Comparing model and full-scale experiments on snow avalanche dynamics

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ABSTRACT

The paper is a part of a Japanese - Norwegian collaboration on snow avalanche dynamics. The results of model experiments carried out at the Institute of Low Temperature Science, Sapporo are compared with full-scale experiments and theoretical models made by NGI.

Avalanching snow is modelled as the flow of granular materials having viscoplastic behaviour. The model experiments indicates that a slip velocity is only found for smooth boundary conditions and there is a distinct velocity gradient at all heights above the bed. The friction at the bed is caused by a Coulomb-friction and a dynamic-friction part, of which the first seems to be most important.

The backcalculation of real avalanches also indicates that the Coulomb-friction represents the major energy dissipation. The backcalculated values for the viscosities fits fairly well into existing theories and the results of the model experiments.

1. Introduction

This presentation is a part of a Japanese-Norwegian collaboration on snow avalanche research with the aim of combining experimental and theoretical research on snow avalanche dynamics in both countries. The Japanese research has mainly concentrated on field and laboratory research, and the Norwegian on field experiments and more theoretical related studies.

The main scope of this presentation is to combine the results of laboratory experiments with the respective data found by full-scale experiments, in order to increase our knowledge of snow avalanche behaviour. The combining of laboratory and full-scale experiments may also make it easier to transfer data and experience from one avalanche site to another site, and between different nations.

The theoretical background for the analysis carried out is the Norwegian model for the dynamic behaviour of granular materials. The laboratory experiments are all made at the Institute of Low Temperature Science and include measurements of friction coefficients and viscosity of snow as well as snow avalanche model experiments. The full-scale experimental data are mainly obtained from the Ryggfonn avalanche site in Norway.

2. The model experiments

The model experiments on avalanche dynamics were carried out in a cold laboratory using granular snow as the model material. The chute used for the experiments was 5.4 m long and 0.08 m wide and the steepness varied between 33.5 and 43.5°, Fig 1. The installations and the experiments are described by Nishimura and Maeno (1986), Nishimura et al. (1989) and Nishimura (1991).

The granular snow was natural snow stored for at least 10 month below -10°C, giving average particle diameters of 0.59 mm. The friction angle of the snow was 31.4° and the cohesion between the particles was assumed to be non-significant.

The granular snow was supplied to the chute with an automatic feeder system to control accurately the flow rate. To study the effect of the roughness at the bed, the chute was covered by either sandpaper, sintered snow or polyethylene film.

The main measurements taken during the experiments were the flow height, the max. velocity and the velocity profile at different sections. For some experiments impact pressure sensors were installed and the pressures as a function of time were recorded. Beside the model experiments the viscosities of the fluidized snow were also measured (Nishimura 1991).

3. The full-scale experiments

3.1 The Ryggfonn experiments

The Ryggfonn avalanche project is a full scale experiment carried out to investigate the impact of avalanches on structures and the effects of a retaining dam in the avalanche run-out zone. The vertical drop of the avalanche path is 910 m and the velocity and the volume of the avalanches vary within 20,000 - 400,000 m^3 and 20 - 70 m/s respectively. The experimental data are described by Norem et al. (1985) and Norem et al (1983 - 1991).

In the lower part of the avalanche path the following constructions have been installed, Fig. 2:

- A 15 m high and 75 m wide retaining dam.
- 200 m upslope from the dam three high voltage transmission line conductors were strung across the avalanche path, 8, 12 and 16 m above the ground (Removed 1990).
- 230 m upslope from the dam a 0.6 m wide and 4.5 m high concrete structure with three load cells, each 0.6 x 1.2 m in size.
- 320 m upslope from the dam a 25 m high tubular steel y-tower has been erected. The tower was replaced by a 10 m high tabular tower in 1990. The main sensors are shear and strain gauges at three sections.

Both natural and artificially released avalanches are recorded.

The avalanche velocities are measured by photographing or calculated by the time of impact on the constructions.

4. Presentation of the continuum flow model

4.1 The constitutive equations

The flow of snow avalanches is assumed to be treated as a granular material where viscoplastic behaviour is predominant. To describe the behaviour of granular materials a set of constitutive equations based on continuum mechanics are assumed to be a realistic assumption when the flow height exceeds approximately 20 times the average particle diameter.

The literature of continuum mechanics provides a variety of constitutive equations for materials having viscous and plastic properties. This presentation is based on the physical model presented by Norem et al. (1987 and 1989), where the constitutive equations for a steady, simple flow give the following expressions for the total stresses (Fig. 3):

$$\sigma_y = p_u + p_e + \rho \nu_2 \left(\frac{dv}{dy}\right)^2 \tag{1}$$

$$\sigma_x = p_u + p_e + \rho (\nu_1 - \nu_2) \left(\frac{dv}{dy}\right)^2 \tag{2}$$

$$\tau_{xy} = a + bp_e + \rho m \left(\frac{dv}{dy}\right)^2 \tag{3}$$

where
σ_x and σ_y = normal stresses
τ_{cy} = shear stress
p_u = pore pressure
p_e = effective pressure
ρ = density of the granular material
ν_1 and ν_2 = normal stress viscosities
v = velocity
a = cohesion
b = friction coefficient
m = shear stress viscosity

Discussion of the parameters

The two first terms of the right hand side of Eqs 1 and 2 explain that the pressure may be divided in two parts; a pore pressure, p_u, and an effective pressure, p_e. The effective pressure is the pressure transferred through the grain lattice.

The total normal stresses are also dependent on the velocity gradient within the avalanche. This term is the product of the density, a viscosity parameter and the velocity gradient squared. Bagnold (1954) called the velocity-dependent normal stress part a dispersive pressure, which is mainly caused by interparticle collisions.

The total shear stress is assumed to consist of a yield stress and a velocity-dependent shear stress. The yield stress represents the minimum shear stress to obtain any velocity gradient, and is described by two terms. The first one, a, is a cohesion parameter determined by the effect of sintering and by surface stresses between the snow macroparticles. The cohesion is mainly dependent on the moisture of the particles and the relative contact area (Fukue, 1979). We assume that the cohesion only have a significant importance for moist and wet snow avalanches.

The friction parameter, b, has the same character as the static internal friction parameters of granular materials, and may be regarded as a Coulomb friction. According to both Savage and Sayed (1984) and Hungr and Morgenstern (1984) the b-value is close to or 2 - 3° smaller than the tangent of the internal friction angle.

The velocity-dependent shear stress:

$$\tau_{dyn} = \rho m \left(\frac{dv}{dy}\right)^2 \tag{4}$$

represents the viscometric behaviour of the granular material. Bagnold (1954) and Savage and Sayed (1984) showed that for a constant volumetric density this stress may also be written:

$$\tau_{dyn} = const\ \rho_s d^2 \left(\frac{dv}{dy}\right)^2 \tag{5}$$

where ρ_s = particle density
d = diameter of the particles

Equations 4 and 5 then yield for the shear stress viscosity:

$$m = const\ \frac{\rho_s}{\rho}\ d^2 \tag{6}$$

The constant is highly dependent on the volumetric density, and for densities of 0.5 and 0.6 the following constants have been found experimentally:

Bagnold (1954) Wax spheres:	C_v = 0.5	const = 1.0
	C_v = 0.6	const = 10

Savage and Sayed (1984) Walnut shells: $C_v = 0.45$ const $= 2.0$
$C_v = 0.52$ const $= 20$

4.2 The numerical flow model

Steady flow

A steady flow of snow down an inclined plane are considered, and the geometry and kinematics are presented in Fig. 4. The height of the snow is assumed to be constant and the boundary conditions are given by:

$$\sigma_y = 0 \quad and \quad \tau_{xy} = 0 \quad at \quad y = h$$

$$v(y) = v(0) \quad at \quad y = 0$$

The equations of motions then give the following equations for the total normal and shear stresses:

$$\tau_{xy} = \rho g\,(h - y) \sin\alpha \tag{7}$$

$$\sigma_y = \rho g\,(h - y) \cos\alpha \tag{8}$$

where
h = flow height
α = angle of inclination
g = coefficient of gravitation

From Eqs 2, 3, 7 and 8 the velocity gradient is:

$$\frac{dv}{dy} = \left[\frac{g(\sin\alpha - b\cos\alpha)}{m - b\mathrm{v}_2}\right]^{1/2} [h - hp - y]^{1/2} \tag{9}$$

where hp is the depth of the plug flow defined by the expression:

$$hp = \frac{a}{\rho g\,(\sin\alpha - b\cos\alpha)} \tag{10}$$

The plug flow is only present for cohesive materials, a > 0.

Integrating Eq. 9 and introducing the slip velocity, v_o, gives the following expression for the avalanche steady velocity (terminal velocity) when assuming that the volumetric density is constant and thus that m is not a function of y:

$$v(y) = v_o + \tfrac{2}{3}\left[\frac{g(\sin\alpha - b\cos\alpha)}{m - b\nu_2}\right]^{1/2}(h - hp)\left[1 - \left(1 - \frac{y}{h - hp}\right)^{3/2}\right]$$

$$for \quad y \leq h - hp \tag{11}$$

$$v(y) = v(hp) \quad for \quad y \geq h - hp \tag{12}$$

For cohesionless materials, a = 0 and thus hp = 0, the maximum velocity v_h and the velocity distribution will be respectively:

$$v_h = v_o + \tfrac{2}{3}\left[\frac{gh^3(\sin\alpha - b\cos\alpha)}{m - b\nu_2}\right]^{1/2} \tag{13}$$

$$v(y) = v_o + (v_h - v_o)\left[1 - \left(1 - \frac{y}{h}\right)^{3/2}\right] \tag{14}$$

Non-steady flow

A general equation for the non-steady flow of a granular material obeying the constitutive Eqs 1 - 3 has been developed by Norem et al. (1989). The equation is based on the assumption that the density is constant, the avalanching snow is cohesionless and that the velocity-profile transverse the bed is identical with the velocity profile of Eq. 14.

The general equation for the acceleration of the flow found by Norem et al. (1989) may be simplified by assuming a no-slip condition, $v_o = 0$, and a constant flow height. In this case the equation of acceleration will be reduced to:

$$\frac{dv_h}{dt} = \frac{5}{3}g(\sin\alpha - b\cos\alpha) - \frac{15}{4}(m - b\nu_2)\frac{v_h^2}{h^3} \tag{15}$$

The term dv_h/dt may be reorganized to:

$$\frac{dv_h}{dt} = \frac{1}{2}\frac{dv_h^2}{ds} \tag{16}$$

and Eq. 16 then becomes a differential equation of v^2 and s, with the following solution when v(s = 0) = 0.

$$v(s) = v_h\left[1 - \exp\left(-\frac{7.5\,(m - b v_2)s}{h^3}\right)^{½}\right] \tag{17}$$

where v(s) = the maximum velocity at y = h for the distance s along the chute

v_h = the terminal, max velocity at an incline angle, α, given by Eq. 13.

5. Analysing the velocity measurements

5.1 Boundary conditions

The model experiments

The experimental results of the model experiments indicated that the roughness of the bed is an important parameter for the flow conditions. A polyethylene film was used to test the effect of a smooth surface, and in this case, a significant slip velocity was found, Fig. 5. The slip velocity was up to 70% of the max. velocity, and the average velocity of the flow also increased with the smooth boundary.

A rough boundary was prepared by gluing snow particles to the bed, or by using sandpaper. Both the snow and the sand particles had the same diameter as the flowing snow particles. Both kinds of bed conditions gave almost the same flow behaviour, Fig. 5. There are almost a non-slip condition and the velocity profiles are very close both for the snow and the sand boundary.

Real avalanches

The only velocity profile of real avalanches so far presented is made by Gubler (1986). This profile has fairly high gradients close to the bed and a tendency of a plug layer, Fig. 6. The profile is thus more blunt than the profiles recorded by Nishimura (1991).

The impact pressure measurements from the Ryggfonn-project show for dry snow avalanches smaller impacts close to the snow cover (Norem et al. 1983 - 1991) while for wet snow avalanches, the high pressures are found more close to the snow cover.

There is thus reasonable to assume that dry snow avalanches consisting of small particles close to the bed has no significant slip velocity and that slip velocities are more significant for moist and wet snow avalanches that usually are forming larger particles.

5.2 Velocity distribution profiles

The characteristic velocity profiles, Fig. 5, seem to be well described by the power function of Eq. 14:

$$v(y) = v_o + \left(v_h - v_o\right)\left[1 - \left(1 - \frac{y}{h}\right)^{3/2}\right] \tag{14}$$

Equation 14 is based on the assumption that the dynamic shear stress is proportional to the velocity gradient squared. The viscometric measurements of the fluidized snow of Nishimura (1991) confirmed this assumption for velocity gradients above 10 s^{-1}. The actual gradients of the model experiments were between 50 and 100 s^{-1}.

The mean deviation between Eq. 14 and the model experiments is found close to the lower boundary, Fig. 5. The results indicate that the profile would have been better described by a higher velocity gradient close to the bed, rather than introducing a slip velocity. Such high gradients may be explained by a reduction of the density close to the bed, caused by the high shear stresses transferred from the flow to the bed at this section.

The velocity profiles, as shown in Fig. 5 have almost no indications of plug flow. The only shear strength parameter to give plug flow is cohesion, and the model material may thus be assumed to be cohesionless. This is also in agreement with the viscometric experiments by Nishimura (1991) showing that the velocity-independent shear stress of the artificially fluidized snow is approximately $2 \cdot 10^{-3}$ N/m^2 at a density of 200 kg/m^3. This value corresponds to approximately 0.01 - 0.1 % of the total shear stress recorded at the actual velocity gradients of the model experiments.

Real snow avalanches my be regarded as either cohesive or cohesionless flows. For dry avalanches the cohesion probably plays a non-significant role compared to the other shear strength parameters. Moist and wet snow avalanches are known to form plug flows, and in these cases cohesion must be important.

5.3 Velocity profile along the chute

Model experiments

The value of the stress terms of the constitutive equations may be found by analysing the velocity profile along the chute. The velocities were recorded 2.5, 4.0 and 5.0 m after the start of the flow.

The equation of acceleration for a flow with constant flow height has been found to be, Eq. 15:

$$\frac{dv_h}{dt} = \frac{5}{3} g (\sin\alpha - b\cos\alpha) - \frac{15}{4} (m - b\nu_2) \frac{v_h^2}{h^3} \qquad \textbf{(15)}$$

Equation 15 predicts that the acceleration in the starting area is only dependent on the slope angle and the friction coefficients. When the flow has been developed, the viscosity parameters and the flow height also plays an important role.

Figure 7 presents the calculated velocities along the chute for 4 different slope angles, and the recorded velocities during the model experiments. The following parameter values have been selected:

$$\begin{aligned} b &= 0.57 \\ m &= 1.4 \cdot 10^{-5} \text{ m}^2 \\ m/\nu_2 &= 0.8 \\ h &= 0.05 \end{aligned}$$

The selection of parameter values are both based on physical assumptions and data fitting to the model results.

The friction coefficient of 0.57 corresponds to a friction angle of 30°. This value is 1.4° lower than the static friction angle and this is in accordance with the recommendations of Hungr and Morgenstern (1984) and Savage and Sayed (1984).

The shear stress viscosity, m, has been found to be expressed by:

$$m = const \frac{\rho_s}{\rho} d^2$$

where the constant probably varied between 2 and 20. This gives the following values for m:

$$m = (2 - 20)\,2.0 \cdot (0.00059)^2 = 1.4 \cdot 10^{-6} - 1.4 \cdot 10^{-5}$$

Nishimura (1991) found that the shear stresses in a Stormer-type viscometer increased with the velocity gradients squared for gradients exceeding 10 s^{-1}. The relationship between his viscosity, η_2, and the shear stress viscosity is:

$$m = \frac{\eta_2}{\rho}$$

and the measured m-values of the fluidized snow were:

$$m_{min} = \frac{2.0 \cdot 10^{-3}}{120} = 1.6 \cdot 10^{-5}$$

$$m_{max} = \frac{7.3 \cdot 10^{-3}}{200} = 3.15 \cdot 10^{-5}$$

The selected m-value of $1.4 \cdot 10^{-5}$ is thus within the range of that predicted by the experiments of Savage and Sayed (1984) and Bagnold (1954) as well as the viscometric experiments by Nishimura (1991).

The ratio of the shear stress and the normal stress viscosity, m/η_2, has been shown by Savage (1984) to be dependent on the coefficient of restitution of the particles. The ratio increases with higher plasticity and is probably close to 0.8 for plastic particles like snow.

Real avalanches

A numerical model to calculate the velocity and run-out distance of snow avalanches based on the constitutive Eqs 1 - 3 has been developed by Norem et al. (1989). Backcalculations of recorded major snow avalanches in Ryggfonn were also presented by them. These calculations were made by the following set of parameters:

$$
\begin{aligned}
b &= 0.4 \\
m &= 0.001 - 0.0028 \text{ m}^2 \\
h &= 1.3 - 2.0 \text{ m}
\end{aligned}
$$

Irgens (1988) presented the results of backcalculating a real avalanche recorded by radar measurements Gubler (1986), Fig. 9. The best fit was found for:

$$
\begin{aligned}
b &= 0.36 \\
m &= 0.001 \\
h &= 2.4 \text{ m}
\end{aligned}
$$

The selected-friction coefficients are lower than those used for the model experiments calculations, and they are in the lower range of friction coefficients found for natural snow by Casassa et al. (1991).

The shear stress viscosities of the back calculated real avalanches are approximately two orders higher than those found by the model experiments. This deviation may be explained by the different types of snow and the two different procedures for estimating the viscosities. The model snow is artificially stored to have no cohesion and the grain diameter is as low as 0.59 mm. The viscosity increases theoretically with the diameter squared, which may cause some of the deviation. Another reason may be that the particles in the fluidized snow is kept apart by an artificial air stream, while in natural avalanches the particles are kept close to each other because of the weight of the overburden. It is thus reasonable to find higher viscosities in real avalanches than in artificially fluidized snow.

The values found by backcalculation may be used to estimate the importance of the Coulomb-friction part and the dynamic part of the total shear stress. Table 2 presents the resulting shear stresses at the bed at the section of maximum velocity and by assuming a density of 200 kg/m^2. The relative magnitude in percent is also presented.

Avalanche	Coulomb-friction		Dynamic drag	
	kPa	%	Kpa	%
Model	0.040	38	0.068	62
Ryggfonn 1	0.835	71	0.339	29
Ryggfonn 3	1.285	69	0.586	31
Aulta	1.468	83	0.300	17

The backcalculated values indicate that for real avalanches the Coulomb-friction probably represents 70 - 80% of the total shear stress at the bed, as for the model experiments the percentage is found to be approximately 40%. These values have, of course, to be checked by careful analysing of additional real avalanche data. But anyway, the effect of the Coulomb-friction seems to play an important role even for dry avalanches and in the part of the avalanche track with maximum velocities.

The ring-shear tests of Casassa et al. (1991) gave increasing friction at higher velocities. The total friction coefficient at 5 m/s velocity was 0.46 at the temperature of -4°C compared to 0.4 at low velocities. For another type of snow the respective values were 0.72 at v = 15 m/s and 0.4 at v = 0. The contribution of the Coulomb-friction part in these experiments are thus 85% and 56%, which confirms the main conclusions found by the backcalculations.

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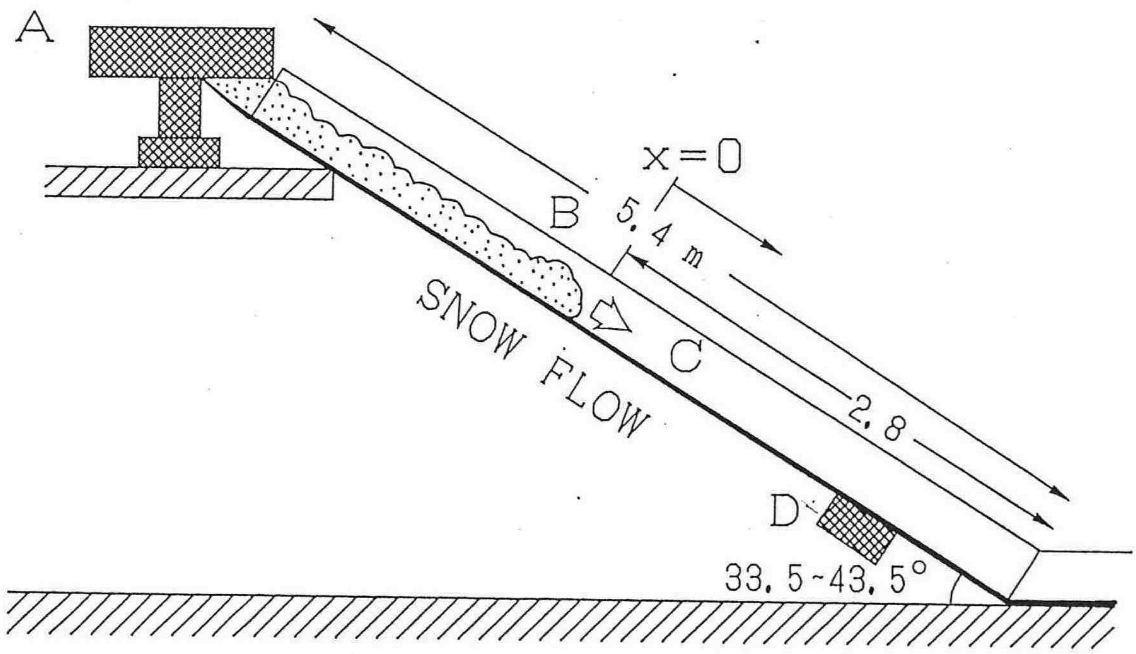

Fig. 1 Schematic diagram showing the experimental set-up.
A: fluidized snow feeder,
B: chute,
C: sand paper or snow,
D: drag meter.

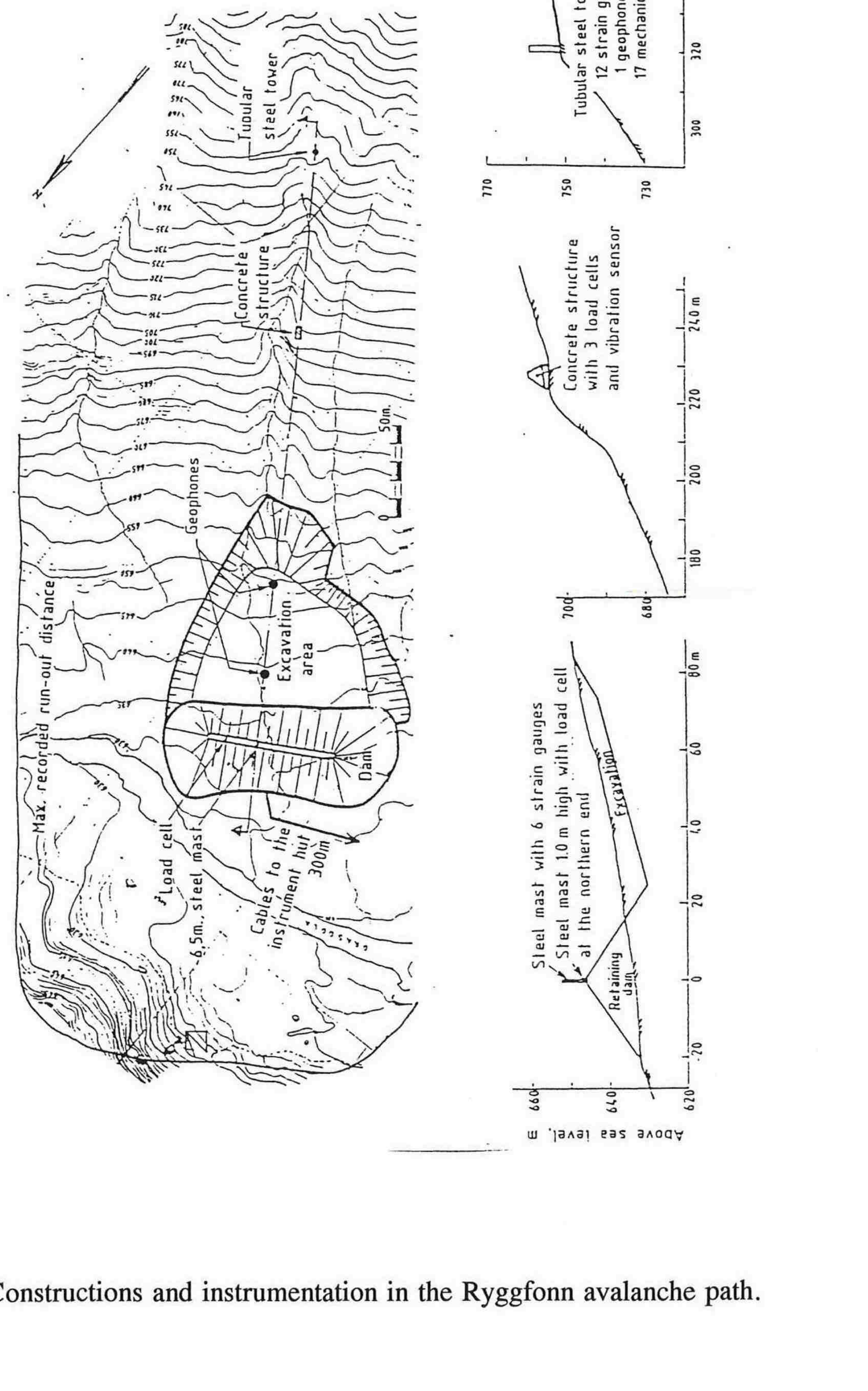

Fig. 2 Constructions and instrumentation in the Ryggfonn avalanche path.

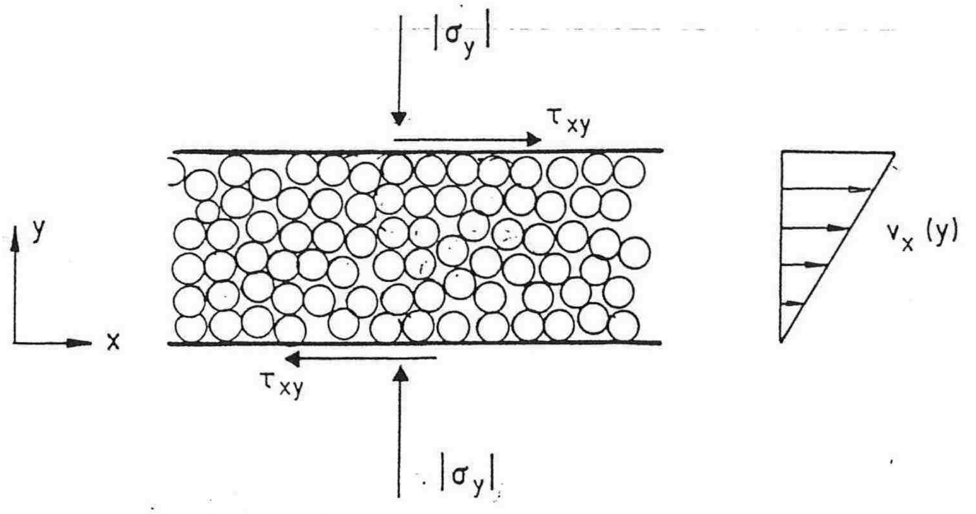

Fig. 3 Definition of normal and shear stresses and the velocity distribution.

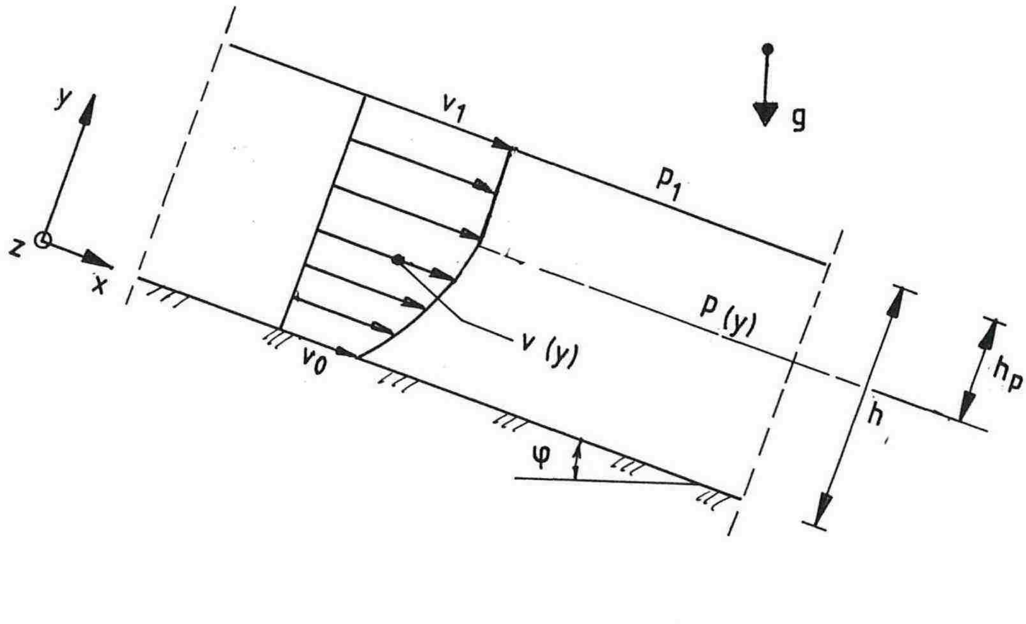

Fig. 4 Definition of steady flow geometry.

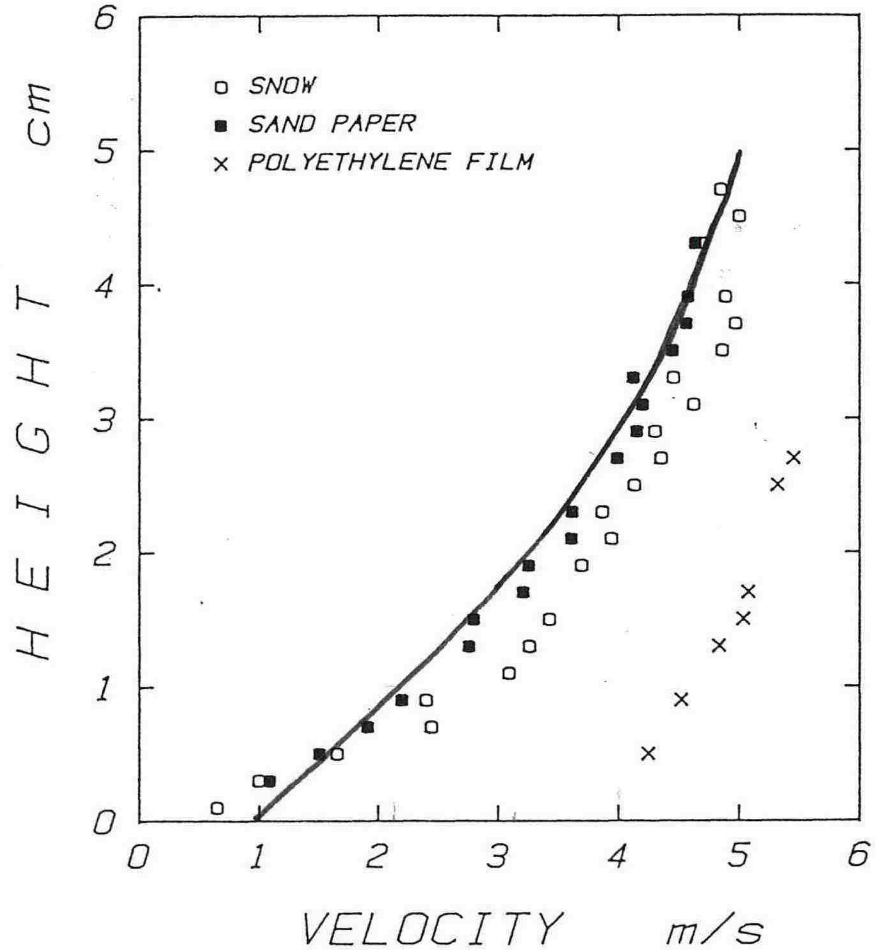

Fig. 5 Measured velocity profiles of the snow flow on various floor conditions. A best fit curve for v_o = 1 m/s and v_h = 5 m/s is presented.

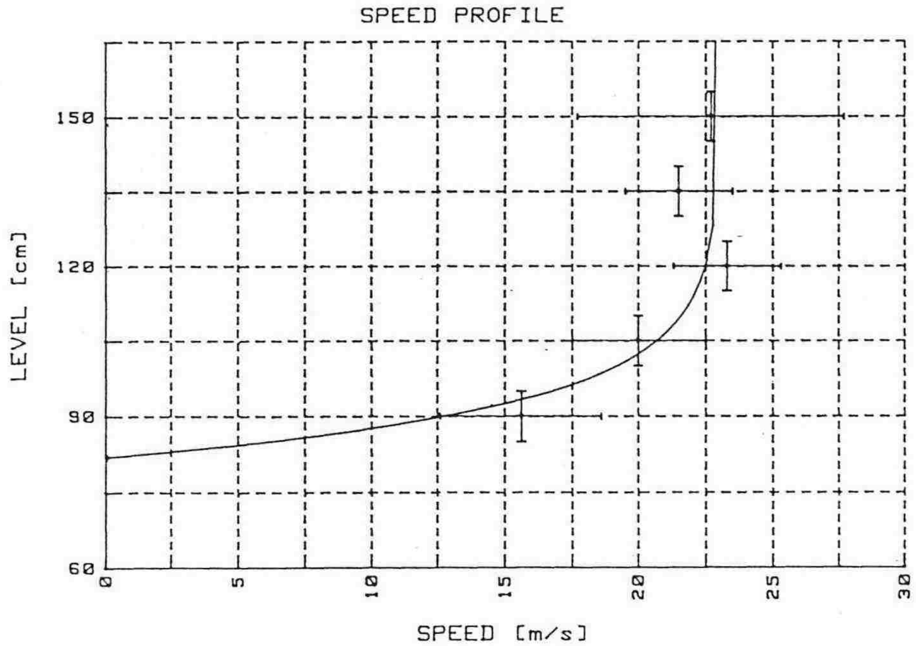

Fig. 6 Measured velocity profile of a snow avalanche (Gubler et al., 1986).

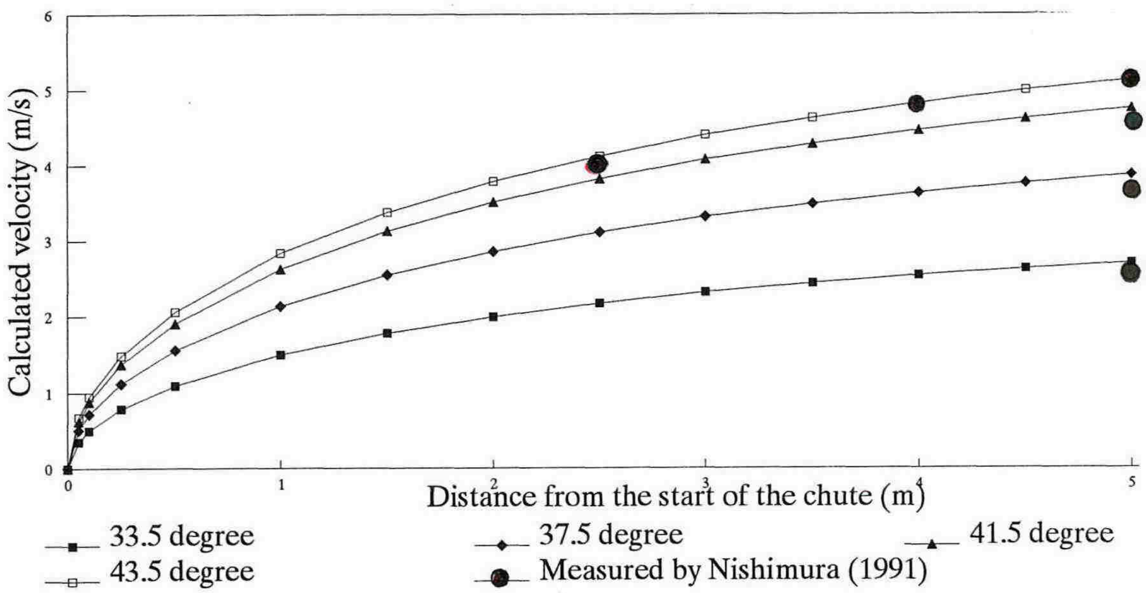

Fig. 7 Calculated and measured velocities along the chute.

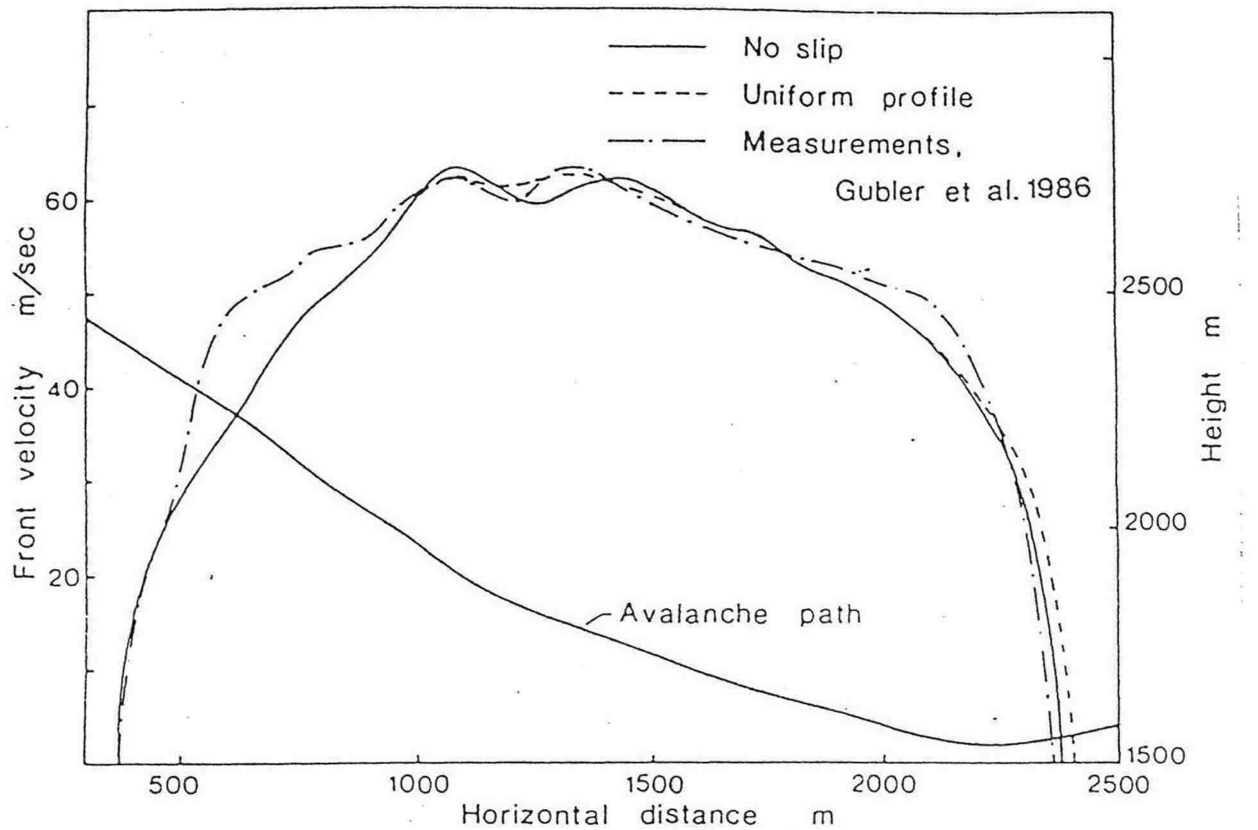

Fig. 8 Calculated front velocity as a function of hoizontal distance, compared with radar measurements made by Gubler et al. (1986).

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