure sensors (approx. 100–150 kNOK)
  - ➢ Pressure profile in powder-snow cloud
  - ➢ Estimate of velocity in powder-snow cloud
  - ➢ Possibly estimate of density in powder-snow cloud

Important note: All cost estimates only give orders-of-magnitude! Planning costs have not been included.

Aerial photogrammetry of snow presents a number of additional difficulties over those encountered on higher-contrast surfaces. Illumination of the slope, visibility and appropriate placing of the marker plates, wind conditions for flights near crests, the quality and format of the camera, and certainly the analysis techniques are among the most important practical issues. Experience at Vallée de la Sionne as well as comparative measurements at the Gaudergrat near Davos have, however, demonstrated the feasibility of the method. While the scatter of the measured snow depths about the true value is fairly large, average snow depths are usually obtained within the precision requirements of model calibrations and tests. Alternative techniques like laser scanning from an aircraft equipped with a GPS are becoming competitive now, but at present it might still be easier to use aerial photogrammetry.

However, as the aspect of the avalanche path is NNW, there is very little direct light on the snow surface during the winter at these latitudes. <u>It is recommended to conduct tests before installing the plates and setting up the analysis system</u>.

Very little data exists on the pressures, densities and velocities within the powder-snow cloud. It would therefore be very valuable to obtain such measurements from both the track and the run-out zone at Ryggfonn. This may in principle be accomplished at the tubular mast or the concrete structure, and on the dam. However, at the latter location, the flow is strongly influenced by the dam and data interpretation will be complicated. Velocity measurements can be effected in principle by the Ka-band radar that is part of AIATR's equipment, but it is unknown so far how sensitive those measurements are to large particles in the dense-flow and saltation layers. It is therefore advisable to apply complementary techniques in parallel with the radar. Density measurements would be best obtained from capacitance sensors, but at approximately 25 kNOK per sensor their cost exceeds the assumed funding level.

Combining measurements of the dynamical and quasi-static pressure at different heights, both the density and velocity in the suspension layer should be measurable with relatively inexpensive equipment. The basic principles and a possible setup are outlined in Appendix A. In essence, one measures both the quasi-static and the dynamic pressure in the avalanche at several heights at the same location. One can then infer the density of the snow-air mixture from the increase in quasi-static pressure, and the velocity from the dynamic pressure and the density. As mentioned in Appendix A, a number of tests should be run before installing equipment in Ryggfonn: The sensor surface must be designed to minimize dependence on the (variable) flow direction and build-up of "snow caps" on the sensor. Experience with similar devices used by AIATR in Innsbruck (L. Rammer) and ILTS in Sapporo (K. Nishimura) might be relevant for the final design.

Main difficulties and drawbacks:

- Photogrammetry is only possible if the weather is good and a helicopter is available. In addition, field survey must be possible for obtaining density measurements from the starting to the deposit zone so that the release mass can be calculated from the release volume.
- Photogrammetry might easily cost 50 kNOK per campaign!
- Complementary pressure, velocity or density measurements in the track are too expensive.
- The instrument tower on the dam remains exposed to dense flow avalanches going over the dam.
- Disturbance of the flow by the dam makes data from the instrument tower on the dam hard to interpret.
- No direct information on internal processes in dense-flow avalanches, entrainment dynamics, and interaction with the dam is obtained.

Assessment: In this way, one obtains significantly more data for a moderate investment, but the data will NOT bring about any break-through in the most pressing questions. Some of the data will be quite useful in the validation of powder-snow avalanche models, though.

4 OPTIONS AT MODERATELY LARGE INVESTMENT (1 MNOK)

Even with the considerable sum of 1 million NOK, it is not possible to install the full equipment recommended for a European avalanche test site in deliverable D6 of SAME (Harbitz and Issler, 1998). The question thus is, Which type(s) of sensor system give(s) the most useful information on the most pressing problems? Among a variety of options, a few of particular interest will be discussed below.

With all these options, the data rates and the number of data channels will be much higher than so far, between 30,000 and 300,000 measurements per second. An important point is whether the existing data acquisition system and the electric power supply in the track will be able to cope with the higher data rates and larger number of sensors. If not, the present centralized data acquisition system with analog cables to the instrument hut may have to be expanded to a distributed one. In such a system, data loggers or computers digitize the analog signals near the sensors, store them locally and send them to the measurement hut after the event. As at Vallée de la Sionne, this would require building an underground power line (230 V) to the measurement locations. Such a system will be very expensive, using up half of the assumed budget or more (the system at Vallée de la Sionne cost around 700 kNOK). However, recent developments in high-data-rate network devices hold promise of a low-power-consumption system transmitting the data virtually in real time, which might be less costly. A considerably more detailed study involving the instrumentation group will be needed to find the optimum system and provide reliable cost estimates.

a) Focus on pressure measurements

One obvious possibility is to reconstruct the tubular tower and equip it with load cells and/or density sensors instead of the previously used strain gauges in the hull. Its height should be increased to at least 10 m if possible, in order to obtain measurements from the lower parts of the powder-snow cloud as well. The load cells should be mounted at heights of 1, 2, 3, 4, 5, and 6 m on cylindrical or conical shafts protruding approximately 1 m upstream of the mast for them to be outside the mast's backfill. At heights of 7, 8.5 and 10 m, a similar measurement system as on the mast on top of the dam should be installed (see also Appendix A). The size of the load cells should be chosen to optimize the detection of particle impacts so that quantities of interest in granular-flow models can be measured. The development of the relevant analysis methods has just started (Schaer and Issler, 2001) and dedicated tests appear to be necessary before well-founded recommendations can be made. In the mechanical design of the structure, care should be taken to minimize and damp vibrations because pressure sampling rates of 2–5 kHz are required by this method.

The cost of reconstructing the tubular tower has been estimated at 400 kNOK by StatNett. Depending on the chosen size, the load cells will cost from 20 to 30 kNOK per piece, including the shafts mentioned above. Including the pressure gauges for the powder-snow cloud, the price of the proposed instrumentation amounts to about 250–400 kNOK. If no extensions of the data acquisition system are needed, some supplementary sensors could be installed within the budget limitations. Prime candidates are an array of mechanical switches for measuring the flow height or load plates mounted flush with the ground for measuring normal and tangential loads.

Such a system would allow the following flow quantities to be obtained at a single location:

- Pressure profile at the bottom of the powder-snow cloud
- Pressure profile in the dense-flow and saltation layers
- Estimate of the velocity in the powder-snow cloud in the track
- Possible estimate of the density in the powder-snow cloud in the track

An interesting alternative is to build a slender yet sufficiently strong and stiff structure on the reconstructed concrete instrument support so that the tubular mast would no longer be necessary and the total cost could be reduced. A critical issue will be the vibrations of such a structure, which could make pressure measurements above 5 m unusable. Experience from Vallée de la Sionne suggests that this may be a serious problem, and further study is required.

b) Focus on velocities, densities and flow regime

Vertical profiles of longitudinal velocity and (if possible) of density are very important for understanding the internal dynamics of avalanches. Since these profiles may change along the path and in time, they should be recorded with sufficient spatial resolution at several points, at least from the tubular tower downhill. The assumed budget allows either reconstruction of the tubular tower, or a new system for velocity profile measurements, but not both. Below, different methods for measuring velocity profiles are compared.

In fast and large avalanches, probably only two methods are currently capable of measuring such profiles. The first uses correlations from a pair of FMCW radars looking through the snow from the ground (Gubler and Hiller, 1984). The second correlates the signals from vertical arrays of horizontally displaced pairs of sensors like light-emitting diodes (LEDs) (Nishimura et al., 1993; Dent et al., 1998) or capacitance probes (Louge et al., 1997). Both techniques have been shown to work under favorable conditions, but data analysis is not trivial. Thus, development of suitable data analysis tools has to be included in the cost estimate.

Pairs of FMCW radars:

\+ Measurement of flow depth in parallel with velocity profiles
\+ Obtain distribution of vertical velocities by alternating between Doppler and frequency-modulation modes (important quantity for granular flow models).
\+ Entrainment/deposition rates directly measured.
\- Multiple reflections may mask upper surface of the dense flow and make cross-correlation of signals difficult.
\- In wet-snow avalanches, signal absorption may be too strong for seeing the upper layers of the flow.
\- Expensive (approx. 150–250 kNOK per radar).

Slope-perpendicular arrays of capacitance probes:

+ Only proven method for density measurements.
+ Cross-correlation between two arrays spaced in flow direction produces velocity profiles.
+ System tests advisable before final decision.

Precision of flow-depth estimation depends on vertical sensor spacing.

- Need instrument support structure exposed to avalanches.
- Expensive (approx. 20–25 kNOK per sensor, need 12–20 sensors per location).

Slope-perpendicular arrays of pairs of LED sensors:

+ Velocity profiles by cross-correlation over relatively small distances (less critical than with radars)
+ Inexpensive hardware.
± Precision of flow-depth estimation depends on vertical sensor spacing.
- Need instrument support structure exposed to avalanches.
- Neither density nor vertical velocities measured.

Both the capacitance probes and the LEDs are ideally mounted on the side of a slim yet strong support structure about 5 m high that disturbs the flow as little as possible. Mounting them on the side of the tubular mast may give distorted results. The cost of such support structures is assumed in the range of 100–200 kNOK per object.

In order to get at least some information on the interaction of the avalanche with the dam, one location should be chosen 20–50 m upstream of the dam (see also Paragraph c) below). Another preferred location is a few meters upstream of the concrete support structure on which pressure measurements are made. It may be quite difficult to find a suitable location due to the particular topographical structure of the gully. The upstream structure must not "shadow" the one downstream and the avalanche flow has to be (nearly) the same at the two measurement locations; otherwise, the data cannot be compared and combined.

For the validation of relatively simple models, LED sensor arrays with many sensor pairs for good flow-depth resolution at several locations appear to be suited best. The dimensioning of the devices needs to be optimized for the large and fast avalanches typical of the Ryggfonn path. A few capacitance sensors might be used to obtain density values for practical use.

For developing and testing granular models, capacitance probes or radars are preferred, but only two locations can be instrumented with the assumed budget. The decision for one or the other method is difficult because they are complementary. With a 50% larger budget, either a third location could be instrumented or two locations could be equipped with paired capacitance-probe arrays and a single radar each (probably better than single capacitance-probe arrays and radar pairs).

c) Focus on entrainment

Some aspects of this complex problem have been discussed in a project proposal by Barbolini et al. (1998). Due to severe budget and time constraints, maximum use was made of laboratory-scale experiments (Weissfluhjoch chute) and measurements at a small test site (Monte Pizzac) in that proposal. Entrainment-rate data from FMCW radars at a large site (Vallée de la Sionne) would have been used mainly to validate the models.

The focus on small-scale experiments still appears justified, thus extension of the Ryggfonn equipment with a view towards entrainment studies should be contingent upon an accompanying project that includes detailed laboratory experiments. In the present context more thought has, however, to be given to extracting the maximum amount of information from large-scale experiments at Ryggfonn.

It is unknown at present, which among several conceivable entrainment mechanisms dominates in a given situation. Very valuable direct information could be gained by high-speed videotaping of a vertical-longitudinal section of avalanche. This would likely be a very expensive endeavor beyond the budgetary constraints imposed here.

Besides direct optical observation through a window, FMCW radar is the only presently known device for measuring the time evolution of entrainment/deposition rates at a given location. A single FMCW radar is able to measure the entrainment rate, the flow depth, and the distribution of slope-perpendicular particle velocities. From this, the stress normal to the slope and the down-slope component of the gravitational force can be obtained if an average avalanche density is assumed. Therefore, one option within the assumed budgetary constraints is to deploy two or three radars at different points of interest. Several options as to the choice of location exist, and it appears too early to develop recommendations.

Using two or three single FMCW radars (rather than one pair of radars) offers the advantage that entrainment rates measured at distinct locations can be compared. But further information must be obtained in order to relate the entrainment rates to other dynamical variables. Which variables are the most relevant appears to depend on the entrainment mechanism. Radar data from Vallée de la Sionne indicates that at least the "ploughing" mechanism at the front and the "sandblasting" mechanism along the avalanche, possibly also the intermittent "ripping" mechanism (in the terminology of Barbolini et al. (1998)) occur. For the ploughing and ripping mechanisms, the shear stress at the interface between the snow cover and the avalanche is the most important variable. For the sandblasting mechanism, particle-size and particle-velocity distributions assume a more prominent role, yet the stresses in the snow cover are still important.

It is possible in principle to measure the shear stress at the bottom of the snow cover, i.e., at the ground by means of appropriately shaped shear plates equipped with strain gauges. Experience at Vallée de la Sionne shows that details like the surface roughness of the plates and their embedding in the ground are important for the accuracy of the measurements. Provided the snow-cover depth and density are known and the slope angle is constant in the neighborhood of the sensors, the shear stress at the interface between snow cover and avalanche can then be calculated.

Freshly entrained snow particles at the interface between the flow and the snow cover at rest need to be accelerated to the velocity of the avalanche. Therefore, the shear stress exerted on them by the avalanche has to be larger in general than the one exerted by the snow cover. This consideration shows that the acceleration profile within the avalanche should also be measured. To this end, triple or quadruple arrays of LED sensors might be the only affordable avenue. Installation of pairs of FMCW radars does not appear useful in this context. Density measurements with capacitance probes would be very useful, but density estimates from field surveys might be sufficient in the beginning.

In summary, these preliminary considerations point towards the following instrumentation if entrainment studies shall be done:

- At two or three locations along the path, where the slope angle is locally constant, FMCW radars are installed in the ground for direct measurement of the entrainment rate and the flow depth. One of the radars will be installed about 10 m upstream of the concrete instrument support structure or the tubular tower if the latter is rebuilt.
- As close as possible to the radars, slender instrument supports about 5 m high and probably 2–3 m long are built and instrumented with 3 or 4 vertical arrays of LED sensors, whose spacing will require careful consideration. They serve for measuring the shear rate and acceleration in the avalanche.
- The instrument supports should be designed so that a few capacitance probes at the sides (for density measurements) and several load cells at the front (for impact and granulometry studies) can easily be installed later. Attention has to be paid to the high-frequency vibration behavior of the support structures.
- The measurement of shear and normal stresses on the ground by means of plates equipped with strain gauges should be attempted.

Before this option is chosen, a more detailed feasibility study that also outlines the analysis methods should be made because the entrainment problem has not been hitherto studied in avalanche research.

d) Focus on interaction with the dam

Present understanding of the physical processes involved in the interaction of an avalanche with a dam indicates that reduced-scale experiments at a chute could be significantly more detailed, and modeling much easier than in a full-scale experiment.

At a chute, the easiest (but not necessarily best) approach would be to deduce empirical correlations from a large number of experiments with systematic variation of essential parameters. Among them would be catching dam geometry (slope angles of terrain and dam wall, height, curvature at the foot of the dam), snow properties (cohesion, density, maybe also particle size), avalanche properties (velocity, flow depth, length). The empirical correlations will attempt to describe the dependence of the kinetic-energy loss on these parameters. The drawback is that the process is not really understood thereby, and the results cannot easily be applied to more complicated geometries.

A better approach would investigate the degree of snow compaction at impact, the temporal evolution and spatial variation of snow-pack deformation, the formation and geometry of shear fracture surfaces, and the influence of snow masses arriving from the rear. For sufficiently homogeneous snow, the impact process will be modeled (in 2D or 3D) taking into account the observed effects. Once a consistent mechanical framework has been established, the model can be tested in more complicated situations and in other ranges of the dynamical parameters.

As a complement to chute experiments, a large site allows to test the scaling behavior of the correlations or mechanical theory developed at the chute. For this purpose, moderately heavy equipment will suffice. However, if no laboratory-scale experiments are carried out, a large number of carefully designed measurement devices are needed to investigate the principles at work in some detail. If only full-scale experiments are carried out, the main difficulties to be addressed are: (i) the small number of experiments, (ii) the lack of control over the initial conditions, (iii) the more or less invariable geometrical setup, and (iv) the large dimensions and forces that make detailed observations risky and costly.

In principle, measurement of the kinetic-energy loss at the dam means comparing the kinetic energy of the avalanche just before and after the dam. There are two conceptual difficulties, however: (i) The dam is so large that the energy loss should be accounted for which the avalanche would have undergone without the dam (by traveling across the streamwise extension of the dam). This is difficult because the friction coefficients are not well known and are expected to change at those low velocities. (ii) At the foot of the dam, the stresses caused by the deflection will affect the approaching parts of the avalanche to some distance upstream. That distance will in general depend on the density, speed and compressibility of the avalanche. In a highly compressible, fluffy dry-snow avalanche (likely to be near the critical speed for upstream compressional shock propagation), the dam will hardly be felt upstream. In contrast, the dam might decelerate parts of a slow wet-snow avalanche (at sub-critical speed) several tens of meters upstream.

Appendix B presents a first analysis of the issues connected with the measurement of dam-avalanche interaction. Those results have to be considered preliminary and will need to be scrutinized by theorists, experimentalists and practitioners because hardly any previous experience seems to exist in this area and the measurements are at the border of what appears feasible. In summary, the main points are as follows:

- The energy dissipation in an avalanche due to the dam at Ryggfonn can probably be measured by combining several types of sensors in sufficient numbers. At the same time, detailed information on the rheological behavior of avalanching snow is obtained—a significant bonus in view of future model development. The precision of the measurements will not be very high, however.

- Several slender yet strong instrument supports 5–8 m high and 3–4 m long are needed on the dam and on either side of it. They carry a large number of light-emitting diode (LED) sensors, arranged in four columns, for measuring velocity and acceleration profiles. In addition, switch arrays for determining the flow depth are to be installed on them. The instrument supports should be designed so that they can later be equipped with load cells and capacitance probes for impact and density measurements.
- Just beneath the instrument supports, plates are to be installed level with the ground, equipped with strain gauges for measuring normal and tangential forces.
- The construction cost is dominated by the instrument supports, which are difficult to build, especially on the dam. The large number of data channels needed may require significant extensions to the existing data acquisition system. It is quite possible that the total construction cost exceeds the assumed budget level of 1 MNOK. In addition, the manpower required for data analysis and interpretation each year will be substantial.
- It would be preferable to carry out such measurements at a sufficiently large chute. For the development of this novel experimental approach (including data analysis), detailed tests at a chute appear indispensable before installation at Ryggfonn.

e) Focus on powder-snow avalanche formation

The dynamics of powder-snow avalanche formation has hardly been charted in earlier work, but it has gained in importance with the development of coupled models of powder-snow and dense-flow avalanches in recent years. One of the main problems is that the phenomenon takes place mainly at the upper surface of the dense-flow layer, which quickly becomes invisible and is extremely difficult to access in full-scale experiments. In the author's opinion, in a first phase specially designed laboratory experiments would offer a better chance of unraveling the essential processes than full-scale measurements.

Some of the essential parameters to measure include the fluctuation velocities in the dense-flow layer, particle fluxes in the vertical direction, aerodynamic shear stresses on the dense-flow surface, and concentration of saltating and suspended particles. It may also be necessary to measure pore pressures in the snow cover during the passage of the dense flow layer. This would allow determining if shock waves in the pore air, caused by the approaching avalanche, are able to disrupt the snow cover. Developing experimental methods for investigating this challenging problem is far beyond the scope of the present report, and the subject is of limited practical interest in Norway anyway.

5 OPTIONS IN CASE OF LARGE INVESTMENT (3-5 MNOK)

The scope of the experiments outlined in the SAME report D6 (Harbitz and Issler, 1998) encompasses most of the options discussed here. Exceptions are the detailed study of the interaction with dams or other man-made structures, and the investigation of PSA formation. It has been argued that the former problem is best studied with the help of reduced-scale experiments. If it is nevertheless desirable to perform full-scale impact measurements, the equipment discussed in Section 4.d) may be installed in addition to that listed in the mentioned report.

There is little new experience on instrumentation beyond what was considered in the SAME report. Therefore, no further discussion of the optimum equipment and its placement in the Ryggfonn path is given here.

Full equipment of the Ryggfonn site to the standards described in the SAME report D6 allows the following types of measurements to be made at the accuracy required for model development and validation:

- Initial conditions (snow density, fracture volume/geometry).
- Movement of avalanche outline along the path (width, length).
- Front velocity, internal velocity spectra (if the AIATR radar is present during a campaign), vertical fluctuation velocities.
- Flow depths at selected points.
- Velocity and density profiles at selected points.
- Global mass balance and temporally resolved local entrainment and deposition rates at selected points.
- Impact pressure profiles at selected points.
- Profiles of snow particle size and velocity distribution at selected points.

Such complete measurements allow exhaustive tests of most features of present and future models. If a sufficient number of events can be collected, an almost ideal situation for modelers is attained.

6 GENERAL CONSIDERATIONS AND FINAL REMARKS

The large investments implied by Sections 4 and 5—and the equally significant operating and maintenance costs they induce—are only justifiable if a consistent long-term effort in model development is undertaken. This can hardly be assured without a dedicated international collaboration that clearly goes beyond the level of the EU projects SAME and CADZIE.

Submarine gravity mass flows share many characteristics with snow avalanches. Measurements at the Ryggfonn test site can help in tackling one of the pressing practical problems in submarine engineering, namely the dimensioning of structures exposed to mudflows and turbidity currents. Comparing the forces on structures exerted by avalanches of different snow types and velocities, the role of cohesive forces versus inertial effects may be elucidated. Scaling the snow-avalanche measurements to submarine mudflows is expected to be difficult, but they will complement small-scale laboratory measurements that may not be able to explore the same parameter range. Similar points of contact exist in model development, in particular between powder-snow avalanches and turbidity currents, and between dense-flow avalanches and mudflows. Coordinating especially the development of user interfaces and numerical techniques should lead to substantial savings. Decisions concerning the future of Ryggfonn should be taken with these aspects in mind.

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Appendix A - Measuring Densities and Velocities in Powder-Snow Avalanches

The most direct method of measuring velocity and density profiles in powder-snow avalanches would use paired arrays of capacitance probes (Dent et al., 1998), but their cost is prohibitive. Rammer (1992) has mounted Pitot tubes on a tunnel bridge in the Bschlabs valley in Austria to obtain estimates of the powder-snow avalanche velocity. The Pitot tube measures the difference between the pressure in the (almost) undisturbed flow and at an artificially produced stagnation point nearby, i.e., the stagnation pressure, $\frac{1}{2}\rho_m u^2$. The mixture density ρ_m being unknown, only an upper limit of the velocity u can be established. Using pressure plates on the upstream side and gauges for absolute pressure on the lee side of the tunnel bridge, Rammer also measured the impact pressures and the lee-side pressure reduction as the avalanche passed. The Sapporo group used absolute-pressure gauges to measure the air velocity inside ping-pong ball flows (Nishimura and Ito, 1997; Keller et al., 1998). They noted a significant uncertainty in their results due to air velocity fluctuations and a pronounced directional dependence of the pressure measurements.

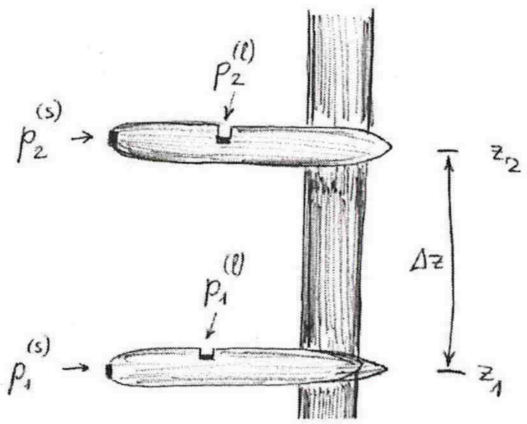

Figure 2. Sketch of two Pitot tubes with a small load cell at the tip for measuring fluid pressure plus stagnation pressure, and a lateral pressure transducer for measuring the fluid pressure. For use in real powder-snow avalanches, the design would have to be changed significantly, see text.

If two Pitot tubes are mounted at points P_1 and P_2 spaced a vertical distance Δz apart (Figure 2), the pressures measured by the sideways (superscript l) and streamwise (superscript s) transducers are

$$\begin{aligned} p_{1,2}^{(l)} &= p_0 + \int_{z_{1,2}}^{h} dz g\rho(z) - \tfrac{1}{2}\rho_{1,2}u_{1,2}^2 , \\ p_{1,2}^{(s)} &= p_0 + \int_{z_{1,2}}^{h} dz g\rho(z) , \end{aligned} \tag{1}$$

where p_0 is atmospheric pressure and h is the height of the powder-snow avalanche. From the difference of the stagnation pressures at z_1 and z_2,

$$\Delta p^{(s)} = \int_{z_1}^{z_2} dz g \rho(z) \approx \overline{\rho}\left(\tfrac{z_1+z_2}{2}\right) g \Delta z, \qquad (2)$$

the average density $\overline{\rho}\left(\frac{z_1+z_2}{2}\right)$ in the interval (z_1, z_2) is obtained. If several Pitot tubes are mounted above one another, a better approximation is obtained by averaging the two neighboring density values. Once approximate densities have been obtained, the velocities at P_1 and P_2 can be determined from the pressure differences $p_1^{(s)} - p_1^{(l)}$ and $p_2^{(s)} - p_2^{(l)}$.

At densities in the range 1–10 kg m^{-3} and with Δz of the order 1–5 m, the pressure differences between neighboring transducers are 10–500 Pa. Since atmospheric pressure is much larger, the devices need to be constructed so that they directly measure the pressure *difference* between two z levels, otherwise the precision would not be sufficient. The stagnation pressures are expected to be in the range 1–10 kPa. It remains to be determined whether it is better to measure fluid pressure at the sideways transducers or the pressure difference within one Pitot tube. At least at one height, however, fluid pressure should be measured also.

The discussion given above serves to illustrate the measurement principle, but significant modifications of the design will be needed: The head of the powder-snow cloud possesses a pronounced vortex-like structure, and throughout the cloud turbulence is very high. This means that the flow direction changes drastically over short times. Pitot tubes are rather sensitive to changes in the flow direction, the angle of attack should not exceed a few degrees. At an average velocity of 50 m s^{-1} parallel to the ground, vertical velocity fluctuations of about 5 m s^{-1} are the limit of what can be tolerated, but much stronger fluctuations are expected to occur. A first idea would be to mount the Pitot tubes like vanes so that they align themselves with the wind. The turbulent structure of PSAs is not well known, but let us assume that the length scale of a vortex with velocity fluctuations up to ±10 m s^{-1} is about 10 m. Thus, the angle of attack would change by ±10° within 0.2 s, the time of advection of the vortex. At best, Pitot tubes with very low moment of inertia will be able to follow flow changes at such rates.

The detailed instrumentation problems cannot be solved here, but Wu et al. (1999) describe a four-tube probe for use in water flows that can cope with angles of attack up to 40°. Such a range should be sufficient for powder-snow avalanches, but some redesign (e.g., membranes instead of open tubes in order to prevent clogging) and extensive calibration would be necessary.

Appendix B - Methods for Measuring Energy Dissipation at the Dam

In this Appendix, the necessary level of investigation of energy dissipation at a dam is discussed by considering a series of systems of increasing complexity. Then, the quantities to be measured for obtaining the local energy dissipation (as well as the bottom shear stresses and longitudinal stresses) are determined from a generalized Navier-Stokes equation. Finally, some proposals for the choice and location of sensors are presented.

a) Why simple approaches do not work

The energy dissipation of an avalanche hitting a dam could be measured in a simple way only if the avalanche flow were quasi-stationary before and again after passing the dam (Figure 3). Under this assumption, the friction forces balance the gravitational force, except during interaction with the dam. Then, with $u_{1,2}$ the center-of-mass velocities before and after impact, $1 - (u_2 / u_1)^2$ would represent the fraction of kinetic energy dissipated in the impact. However, when approaching the Ryggfonn dam the avalanches are already in their deceleration phase so that the formula above significantly overestimates the energy dissipation due to the dam. Moreover, a large fraction of the avalanche mass is usually held back by the dam and center-of-mass considerations are not adequate in this situation.

Now suppose that the avalanches could be neatly split into two equal halves, left and right, with one half impacting on the dam and the other half proceeding undisturbed (Figure 4). Then the kinetic energy of the undisturbed half at the position where the disturbed one comes to a halt would seem a convenient measure of the energy dissipation at the dam. This idea cannot be realized at Ryggfonn for obvious practical reasons. Alternatively, the kinetic energy of the undisturbed half of the avalanche at the stopping point of the disturbed one could be determined with a dynamic model, but no current model appears to be precise enough for this purpose.

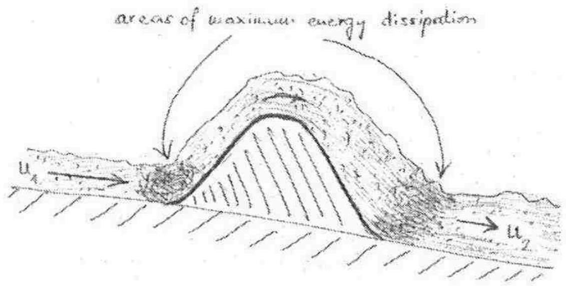

Figure 3. Sketch of avalanche flowing over dam and decelerating from u_1 to u_2.

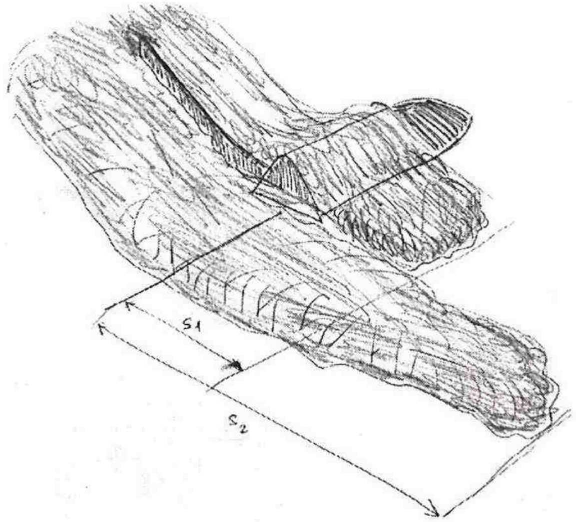

Figure 4. Comparison of runout distances with dam and without dam in an attempt to measure the energy dissipation due to the dam in a simple way.

It may also be illuminating to idealize the avalanche as a ''train'' of very loosely coupled point masses sliding on the ground with the appropriate friction forces. If we consider the balance of kinetic and potential energies at the dam, we observe the following points:

- If the kinetic energy is sufficient, the dam is overflowed.
- The kinetic energy lost to potential energy on the upstream side is regained descending on the downstream side.
- With constant coefficient of dry friction, energy dissipation is the same with the dam as without it—the longer path over the dam cancels with the reduced normal force on the slopes except for minor differences due to the centrifugal forces at the bends.
- Due to lower velocities, the energy loss due to "turbulent" friction would be smaller with a dam than without one over a realistic range of conditions. This is not a big effect, however.

These considerations imply that if a catching dam is overflowed by an avalanche, its protective effect has to come mostly from the energy dissipation through shearing and compression occurring in the bends (cf. Figure 3). Furthermore, the run-up height and thus the necessary dam height depend crucially on the energy dissipation in the bend. It is therefore important to determine the energy loss at a scale significantly smaller than the dam height. As will be shown below, this implies that quite detailed measurements need to be made at and near the bend.

Whether an avalanche is completely stopped by a dam or partly overflows it depends, not only on the ratio $u^2/(2gH_{\mathrm{dam}})$ and the energy dissipation in the bend, but also on how strongly the rear parts of the avalanche push the head up along the dam slope. This implies that the longitudinal normal stresses (also known as the "earth pressure" in soil mechanics) should also be measured.

b) Simple settings

For a more systematic treatment, first consider a block of mass m sliding on a surface, see Figure 5. Disregarding vibrations of the block, energy dissipation occurs only at the interface of the block with the inclined plane. The down-slope, normal and frictional forces are

$$F_S = mg\sin\psi, \quad F_N = mg\cos\psi, \quad F_F = -\mu F_N. \tag{3}$$

μ is the coefficient of dry friction, g the gravitational constant.

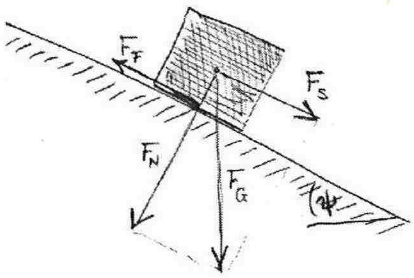

Figure 5. Definition of forces acting on a block sliding on an inclined plane.

The rate of energy dissipation (or increase of heat/internal energy) is given by

$$D = |F_F| \cdot |v| = mgv\mu\cos\psi. \tag{4}$$

The total energy balance is zero, as it should:

(change in potential energy) + (change in kinetic energy) – (energy dissipation)
$= -mgv\sin\psi + mva - D = -mgv\sin\psi + mvg(\sin\psi - \mu\cos\psi) - mgv\mu\cos\psi$
$= 0$.

v and a are the velocity and acceleration, respectively.

Now replace the solid block by an incompressible Newtonian fluid (characterized by the linear relation between shear rate and shear stress, $\tau = \rho\nu\partial_z u$) of kinematic viscosity ν, but admit a non-zero slip velocity u_0 at the bottom. Suppose the flow to be laminar and stationary. We trace a fluid element and write its equation of motion, resolved for the acceleration a:

$$a = -\frac{1}{\rho}\partial_x p + \frac{1}{\rho}\partial_z \tau + g\sin\psi = -\frac{1}{\rho}\partial_x p + \nu\partial_z^2 u + g\sin\psi . \quad (5)$$

If the stationary flow depth and velocity nor depend on the x-coordinate, then a=0 and also the pressure $p = p(z)$ is independent of x. Hence, one obtains for the shear stress τ:

$$\begin{aligned} &\partial_z \tau = -\rho g \sin\psi \quad \text{with} \quad \tau(h) = 0 \\ &\Rightarrow \tau(z) = \rho g(h-z)\sin\psi \quad \text{and} \quad \tau(0) = \rho g h \sin\psi . \end{aligned} \quad (6)$$

Expressing the shear stress through the shear strain rate $\partial_z u$, the velocity profile can be obtained:

$$\begin{aligned} &\partial_z u = \frac{g\sin\psi}{\nu}(h-z) \quad \text{and} \quad u(0) = u_0 \\ &\Rightarrow u(z) = u_0 + \frac{g\sin\psi}{\nu} z(h - z/2). \end{aligned} \quad (7)$$

The average velocity is obtained as

$$\bar{u} = u_0 + \frac{g\sin\psi}{3\nu} h^2 . \quad (8)$$

The rate of energy loss per unit volume due to friction and compression or dilation of the fluid is generally given by

$$\varepsilon = \frac{1}{2}\left(\partial_i u_j + \partial_j u_i\right)\sigma_{ij} = \sigma_{xx}\partial_x u + \sigma_{zz}\partial_z w + \tau_{xz}\left(\partial_z u + \partial_x w\right). \quad (9)$$

$u(x,z)$ and $w(x,z)$ are the velocities in the Cartesian x and z directions and $\partial_x \equiv \partial / \partial x$, etc.; σ_{xx}, σ_{zz}, and τ_{xz} are the normal and shear stresses. In the simple situation considered above ($\sigma_{xx} = 0$, $\partial_z u = 0$, $w = 0$) this expression reduces to $\varepsilon(z) = \tau_{xz}\, \partial_z u$, with $\tau_{xz} = \rho(h - z)g \sin \psi$ at a distance z from the ground. So,

$$\varepsilon(z) = \rho \frac{g^2 \sin^2 \psi}{\nu}(h-z)^2 . \quad (10)$$

The depth-integrated dissipation rate is obtained correctly only if one takes into account the contribution from the infinite shear strain at vanishing gradient of the shear stress at the interface. It is useful to express it in terms of the depth-averaged velocity:

$$\int_0^h dz\varepsilon(z) = \rho\frac{g^2\sin^2\psi}{3\nu}h^3 + \rho u_0 g h \sin\psi = \left(u_0 + \frac{g\sin\psi}{3\nu}h^2\right)\rho g h \sin\psi = \bar{u}\tau(z=0) \quad (11)$$

The equation above shows that—in this simple setting only—the dissipation rate can be determined by measuring the shear stress at the bed and the average velocity. It is of course equal to the rate of potential energy loss.

c) Analysis of the general situation

At the foot of the dam, the situation is much more complicated due to longitudinal compression, piling up and the development of shear planes. Therefore, all three stress components and all four strain components appearing in Equation (9) have to be taken into account. If avalanching snow behaved as a Newtonian fluid of known shear and bulk viscosities, measurement of the strain rates would be sufficient for calculating the stresses and thus the dissipation rate, but this is clearly not the case. As discussed below in the subsection on instrumentation issues, local velocities and their derivatives can be measured in the flowing avalanche, albeit only with a significant effort. In contrast, direct measurement of the stresses does not appear possible. The objective of the present subsection is therefore to outline approximate methods of inferring the stresses from the dynamics of the avalanche.

This means that the momentum balances have to be applied in order to obtain the forces from the measured kinematics. However, they immediately reveal the problem one faces thereby:

$$\begin{aligned} \partial_t(\rho u) + \partial_x\left(\rho u^2\right) + \partial_z(\rho w u) &= \partial_x \sigma_{xx} + \partial_z \tau_{zx} + \rho g_x, \\ \partial_t(\rho w) + \partial_x(\rho u w) + \partial_z\left(\rho w^2\right) &= \partial_x \tau_{zx} + \partial_z \sigma_{zz} + \rho g_z. \end{aligned} \tag{12}$$

In this simplified two-dimensional world, there are three unknown stress components σ_{xx}, σ_{zz}, and $\tau_{xz} = \tau_{zx}$, but only two equations (six components vs. three equations in three dimensions)—the problem is not determined without specifying constitutive equations, which we do not know. Therefore, certain simplifying assumptions are needed.

If we consider depth-integrated slices of the avalanche (in the y-z-plane perpendicular to the x-direction), we obtain the equation

$$\begin{aligned} &\partial_t \int_0^{h(t,x)} dz \rho u + \partial_x \int_0^{h(t,x)} dz \rho u^2 + \left[\rho w u\right]_0^{h(t,x)} \\ &= \partial_x \int_0^{h(t,x)} dz \sigma_{xx} + \left[\tau_{zx}\right]_0^{h(t,x)} + h\bar{\rho} g_x + \left[\rho u(\partial_t + u\partial_x)h - \sigma_{xx}\partial_x h\right]_{z=h(t,x)} \end{aligned} \tag{13}$$

From the kinematic constraint of a material surface,

$$\partial_t h(t,x) + u(t,x,h(t,x))\partial_x h(t,x) - w(t,x,h(t,x)) = 0, \tag{14}$$

and $\sigma_{xx}(t, x, h(t, x)) = 0$, the square bracket at the end of the right-hand side reduces to $\rho u w(t, x, h)$ and cancels an identical term on the left-hand side. At the bottom, $\rho u w(t, x, 0) = 0$, so we are left with

$$\partial_t \int_0^{h(t,x)} dz \rho u + \partial_x \int_0^{h(t,x)} dz \rho u^2 = \partial_x \int_0^{h(t,x)} dz \sigma_{xx} - \tau_f + h\bar{\rho} g_x . \quad (15)$$

This means that the "earth pressure force" $\partial_x \int dz \ \sigma_{xx}$ can be determined from measurements of u over the avalanche depth and of the bottom shear stress, τ_f.

Further assumptions are needed in order to obtain an estimate of σ_{xx} from Equation (15). First, $\sigma_{xx} = 0$ at the front and tail of the avalanche. Integration along x in either direction yields $\int dz \ \sigma_{xx}$ and allows checking the consistency of the measurements and calculations. For the vertical profile of the longitudinal normal stress, σ_{xx}, among the many possible assumptions we mention a linear profile or proportionality to $(\partial_x u)^2$. Presumably, various hypotheses have to be evaluated and tested for consistency. Note that the dissipation rate obtained from an assumed linear profile will be a lower bound to the true dissipation rate, particularly underestimating the true value in plug flows with a thin, very strongly sheared bottom layer.

The next step of the analysis aims at obtaining τ_{zx} throughout the avalanche. Equation (12) shows that $\partial_z \tau_{zx}$ is determined once the vertical velocity w and the horizontal velocity u is known. As w is presumably much smaller than u, it may be quite difficult to measure in practice. Lacking better ways, one may try to deduce its value at the surface from the time rate of change of the flow depth $h(t, x)$ and the horizontal velocity $u(t, x, h(t, x))$. The flow depth may be measured using the relatively simple and inexpensive electro-mechanical switch array used at Monte Pizzac, see Figure 7 (Issler, 1999). From the kinematic constraint of a surface, Equation (14), w can be readily computed. Then, one supposes that w varies linearly with height from 0 at the bottom to $w(t, x, h)$ at the surface:

$$w(t,x,z) = \frac{z}{h(t,x)} w(t,x,h(t,x)) \quad (16)$$

There is no rigorous justification for this assumption, and it is certainly not valid if a shear fracture plane develops at some height.

Note that $\tau_{zx} \approx 0$ at the surface of the avalanche and $\tau_{zx} = \tau_f$ at the bottom. This circumstance again allows a consistency check. One has to expect to find significant discrepancies, necessitating modifications of the assumed profiles until a reasonably self-consistent solution has been found. Incidentally, the second equation in (12) provides yet another consistency check because $\sigma_{zz}(t, x, 0)$ is the normal load at the bottom that can be measured and $\sigma_{zz}(t, x, h) = 0$. Once this component is also determined, the calculation of the dissipation rate can proceed.

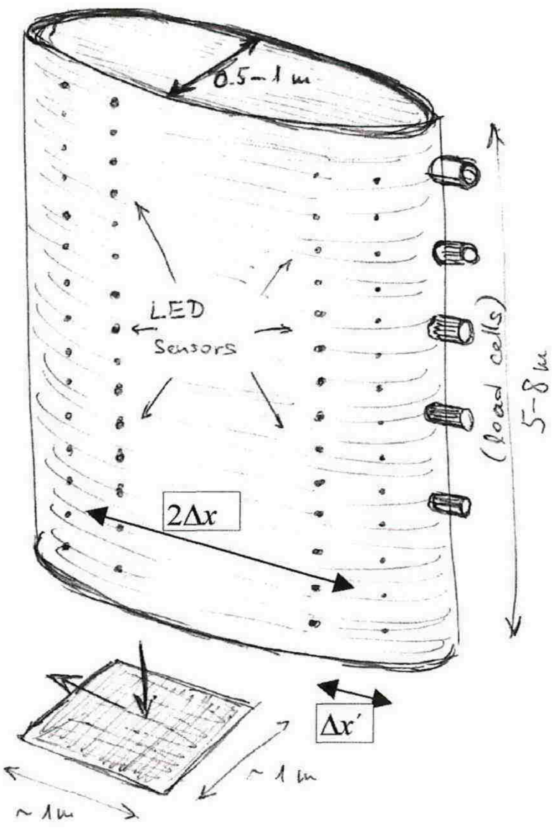

Figure 6. I nstrument support with LED sensors for velocity measurements. Load cells could be mounted on its front as indicated. A pressure/shear plate is mounted in the ground to the side of the support. In the middle of the sidewall, a switch array as in Figure 7 is mounted (not shown).

Figure 7. Electro-mechanical switch array at the Monte Pizzac site of the Centro Valanghe di Arabba (Veneto, Italy). A similar device should be installed on the instrument support shown in Figure 6. (Photo: B. Sovilla.)

d) Instrumentation issues

The strain rates $\partial_x u$ and $\partial_z u$ at some given longitudinal coordinate x can be measured by using four vertical arrays of LED sensors as sketched in Figure 6. If the sensors are numbered by (row, column), cross correlation of the output signals $(i,1)$ with $(i,2)$ and of $(i,3)$ with $(i,4)$ yields an approximation to the instantaneous velocities $u(t, x-\Delta x, z_i)$ and $u(t, x+\Delta x, z_i)$, provided the distance $\Delta x'$ between the sensors in a pair and the time interval $\Delta t'$ over which the correlation is computed are significantly smaller than the characteristic length and time scales of velocity changes in the flow. The spatial derivative $\partial_x u(t, x, z_i)$ is approximated as $[u(t, x+\Delta x, z_i) - u(t, x-\Delta x, z_i)] / (2\Delta x)$, and Δx should be significantly larger than $\Delta x'$. Similarly one obtains $\partial_z u(t, x\pm\Delta x, z_i) = [u(t, x\pm\Delta x, z_{i+1}) - u(t, x\pm\Delta x, z_{i-1})] / (\Delta z_{i+1} - \Delta z_{i-1})$. Crude estimates based on the assumption of a typical avalanche velocity of 20 m/s at the dam would indicate $\Delta x' \approx$ 0.1–0.5 m and $\Delta x \approx$ 1–2 m. For Δx, a compromise has to be found between measurable velocity changes ($\rightarrow$ large Δx) and sufficient spatial resolution ($\rightarrow$ small Δx). In order to obtain a velocity resolution better than 1 m s^{-1} at $x\pm\Delta x$, the sampling rate would have to be of the order of 5–10 kHz.

The snow density at different heights can be measured by means of capacitance probes (Louge et al., 1997), but they are very expensive. If it is assumed that the snow density is nearly uniform throughout the depth of the avalanche, a combined pressure/shear plate beneath the flow depth sensor can be used to obtain an approximate density value. Vertical acceleration of the snow and/or non-zero $\partial_x \tau_{xz}$ will distort the results, though. It may be necessary to measure the snow depth and normal load just before the avalanche event in order to correct for the contribution of the snow cover.

When installing pressure/shear plates, care has to be taken to select a plane location (not necessarily horizontal), otherwise the measurements may yield far too large or too small values: In a concave area, the snow may arch above the sensor and have only limited contact with it, giving too low normal loads and shear stresses. In a convex area, the sensor may feel the load from a much larger area than its own, suggesting far too high stresses. Another requirement is to match the surface properties of the surroundings as closely as possible. If the plate is too smooth / too rough, the measured shear stresses will be too low / too high. If the soil surface consists of well packed gravel, e.g., it might be best to cement the same kind of gravel onto the plate.

It should be stressed again that most of these measurement techniques should be tested under controlled conditions in the laboratory or at a chute before installing them in Ryggfonn.

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