VELOCITY AND MASS TRANSPORT MEASUREMENTS IN A SNOW AVALANCHE

J.D. Dent, E.E. Adams, I.J. Bailey, T.G. Jazbutis, and D.S. Schmidt
Department of Civil Engineering
Montana State University
Bozeman, MT 59717
(406) 994-6124 FAX: (406) 994-6105

ABSTRACT

A small avalanche path near the Bridger Bowl Ski Area in Southwestern Montana has been instrumented to measure avalanche velocities in the interior of an avalanche. The instrumentation consists of photoelectric detectors mounted in the avalanche path that measure reflected infrared light from the snow as the avalanche passes by the sensors. A cross correlation of two signals from a pair of sensors then yields the velocity of the snow. A vertical arrangement of photosensor pairs produces a measurement of the avalanche velocity as a function of height within the avalanche. Measurements are also made of how much and from where snow is transported in the avalanche. Topographic surveys are made of the avalanche slope before and after the avalanche has run. Over 450 points are surveyed to accurately define the location of the pre- and post-avalanche snow surface. A comparison of the two surfaces then provides information on where snow has been removed and where it has been deposited by the avalanche.

INTRODUCTION

In order to predict avalanche runout distances, models of avalanche dynamics have utilized linear and non-linear fluid constitutive representations. Unfortunately many of these constitutive models have not worked well because they contain parameters that are not easily measured for snow. To use the models, they must first be "calibrated" by modeling known avalanches. Model parameters are back calculated by matching speeds and final runout position of the avalanche. 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 not only permits virtually any model to be "calibrated", but it also presents difficulties in predicting avalanche movement 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 granular flow models, which treat snow in an avalanche as a collection of individual grains. However, due to a lack of detailed flow information, evaluation of these models also suffers. In order to build better models of snow avalanche motion more detailed information about that motion must be gathered.

One idea that has come out of granular materials modeling (Dent 1994) is the hypothesis that under steady uniform flow conditions a thin granular shear-layer develops at the base of the avalanche. It is in this layer that the majority of deformation in the avalanche takes place. The layer is made up of individual snow particles broken up by the motion of the avalanche as it flows down the slope. The layer occurs as a result of the mechanical forces between those grains and forms most readily when an avalanche flows down a smooth slope with only small terrain irregularities. The main body of the avalanche, which includes all of the mass above the shear-layer, deforms much more slowly than the shear-layer. Its motion can therefore usually be neglected and the avalanche can be approximated as a semi rigid mass riding on top of the shear-layer. The action of the thin shear-layer can be thought of as a retarding force that acts on the base of the avalanche mass. Deformation within the main body of the avalanche contributes only to the spreading and the thinning of the avalanche but not to its speed and overall motion. In order to check this hypothesis a field experiment to measure the velocity profile within an avalanche was undertaken.

VELOCITY PROFILE

Measurements of the velocity profile within an avalanche were carried out last winter on the Revolving Door slide path near Bridger Bowl Ski Area in Southwestern Montana. The path has a nearly uniform 35^0 slope and is about 100 m long. In the middle of this avalanche path, an instrument shed has been constructed behind the protection of a large automobile-sized rock that becomes buried by the mid-winter snowpack. By removing snow from the track beside the rock and adjacent instrument shed, the top 30-40 cm of one wall of the shed that is parallel to the avalanche flow direction can be exposed to avalanches as they descend the Revolving Door path. A bomb wire is used to hang an explosive charge above the snow in the avalanche starting zone. Triggered slides flow down the avalanche path, over the buried rock, and along the exposed wall of the instrument shed. The avalanche can be observed and photographed through an acrylic window fitted in the wall. In addition, instrumentation is mounted on this wall to measure avalanche properties as the avalanche flows by.

Velocity measurements are made using an array of photoelectric sensors. Each photoelectric sensor is made up of an infrared light emitting diode (LED) and an infrared sensitive phototransistor together inside a 7 mm diameter acrylic tube. The LED and phototransistor are mounted in such a way that the phototransistor sees only light from the LED that is reflected from objects that pass in front of the sensor. In this application, as the avalanche passes in front of the sensor, light from the LED is reflected from the avalanche back to the phototransistor. Since the orientation, size, and density of snow grains changes from point to point in an avalanche, the amount of light reflected from the avalanche varies with time as an avalanche passes the sensor. A second sensor placed a short distance immediately downstream from the first sensor (typically 2 cm), will see nearly the same snow patterns that passed by the first sensor. The output of the two phototransistors will thus be similar time varying signals except that the second signal will lag the first by a short amount of time. This is illustrated in figure 1. In these plots the phototransistor output signal has been conditioned in such a way that a signal strength of 1.0 represents no light falling on the phototransistor, that is the sensor is below its threshold sensitivity, and 0.0 represents the maximum reflection, or a saturated condition for the sensor. To facilitate comparing two signals on the same plot, the magnitude of the downstream sensor has been reduced by a value of 0.3. Note in figure 1 that as the avalanche arrives at $t = 0$, the output signal starts from maximum light input (0.0) due to the large infrared background from the sky that saturates the phototransistors. The powder cloud at the leading edge of the avalanche can then be seen as it progressively shades the sensors from the infrared background of the sky. This results in a decreasing input to the phototransistor until no infrared light is detected at all at about $t = 0.2$ s. At this point the powder cloud is thick enough to occlude the sky, but is either not dense enough or the snow particles are not close enough to the sensor to reflect light from the LED. After the core of the avalanche arrives, reflection from the dense snow creates the rapidly time varying signal shown.

The velocity of the snow passing in front of the sensor pair can be calculated from a cross-correlation of the two photodetector signals computed as a function of the difference in time between the two signals. The time difference that produces the maximum correlation between the sensor signals represents the length of time it takes for spatially averaged snow features to travel from the upstream sensor to the downstream sensor. The velocity of the snow can then be calculated from this transit time and the sensor spacing. Using this process a pair of sensors can provide a continuous measurement of avalanche velocity. Several sensor pairs arranged vertically then determine velocity as a function of height as the avalanche flows past the wall of the instrument shed.

VELOCITY RESULTS

In figure 2 results are shown for the velocity measured in the first 1.3 seconds of an avalanche set off February 3, 1994. In this test, 6 pairs of sensors were used. The bottom sensors were mounted 1 cm above the avalanche running surface. The remaining pairs of sensors were mounted upward, perpendicular to the running surface, at 4 cm intervals to a height of 21 cm. The natural snow running surface next to the sensor location was carefully smoothed and graded for a distance of 6 m upslope. This produced a smooth uniform 34^0 surface for the avalanche as it approached the sensors.

For reasons that are not clear, 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. Too much mixing of the snow occurred between sensors. It is speculated that there must have been a small obstruction or variation in the snow running surface that created a flow disturbance near the bottom pair of sensors. The problem with the bottom sensors corrected itself by t = 3.5 s, when correlations increased to provide acceptable velocity data. Perhaps a bump near the sensors was worn away or a cavity nearby was eventually filled as the avalanche passed by. Figure 3 plots the velocities from all the sensor pairs from t = 3.3 s to t = 4.6 s. Other gaps in the velocity shown in figures 2 and 3 are caused by the sensor pairs not correlating to an acceptable degree.

Large variations in the velocity between t = 0.0 s and t = 0.2 s can be seen in figure 2 for the records of sensor pairs 3, 4 and 5. These velocities are from the powder snow cloud at the leading edge of the avalanche. Note from figure 1 (for sensor pair 5) that the powder cloud can be seen to traverse those sensors from t = 0.0 s to about t = 0.4 s, at which time the main flow of the avalanche arrives. From t = 0.0 s to t = 0.2 s the powder cloud is transparent enough so that variations in the density of the cloud can be measured from the transmittance of the background infrared from the sky. Correlations of this signal between the sensor pair produce the valid velocity fluctuations seen at the beginning of the velocity plot for sensor pair 5. From t = 0.2 s to t = 0.4 s the powder cloud becomes too dense, completely blocking light from the sky. The resulting constant signal of 1.0 from the sensors results in invalid velocity measurements. As reflected in figures 2 and 3, the powder cloud traversed sensor pair 6, located 21 cm above the running surface, for most of the recorded time. Thus the depth of this avalanche was less than 21 cm for most of its running length. This result is confirmed by observation and video tape of the avalanche from behind the window in the wall next to the photosensors. Viewed from beside the avalanche path, the depth of the avalanche was observed to be well over 1 m. This reinforces the obvious contention that the dense core of the avalanche is obscured from view by the powder cloud in a dry snow avalanche. Actual avalanche depths are often significantly less than the powder cloud depth observed.

In general, the data in figures 2 and 3 show that for this avalanche, the velocity decreases with time as the slide passes the sensors. The leading edge of the avalanche is moving faster than the back of avalanche. This general trend is interrupted from t = 0.9 s to t = 1.3 s. During this time it appears that some kind of pulse or wave passes the sensors. The snow not only moves faster, but is also deeper during this time. This is most likely due to snow coming from another part of the starting zone that is larger in extent and higher than what initially contributed to the avalanche. Variations in the velocity of up to 1 m/s over time periods of about 0.1 second can also be seen in some of the velocity plots. These variations do not correlate with depth and their origin is unknown.

In figure 4 velocity profiles derived from the data presented in figures 2 and 3 are plotted at times when a majority of the sensors were providing good data. 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 about 3 m/s, at 1 cm above that surface. This is reflected in the data collected after t = 3.5 s. Data from the velocity profile at t = 4.35 s is used to produce figure 5, where the rate at which the velocity is changing is plotted. This shear rate is found to be an order of magnitude larger in the first centimeter above the running surface than anywhere else. At least for this avalanche, a highly active layer of snow no deeper than 1 cm is evident. Above 1 cm the snow deformation is occurring at a rate at least 10 times slower. Although not necessarily negligible in the overall final shape of the avalanche, the shear rate in the upper 19 cm of this avalanche is small enough that the dissipation there can be neglected compared to that occurring in the thin layer at the bottom of the avalanche. Thus the overall speed of the avalanche is primarily governed by the shear force developed in that thin high shear rate layer. To understand and predict avalanche motion and avalanche runout, the mechanics of this thin granular shear-layer of snow that is at the base of an avalanche must be understood.

MASS TRANSPORT

This section of the paper will focus on the survey techniques developed over the last two winters to determine the quantity and relative distribution of snow that moved during each avalanche, including the subsequent calculations and modeling techniques involved. The main objective of this portion of the project was to take conventional survey techniques and modify them so that accurate topographic data could be collected at this rugged experiment site. In order to obtain volume and distribution data for each avalanche experiment, a model of the before and after snow surfaces was necessary. This required two separate surveys and a digital comparison of the resulting snow surface models. The logistical problems involved in obtaining enough accurate data points at an exceptionally steep and remote site were also complicated by the fact that survey reflectors could not be hand placed on the slope. Reflectorless measurements were necessary in order to avoid placing a rod person in the avalanche path and to avoid disturbing and compacting the generally delicate snowpack.

The measurement techniques ultimately developed utilized a LEICA/Wild electronic theodolite with an attached reflectorless distance meter. Large numbers of data points were necessary to construct an accurate snow surface model (up to 450 per survey), therefore an electronic data recording system was incorporated into the LEICA system.

Once the survey was completed for a particular avalanche experiment, an efficient method for comparing the data from the pre- and post-avalanche surveys was necessary. Most standard software for this type of application was not very suitable for our purposes since the programs generally use cross-sectional areas at regular intervals to compute volumes by the end area method. Furthermore, these programs are generally best suited for one of the surfaces to consist of specifically designed regular slopes and grades. In this situation, both topographic surfaces are highly irregular, necessitating a program that can compare 3-D data points for two irregular surfaces. Therefore, in order to reduce the data into an accurate three-dimensional model, we utilized the TERRAMODEL digital terrain modeling software. In addition to computing volumes from two sets of 3-D points, Terramodel will compute the volume distribution for specified depths and the areas for slopes of similar inclination ranges. The program will also produce 3-D mesh views for any set of 3-D data points.

SURVEY TECHNIQUES

The field measurement system consisted of three basic components: 1) Wild T1600 universal electronic theodolite; 2) DISTOMAT Wild DIOR 3002, timed-pulse laser distance meter; 3) HP 48sx calculator with program card for survey data collection.

The T1600 theodolite is a highly accurate electronic theodolite with a vertical and horizontal angle standard deviation of +/- 1.5 seconds. It has an automatic index pendulum compensator with a working range of +/- 5 minutes and automatic corrections for circle eccentricity, horizontal collimation error, earth curvature and mean refraction. The readings are displayed in liquid-crystal displays and data can be recorded in an on-board recording module or sent to a data terminal (HP 48sx calculator). The operating temperature range is -20°C to +50°C.

The DIOR 3002 is a laser distance meter capable of measuring distances with or without prism reflectors. It uses an infra-red beam and measures distances using a timed pulse principle. The stated measuring accuracy is +/- 10mm without reflectors and +/- 5mm to Wild circular prisms. Maximum ranges without reflectors depend on the reflectance of the target and the ambient light conditions. Maximum ranges vary from 100m to 250m for bright sunlight and darkness, respectively.

The HP 48 calculator serves as a an electronic fieldbook with the addition of extended memory and a Tripod Data Systems surveying program card. The calculator is cabled to the theodolite/distance meter system and sends commands to the instruments to collect survey data then receives the data, adds point and breakline descriptors, and stores the raw data. A coordinate file consisting of north and east coordinates, elevations and descriptions is also created. The stored data can be downloaded to a computer and configured for use in the Terramodel program after the survey is completed.

Two complete surveys were conducted for each avalanche run. The pre-avalanche survey established the undisturbed surface of the snowpack and the post-avalanche survey recorded the changes in the snow depth due to the avalanche. The pre-avalanche survey typically covered more surface area in order to be sure to include all areas were the snow surface might change. Three avalanche surveys were completed in all. Two of these were surveys of the entire slope and the third included only the starting zone down to the observation shed. The total number of data points taken during the before or after portion of the survey ranged from 252 to 476 points. Data point density was calculated for each survey and an average point density of 600 points/acre was accomplished. The actual distribution of these points is subjective, with certain areas requiring much higher point densities than others.

After completion of the survey, the data was down-loaded from the electronic field book to a computer using a file transfer and configuring program. The raw data was then processed into a data point file consisting of: point numbers, north and east coordinates, elevations, and an eight character point or breakline descriptor. The data point file was then imported into the Terramodel program. Breaklines were refined from field versions so that a more accurate three-dimensional model would be calculated. Terramodel forms a Triangulated Irregular Network (TIN) by linking 3-D points with interpolation lines. The design surfaces are created by linking each point with its surrounding points in a series of triangles. The triangles form a mathematical model of the actual surface. All subsequent calculations are based on this mathematical model. The breaklines mentioned above are used to define surface irregularities, such as peaks and valleys of snow drifts, gullies and cornices. Placing breaklines along these features revises the way that the triangles are drawn when formulating the TIN. The addition of breaklines adds another level of intelligence to the terrain contouring process.

After proper breaklines have been established for the pre-avalanche and post-avalanche surveys, Terramodel will link the points and create a TIN for each survey. Using this mathematical surface, Terramodel can create contour maps, slope area maps, and 3-D mesh views of the slope. These operations have been performed for each of the surveys.

SURVEY CALCULATIONS AND RESULTS

After Terramodel has created a TIN for each snow surface survey, volume differences can be calculated by digital comparison of the two surfaces. The surface to surface volume change is calculated by first computing the "isopach" between the pre-avalanche and post-avalanche surfaces. An isopach is defined as a "line drawn on a map through points of equal thickness of cut or fill". Volumes are designated as "cut" or "fill" depending on whether snow has been removed (cut) or added to (fill) a particular area. "Cut" volumes generally designate the amount of snow removed from the starting zone and any other scour areas. "Fill" volumes represent the snow deposition that results in a greater final elevation than the original snow surface elevation. The isopach is computed by projecting the points from one surface onto the opposing surface and calculating the difference in elevation. The points of the isopach now represent a new digital terrain model (DTM) and a TIN is generated by linking the isopach points. All previous breaklines and common points are considered during the TIN formation. The triangulated isopach is broken down into tetrahedral components and the volumes are determined by computing the volumes of the tetrahedrons and adding them together with respect to their cut or fill designation.

This surface to surface volume calculation method is generally considered more accurate than the typical method utilizing cross-sections and the average end area computations. Cross-section intervals must approach very small distances before the two methods of volume computation will agree for irregular surfaces.

The volumes are divided by depth range. Approximately 90% of the avalanche volume came from the top foot of the snowpack during the Jan. 13 and March 27 avalanches while less than 75% of the volume came from the same depth range in the Feb. 3 avalanche. Analysis of the depth range vs volume calculations shows that the Feb. 3 avalanche ran considerably deeper than the other two.

A visual inspection of the avalanche volume and depth distributions can be seen in the 3-D view and contour models of the isopach for each of the avalanches. As discussed above, the isopach layer is the actually the difference between the two surfaces or, in this case, it shows the depths to which the avalanche ran. By viewing the isopach drawings one can get a good overview of the depth distribution of the avalanche. Contouring the isopach is also an excellent way to spot random survey errors. The bogus data will show up as impossibly thick points of cut or fill. These points can then be identified and removed from their respective surface models.

Field snow densities were taken at various depths before the Feb. 3 avalanche was triggered. Combining these densities with the avalanche volume for the same relative depth, the mass of snow that moved during the avalanche can be computed. Mass calculations for the Feb. 3 avalanche are shown below.

FEBRUARY 3, 1994 AVALANCHE MASS CALCULATIONS for CUT VOLUMES

DEPTH RANGE	VOL.(m^3)	DENSITY (kg/m^3)	MASS (kg)
0" - 3"	128.4	118.4	15,208
3" - 6"	108.9	149.2	16,232
6" - 9"	89.3	169.4	15,127
9" - 12"	70.5	189.6	13,365
12" - 15"	54.7	220.0	12,043
15" - 18"	39.5	234.8	9,281
18" - 21"	24.4	315.6	7,697
21" - 24"	12.7	315.6	4,005
> 24"	11.5	400.0	4,587
		TOTAL =	97,547 kg (107.5 tons)

Due to the high spatial variability of snow density, these calculations can only be used as an estimate of the mass movement during the avalanche.

CONCLUSIONS AND RECOMMENDATIONS

The LEICA/Wild DIOR 3002 reflectorless distance meter was the key to making these measurements possible. There were two major benefits to incorporating this distance meter into the survey system: 1) The time needed to complete the survey was reduced. We were able to more than triple the number of survey points in a given time period over standard survey methods using reflectors. The grid density and volume accuracy of the survey was greatly increased. 2) Rodmen did not have to go out on the avalanche slope before or after the avalanche. This lessened personnel exposure to avalanches and also kept the snowpack from becoming packed out by repeated ski traverses. More efficient use of field breakline codes also added to the accuracy of the computer digital terrain model and therefore the volume and mass calculations.

The accuracy of the Wild T1600 electronic theodolite combined with the DIOR 3002 distance meter was completely adequate. The systematic error analysis showed that the system was far more accurate than the possible interpolation errors involved in creating the mathematical surfaces for the irregular terrain.

Random errors caused by the distance meter's beam being interrupted by branches or polyline strung across the chute were a continual problem. These errors generally showed up when the isopach layer was contoured, however, one cannot be sure that all the erroneous shots were apparent. This fact leaves some doubt as to the ultimate accuracy of the final volume calculations. Mitigation of this problem would involve removing all unnecessary polylines from the avalanche chute and removing the limbs from some of the trees that are frequently in the way. Sight lines should be cut through the small growth, especially in the starting zone above the bomb wire.

In the future, a possible way to gauge the overall accuracy of the survey system would be to conduct two surveys of the same surface on the same day. After the surveys were reduced and the surface models were compared, the volume between the two surfaces should be zero. Once the surveyed volume accuracy is known, more effort could be directed toward the density measurements and mass calculations and their accuracy could also be estimated.

In conclusion, the snow surface surveying and modeling system developed this winter has been a vast improvement over the previous system. The results appear to be within acceptable limits but this still needs to be verified.

REFERENCES

Dent, J.D. "The Dynamic Friction Characteristics of a Rapidly Sheared Granular Material Applied to the Motion of Snow Avalanches" Annals of Glaciology, Vol. 18, 1994.

Bailey, I.J. "Mass Transport Measurements in a Snow Avalanche" Department of Civil Engineering, Montana State University internal report, April 1994

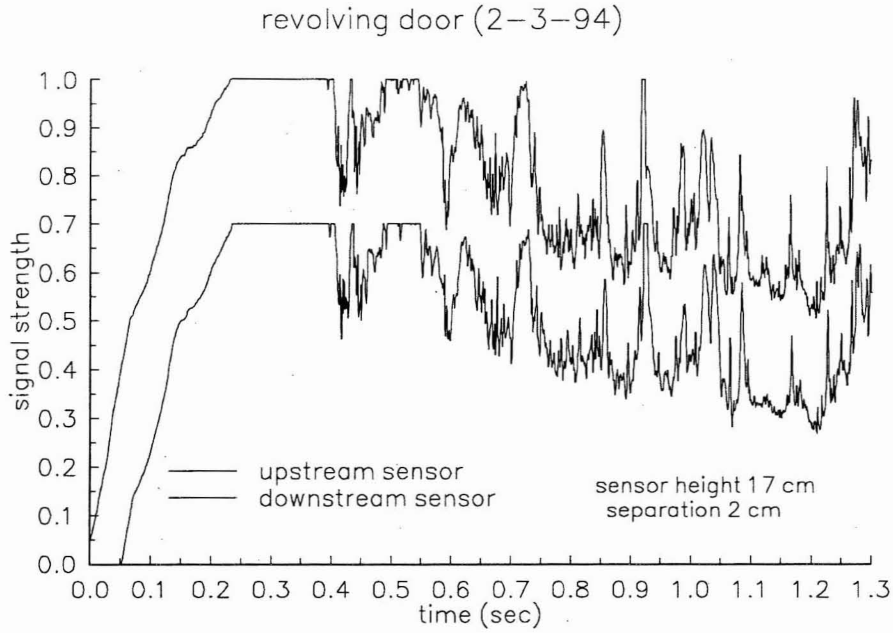

Figure 1. Photosensor signal strength. 0.0 = maximum reflection (saturation), 1.0 = minimum reflection (no light).

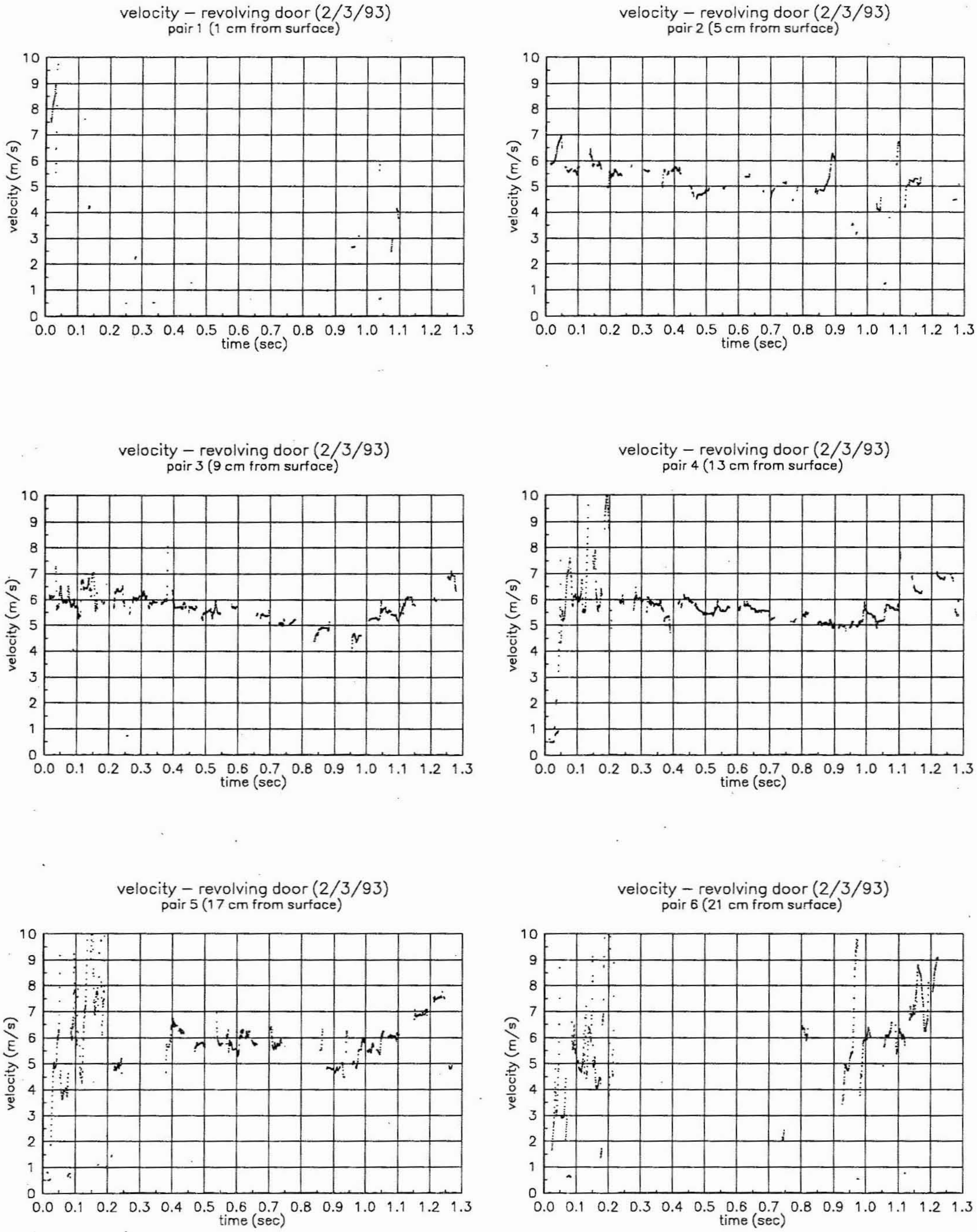

Figure 2. Avalanche velocity versus time at various heights above running surface.

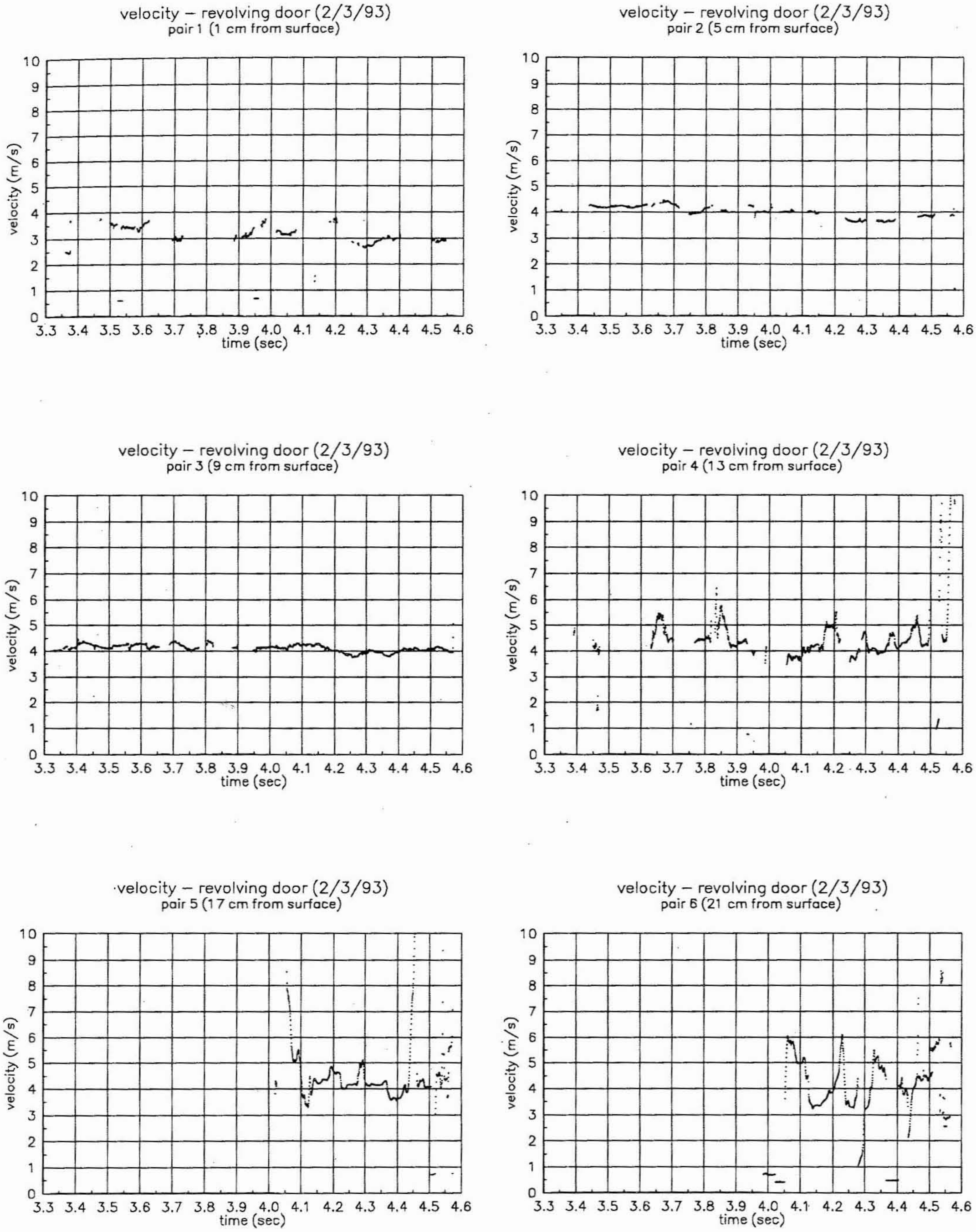

Figure 3. Avalanche velocity versus time at various heights above running surface.

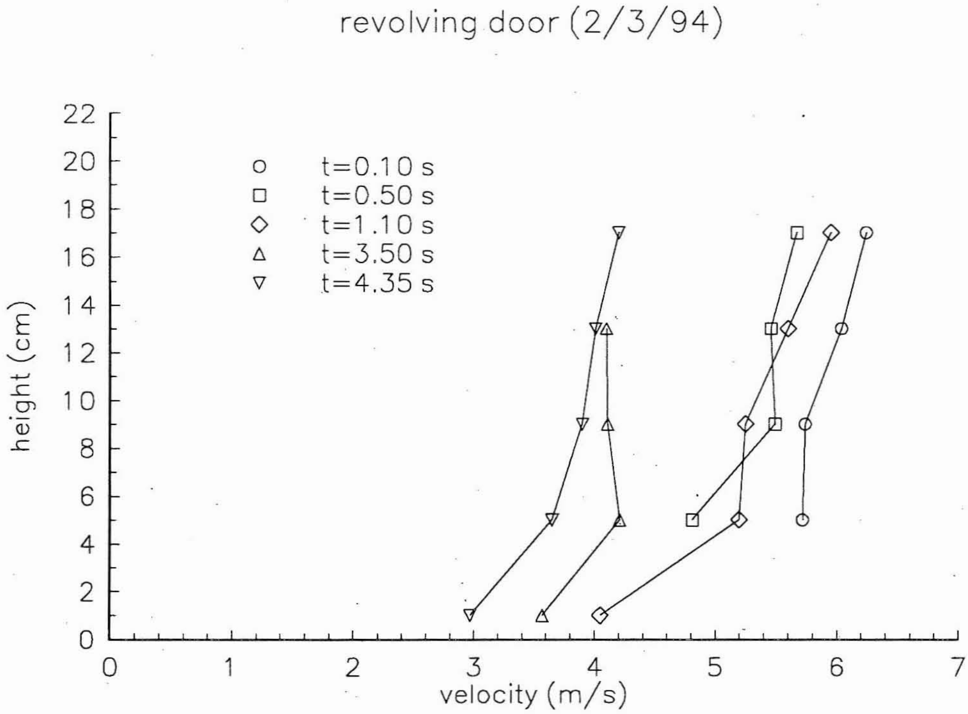

Figure 4. Avalanche velocity profile.

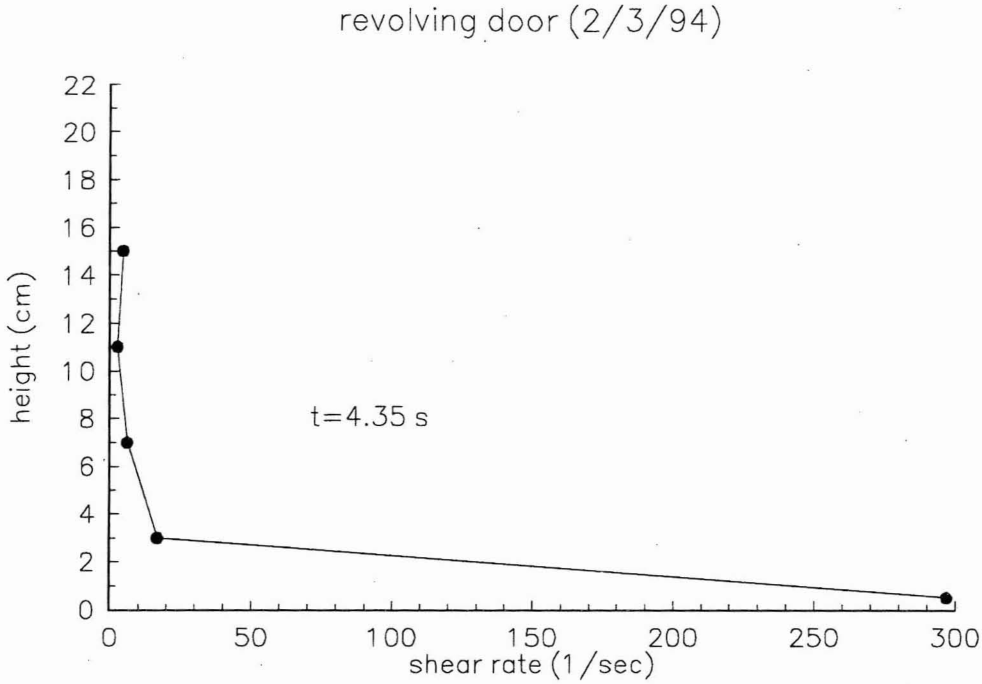

Figure 5. Avalanche shear rate profile at t = 4.35 s.