DENSITY, VELOCITY, AND FRICTION MEASUREMENTS IN A DRY SNOW AVALANCHE

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ABSTRACT

A small avalanche path near the Bridger Bowl Ski Area in Southwestern Montana has been instrumented to measure density, velocity, and dynamic friction in a flowing avalanche. These measurements, made by an array of sensors mounted in the avalanche path, have been carried out for several dry snow avalanches. Measurements of density were made using a capacitance probe developed by Michel Louge (Louge et al 1997). The capacitance probe measures the dielectric constant of any material that passes in front of it. Through a calibration procedure, the dielectric constant ofa given type of snow can be related to the density of that snow. Optical sensors were used to measure light reflected from the avalanche as it passed by the sensors. Signals from adjacent optical sensors were cross-correlated to determine velocity. Density and velocity measurements were made at several heights in the avalanche, with particular attention directed near the running surface. Vertical resolution of the capacitance probe and optical sensors is 5 mm and 8 mm respectively. Results indicate that avalanche deformation is concentrated near the running surface where the snow density is found to be the largest. Upward from the surface the velocity gradient falls off greatly while the density also declines.

Finally, the dynamic friction coefficient atthe base of the avalanche was found by measuring shear and normal forces on a roughened 23 cm x 28 cm aluminum plate mounted parallel and flush with the avalanche running surface. The ratio of the shear force to normal force on the plate provides a measure of the dynamic friction coefficient at the base of the avalanche.

INTRODUCTION

In order to predict avalanche runout distances, models of avalanche dynamics have utilized linear and non-linear fluid constitutive representations (Salm 1966, Perla et al 1980, Dent and Lang 1983). Unfortunately many of these constitutive models have not worked well because they contain parameters that are not easily measured. To use the models, they must first be "calibrated" by modeling known avalanches. Model parameters are back calculated by matching speeds and final runout positions. These model parameters must then be correlated with avalanche type, size and terrain until enough experience is gained to allow the parameters to be estimated for different kinds of avalanches. This procedure permits virtually any model to be "calibrated". It also presents difficulties in new or unique situations. Lately other less empirical models of avalanche motion have been proposed. These models are based upon mechanical properties of snow that can be measured. Most notable are the granular flow models, which treat an avalanche as a collection of individual snow grains (Dent 1994). However, due to a lack of detailed flow information, evaluation of these models is also difficult. In order to build better models of snow avalanche motion more information about that motion needs to be gathered.

REVOLVING DOOR AVALANCHE PATH

An avalanche experiment facility has been constructed on the Revolving Door avalanche path near the Bridger Bowl Ski Area in Southwestern Montana. The path is about 100 m long on a nearly uniform 35^0 east facing slope. A bowl shaped starting zone provides snow for avalanches of up to 1.5 m deep. Near the middle and slightly off to one side of this avalanche path, an instrument shed has been constructed behind the protection of a large automobile-sized rock. The shed is about 2.5 m square and 2 m high. Both the rock and the shed become mostly buried by the mid-winter snowpack. By removing snow from the track beside the rock and wall of the instrument shed, the top 30-40 cm of one wall of the shed parallel to the avalanche flow direction can be exposed to avalanches as they descend the Revolving Door path. A bomb wire is used

Figure 1 - *The Revolving Door avalanche path looking up slope from the instrument shed.*

to hang an explosive charge in the avalanche starting zone. Triggered avalanches flow down the path, over the buried rock, and along the exposed wall of the instrument shed. Instrumentation mounted on this wall is used to measure flow properties as the avalanche goes by. Prior to each avalanche test new snow must be removed from in front of the shed to a depth that exposes the instrumentation. Care is taken to smooth the slope in front of the shed and for at least 10 m upstream. This provides the avalanche a smooth constant slope on which to travel as it passes the instruments. Finally, the shed is fitted with a large window that allows the avalanche to be observed and photographed from inside the shed.

OPTICAL SENSORS

Mounted in the wall of the instrument shed are an array of photoelectric sensors. Each 7.3 mm diameter sensor is comprised of an unfocused infrared light emitting diode (LED) and an infrared sensitive phototransistor. These sensors, manufactured for use in industrial counting applications, are quite rugged and cost only $2.00 U.S. each. The LED and phototransistor are mounted in the instrument shed wall to look out at the avalanche as it passes. Light from the LED is back scattered by the avalanche to the phototransistor where it is registered as base current in the transistor. The base current determines the amount of current conducted between the emitter and collector of the transistor. The simple circuit shown in figure 3 produces a voltage output that is

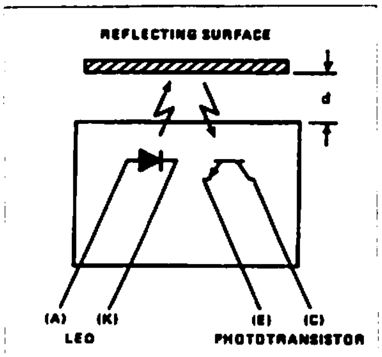

Figure 2 - *Optical sensor operation.*

proportional to the light intensity seen by the phototransistor. The amount of infrared light reflected from the snow surface is a function of the structure and density of the snow. Since that structure and density changes from point to point in the avalanche, the amount of light reflected from the avalanche varies with time as the avalanche passes the optical sensor. A second sensor placed a short distance downstream from the first, sees nearly the same snow patterns. The output of the two phototransistors produce similar time varying signals with the second lagging the first by a short time. Finding the time lag between the two signals enables the velocity of the snow to be calculated.

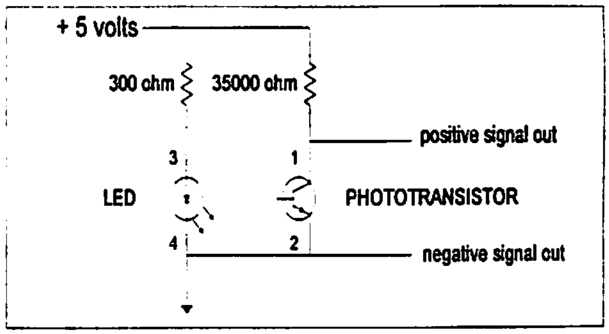

Figure 3 - *optical sensor detection circuit*

CAPACITANCE SENSORS

Michel Louge (Louge et al 1997) has developed a capacitance probe that can be calibrated to measure snow density. The device measures the dialectric constant of material that passes in front of it by sensing the impedance change that occurs in a connected bridge circuit. The sensitivity of this probe can be increased by three to six orders of magnitude by eliminating stray capacitances at the probe and in the connecting cables. This is done by surrounding the probe sensor and connecting cable with a conducting guard that carries a signal of precisely the same sinusoidal voltage as the sensor. External influences that would distort the field lines in the capacitor or in the

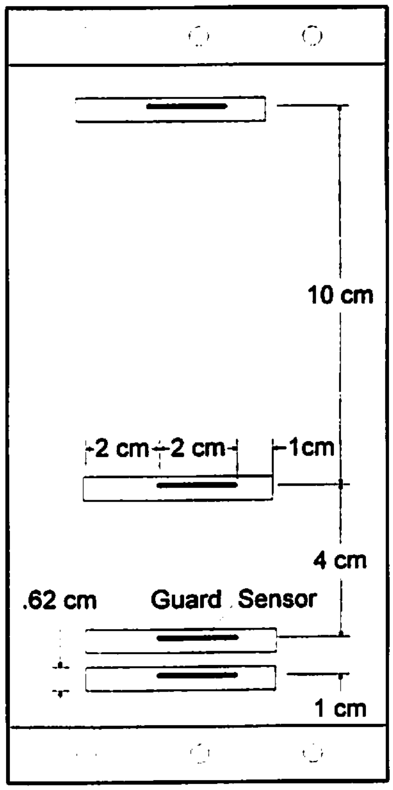

Figure 4 - *Capacitance wall probe. Flow is from left to right.*

cable are shielded from the sensor by this guard and are thus eliminated. For our application a flat wall probe was constructed to mount in the wall of the Revolving Door instrument shed. The probe sensor plate consists of a 1 mm high by 20 mm long brass strip surrounded by an anodized aluminum guard. The electric field lines emanate from the brass strip and terminate on the aluminum body of the probe. With the avalanche flow parallel to the sensor strip the probe measures the inductance in a volume about 20 mm wide, 5 mm high, and 2.7 mm into the flowing snow. The inductance measurement is converted to a density measurement by calibrating the probe with samples of snow of known density.

SHEAR BOX AND DEPTH GAUGE

Shear and normal stresses were measured using a shear plate. The shear plate is a roughened 23 x 28 cm aluminum plate. The plate is mounted in a sturdy box by two cantilevered arms. Each arm is fitted with strain gauges top, bottom, and sides, which then connect in a Wheatstone full bridge configuration. The box is rigidly mounted to the side of the instrument shed below the avalanche running surface so that the plate is flush and parallel with the surface. As the slide flows over the plate, the cantilevered arms deflect parallel and normal to the flow direction. This deflection is recorded as voltage changes across the Wheatstone bridge. Signals from the two arms are averaged to produce a measure of the plate's total normal and shear deflection. These deflections are converted to forces using a calibration curve produced by placing a series of known weights on the plate and recording the bridge voltage.

In order to measure the flow depth of the avalanche as it passes the instrument shed, a small skid plate was attached to a one meter light aluminum arm. The other end of the arm was attached to a rotary potentiometer mounted 60 cm above the snow surface. The resistance from the potentiometer provided a measure of the depth of the flowing avalanche.

VELOCITY

Shown in figure 5 is the first one second of output from a 12 optical sensor array for an avalanche triggered on February 3, 1994. On this date only the optical sensors had been installed. In these plots the relative reflection intensity for each sensor is plotted as a function of time. The array consists of pairs of sensors spaced 2 cm apart in the flow direction, with the pairs located 1, 5, 9, 13, 17, and 21 cm from the avalanche running surface. Due to background radiation from the sun each sensor initially reads an intensity of one. As the avalanche arrives the lower sensors in the array pick up the snow and produce a rapidly varying signal in time. Data here was taken at a sampling rate of 2000 Hz, chosen so that at typical avalanche speeds of 7 m/s, snow traverses about ½ of the optical window of each sensor. Snow structures lasting from 1 time step to

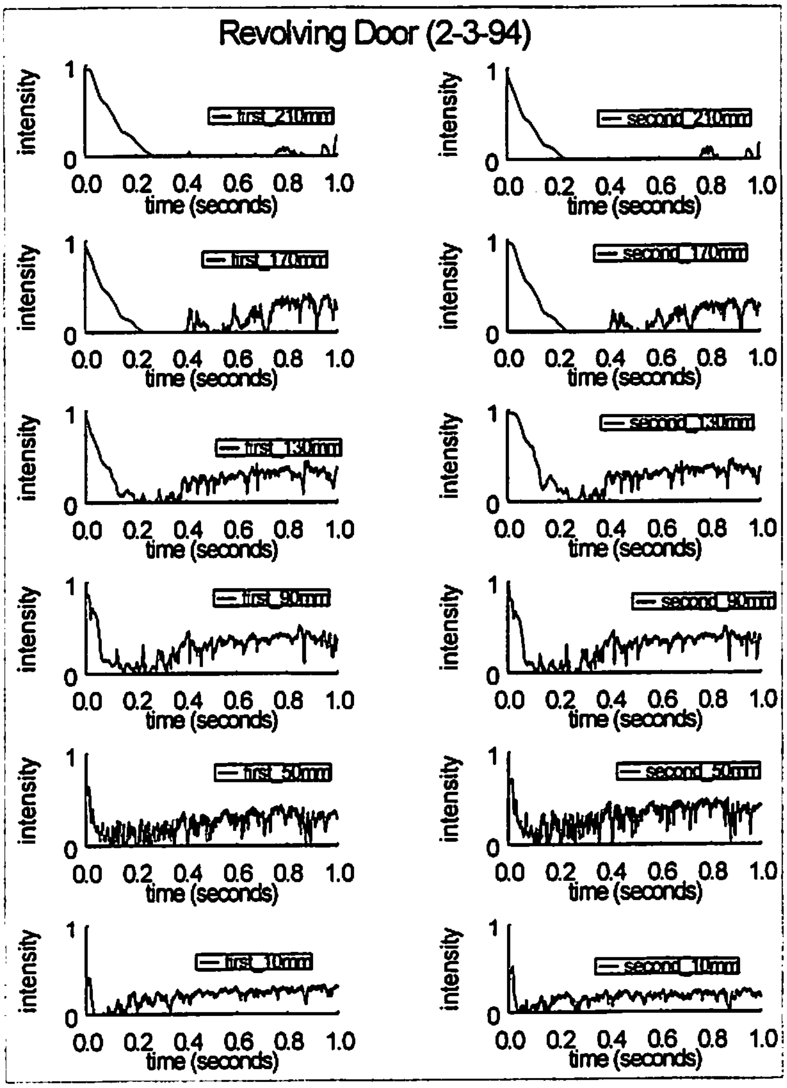

Figure 5 - *Normalized optical sensor reflection measurements taken at a rate of 2000 Hz.*

many time steps can be seen in the data. The magnitude of the back scattered light depends upon the type, size, and orientation of the snow crystals in the avalanche. In addition, the intensity of the reflection is also sensitive to sensor mounting. Attempts were made to correlate reflection intensity with snow density. These attempts failed because crystal size and type were found to be more important in determining signal strength than was the density.

In figure 5, the passage of a powder cloud may also be seen. It shows up as a decrease in the light intensity reaching each phototransistors at the beginning of the avalanche. The powder cloud progressively shades the sensors from the sun, yet doesn't reflect enough light from the LED to be picked up by the phototransistor. For the most part, the top sensors at 21 cm see only the powder cloud, which indicates that the core of this avalanche never exceeded 21 cm in depth. Visual observation put the apparent depth of the avalanche at over 1 m, but what was observed was the cloud surrounding a flow of dense snow that was less than 21 cm deep.

Data from sensors at the same height are plotted next to each other in figure 5. Looking at these pairs of plots it is easy to see that the signals are very similar. Structures that cause a particular response in the upstream sensor are carried by the avalanche to the downstream sensor where a similar response is recorded. Mixing and deformation degrade the structures to varying degrees between the sensors, but similar plots tend to result. The difference in time between similar responses represents the time of transit of a particular piece of snow between the two sensors. That time difference can be used to find the snow velocity. To accurately find the time delay between two correlated signals, x_i and y_i, the covariance function (cross-correlation) ρ_{xy}, between the two signals is computed.

$$\rho_{xy_j} = \frac{\sum (x_i - \bar{x})(y_{i+j} - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2}\sqrt{\sum (y_{i+j} - \bar{y})^2}}$$

The covariance is found as a function of the time delay j, between the two signals. The sums are taken over a fixed interval that represents the specified window in time for which the covariance is found. The time delay, to the maximum covariance is then used to compute the velocity of the snow. The variables $\bar{x}$ and $\bar{y}$ are the window averages of the two signals and j again is the offset in time between the two series of numbers. Typical covariance functions are shown in figure 6 for three different sized data windows all starting at the same time. The data window must be chosen large enough to contain at least one unique feature or multiple correlation peaks become possible as seen for the window of just 4 points (2 ms). On the other hand, if the window is chosen too large, the changes in the snow structure that naturally occur in the flow tend to degrade the correlation. In addition, the correlation found is the correlation for the entire window, which effectively averages the motion of the snow over the length of the window. As a result, if the avalanche is speeding up or slowing down, smaller windows provide more accurate calculations of the instantaneous velocity.

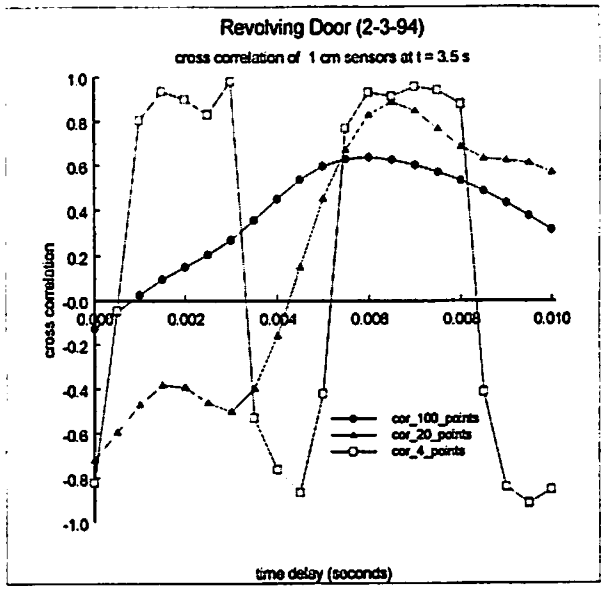

Figure 6 - *Covariance function starting at the same time for 3 different sized data windows.*

Velocities can be computed at different times by shifting the data window to another time period and finding the covariance function. In practice the window is shifted one point forward at a time, and the velocity is found consecutively at each point in time for the data set.

VELOCITY RESULTS

Velocity results for the data in figure 5 above is shown in figure 7. The bottom sensor pair during this time period produced signals that did not correlate well with each other. Because of the poor correlation, most of the velocity measurements were invalid. Possibly a small obstruction or variation in the snow running surface created a flow disturbance near the bottom pair of sensors. The disturbance was eventually worn away or filled in as the avalanche passed, since the problem disappeared and velocities were found later in the flow. A data window of 100 points (0.05 s) was used to calculate these velocities. In general the avalanche is slowing down as it passes the instrument shed, but at any time the velocity is nearly the same at all sensor levels. Also note the passage of the powder cloud. It can be seen clearly in the top three sensors at the beginning of the avalanche as highly fluctuating velocity values. The velocity of the powder cloud was found from the sunlight transmitted through the cloud of varying density. For the top most sensor, the cloud finally becomes too dense for the sunlight to get through and no velocities can be measured.

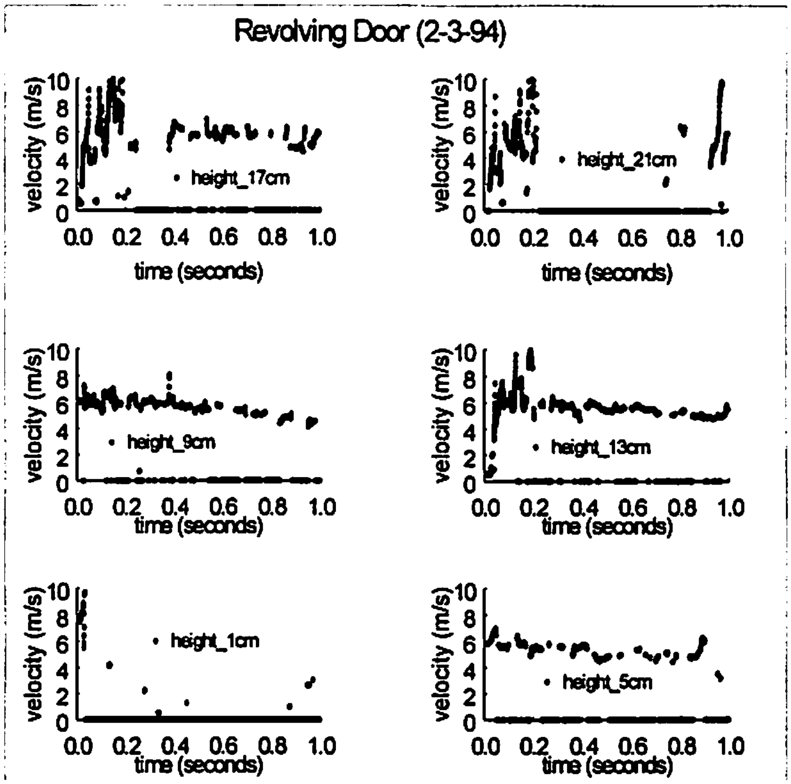

Figure 7- *velocity versus time plots for the avalanche of Feb. 3, 1994 (0.05 s correlation window)*

The data collection system used for this test allowed the first 1.3 seconds of this avalanche to be recorded, then the next two seconds were required to transfer the data from volatile to permanent storage. Then another 1.3 seconds of the avalanche data was obtained. Velocity profiles, plotted at times when a majority of the sensors were providing velocity readings is presented in figure 8. As noted before,

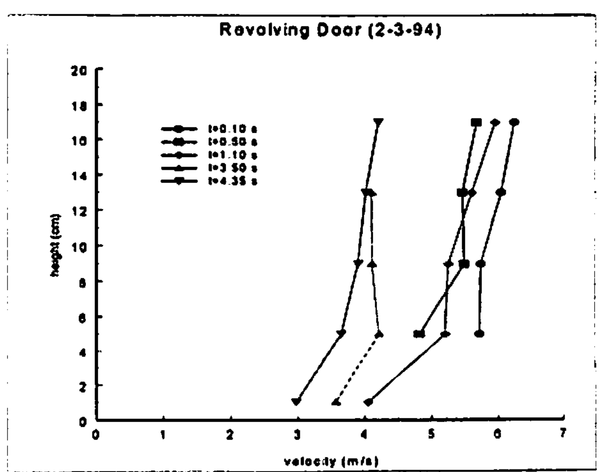

Figure 8 - *Avalanche velocity profiles.*

most of the deformation can be seen to occur below the 1 cm sensor. The avalanche velocity increases from zero at the running surface to 3 - 4 m/s, 1 cm above the surface. The rate of shear is an order of magnitude larger here than in the region above 1 cm. This highly active layer of snow is primarily responsible for the speed of the avalanche, so in order to be able to understand and predict avalanche motion and runout, the mechanics of this thin shear-layer need to be understood.

DENSITY

The capacitance sensors were tested for the first time in the winter of 1996. Unfortunatdy snowfall and wind patterns ended up producing a snow pack in which the Revolving Door avalanche path had a significant concavity in the slope at the instrument shed. The slope at the shed was about 5^0 less than the 35^0 average and as a result, all of our avalanches last year deposited a lot of snow at the shed as they went by. Many of our sensors ended up getting buried in this deposition. Figure 9 shows the avalanche of February 27, 1996. This avalanche ran about 40 cm deep in very cold dry snow. Improvement in the data collection system allowed the collection of 10 seconds of continuous data, sampling at 3000 Hz, however only the first second of the avalanche is shown. A new optical array was also built in which three sensors, spaced 1 cm apart, were mounted at heights of 0.5, 2.5, 8.5, and 20.5 cm. Only 2 out of each of the three sensors is plotted in figure 9. Also shown is the density measurements from the capacitance sensors operatingat the two levels, 1 cm and 6 cm above the snow surface. The capacitance sensors were mounted 20 cm upstream of the optical array.

As snow got deposited next to a sensors the output from that sensor becomes stationary. After 0.1 seconds, snow is seen to quit moving at the bottom optical and capacitance sensors. At about 0.4 seconds the optical sensors at 2.5 cm and the upper capacitance sensor quit seeing moving snow. Then motion stops at the 8.5 cm sensors at about 0.7 seconds. The capacitance sensors show the same type of temporal variation seen by the optical sensors, with fluctuations between 100 and 400 Kg/m^3. This, even though the measurement volume is several times the volume seen by the optical sensors. The capacitance sensors could also be used in correlated pairs to determine velocity.

Data from the capacitance sensors indicate that the snow density at the front of this avalanche is greater than the density later in the flow. A snow pit near the slope showed snow density varying from 80 Kg/m³ at the new snow surface to 280 Kg/m³ in older snow ½ meter below the surface, to 400 Kg/m³ near the bottom of the snow pack 2 m below the surface.

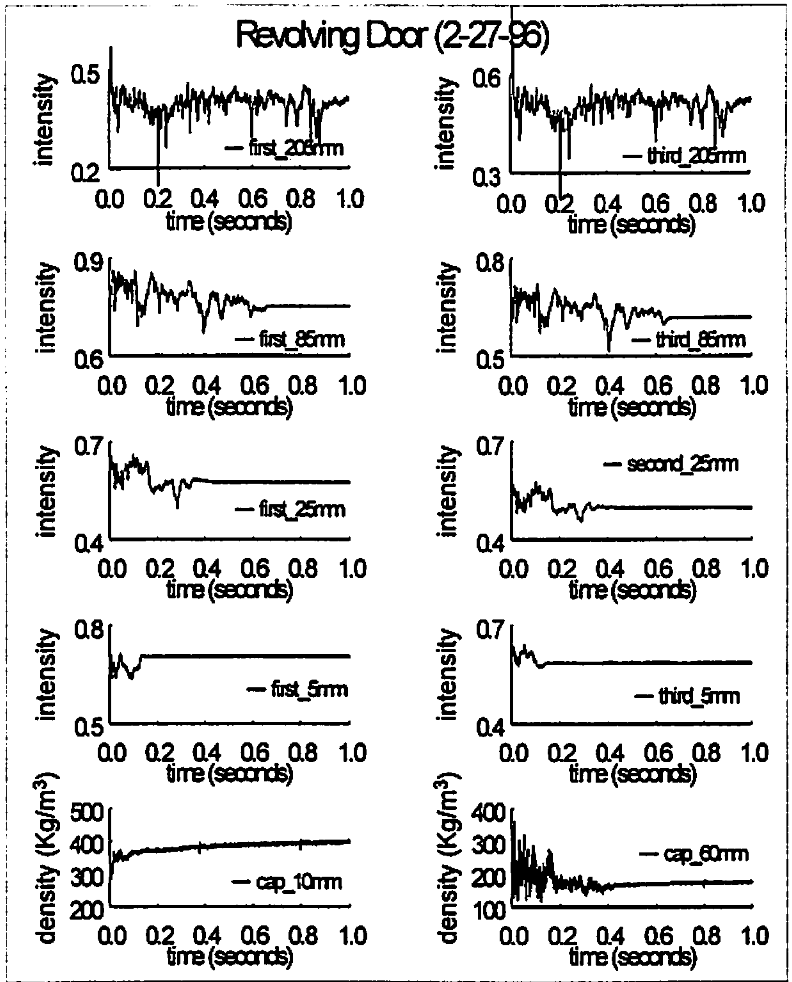

Figure 9 - *Optical and capacitance sensor output.*

From the data, snow around 350 Kg/m³ deposits next to the bottom sensor almost immediately at the front of the avalanche. At the upper capacitance sensor during this time the snow density varies greatly, but averages 250 Kg/m³. In the later part of the flow past the upper sensor the density falls to about 180 Kg/m³, this, even at the bottom of the avalanche when the sensor is being buried. Either, the avalanche front contains more snow from deeper in the snow pack where the snow is more dense, or more likely, the snow at the front has been more ground up to produce an aggregate of snow particles that can be better compacted. If this is the case then snow at the front of the avalanche is getting ground up more than snow at the bottom of the flow later in the avalanche. Additionally figure 9 shows the stationary snow in front of the sensors densifying as the avalanche continues to flow over the snow deposited next to the sensors. The consolidation stops after the avalanche has quits moving. The final density readings of 430 Kg/m^3 at the bottom sensor and 190 Kg/m^3 at the upper sensor compare well with measurements of 400 Kg/m^3 and 250 Kg/m^3 made from 250 cm^3 samples of snow taken from in front of the two sensors.

The velocities for this avalanche, found using 200 point (0.067 s) data correlation windows, are shown in figure 10. Obviously, the avalanche is slowing and the three lowest levels come to rest by t = 0.6 s. Three plots are shown for the velocity taken from the sensors at 20.5 cm. Each plot is from correlating a different pair of the 3 sensors. As can be seen, the velocities found are nearly the same. The difference in the velocity can be attributed mostly to a small variation in the spacing of the three holes in which the sensors are mounted.

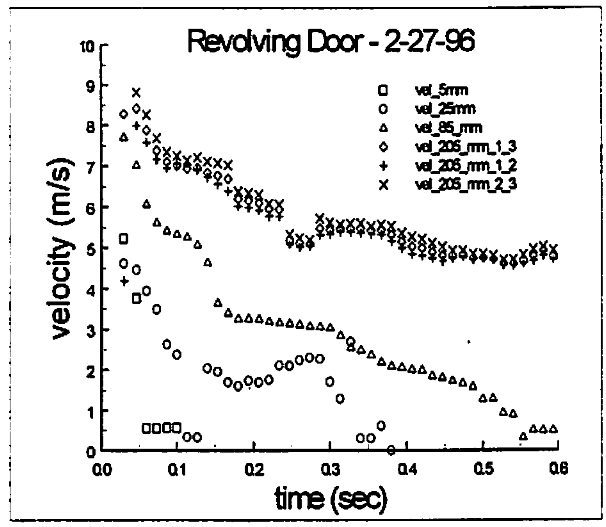

Figure 10 - *Avalanche velocity at 4 depths.*

SHEAR AND NORMAL STRESS RESULTS

On March 30, 1996 an avalanche was triggered with the new shear box and depth gauge installed at the instrument shed. The capacitance sensors were not available for this test. This avalanche was made up of about 20 cm of fresh relatively heavy ($\rho = 275$ Kg/m^3) dry snow. The flow came by the instrument shed in two waves from different locations in the starting zone. The first wave was a shallow flow that came from an area above and to the right of the shed. This flow hit the shed at an angle so that the snow did not flow against the instrument wall. During this first 0.4 s velocities could not be measured. The second wave of snow from the main part of the starting zone was much deeper and overtook the first wave and filled in the area next to the sensors such that the sensors below 8.5 cm never did see moving snow that could be correlated. The upper optical sensors did produced velocity measurements until t = 4.0 s when the avalanche

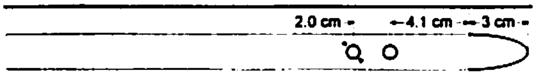

Figure 11 - *Velocity probe. Avalanche flow from right to left.*

was nearly over and dropped below the height of the sensors. A new optical instrument was constructed and used to measure velocities in this test. The probe, shown in figure 11, is a 2 cm diameter cylinder in which optical sensors are placed 2 cm apart. It was mounted on a 15 cm long arm attached to the instrument shed wall 11 cm above the shear plate.

Shown in figure 12 are the measurements of depth, normal stress, shear stress, dynamic friction coefficient, and velocity made during this avalanche. The sharp peak shown at t = 0.6 s for the depth gauge is the foot of the gauge bouncing into the air when the second wave of the avalanche hits the foot at 0.4 s. Later, at the tail of the avalanche snow chunks and powder can be seen going by the depth gauge from t = 5 to 7 s. Using an average snow density of 300 Kg/m^3, the normal stress and depth gauge track each other closely until near the end of the avalanche. From about 0.4 s onward the optical sensors show a deposit of about 10 cm of stationary snow on the shear box. The ratio of the shear-to-normal stress (S/N = 0.42) during the main part of the flow from t = 1 to t =3 seconds is found to be less than the tangent of the slope angle (0.57) in front of the shed , even when the normal stress is reduced by the ~10 cm of stationary snow residing on the plate. The result is accelerating flow as seen by the velocity measurement. As the avalanche comes to rest, the normal stress does not decrease to the static level that would be expected from the 15 cm of deposited snow

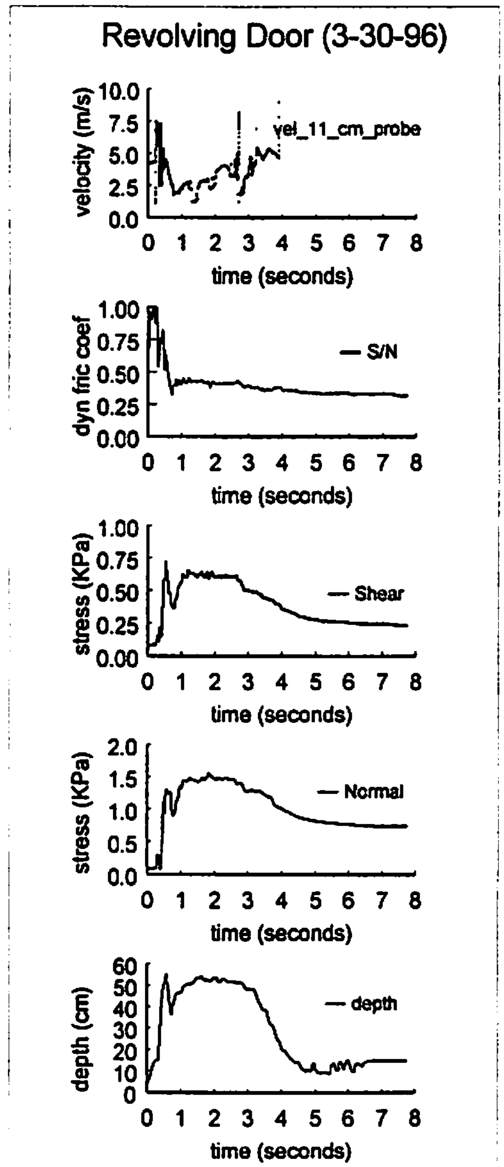

Figure 12 - *Avalanche velocity, normal and shear stress, stress ratio, and depth.*

left at the end of the avalanche. In addition the shear-to-normal stress ratio does not approach the slope angle as it should for an unsupported column of snow. The surrounding snow provides support for the snow on the shear box in such a way that the normal stress reading is almost twice what it should be. If the normal stress is reduced to the value for 15 cm of 300 Kg/m^3 snow on a 30^0 slope (N = 0.4 KPa) the shear-to-normal stress ends up being 0.6 which works out close to the tangent of the slope angle in front of the shed.

CONCLUSIONS

Revolving Door has evolved into an avalanche test facility where instrumentation has been developed to measure velocity, density, depth, shear, and normal stress in a moving avalanche. Several tests have been accomplished, but none where all the instrumentation has been operating at the same time. It remains to collect data on avalanches in various types of conditions in order to determine as much information as possible for use in constructing models of avalanche motion. Also additional instrumentation is being developed to measure air pressure and velocity in the powder cloud or air blast that accompanies the avalanche. Temperature measurements in the flow are planned as well as the use of load cells to measure pressure distribution against various obstacles.

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