Shear stresses and boundary layers in snow avalanches

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For the Norwegian Geotechnical Institute

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Foreword

The present report is made possible by the Norwegian Research Council (NFR) in the EU-program «Human Capital and Mobility». NGI is grateful for this support.

Dr. Harald Norem worked on the project as an employee at NGI. When Harald Norem started as a private consultant, he completed this work on a research contract with NGI.

Contents

SUMMARY

Full-scale experiments on snow avalanches have shown that the major part of the avalanches are mixed flow avalanches, and that they consist of at least two parts, a dense flow part and a turbidity part. The report is based on that a fully developed avalanche can be divided in four flow layers:

dense flow layer, where the particles are in close contact, and the volumetric density is high. The density is assumed to be almost constant in the dense flow layer, and the particles have liquefied behaviour. The dense flow layer represent the major volume of the avalanches.

saltation layer, which is a transition layer between the dense flow layer and the suspension layer. The particles in the saltation layer are transported in jumps similar to saltating particles in drifting snow. The volumetric density is reduced with a power of 3 with height in the saltating layer

suspension layer represents the snow cloud of snow avalanches and transport the particles in suspension. Suspended particles are assumed to have a behaviour similar to the vapour phase. Both the density and the velocity are reduced almost linearly with height in the suspension layer.

Recirculation layer represents the backflow of air above and around the avalanche. The height of the recirculation layer is one to three times the height of the suspension layer.

A fully developed avalanche has zero shear stress close to the upper boundary of the dense flow layer. The level of zero stress also represents the level of the maximum velocity, and in the initial stage of the avalanche the maximum velocity is found within the dense flow layer. When the suspension layer is gradually developed, the level of the maximum velocity is increased into the saltation layer and further into the suspension layer.

1. INTRODUCTION

The author of the present report, Dr Harald Norem, received as employed by the Norwegian Geotechnical Institute (NGI) in 1994 a grant through the European Program "Human Capital and Mobility" to cooperate with the Swiss Federal Institute of Snow and Avalanche Research (SFISAR) to exchange ideas on the flow of snow avalanches. The contact person on the Swiss side was Dr. Dieter Issler.

Norem visited SFISAR for 12 days in June 1994, and the intention was to have a revisit of Issler at NGI in 1995. Due to lack of time, and because Norem left NGI in September 1995, it was not possible to arrange the revisit. Norem was then asked by NGI to prepare a report based on the discussions and the notes that were made during his stay at SFISAR.

NGI and SFISAR have for the last ten years concentrated on different parts of the avalanche flow. SFISAR has mainly concentrated on the flow of the turbidity part of the avalanches, and has made and taken active part in model studies on such flows at the Technical University in Zurich (ETH). On the other hand, the NGI-activity has been concentrated on full-scale experiments on snow avalanches and theoretical studies on the dynamics of the dense flow part of the snow avalanches.

The main idea of the co-operation was to exchange the experience assembled at both institutions, and particularly to look into the physics of the boundary between the dense flow part and the turbidity part. The secondary scope was to see how the experience from the full-scale and the model experiments could be brought together.

The division of the snow avalanches into different flow layers, and analysis of the interaction between the flow layers have hardly not been discussed in published reports. The present report is mainly a discussion on the behaviour in each flow layer, and a discussion of the energy and mass transfer at the boundaries between the layers.

The report presents the authors main ideas based on his experience rather than it is the presentation of facts based on scientific experiments. The report has thus to be read as a personal presentation on the development and flow of snow avalanches. For this reason the references to own reports may be overrepresented. It is, however, the hope of the author that the presentation may be a contribution to the understanding of the physics of snow avalanche flow.

2. AN INTRODUCTION TO THE AVALANCHE FLOW LAYERS

2.1 General

All avalanches are released as a solid material, and during the flow the released material disintegrate partly or totally into smaller particles, and finally ends as a solid material when the avalanche stops in the runout zone. Traditionally, the avalanche flow is divided in three groups, dense flow avalanches, powder avalanches and mixed flow avalanches. Experience from full-scale experiments have shown that mixed flow avalanches represents the major part, and the other two types are the exceptions (McClung and Schaerer 1985 and Norem et al 1983-1991).

The existence of both a dense flow and a turbidity part layer in snow avalanches has been shown by Norem et al (1989) to be a consequence of snow avalanches to be pure two-phase flows. Other natural avalanches that are pure two-phase flows are rock slides and submarine slides. The presented ideas are thus assumed to be valid also for these two kinds of natural avalanches.

2.2 Presentation of a phase diagram for granular materials.

The main requirement to understand the flow of snow avalanches is to understand the development of shear and normal stresses that make it possible to disintegrate the released slab and to keep the particles some distance apart during the avalanche event. These stresses have to be velocity-dependent, and are not found in a granular material in rest.

The behaviour of granular materials are highly dependent on the volumetric density and the physical effects that keep the particles apart. The volumetric density is defined as the ratio of the volume of the particles to the total volume of the particle-fluid mixture.

A phase diagram for granular materials have been proposed by Norem (1995) to classify the dynamic behaviour into the solid, the liquid, and the vapour phase, Fig 1. The characteristics for the different phases are:

The solid phase:
The solid phase of a granular material is characterised by no internal velocity gradients and that the particles are in steady and close contact. The solid phase of granular materials is usually well described by a Mohr-Coulomb behaviour where the constitutive equations may be written

$$\sigma_y = p_o + p_e \qquad 1$$
$$\tau_{xy} = a + p_e \tan\phi \qquad 2$$

where:
σ_y=normal stress
τ_{xy}=shear stress
p_e=effective pressure
p_o=pore pressure
a=cohesion
φ=friction coefficient

Eq 1 describes that the total normal stress is represented by the sum of two parts, the pore pressure and the effective pressure. The latter represents the normal stress going through the grain lattice. The pore pressure is assumed to be equal the air pressure for snow, but may be well above the hydrostatic pressure for saturated materials, like submarine sediments and silt and clay deposits, at critcal stability levels.

The shear strength is also described by two terms, eq 2, of which the first represents the pressure-independent shear strength, usually called cohesion. Cohesion is found in moist and wet snow, and has less importance in dry snow and slush. In loose-deposit materials the cohesion is mainly dependant on the content of fine materials, < 0,002 mm.

The second term in eq. 2 is the Coulomb friction, which is the product of the effective pressure and the tangent of the friction angle.

The liquid phase

The liquid phase is defined as a phase where the granular material has none or only minor shear strength, and where the particle collisions or fluid viscosity represent the dominant energy dissipation.

The main requirement to obtain a pure liquid phase, and thus avoid the effect of the Coulomb friction, is to have velocity-dependant normal stresses (dispersive stresses) equal the effective normal stresses found in the material at rest to neutralise the effects of the effective pressure. For the dense flow part of snow avalanches, Norem et al (1987) showed that particle collisions are the main physical effect to cause such dispersive stresses. Because the dispersive stresses are dependant on the number of collisions, which is favoured by a short distance between the particles, the volumetric density is assumed to be relatively high in the liquid phase. The liquefied material is also assumed to have an upper boundary surface similar to ordinary liquids.

The vapour phase;

In the vapour phase the particles are transported as suspended particles, and the dominant energy dissipation in the vapour phase is caused by turbulence in the interstitial fluid. The energy dissipation due to particle collisions are negligible, and it may be hard to distinguish the upper boundary surface of the vapour mixture to the surrounding fluid.

Particles are known to depress turbulence in particle-fluid mixtures, and necessary turbulence to keep the particles in suspension are not possible unless the volumetric density is relatively low. According to Bagnold (1954) a volumetric density of 9% should be considered as an upper limit to have turbulence in a particle-fluid mixture. A pure vapour phase is thus only to be expected with only very diluted mixtures, and there seems to be an upper limit for the volumetric density for the turbidity part of snow avalanches.

The inter-phase transition zones

The gradual disintegration of the solid material and the reduction of the volumetric density may either develop gradually along the solid-liquid axis or along the solid-vapour axis, Fig 1. It is assumed that slides develop gradually along the solid-liquid axis, and for the turbidity part further along the liquid-vapour axis. On the other hand, a direct development along the solid-vapour axis represents erosion and transport of drifting snow as suspended particles.

Mixed flow avalanches are at least represented with materials both in the liquid and the vapour phase. There is also a high probability that there are some parts that are in the transition zones between the three pure phases.

2.3 Definition of the different flow layers in a well developed flow avalanche.

A well developed snow avalanche is assumed to consist of the following flow layers, which are discussed in more detail in chapter 4, and shown schematically in Fig 2:

The dense flow layer

The dense flow layer represent the major volume of the avalanche and consist of snow either partly or totally liquefied. The volumetric density of the dense flow layer has to be relatively high, with a lower and upper limit of 0,25 and 0,5 respectively. The lower limit of 0,25 is needed to have necessary amounts of particle collisions to generate sufficient dispersive pressures to keep the particles apart. The upper limit is the absolute upper limit to have internal particle movements. Some moist and wet snow avalanches may, however, have volumetric densities above 0,5, if they flow as a plug flow.

The lower boundary for the avalanche may be the original snow cover or snow-free ground. In the case of a snow-free ground the avalanche are seldom erosive, and probably have a zero velocity at the bed surface. This assumption is consistent with the theories for no-slip conditions for the flow of Newtonian and Bingham fluids in pipes and channels.

The flow conditions at the lower boundary is far more difficult to analyse when the original snow cover represent the lower boundary of the avalanche. In this case there may be both erosion and entrainment at the lower boundary, as well as no-slip conditions never has been proved.

The Ryggfonn full-scale experiments indicates frequent erosion due to snow avalanches, and the maximum recorded erosion is four meter (Norem 1983-1991). The depth of erosion seems to be dependant on the magnitude of the avalanche, the moisture of the avalanche, and the strength of the original snow cover. Generally one may assume that the transferred shear stresses at the lower boundary has to exceed the strength of the original snow cover (Norem and Schieldrop 1991).

The saltation layer (The transition dense flow-suspension flow layer).

McClung and Schaerer (1985) and Norem et al (1983-1991) have recorded the impact pressure on load cells from snow avalanches. The impacts from the dense flow part usually show continuos impacts, while the load cell recordings above the dense flow part often show frequent, separate impacts, indicating hits of single snow balls with a significant size. Both reports assume these recordings to be an indication of a transition layer between the dense flow part and the turbidity part.

The dynamics of the transported particles in the transition zone are probably similar to saltating particles in drifting snow, where the particles are brought into the air due to the effects of turbulence. If the particles are too heavy to be kept in suspension, they will fall toward the surface where the effect of the particle collisions may release new particles into a saltation movement. The dynamics of saltating particles thus incorporate both the effects of particle collisions and turbulence, and the particle-fluid mixture in saltation have a behaviour in the transition between the liquid and the vapour phase.

By the Ryggfonn experiments it has also been surveyed snow balls, 0,1-0,5 m in diameter, 10-30 m outside the main deposits of the avalanches (Norem et al 1983-1991). These snow balls have been assumed to be an effect of the drag from the snow cloud on saltating particles. Similar patterns in the deposit area of submarine slides have been reported by Prior (1984), who called them "outrunner blocks".

The suspension layer.

The suspension layer or the turbidity part of the snow avalanches consists of particles suspended in the air due to turbulence generated by the flow of the avalanche. Model experiments have proved that the volumetric density and the velocity are reduced with height in the suspension layer (e.g Tesaker 1969 and Hermann et al 1987).

The height of the suspension layer may be up to 50 m, but the volume of transported particles in that layer is surprisingly small when considering the total volume of the layer. It is seldom the deposits of the suspension layer exceed 0,05 m, as the deposits of the dense flow layer usually are 2-5 m and may be 10 m or more.

The recirculation layer.

The flow of the snow avalanche results in a compression of the air in front of the avalanche, and the development of vacuum at the tail, which results in a backflow above and around the avalanche. This backflow or recirculation layer has been recorded by the model experiment at

ETH, and has a height of approximately one to three times the height of the suspension layer (personal communication by Dieter Issler).

The recirculation layer has, to the knowledge of the author, not been discussed in published reports, but has to be existent due to the continuity equations. The velocity in the recirculation layer is probably less than the velocity of the avalanche, and no major velocity gradients are expected to be found within that layer.

3. THE DEVELOPMENT OF THE AVALANCHE AND THE FLOW IN THE STARTING ZONE.

3.1 The conditions at the lower boundary.

The major part of snow avalanches are released as slab avalanches where the lower boundary of the slab is a snow layer with reduced shear strength, the gliding layer. The thickness of the slab may vary between 0,3 m and up to several meters. Immediately after the release of the slab, the avalanche starts to accelerate, showing that the dynamic shear strength of the gliding layer has to be smaller than the static shear strength.

The transferred shear stresses along the gliding layer will be more and more influenced by the dynamic effects where high velocity gradients develop as the acceleration of the slab progresses. The dynamic shear stresses transferred at the lower boundary can be quantified based on the theories developed by Irgens and presented in Norem et al (1987) and Norem et al (1993), by the following equation:

$$\tau_{dynamic} = 0,01 \rho_s \lambda^2 d^2 \left(\frac{dv}{dy}\right)^2 \qquad 3$$

where: ρ_s=density of the particles
λ=linear density ($\lambda = ((0,74/c)-1)^{-1}$)
c=volumetric density
d=particle diameter
dv/dy=velocity gradient

Eq. 3 describes that the dynamic shear stress is increasing with the square of both the linear density, (which will vary between 5 and 10), the average particle diameter and the velocity gradient.

The back-calculation of recorded major snow avalanches has been made by selecting the following parameter values to give a dynamic drag at the lower boundary to $0,2v^2$ (Pa for v in m/s)for avalanches with a flow height of 1,5 m (Norem and Bakkehøi 1992).

To obtain the same dynamic shear stress for a typical avalanche in the accelleration stage with lamda=5 (c=0,43) and the particle diameter to 0,01 m require the thickness of the gliding layer at 10 m/s velocity to be 0,25 m. It is thus a requirement for the high velocities of snow avalanches that the gliding layer gradually disintegrate into small particles and develop in thickness.

3.2 The conditions at the upper boundary of the dense flow part.

At the upper boundary of the slab, velocity-dependent shear stresses will also be generated due to the velocity gradients caused by the flowing slab and the air above in rest. Schieldrop, in Norem et al (1991), quantified these stresses by comparing the flow of the slab with boundary layer theory for turbulent flow over a flat, rough plate. Based on the experimental results of Schlicting (1968) the shear stress at any point at the upper boundary was estimated to:

$$\tau = \rho v^2 [\, 2.87 + 1.58 \log(x / k) \,]^{-2.5} \qquad 4$$

where: ρ=the density of the fluid above the plate (air)
v=the velocity at the top of the slab
x=the distance from the front of the slab
k=the roughness of the plate

The roughness length, k, has to be determined by qualified guessing. Bagnold (1962) considered ripples formed on the beds of sand or silt and concluded that k would be likely to be found somewhere between the ripple length and the particle diameter. Thus k will probably be in the range of 0.01 and 0.2 m, and 0.1 m has been selected for the further analyses.

The highest shear stresses given by eq.4 are found close to the front of the avalanche, Fig 3. This figure presents the shear stress for a slab moving whith a velocity of 10 m\s. The shear stress 5 m from the front is 0.8 Pa, and 100 m from the front it is reduced to 0.38 Pa. The shear stresses at the upper boundary are thus insignificant compared with the shear stresses at the lower boundary and has no influence on the acceleration and the maximum velocity of the avalanche.

Fig. 3 also presents the magnitude of the shear stresses transferred to the snow cover by a wind of 10 m/s velocity blowing over a snow covered surface. The data are based on the estimates made by Liljequist (1957) from the Antarctic.

The value of 10 m/s is selected since this wind velocity is known as the lower limit for significant snow drifts to occur. Fig.3 shows that the shear stress at the front of the avalanche at this velocity is 3-4 times the wind shear stress, and 1.5 higher 100 m or more from the front. The shear stresses at the upper boundary of the slab is thus well above the necessary shear stresses to erode and bring snow particles into saltation or suspension.

It is the opinion of the author that the high shear stresses found at the front of the avalanches explain the generation of the snow cloud, and particularly the intense activity that are visible at the front.

There are three modes of transportation of drifting snow particles; creep, saltation and suspension (Mellor 1965). The three modes of transportation are dependant on the magnitude of the shear stresses at the boundary and the diameter and the density of the particles that are eroded and transported. Creep is found where the shear stress is small, and the particles are then rolling along the boundary surface. Saltating particles are dominant at shear stresses where the lift and drag on the particles are just sufficient to lift them a short distance from the surface. Saltation represents the major transportation mode in drifting snow up to wind velocities of 10-12 m/s. At higher velocities, suspension is the dominant transportation mode.

It is likely to assume that the same transportation modes also are found at the upper boundary of the dense flow part, as in both cases there are generated shear stresses that cause the erosion and the transportation of the particles. In the present case there are, however, the erosive surface that moves below a fluid in rest. The high shear stresses found at the boundary, particularly at the front indicate that most of the particles are transported as suspended particles, and the snow cloud thus has to be generated close to the front of the dense flow part. However, a significant part of the particles should also be transported in saltation, particularly more heavy particles.

Bagnold (1954) and Liljequist (1957) have shown that the effect of the saltating particles on the flow is to increase the roughness height of the surface. The roughness height of o,1 m that has previously been assumed may thus be too small when the saltation process has been developed.

Unfortunately, the author has not found any publications on the relationship between the shear stress at the boundary and the rate particles are brought into saltation and suspension. It is thus not possible to estimate how fast the turbidity part of the snow avalanche can develop. This need to be an important issue for further research on the flow of the turbidity part.

4. THE FLOW CONDITIONS AT THE PART OF THE SLOPE WITH STEADY FLOW.

4.1 Definition of steady flow conditions

Steady flow is defined as a flow stage where both the velocity and the flow height at the observed point are independent with time.

For snow avalanches there will always be an exchange of energy and particles between the different flow layers. Obviously, there cannot be any pure steady flow for snow avalanches, and one should be careful to use this scientific expression.

In the present report the expression "steady state" is used for the part of the avalanche slope where all gradients with time is very small, and the flow may be regarded as an apparent steady state flow.

4.2 Presentation of the velocity and density profiles based on experimental data.

Our knowledge on the vertical velocity and density profiles are mainly based on the following kinds of experiments:

- Full-scale experiments by recording the impact pressures in different heights.
- Radar detection of snow avalanches.
- Model experiments with granular materials
- Theoretical studies on the rheology of granular materials, and their behaviour in gravity flows.

The following is a concentrate of our knowledge at present on the vertical profiles for the density and the velocity for the different flow layers, Fig 4.

The dense flow layer

To the knowledge of the author there is only reported one velocity profile for snow avalanches (Gubler 1987), Fig 4. This profile indicates small velocities at the lower boundary, high velocity gradients above that boundary, and indications of plug flow at the upper part of the flow layer.

Nishimura (1990) has presented velocity profiles of model experiments with non-cohesive snow. His recorded velocity profile had no slip (zero velocity) at the bed, and gradually increasing velocity with height.

The constitutive equations developed by Norem et al (1987) for snow avalanches gives a theoretical velocity profile increasing with height with a power of 3/2, plug flow for cohesive snow, and there also might be assumed a slip velocity at the bed. The profile can easily be matched reasonably well to the profile recorded by Gubler (1987) and is consistent with the model experiments performed by Nishimura (1990)

A velocity profile as proposed by Norem et al (1987) with no-slip conditions is probably a reasonable assumption for the velocity profile, at least when the erosion is non-significant. The theoretical profile is developed by assuming constant diameter of the snow particles. Savage and Lun(1988) have shown by model experiments that the small particles have a tendency to concentrate close to the bed. If this is true also for snow avalanches the velocity profile should be more blunt (higher velocity gradients at the bed).

The impact pressures of major dry snow avalanches recorded by the Ryggfonn full-scale experiments clearly shows that the highest impacts are found some distance from the lower boundary. These findings have to be explained by a velocity profile having almost no-slip conditions at the lower boundary and highest speeds at the upper boundary. These experimental results also confirm the recorded velocity profile by Gubler (1987)

There exist theories indicating that the volumetric density of the dense flow layer may either increase or decrease towards the lower boundary. Model experiments show no significant difference with height for granular flow in the liquefied phase (e.g. Nishimura 1991).

One may argue that the high velocity differences found close to the bed give conditions for a reduced density in that area. On the other hand the weight of the overburden will try to densify the flowing granular material. There is nothing in the theories for liquefied granular materials that are exposed to high normal stresses that can explain a significant reduction in the volumetric density. One can thus assume that the volumetric density is almost constant with depth in the dense flow layer.

The saltation layer

The particles involved in saltation leaves the erosive surface with the same velocity in the flowing direction as the velocity of the surface. In the present case this will be the velocity at the upper boundary of the dense flow layer. When exposed to the air above the particles are slowed down or accelerated dependant on the velocity difference between the dense flow and the suspension flow layers,

Bagnold (1941) has analysed the behaviour of saltating particles, and has shown that the main effect of the particles is to increase the roughness of the surface. There will thus be an exchange of energy between the air and the eroded particles; the transferred energy to the particles results in a reduced flow velocity at a certain level.

In the present case, with the suspension flow having less velocity than the dense flow, the physical effects are just opposite of that found in the drifting snow conditions. The release of particles with a certain velocity will transfer kinetic energy to the air above and accelerate the air close to the surface. The effect of the saltation is thus that the entrainment and the acceleration of air will be more effective with saltating particles than without.

The velocity profile close to the dense flow layer will be totally dominated by the velocity of the particles, and at this level there will be only small velocity gradients. Higher up, higher velocity gradients are to be expected.

The density profile with height has to be similar with those recorded for drifting snow conditions. Kobayashi (1972) recorded that the density was reduced with a power of three, which is also similar with those recorded by Bagnold (1941). There must therefore be high density gradients with height within the saltation layer.

Kobayashi (1972) recorded the height of saltating particles and found them to be 0.2-0.4 m, for wind velocities of 12-14 m/s. The height of the saltation was assumed by Kobayashi to be dependant on the wind velocity, and to increase linearly with speed. One may thus assume that saltation heights of 1-3 m to be reasonable for velocities at the upper boundary of the dense flow between 60-80 m/s (front speeds of 40-55 m/s).

The suspension layer

The development of the suspension layer has to be explained, as previously discussed, by the erosion of snow particles at the upper boundary of the dense flow part. As more and more particles are brought into suspension, there will be a significant density difference between the suspended layer and the surrounding air. The requirements for a turbidity current to gradually develop are then fulfilled. The development of turbidity currents from current-eroded particles on slopes is for instance analysed by Brørs (1991). It is also known that turbidity currents frequently develop on delta slopes of major rivers in periods with high sedimentation rates.

The front velocity of turbidity currents can be estimated by the expression presented by Simpson (1982), and which is based on model studies:

$$v = \frac{\sqrt{2}}{2}\sqrt{\frac{\Delta\rho}{\rho}gH} \qquad 5$$

Where: $\Delta\rho$=density difference between suspension layer and the surrounding fluid
ρ=density of the suspension layer
g=coefficient due to gravity
H=flow height of the suspension layer

Eq. 5 describes that the critical product of the density ratio and the flow height to obtain a front velocity of 30 m/s is 183 (m). This will be obtained with a flow height of 30 m and a density ratio of 6, which represents a volumetric density of 0,7%.

The vertical density and velocity diagrams have been studied extensively by model experiments, and maybe the results presented by Hermann et al (1987) are among the most reliable. Their experiments indicated an almost linear decrease of both the velocity and the density with height. They found, however, a small maxima for both parameters a short distance above the bed surface.

The physical conditions for the model experiments and for the natural snow avalanches are quite different. The natural avalanches have a surface below the turbidity current that moves with a higher velocity than the turbidity current, and the model slides flow above a fixed surface. The directions of the shear stresses at the bed are thus opposite.

The development of the suspension layer to a magnitude sufficient to behave as a turbidity current layer, thus gives a tendency to reduce the shear stresses at the boundary between the dense flow and the turbidity layer. The fact that the highest densities are found close to the surface indicates, however, that the highest shear stresses and intensity of turbulence are found at this boundary, compared to the other boundaries of the turbidity current part.

The density in the transition zone between the saltation and the suspension layer is difficult to estimate. The back-calculations of the Ryggfonn impact pressure recordings may indicate an approximate density of 10 kg/m^3, which corresponds to a volumetric density of 1,3 %. A rough estimate with an average density of 0,6%, and a flow height of 30 m, makes an evenly distribution of the deposits of the turbidity part to approximately 0,25 m. Based on the experience from recording the deposits of snow avalanches this may seem to be a little too high. On the other hand, the deposits are often distributed over large areas, so the rough estimate may give an expression for the volumetric density often found in the snow cloud of snow avalanches.

4.3 Presentation of the resulting shear stress diagram

There is a close relationship between the shear stress diagram on one side and the density and the velocity profiles on the other side, since the shear stress for Newtonian fluids is the product of the dynamic viscosity and the velocity gradient.

The dynamic viscosity of granular materials are extensively studied, and numerous relationships between the volumetric density and the viscosity has been proposed. For the present report it is sufficient to conclude that all relationships propose that the viscosity increase more than linearly with the density, and for densities above 25%, the increase is a lot more than linearly. The highest shear stresses are therefore to be found in the dense flow part of the flow, and within the layers with highest velocity gradients.

The dependency between the shear stress and the velocity gradient gives the following important guidelines for the relationship between the shear stress diagram and the velocity diagram:

- Positive shear stresses (in Fig 5) gives a velocity diagram increasing steadily with height.
- Zero shear stress gives a velocity maxima or minima.
- Negative shear stresses gives reduced velocity with height.

In the steady flow case the actual shear stress diagram also have to be identical to the shear stress diagram given by the acceleration shear stresses. These stresses are the slope parallel component of the submerged weight of the avalanche, given by the equation:

$$\tau = {}_y\int^H \Delta\rho g \sin\alpha dy$$

Where: Δρ=submerged density
H=Total flow height
y=distance from the lower boundary(bed)
α=slope angle

The shear stress diagram presented in Fig 5 is based on the following assumptions:

Suspension layer:	Flow height:		20 m
		Average vol. density:	0,001(ro=8 kg/m^3)
Saltation layer:	Flow height:		1 m
		Average vol. density:	0,01 (=57 kg/m^3)
Dense flow layer:	Flow height:		2 m
		Average vol. density:	0,3 (ro=210 kg/m^3)

The resulting shear stress at the three boundaries are 17,5, 105 and 2205 Pa respectively.

The downward directed shear stresses need to be counterparted by shear stresses at the lower and upper boundary, and which in sum are equal the total submerged weight component.

The shear stress at the upper boundary of the suspension layer need to be a friction stress since the velocity in the flow direction is smaller above than beneath the boundary layer. The velocity gradients at this boundary are probably small, which is the same for the volumetric density, and the magnitude of the shear stresses at the upper boundary thus have to be small compared to the conditions at the more dense part of the avalanche.

The shear stresses at the upper boundary are necessary to generate the recirculation flow. The shear stress diagram for the recirculation layer need to have a pattern as presented in Fig 5. Above the boundary the shear stress is gradually reduced, and a velocity maxima for the recirculation layer is found where the shear stress is zero. Higher up the velocity and the velocity gradient in the recirculation layer is reduced to zero, and the shear stress also need to be zero at the upper part of the recirculation layer.

Below the upper boundary of the suspension layer the shear stress diagram is increasing steady toward the bed. At a certain point, the shear stress need to be zero, and the maximum avalanche velocity has to be found at this level.

The magnitude of the shear stress at the upper boundary of the suspension layer is obviously dependent both on the velocity of the avalanche and the volume of the recirculated air, and probably most dependant on the velocity. For a given flow velocity the height of the point with zero shear stress is mainly dependant on the submerged weight of the suspension and the saltation layer. With only small amounts of particles in saltation or suspension, the zero shear stress will be found in the dense flow layer, which is similar to the acceleration stage previously discussed. When the avalanche contains more particles in saltation or suspension, the zero shear stress is found in either of these two layers.

Zero shear stress in the saltation layer means that the particles gain velocity due to the effect of gravity during each saltation jump. The saltation layer will in this case contribute to the flow of the avalanche.

Similar analyses can be made for the case when the zero shear stress is found in the suspension layer. In this case the suspension layer has a maximum velocity above the velocity of the dense flow layer. A further increase of the height with zero shear stress probably indicates that the average velocity of the suspension layer is higher than the respective for the dense flow layer. This represents the conditions in the runout zone where the snow cloud bypass the dense flow layer.

In the case of a pure turbidity current flow, either a pure powder snow avalanche or after the turbidity layer has bypassed the dense flow layer, both the upper and the lower boundary have to have frictional shear stresses, and zero shear stress has to be found some distance above the bed. This is consistent with the experimental results of Hermann et al(1987), who found both a velocity and a density maxima a short distance above the bed.

4.4 Variations in the flow direction

The dense flow layer

The impact pressure measurement on the load cells in the Ryggfonn full-scale experiments shows that the impacts develop usually over a very short time (Norem et al 1983-1991). This indicates that the front of the dense flow layer is relatively steep and distinct. This may be explained by additional friction at the front due to ploughing and increasing dynamic shear stresses for thin flow layers. There is thus probably that particles from the core of the avalanche continuously bypass the front particles and create a new front, like a caterpillar belt.

The highest impacts of major snow avalanches are usually recorded 5-10 second after the first impacts. There is also a tendency to record the high impacts on the upper load cells at the same time as the time of the maximum pressure. Both the maximum height and the maximum velocity thus have to be found in the core of the avalanche.

The saltation and the suspension layers

The Ryggfonn impact measurements were made both on load cells up to 4 m above the ground, and on cables located 8, 12 and 16 m above the ground. The time of the impacts for major snow avalanches indicated that the front of the dense flow in the steep part of the slope is 20-40 m ahead of the front of the snow cloud. These measurements have been taken as a proof that the saltation and suspension layer is generated due to the high shear stresses at the upper boundary of the dense flow layer. The highest impacts of the snow cloud are also recorded close to the front of the cloud. The highest densities are thus probably found where the generation of turbulence has a maximum.

The height of the suspension layer increases with the distance from the front of the avalanche, as new particles are brought into suspension at the front. The shear stress on the upper boundary of the dense flow layer will thus be reduced due to the submerged weight component of the suspension flow, and the shear stress at the saltation-suspension transition zone has to be close to zero. Saltation is closely related to shear stresses generated at a boundary layer, and probably the process of saltation plays only a minor role at the core and the rear of the avalanche.

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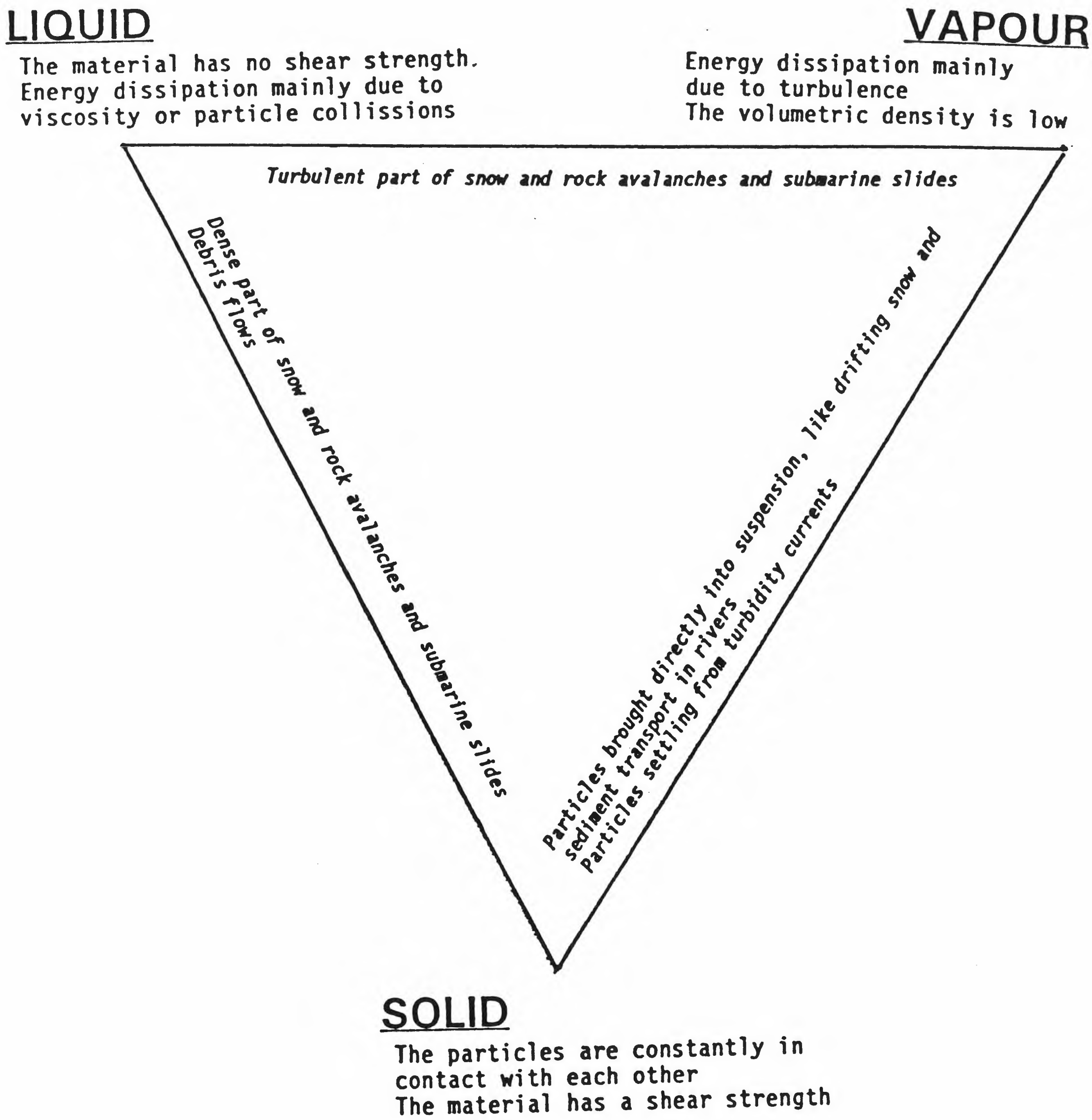
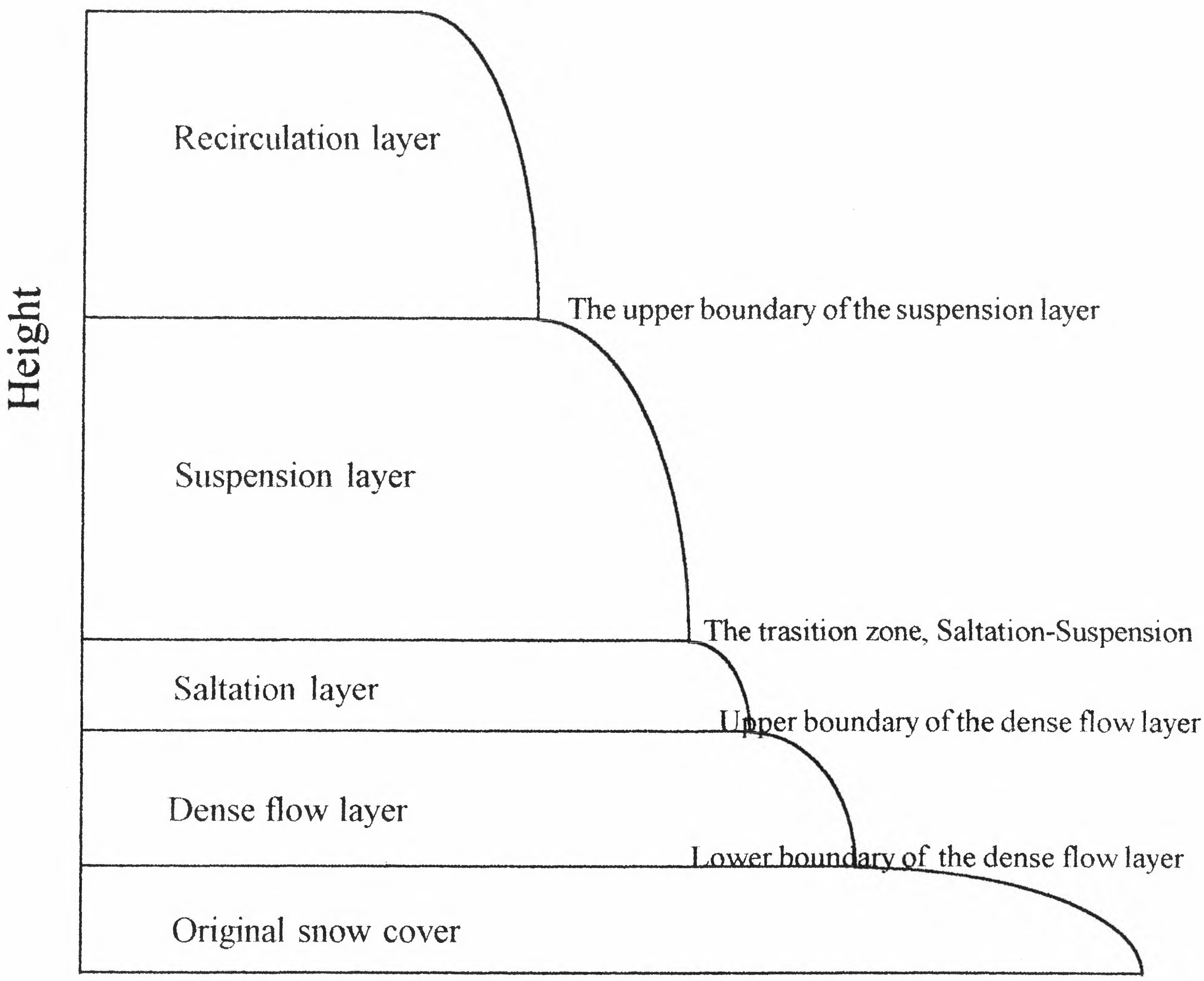
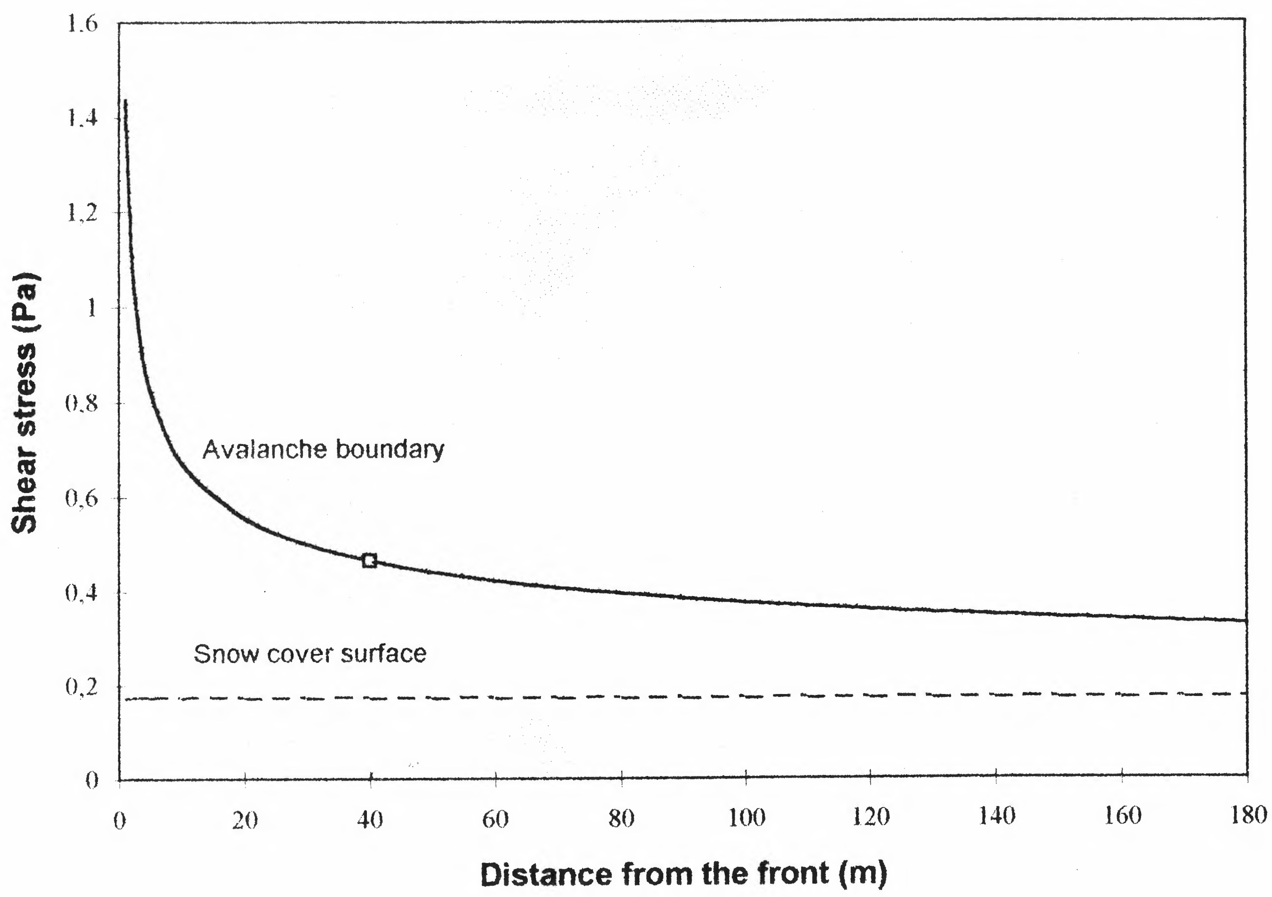


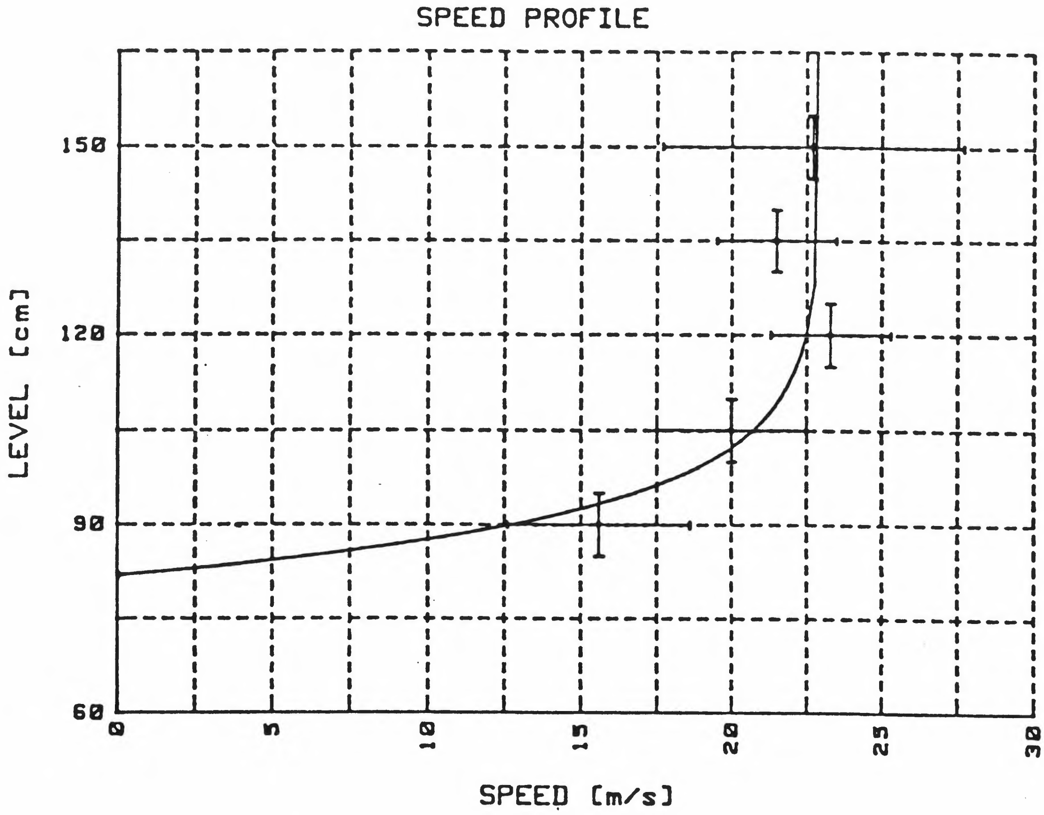
NORWEGIAN GEOTECHNICAL INSTITUTE	Report no **A951-1**
Flow layers and boundaries in snow avalanches	Figure no **1**
Phase diagram for granular materials. (Norem 1995)	Date 95.10.19
	Drawn by HN *HN*
Dr. ing Harald Norem, Consultant in snow engineering	Scale



NORWEGIAN GEOTECHNICAL INSTITUTE	Report no **A951-1**
Flow layers and boundaries in snow avalanches	Figure no **2**
Definition of the flow layers and the boundaries between the layers	Date 95.10.19
	Drawn by HN HN
Dr. ing Harald Norem, Consultant in snow engineering	Scale



NORWEGIAN GEOTECHNICAL INSTITUTE	Report no **A951-1**
Flow layers and boundaries in snow avalanches	Figure no **3**
Shear stresses generated on the upper boundary of the dense flow layer, and wind shear stresses on a snow surface. Avalanche and wind velocity: 10 m/s.	Date 95.10.19 Drawn by HN HN
Dr. ing Harald Norem, Consultant in snow engineering	Scale



NORWEGIAN GEOTECHNICAL INSTITUTE	Report no **A951-1**
Flow layers and boundaries in snow avalanches	Figure no **4**
Velocity profile of a snow avalanche recorded by radar measurements .(Gubler 1987)	Date 95.10.19
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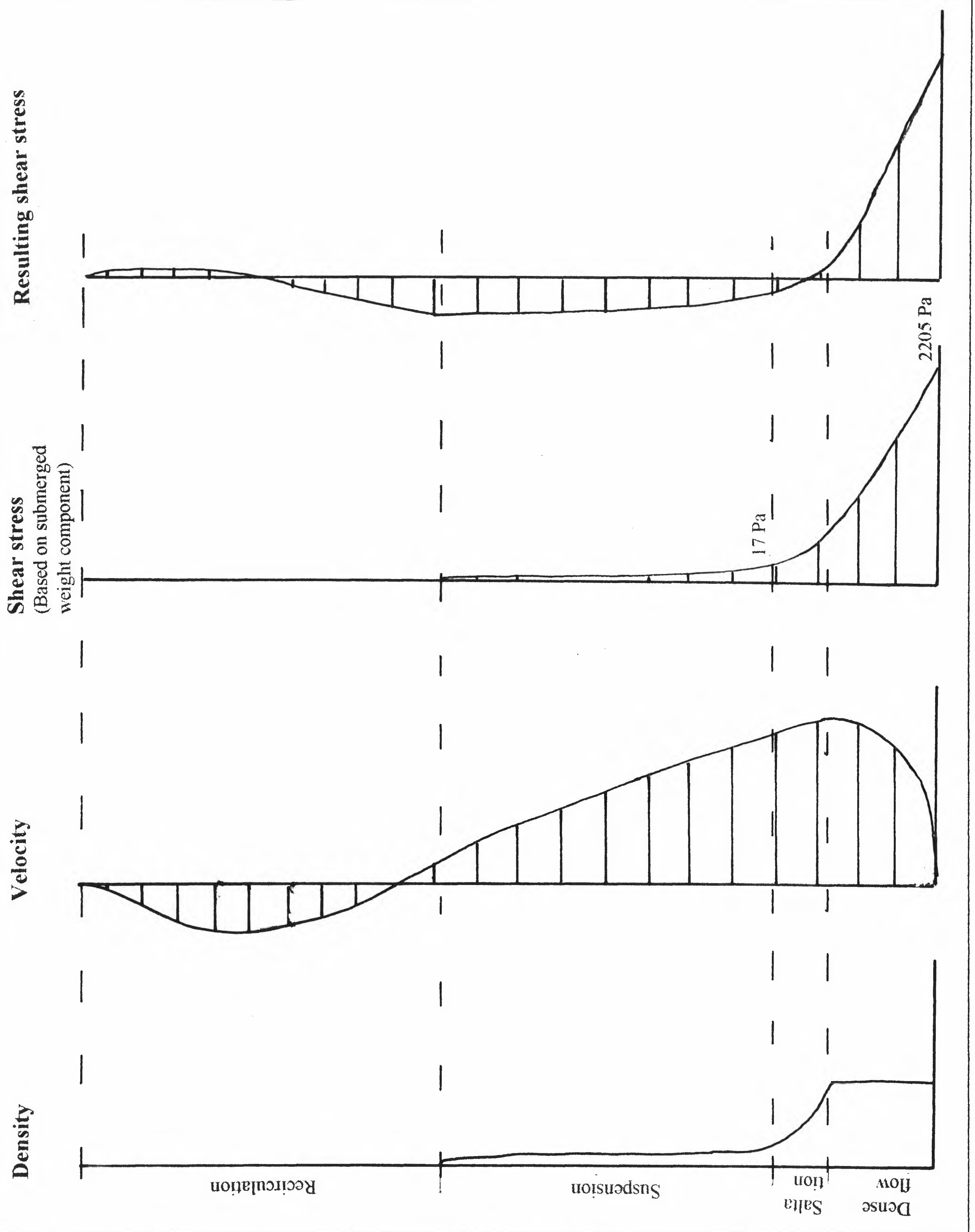
Dr. ing Harald Norem, Consultant in snow engineering	Scale



NORWEGIAN GEOTECHNICAL INSTITUTE	Report no **A951-1**
Flow layers and boundaries in snow avalanches	Figure no **5**
Assumed vertical density, velocity and shear stress profiles for snow avalanches in the steady flow stage	Date 95.10.19 Drawn by HN *HN*
Dr. ing Harald Norem, Consultant in snow engineering	Scale

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