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SOMMAIRE

Une avalanche a été surveillée au moyen de sismographes placés le long du couloir de l'avalanche et les forces d'impact ont été mesurées à l'aide de transducteurs à pression. Des résultats preliminaires indiquent que les sismographes peuvent constituer une méthode fiable et peu coûteuse pour détecter les risques d'avalanche. Les signaux émis par ces détecteurs peuvent servir à mettre l'équipement d'enregistrement en marche. Les corrélations existant entre les signaux du sismographe et du transducteur permettent de déterminer approximativement les vitesses de l'avalanche à évaluer. Le présent article analyse ces signaux et traite des caractéristiques de l'avalanche.

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A SEISMIC AND PRESSURE TRANSDUCER SYSTEM FOR MONITORING VELOCITIES AND IMPACT PRESSURES OF SNOW AVALANCHES

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ABSTRACT

An avalanche was monitored with seismic geophones placed in its track and impact forces were measured using pressure transducers. Preliminary results indicate that geophones may provide an inexpensive and reliable method of detecting avalanche events. Signals from these sensors can be used to start recording equipment. Correlations between the seismic and pressure signals enable approximate velocities within an avalanche to be estimated. The pressure signals are analyzed and the characteristics of the avalanche discussed.

INTRODUCTION

Ives *et al.* (1973) and Harrison (1976) investigated the possibility of monitoring avalanche occurrences using seismic equipment but encountered problems differentiating avalanche signals from background noise. Seismic and infrasonic detectors were some distance from the avalanche track and the frequency response of the instrumentation was rather low. St. Lawrence and Williams (1976) successfully recorded several avalanches using a 28-Hz vertically mounted reflection geophone in the starting zone of an avalanche path. In this current study, geophones were placed in the track (middle section) of an avalanche path along with pressure sensing equipment, so that seismic signals and impact pressures of a moving avalanche could be recorded.

Accurate studies of avalanche impact pressures are important in the design of structures exposed to avalanches such as electric transmission line towers, bridges and snow sheds. Schaerer (1973) has analyzed eight avalanches during 2 yr of observations. In these and subsequent studies many events were not recorded. Impact pressure microswitches have been employed to trigger (start) the recording instrumentation. These triggers rely on actual avalanche impacts to create an open circuit; they are vulnerable to damage and prone to jamming. A more reliable triggering system is therefore needed. If seismic signals associated with avalanches can be recognized and distinguished from background noise, geophones can be used to trigger the instrumentation.

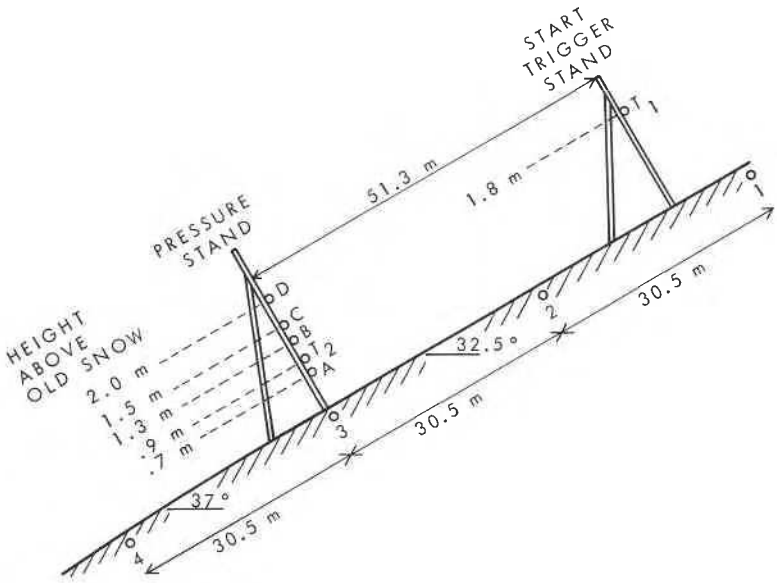
Avalanche velocities must also be measured along with impact pressures in order to determine the relationship between these factors. Schaerer (1973) obtained rough estimates of avalanche velocities by measuring the times required for avalanche fronts to travel from the start trigger to the pressure stand (Figure 1). Because the actual front may miss the start trigger and hit the pressure cells, or vice

versa, these estimates of frontal velocities can be in error. Furthermore, the core or surface flow of the avalanche may be travelling faster or slower than the front. Within the core there may be surging during which various phases of the avalanche are travelling at different speeds. Ideally, velocity and pressure distributions should be monitored for the duration of the avalanche, if the relationship between these quantities is to be properly understood.

INSTRUMENTATION

Four Geospace GSC-20D 14-Hz vertical geophones were buried about 150 mm deep (for maximum ground coupling) in the bed of an avalanche gully, Tupper 1, at Rogers Pass, prior to the start of the 1976/77 avalanche season. These geophones were connected via 350 m of buried armored cable to four operational amplifiers and a Hewlett Packard 3968A FM eight-channel tape recorder situated in a highway snow shed. The other four channels of the tape recorder were connected via signal conditioners and bridge amplifiers to two Statham UC3 load cells and two Kulite TC 2000 cells, rigidly mounted on a stand in the track. These pressure cells are similar to those described by Schaerer (1973). They are small, presenting a loading surface of 645 mm² (1 in²) to the avalanche flow; the outer cases are cylindrical and streamlined to minimize flow disturbance. The configuration of seismic and pressure sensors in the avalanche track is shown in Figure 1.

A start trigger, T_1, consisting of a pressure plate and housing similar to one of the pressure cells, is fixed to a stand high in the avalanche gully, above the pressure stand. This trigger contains a microswitch, normally closed, that opens on receiving an impact of sufficient magnitude. If the start trigger circuit is opened, a "timer trigger control" generates a start function at the tape recorder and recording begins. Recording ceases after a preset delay time (up to 99 s) has elapsed. An open stop trigger, T_2, stops a timer that was activated by the opening of the start trigger circuit. The timer indicates the inter-



1,2,3 AND 4 ARE SEISMIC GEOPHONES
A,B,C AND D ARE PRESSURE CELLS
T_1 IS THE START TRIGGER
T_2 IS THE STOP TRIGGER

FIGURE 1. Seismic and pressure sensors in gully of Tupper 1 avalanche site.

val that elapsed between triggers. Small avalanches tend to deposit more snow at the start trigger stand than at the pressure stand. Hence, to ensure that snow did not cover T_1, it was situated higher above the surface than T_2.

Static calibration of the pressure cells was carried out in the field laboratory by loading each one with standard weights and recording signal levels on the tape recorder for each channel. Calibration of the geophones was unnecessary because relative amplitudes only were required for this study.

SOME PRELIMINARY RESULTS

A dry avalanche of medium size and of mixed type (partly airborne powder and partly flowing) occurred on Tupper 1 at approximately 2000 h on 10 February 1977. Chunks of snow, between 100 and 150 mm in diameter, were found in the deposit. This was a natural avalanche resulting from a steady buildup of new snow, approximately 45 cm measured at Rogers Pass observatory over 2-1/2 days, combined with steady winds, 35 to 60 km h^{-1} during the 4 h preceding the avalanche; temperatures were close to freezing. The timer trigger control was successfully activated and the avalanche was recorded. The stop trigger circuit was apparently not opened until sometime after the avalanche front had passed since the time interval between triggers was excessively long. An accurate estimate of the velocity of the front could not therefore be obtained from the timer.

SEISMIC SIGNALS AND VELOCITY ESTIMATION

Geophone 2 provided the only reliable seismic signal for this avalanche (Figure 2). A power spectrum produced by Fourier transforming the geophone 2 trace over the time interval F_1F_2 indicated that most of the seismic energy associated with the avalanche, after filtering by snowpack and ground, lay within a frequency bandwidth of about 2 to 30 Hz.

The general characteristics of the seismic signal suggest that the avalanche passed over geophone 2 in a succession of waves or surges. This is borne out when the pressure traces for cells A and C are examined (Figures 3 and 4). Peaks, x, y, z on the pressure trace for cell C appear to correlate well with x', y', z' on the seismic trace. Because geophone 2 was 30.5 m upslope from the pressure stand (Fig-

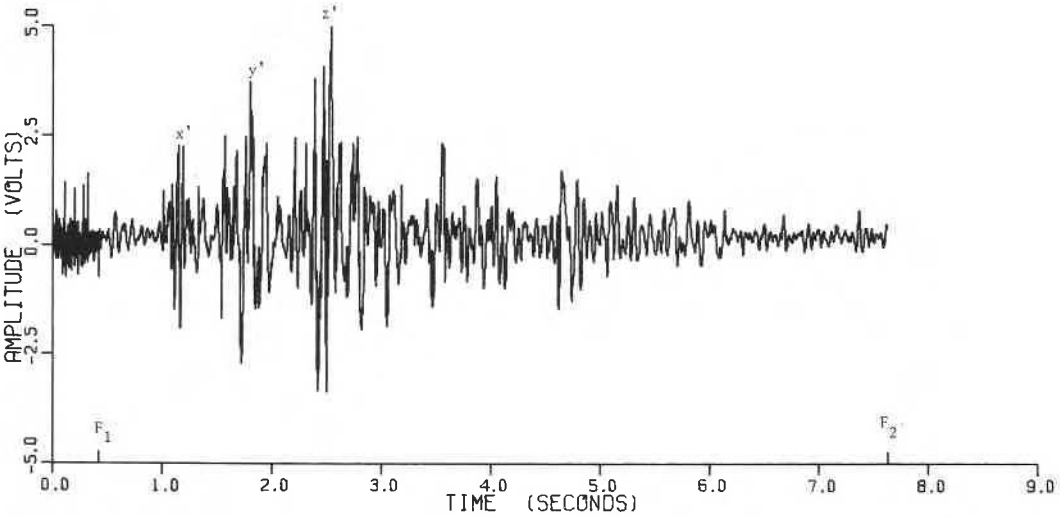


FIGURE 2. Seismic record from geophone 2.

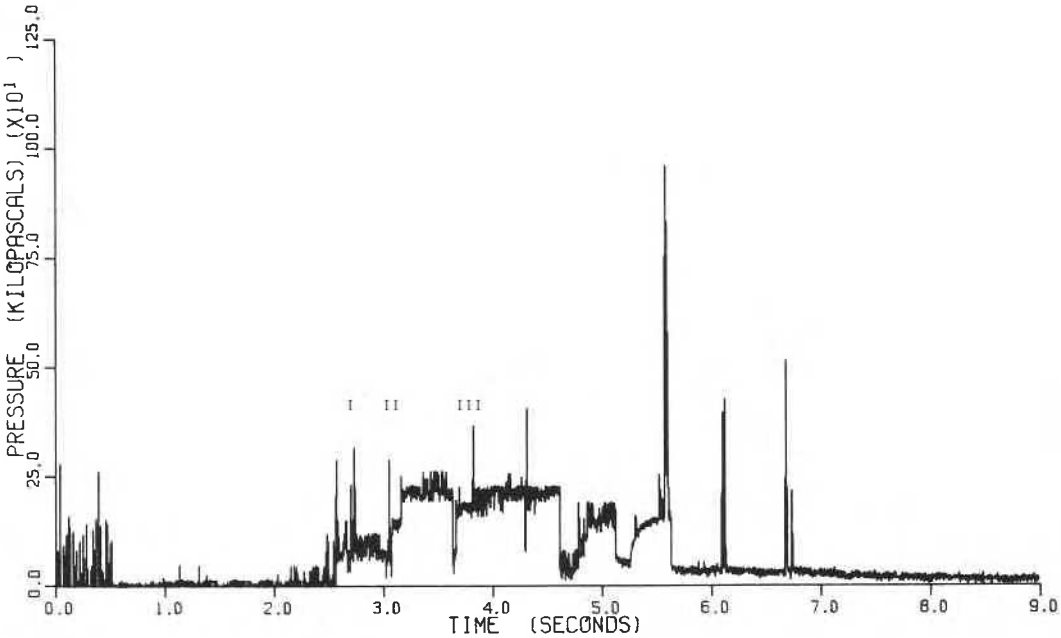


FIGURE 3. Pressure record from cell A.

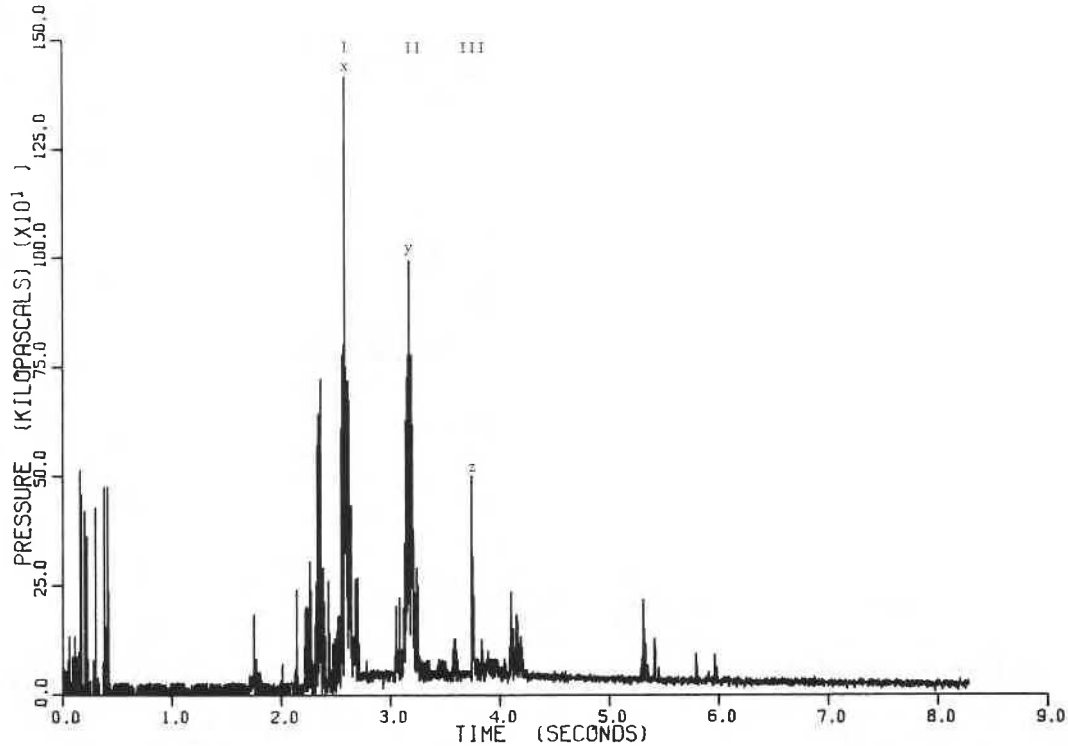


FIGURE 4. Pressure record from cell C.

ure 1), these correlations can be used to obtain estimates of downslope velocity. Values of 21.6, 22.1, and 24.2 m s^{-1}, respectively, were obtained for the first three phases, I, II and III of the avalanche. For future investigations it is expected that more than one seismic record will be obtained, in which case accurate estimates of avalanche downslope velocities may be achieved by cross-correlating the seismic traces. The velocities obtained in this study, by correlating a seismic trace with a pressure record, appear to be reliable estimates as three phases within the recorded avalanche were well defined.

IMPACT PRESSURES

Theoretical studies made by Voellmy (1955), Mellor (1968), and Shen and Roper (1970) suggest that avalanche impact pressures on a rigid obstacle can be described by

$$p = kv^2 \tag{1}$$

where p is the pressure, v the velocity, and k is a coefficient. The coefficient, k, is thought to be a function of snow densities before and after impact. Deformation of the avalanche snow may be partly elastic or plastic depending on its density, free water content, and temperature. The avalanche may behave as a fluid or a collection of solid particles or blocks.

Load cells A and C gave the only reliable pressure recordings for the 10 February 1977 avalanche event. The pressure records, Figures 3 and 4, consist essentially of a series of high pressure peaks superimposed on a relatively uniform base pressure. Substituting, into equation 1, the estimated velocities and impact pressures obtained from these recordings for phases I, II, and III of the avalanche, values for k were calculated. Average k was 600 kg m^{-3} for peak pressures on cell A and 2000 kg m^{-3} for cell C. Schaerer (1973) found that mean peak pressures could be approximated by

$$p = c\rho_d v^2 \tag{2}$$

for eight avalanche events at Rogers Pass, where ρ_d is the density of the deposited snow and c is a constant equal to 0.5. For the avalanche under investigation in this study, the mean density of the deposit was measured and found to be 330 kg m^{-3}. The coefficient c was therefore approximately 2.0 for cell A but about 6.0 for cell C. Reexamination of original data used by Schaerer (1973) suggests that c could be close to unity for peak pressures. He thought that peak pressures were caused by individual impacts of snowballs of density approximately equal to that of the final avalanche deposit. Kotlyakov *et al.* (1976) report results indicating that c could be as high as 2.0. Some "overshooting" of the pressure plate due to underdamping may have caused higher than actual pressures to be recorded by cell C.

Average k was 320 kg m^{-3} for base pressures on cell A and 90 kg m^{-3} for cell C. Using 330 kg m^{-3} for the density of the avalanche deposit, c was therefore approximately unity for cell A and about 0.3 for cell C. Schaerer (1973) found that c was 0.17 for base pressures. He thought that base pressures were caused by flowing snow. By comparing avalanche flow depths with depths of deposit, he proposed that for dry snow

$$\rho_s \approx 0.3\rho_d \tag{3}$$

where ρ_s is the bulk density of the flowing snow.

DISCUSSION

A dynamic model for the 10 February 1977 avalanche on Tupper 1 can be constructed from the estimated velocities and pressures for phases I, II, and III. This model is shown in Figure 5 and is, of course, somewhat speculative as only a limited amount of information was available. Base pressures recorded by cell A were probably produced by the dense flowing core of the avalanche. The upper part of this flow caused lower base pressures to be re-

corded on cell C. Peak pressures on cell A were probably due to small chunks within the core, while the higher peak pressures on cell C may have been the result of larger blocks tumbling in turbulent vortices near the upper boundary of the main flow. Debris drops out continuously as new snow is picked up from the track. This energy exchange process is probably a major factor causing the variation of velocities within the avalanche.

CONCLUSIONS

Seismic geophones can be employed to detect avalanche occurrences and start recording instrumentation. Seismic signal threshold detection triggers were included in the recording system for the 1977/78 avalanche season and worked well. Avalanches produce characteristic signals that can be used to determine velocities within the avalanche. These velocities are required for the analysis of avalanche pressure measurements.

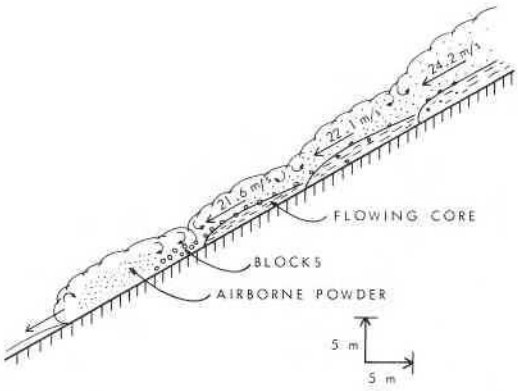


FIGURE 5. Dynamic model of 10 February 1977 avalanche on Tupper 1 between geophone 2 and pressure stand.

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