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16. Abstract

The Alternate Methods of Avalanche Control project has been funded by the Washington State Highway Commission since August 1974 in order to develop simple, reliable and repeatable methods of triggering avalanche release which are free from the storage, handling and availability problems of explosives and artillery shells and which can readily be applied to avalanche paths typical of the many smaller ones causing frequent hazards for highways.

The research involved tests in both Washington and Colorado to permit evaluation of the control methods in diverse climates and snow conditions, leading to more generally applicable results than could be obtained at a single site.

The technical and scientific aspects of the work in Colorado were coordinated by the San Juan Avalanche Project of the University of Colorado. Field work in Washington state and the general supervision of the program and the engineering design were carried out by the University of Washington Geophysics Program.

The U.S. Forest Service at Alta, Utah, also joined in a cooperative test of our methods and equipment.

This Final Report describes the 1977/78 tests and summarizes the results of the entire project.

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ALTERNATE METHODS OF AVALANCHE CONTROL

by E. R. LaChapelle and
D.B. Bell, J.B. Johnson, R.W. Lindsay, E.M. Sackett, and P.L. Taylor

FINAL REPORT

Research Project Y-1637 Phase 4

Co-principal Investigators
E.R. LaChapelle
R.J. Evans

Geophysics Program and
Department of Civil Engineering
University of Washington

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INTRODUCTION

The Alternate Methods of Avalanche Control project has been funded by the Washington State Highway Commission since August 1974 in order to develop simple, reliable and repeatable methods of triggering avalanche release which are free from the storage, handling and availability problems of explosives and artillery shells and which can readily be applied to avalanche paths typical of the many smaller ones causing frequent hazards for highways.

The research involved tests in both Washington (at Stevens Pass) and and Colorado (at Red Mountain Pass) to permit evaluation of the control methods in diverse climates and snow conditions, leading to more generally applicable results than could be obtained at a single site.

The technical and scientific aspects of the work in Colorado were coordinated by the San Juan Avalanche Project (under a sub-contract between the University of Washington and the University of Colorado, Institute of Arctic and Alpine Research (INSTAAR)). Field work at Stevens Pass, Washington, and the general supervision of the program and the engineering design were carried out by the University of Washington Geophysics Program. The U.S. Forest Service at Alta, Utah, also joined in a cooperative test of our methods and equipment in Utah.

Previous reports published by this project include the Interim Report, July 1975 (Report No. 19.1) and the Interim Report, July 1976 (Report No. 19.2). An unpublished Executive Summary Report was prepared in June 1977.

The Alternate Methods project was planned as a three-year program, but extraordinary circumstances led to a fourth year of research and operations. The winter of 1976/77 was exceptionally dry in the San Juan Mountains of Colorado where only a very shallow and transient snow cover developed. Almost no avalanches occured and sufficiently unstable snow conditions failed to develop at the test sites. A very light snow year was also experienced in the Cascade Mountains of Washington. Virtually no tests for actual avalanche releases were possible until March, when enough snow accumulated from late storms to permit unstable conditions to develop. This was an improvement over the Colorado situation where no tests at all were possible, but the opportunities in the Casades were limited to a short time later in the winter and did not involve the normally deep snow cover common to the area. It became readily apparent that a fourth year of work was required in order to complete the project. The Washington project was extended for another winter season to allow adequate tests. The Colorado phase of the work was discontinued at the end of the third year owing to lack of further funding from the Colorado Highway Department. This Final Report describes the 1977/78 tests in the Cascade Mountains and summarizes the results of the entire project.

I. BRIEF DESCRIPTION OF SYSTEMS TESTED

The alternate methods sytems for avalanche control developed and tested during this study have been described in detail in the previous reports. For the benefit of the reader of this Final Report who may not have access to these earlier documents, the systems are very briefly described and illustrated here.

A. Air Bags

The inflation of air bags underneath the snow cover is a simple means of disrupting the snow and inducing fracturing at the surface. The assumption of this method of avalanche control is that such fracturing induced at the right time and place will result in slab avalanche release. It applies the same principle formerly used for aircraft de-icing which depended on inflation of a rubber boot along the leading edge of a wing.

The method is attractive in theory. Only very modest air pressure, in the order of 5 psi, is required to lift the weight of any reasonable winter snow cover of average density. Calculations show that, if the snow cover is very hard with a high tensile strength, pressures up to 20 psi may be needed to fracture the snow beam resting upon the air bag. Air at these pressures can readily be provided by small compressors or from high-pressure cylinders through reduction valves. Large compressors are required only if a fast inflation is desired.

Air bags are readily available commercially in the form of dunnage bags used to pack cargo securely in ships and rail cars. The size adopted for these tests was 4 x 9 feet. These bags are fabricated from nylon-reinforced neoprene with a separate neoprene air bladder inside (inner tube). They are rated at 10 psi maximum working pressure when restrained and have a nominal 30 psi bursting strength. A larger and heavier bag, 4 x 20 feet, was also used. This was adapted from a style of air bag used as a temporary plug for large sewer lines.

The bags was deployed at a number of sites by placing them on the ground surface prior to winter snowfall. They have been tested both at cornice sites and at avalanche release zones (Figure 1) in three different climates. Both slow and fast inflation have been used from air cylinders, on-site compressors and remote compressors working through air lines. When properly placed, the bags are effective for dislodging cornices, but they have been largely unsatisfactory for initiating avalanches directly. There have been numerous problems with damage from overinflation.

B. Gas Exploders

The basic idea of the gas exploder system is to deliver a repeatable explosive impulse to the snow cover without the use of conventional explosives. The application of this idea developed here is to adapt for avalanche release the principle of the seismic "thumper." This device is a large, truck-mounted cylinder which is charged with a mixture of propane and oxygen. When the mixture is detonated, a piston is driven violently against the ground, generating a seismic signal. Adaptation of this principle to avalanche control consists of inverting the "thumper," burying it in the ground, and driving a piston upward against the snow cover. In this case an arrangement is used which also permits the explosive discharge of vented gases to provide further disruption of the snow cover. The aim of such disruption is the same as that for convectional explosives: to fracture the snow cover and initiate slab avalanche release. The efficiency of release can be improved by installing several gas exploders in a single release zone where they are fired simultaneously. The big improvement over conventional explosives stems from the fact that the exploders can be recharged with a gas mixture and fired as often as need, requiring only an initial installation at the beginning of a winter.

Figure 1. Section of snow cover broken loose and tilted by inflated air bag. Silver Ledge Mine, Red Mountain Pass, Colorado, 3/23/76.

The safety and convenience of handling separate gases in convectional pressure cylinders is an improvement over the storage safety problems associated with conventional explosives. The system is inherently safe to install and operate, for the explosive mixture is formed and introduced into the cylinders only seconds before it is detonated.

A useful amount of explosive energy can be obtained in a convenient volume from oxygen and acetylene. Although acetylene has a lower heat value than propane, it has a much wider range of flammability, is less expensive, and permits the straight-forward adoption of standard oxy-acetylene welding components. A volume of 3 cubic feet is an optimum mixture of these gases contains the same chemical energy as 1 pound of TNT. While these amount of explosive is sub-marginal as a single charge for avalanche release, it has been shown to be effective when detonated in multiple charges in a single release zone.

Heavy steel canisters with displaceable lids were designed as the firing chambers for the gas exploder system. An example is Shown in Figure 2. These canisters are partially buried in the ground with the lid exposed. When the gas mixture is detonated, the lid is thrust violently upward against the overlying snow and the gases are discharged. This sytem is effective in shallow, cold snow covers. It proved unsatisfactory in deep, isothermal snow and a different device was introduced consisting of a large truck tire affixed to one-half of a split-rim wheel and filled with the explosive gas mixture through a manifold. This provided a more energetic impulse, enhanced by the elastic recoil of the tire, but no conclusive tests have yet been made in deep snow.

The heart of the gas exploder system is the control unit (Figure 3), which by remote control valves the gases into a mixing chamber, distributes the mixture to the exploders and provides spart ignition to fire the system. The

Figure 2. Gas exploder canister fabricated of one-quarter inch steel. The lid is shown in the fully extended position with the guide rods exposed. Heavy steel springs at the bottom of each guide rod return the lid to the closed position following gas mixture detonation.

Figure 3. Gas exploder control unit installed at Old Faithful No. 7 slide path, Stevens Pass, Washington.

control unit includes storage batteries to operate solenoid valves and the ignition system is housed in a weatherproof case for field installation.

C. Gas Cannon

A variation on the gas exploder system was introduced during the third and fourth winters of the project. This consists of a large fiberglass pipe (8 inches x 20 feet) closed at one end and suspended above the snow surface in an avalanche release zone. An explosive gas mixture is introduced through the closed end from the same gas control unit used for the other exploder systems. On ignition, the gas mixture explodes outward through the open end against the snow surface. This configuration takes advantage of the high efficiencies of air blast release demonstrated by Gubler (1977) in Switzerland. Gubler found through accelerometer measurements that larger amounts of energy could be communicated to a larger area of snow from an explosion located above the snow surface than from one located within the snow. Current tests have confirmed the efficiency of this method of avalanche release with the gas cannon. Its principal drawback is the necessity of suspending a long pipe in the air above the release zone. This can be done in narrow gulleys or where large trees are available for support, but is difficult on open slopes. See the cover photo on this report for an illustration of a gas cannon at the moment of detonation.

D. Vibrator

Part of this research has addressed the fundamental questions of how sound (mechanical vibration) is propagated in snow and whether mechanical resonance can be established in bounded snow slabs. Owing to the well-known ability of snow to absorb and dampen sounds and vibrations, there are some legitimate theoretical questions about the efficacy of vibrating for avalanche release. On the other hand, long-standing field experience with avalanches

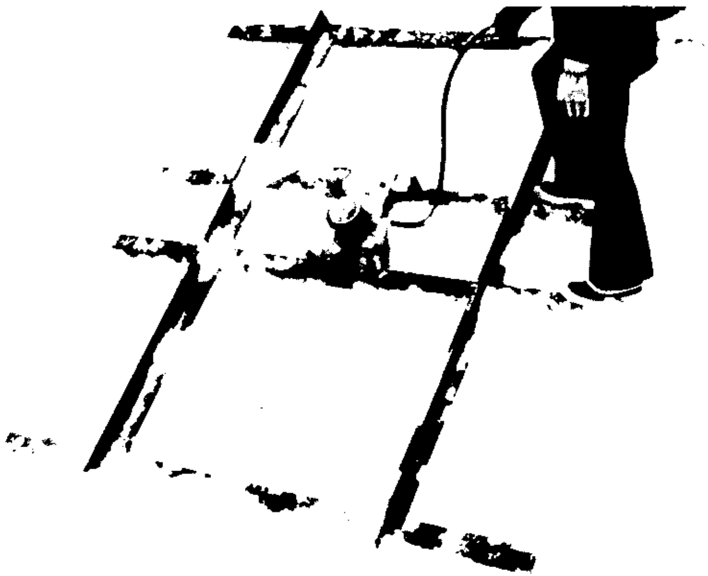

Figure 4. Vibrolator attached to heavy aluminum frame for use as vibrator test unit at Little Windy cutbank near Stevens Pass, Washington.

has shown that seriously unstable snow can be triggered into avalanching by very small signals, including, traditionally, the sound of a human voice.

Three test devices were constructed, all using compressed air for power. An oscillating platform driven by a large jackhammer was installed flush with the ground surface at the Blue Point avalanche path near Red Mountain Pass; a portable metal grid driven by a commercial vibrator (car-shaker) was used for tests on a highway cutbank near Stevens Pass, and a free-piston vibrator was mounted on a buried plywood sheet at the Brooklyns slide path near Red Mountain Pass.

A substantial amount of power is available from these vibrators. The jackhammer and car-shaker draw approximately 5-10 and 10-15 horsepower respectively. The main problem is to communicate this energy efficiently to the snow. Because snow is soft and easily deformed, vibrating bodies initially deliver a large percentage of their output to compressing the adjacent snow, and then rapidly become decoupled from it by the air cavities developed. Experience to date suggests that the grid-style of vibrating unit (Figure 4) quickly decouples from the snow and tends to build small, persistent cavities around the grid members. The platform surface parallel to the normal snow deposition appears to retain better contact.

Tests to date have demonstrated that vibrators can, in principle, release avalanches, but they appear to do so only very unreliably at the available energy levels.

E. <u>Interface Modification</u>

Avalanches can form only where snow can build up on a sloping ground surface. One control technique is to prevent this build-up. Most commonly this is done by inhibiting wind transport of snow into an avalanche release zone, but in this study a different approach has been investigated: the prevention of snow build-up after it arrives at the ground in the release zone. This is done by modifying the snow-earth interface so that snow will not adhere but instead is continually removed by sliding away. A series of tests have been made in both Colorado and Washington using plastic films to which the snow will not adhere. These tests have shown that snow readily slides away as fast as it is deposited on polyethylene and similar surfaces in both dry and wet snow conditions. A major difficulty has been anchoring the plastic sheets against the destructive effects of high winds. Very strong material and continuous tie-down around the edges are both essential.

References

Gubler, H. (1977) Künstliche Auslösung von Lawinen durch Sprengungen, Mitteilung No. 35, Swiss Federal Institute for Snow and Avalanche Research.

II. CASCADES FIELD TESTS, WINTER 1977/78

The only field tests of alternate methods in the winter of 1977/78 were conducted at Stevens and Snoqualmie Passes in the Washington Cascades. The Colorado tests in the San Juan Mountains were terminated at the end of the previous winter owing to discontinuation of support from the Colorado Department of Highways.

The winter of 1977/78, though much improved in respect to snowfall over the previous year of drought, was still far from ideal for avalanche control research. The winter as a whole produced adequate precipitation, but mild temperatures persisted and the freezing level was often high. This meant that the test sites at Stevens Pass in the 5000-foot elevation range received a considerable amount of snowfall and produced a reasonable spectrum of avalanche activity. It also meant that the test site at Snoqualmie Pass around 3700 feet elevation received much of the winter precipitation as rain. Snowfall recorded at the latter pass amounted to only 55% of normal and arrived mostly in small increments with few major storms of the type apt to produce avalanching. The Snoqualmie tests produced further experience with equipment operation, but very little gain in information about actual release of avalanches. A substantial gain was made at Stevens Pass, however, leading to some important conclusions about the air bag and gas cannon systems.

An unexpected difficulty developed at Stevens Pass in late November when the ski area management raised some serious questions about their liability while the research crew rode the chairlifts to the research site at the Barrier. This has not been a problem in previous years, and still was not one during normal hours of public lift operation. The research personnel were accustomed to joining the professional ski patrol for early morning avalanche control work before the lifts were open to the public and to carry out tests at that time. It was the latter activity that raised the questions. The whole liability question received extensive review and discussion among University, Department of Transportation and ski company officers and was not finally resolved until mid-March. During the interim, which embraced much of the avalanche season, the research work was severely handicapped by exclusion of the staff from the lifts during non-public hours.

The Cascade field tests in 1977/78 were under the supervision of David Bell, a field technician who transferred to this project from the University's arctic sea ice program. He was later joined by Ronald Lindsay, who had worked on the Alternate Methods project in Colorado for part of the previous season.

Field work began in mid-September with preparation of the test sites and repairs to the equipment. The gas exploder and cannon systems were assembled and test-fired before being transported to the experimental avalanche release site. Air bags were repaired and modified to minimize the bursting problems encountered the previous year. The air bag distribution manifold was rebuilt and improved. Signal wires and circuits were also revised. A gas cannon was installed at the Stevens Pass test site and the air bags re-organized. Fall preparation work was essentially completed by early December, and earlier in some of the systems. The first alternate method control test came on 17 November with a firing of the gas cannon at Snoqualmie Pass East Side Snow Shed. The last control test of the season involved both cannon and air bags at Stevens Pass on 5 April. Post season securing and storage of the equipment was completed by mid-May.

A. Air Bags

All air bag tests were made at Stevens Pass in the Bobbie and Nancy Chutes slide paths at the west end of the Barrier above the ski area. Access was by the Seventh Heaven chairlift. A large compressor furnished by the Department of

Transportation was located underneath the warming hut at the bottom of the Seventh Heaven lift and fed an air line running up the hill to a distribution manifold located near the ridge-top. Solenoid valves at this manifold were controlled through a signal cable paralleling the air line, enabling the operator at the compressor to select which groups of bags were to be inflated. The valving was arranged so that either the cornice bags or the slope bags could be inflated as a group.

A total of eight bags were installed in Bobbie's Chute, five at cornice sites and three at slope sites within the avalanche release zones. These were numbered 1 through 8, No. 1 being closest to the high point of the ridge above Nancy's Chute (see Figure 5). Number 8, a cornice bag, was connected for inflation along with the slope bags owing to the way the manifold was arranged. All bags were 4' x 9' dunnage bags. All bags were placed on the ground surface prior to snow accumulation except No. 1, which was sandwiched between two 4' x 8' sheets of 3/4" plywood hinged together along one long edge and placed on the ground. Bag inflation pushed apart the plywood sheets, causing them to lever up a section of the snow cover.

A single 4' x 20' air bag was placed in the release zone of Nancy's Chute. This bag was a sewer plug bag of heavier construction than the dunnage bags. It was connected to the manifold in such a fashion that it was inflated each time air was pumped, regardless of the status of the solenoid valves controlling flow to the other bags.

The effectiveness of the air bags for avalanche release was disappointing. In some instances cornice snow was dislodged and in others the slope bags displaced snow downhill, but there was little effect for starting avalanches. Several difficulties were found with getting all the bags to inflate at the same time. One bag had to be dug up at considerable effort and moved to a new

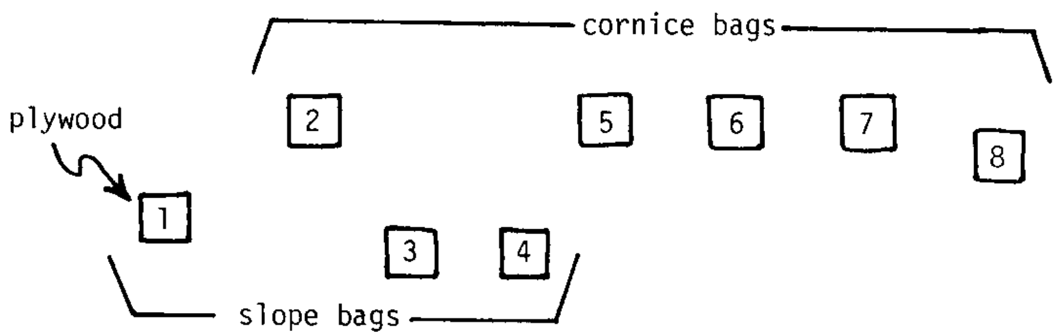

Figure 5. Arrangement of air bags at Stevens Pass test site (Bobbie's Chute).

position in January after it had consistently failed to inflate. On 25 January inflation of No. 1 bag lifted plywood and a snow wedge as intended but the bag also ruptured, apparently from stresses induced by the plywood. A new bag was installed at this position without the plywood. There was a tendency for the air bags to deflect snow on inflation and then leave a void behind following deflation. Subsequent inflations then expanded the bag into the void and placed little stress on the snow. It appeared that the high-density snow at Stevens Pass did not collapse or readily deform to fill the voids after deflation.

The overall performance of the air bags was unsatisfactory, for they seemed to have poor effectiveness for avalanche release and required a substantial amount of winter maintenance to keep them working at all. Thus, they are not an appealing method for avalanche control in the Cascade climate. A summary of the operational tests and their results is given in Table I.

B. Gas Exploders

An array of gas exploders was installed at the main chute of the East Side Snowshed path at Snoqualmie Pass in the same location as the previous winter. These were the tire type described earlier in Interim Report 19.2. There was never enough snow to bury the exploders properly and hence no real test was conducted. Their performance in shallow snow was not satisfactory for they are mounted a short distance above the ground surface and the principal effect of the explosion is directed upward away from the snow surface. If a successful control program keeps the snow from ever building up to any significant depth in the release zone even in a normal winter, it may well be that this type of exploder would never be satisfactory at this site. Their effectiveness in deep snow has yet to be tested.

TABLE I

AIR BAG INFLATION DATA, STEVENS PASS

DATE	TIME	TYPE	SIZE CLASS	RUNNING SURFACE	SLAB DEPTH	DEBRIS LOCATION	REMARKS
1-3-78	1030	AO-	NONE				5 bags pushed snow to the lower slopes but did not initiate an avalanche
3-15-78	0700	AO -	NONE				
		AE - SS	1	N	8"	Mid Track	Slope and Nancy's Bags
		AO - SS	1	N	8"	Mid Track	Cornice Bags
		AE - SS	1	N	8"	Mid Track	
4-5-78	0730	AO	NONE				
		AE - SS	2	N	4"	Mid Track	Bobby's Bags(Cornice and Slope)
		AO	NONE				
		AE - SS	2	N	4"	Mid Track	Nancy's Chute

(AO = artificial release by air bag; AE = artificial release by explosives)

Test firing of the array proved the system to still be working from the mechanical standpoint. On the final test firing at the end of March there was a malfunction of the gas control unit and a cyclic spontaneous firing pattern was induced. The cause of this has not yet been deduced, but the most likely causes seem to be some kind of combustion in the lines or exploders persisting after the initial firing, or acetylene line pressure high enough to induce spontaneous ignition.

The record of test firing for the exploders and gas cannon at the Snoqualmie site is given in Table II.

C. Gas Cannons

A variation of the gas exploder was introduced during the 1976/77 test season. This consists of a long fiberglass pipe closed at one end and charged with the explosive gas mixture through the closed end. Detonation of the mixture produces a vigorous blast out the open end. This device is designed to be suspended in the air above an avalanche release zone so that the muzzle blast is directed downward against the snow. This configuration takes advantage of the increased effectiveness of an air blast, over a buried explosive charge, in starting avalanches, an effectiveness that has been demonstrated by research and field tests in Europe. Use of the gas cannon is obviously limited to those avalanche paths where an overhead suspension system can easily be arranged.

Two sites were equipped with gas cannons during the 1977/78 winter. One was at the Eastside Snowshed on Snoqualmie Pass, where a control unit was already installed to operate the gas exploder system (tires). A valve was installed to divert the gas flow to the cannon and the latter was suspended over an adjacent avalanche chute from nearby trees. The cover of this report shows this cannon at the moment of detonation when it is illuminated from within by ignition of the gas mixture. The second site was at Stevens Pass in

TABLE II

GAS EXPLODER AND GAS CANNON DATA, SNOQUALMIE PASS

DATE	TIME	TYPE	SIZE CLASS	RUNNING SURFACE	SLAB DEPTH	DEBRIS LOCATION	REMARKS
11-17-77	1100	AO - L	2	0		Mid Track	Cannon test only No Tires
2- 1-77	1200	AO -	NONE				Tire Thumpers Test
		AE - SS	2	G	6"	Lower Track	
		AO - SS	2	0	6"	Lower Track	Cannon Test
		AE - SS	2	0	6"	Lower Track	
*3-29-78	1200						

* Attempt to operate equipment discontinued because of malfunction of the control box.

(AO = artificial release by exploders; AE = artificial release by explosives) the Terminal Chute avalanche adjacent to the top terminal of the Seventh Heaven chairlift. This was only a short distance from the air bag site. Again the cannon was suspended above the release zone from adjacent trees, with a gas control unit installed in the operator's shack at the top of the lift.

Tests of the cannon at Snoqualmie Pass suffered from the same lack of opportunities as did the gas exploder system. Only two operational tests were made, both catalogued in Table II. Both released small avalanches.

Much more abundant snowfall at Stevens Pass allowed a total of 10 operational tests during the winter. One of these was in known stable snow, 2 others produced no avalanching, and the balance produced avalanche activity ranging from sluffs to class 2 soft slabs. In only one instance was an avalanche released with a regular explosive charge after the cannon had failed to do the job. The cannon performance was well-received by the professional ski patrol staff who operated it for some of the tests.

Early in February the snow had accumulated deep enough in the terminal chute that the cannon muzzle became buried, and it was necessary to raise it to provide the necessary clearance for the air blast effect. Routine maintenance at this time also replaced the batteries and torch handle (mixing chamber) in the control unit, as there has been some difficulty getting the cannon unit to fire on the previous test. The difficulty was eventually traced to excess oxygen pressure delivered to the control unit. Reduction of pressure from 25 psi, common for welding use, to 15 psi resolved the problem. This lowering gas pressure appears to be a general necessity for reliable operation of the gas systems. (The possible problems from excess acetylene pressure have already been mentioned above.)

The gas cannon tests were sufficiently successful to raise this technique to a high position on the scale of results from the alternate methods study. It appears to be by far the most effective gas system for use in the maritime snow cover of the Cascades, for the air burst technique circumvents the problem of energy absorption with a buried detonation in a deep snow cover. The tire gas exploders have yet to be tested underneath deep snow, so their efficacy remains unproven in such conditions. Since the maritime snow cover is predominantly stable at depth and avalanche control has to deal mostly with surface conditions, the gas cannon seems to be the best approach to take advantage of the remote control and repeatability advantages of the gas systems.

The gas cannon test record at Stevens Pass is summarized in Table III.

D. Interface Modification

The test of plastic film to inhibit snow accumulation on a steep slope was repeated in the same fashion as the previous winter, with modifications to improve anchoring the plastic. As before, the plastic was installed in mid-winter on top of the existing snow surface in order to simplify anchoring it to utilize a smooth undersurface. On 10 February a sheet of black Tu-tuf-4 polyethylene plastic, 40' x 100' was installed on a steep (40°) part of the Barrier Ridge with the long axis parallel to the fall line. It was attached to 2 x 4 boards all the way around the perimeter and these were buried in a shallow trench dug into the snow. This method of anchoring proved successful and the experiment was not damaged by the wind for the rest of the season. The plastic sheet was removed on 9 May, still intact, with considerable local melt having occurred around it.

The inhibition of snow accumulation was completely successful. Only light, transient amounts of snow built up on the sheet and these readily slid off, so the plastic surface remained exposed the rest of the winter. It appears that even in a climate that affords frequent chances for thaw and refreezing the snow will simply not adhere to this kind of a surface. The sheding of snow is

TABLE III

GAS CANNON OPERATION DATA, TERMINAL CHUTE, STEVENS PASS

DATE	TIME	TYPE		SIZE CLASS	RUNNING SURFACE	SLAB DEPTH	DEBRIS LOCATION	REMARKS
1-4-78	1750	AO	SS	2	0	10"	Lower Mid Track	
		AE	SS	1	0	6"	Lower Mid Track	
1-5-78	0800	AO	SS	1	0	6"	Upper Track	
1-6-78	0800	AO		*				No slide activity in area
1-8-78	0815	AO	SS	1	0	2"	Upper Track	Similar results in other chutes in the area
1-23-78	0830	AO		NONE				No slides in the area.
2-3-78	0800	AO		NONE				Cannon muzzle two feet into the snow
		AE	SS	2	0	10"	Mid Track	
2-14-78	1030	AO		NONE				Stable snowpack--elevated cannon
3-1-78	0745	AO	SS	2	0	4"	Mid Track	Similar results in other chutes in the area.
3-15-78	0715	AO	SS	1	0	8"	Mid Track	
4-5-78	0730	AO	SS	2	N	3"	Mid Track	

*Sluffing of new snow

(AO denotes use of cannon--if hand charges were used in the same chute, the results are noted as AE. Any hand charging in the same chute was done after trying the cannon.)

Cannon fired ten times: 3 class 2 releases, 3 class 1 release, 1 sluffing, 3 no results (1 for test in known stable snow), 1 class 3 AE following NONE from cannon most effective on slopes steeper than about 40°. As the slope angle diminishes, there is an increasing tendency for snow to accumulate at the bottom of the sheet and gradually build an accumulation extending up from the foot of the sheet. This can be mitigated by providing adequate space for discharge at the foot. It appears, in the light of experience to date, that plastic sheets will be much more effective at inhibiting winter-long snow accumulation on convex slopes than on concave ones.

The main problem with plastic sheets for interface modification is anchoring them against wind damage. The use of sufficiently heavy and stiff lumber around the perimeter of very strong plastic appears to be feasible, but this method would be applicable only on fairly smooth ground where the sheet would lie flat against the surface. An alternate experiment was tried based on covering 4' x 8' sheets of plywood with plastic, the aim being to form a more or less continuous coverage of the ground by these 4' x 8' elements. A single such panel was prepared by covering it with Tu-Tuf plastic cut up into small pieces about 8" square and stapled to the plywood as shingles. This panel was set up to test its snow-shedding qualities near the Department of Transportation snow study plot at Stevens Pass. An initial observation showed that the panel was shedding snow just as the large plastic sheet was doing, but the experiment was abruptly terminated when the panel was stolen by vandals. This approach to installing interface modification films is thought to be valid, but still remains to be properly tested in the field.

III. STRESS WAVES IN SNOW AND THEIR RELATIONSHIP TO AVALANCHE CONTROL

A large number of slab avalanches are released yearly by dynamic loads resulting from cornice falls, explosive charges, sonic booms, etc. The mechanism by which these dynamic loads release avalanches is not well understood and little theoretical work has been done to determine these mechanisms. This lack of knowledge has resulted in confusion as to how a dynamic load interacts with the snowpack. Previous explanations of snow slab failure under dynamic loading conditions consider the mechanical fracturing associated with surface or interior craters to be important. A dynamic surface load is thought to briefly increase the normal stress and downslope shear stress of a snowslope. Stress waves propagating within the snowslope have not been considered as an important influence on snow slab failure (Mellor, 1968, 1973; Perla and Martinelli, 1976).

It is the premise of this chapter that stress waves are an important triggering mechanism for dynamically loaded snow slabs. The development describing stress wave interactions with snow and their significance in avalanche control is presented in three parts:

- The general response of snow to stress wave loading;
- A theory for snow slab failure resulting from the application of a dynamic load; and
- The significance of stress wave induced slab failure to avalanche control methods.

A. The General Response of Snow to Stress Wave Loading

Johnson (1978) has demonstrated that three waves may propagate in snow: two dilatational waves and a shear wave. In homogeneous, isotropic snow, the propagation characteristics of the three waves are uncoupled from one another but involve coupled motion between the fluid and solid. The dilatational wave of the first kind (fast wave) and shear wave result from the presence of the solid ice frame; they would occur even if the snow were in a vacuum. The dilatational wave of the second kind (slow wave) propagates in the fluid filled pores interacting with the ice frame to produce stresses in the frame. The slow wave is highly attenuated because of frictional losses. This rapid attenuation results in a rapid loss of energy for slow waves near the dynamic loading source. Stress wave energy transmission over any significant distance must, therefore, be the result of fast waves and shear waves. Slow waves are not considered to contribute to stress wave induced slab failure.

If a transient dynamic load, e.g., an explosion, is applied to the surface of a snow halfspace and exceeds the compressive yield or fracturing strength of the snow, a surface crater is formed. The crater region will continue to grow until the loading stress drops below the compressive strength of the snow at which point the load will be transmitted as a stress wave propagating at the speed of sound in snow.

The impedance match between the loading source and the snow is thought to determine the amount of energy transmitted to the snow. As a crater is growing and the snow is compressed, this impedance match is continually changing. The compaction of snow causes the impedance of the snow in the crater region to increase and results in a complex loading history. The mechanism of crater formation and its affect on loading is complex and little understood and will not be dealt with here.

The loading at any given point in the snow will be of short duration, on the order of milliseconds as the stress wave propagates through the region (Gubler, 1977). The crater is surrounded by a small roughly hemispherical region of cracks radiating from the point of loading. These carcks are produced by tensile stresses, which are set up by the outgoing spherical compression wave parallel to the wave front, the hoop stresses. The radial cracks extending from the crater region will continue to grow until the stress wave passes through the region or its intensity is reduced below the level which causes tensile failure. These effects have been well documented for snow (Fuchs, 1957; Mellor, 1965, 1968, 1973; and Livingston, 1968) and are similar for other materials as well (Kolsky, 1963, 1968; Cristescu, 1967).

The fractures obtained under conditions of a high intensity dynamic load differ from those obtained when the specimen is statically stressed. This results because the stress under dynamic loading is applied for such a short period of time that any cracks formed do not have time to spread. Crack tip velocities for many materials are about one third that of the compressional wave velocity (Kolsky and Rader, 1968). Instead of long running cracks, a large number of separate fractures occur which sometimes join up to form a somewhat continuous irregular surface (Kolsky, 1963). When a large fracture area is desired around the crater region, e.g., for cornice removal or rock blasting, a dynamic load of long duration would be preferred to an extremely rapid load so that the radial fractures have an opportunity to run. This has been demonstrated experimentally for snow by Fuchs (1957).

Outside of the fracture region the stress wave continues to propagate radially and lose energy. If interface boundaries are not encountered, no further fracturing will occur. Most of the dynamic energy is lost in or near the crater region, probably as a result of impedance mismatching, fracturing, viscous damping, and melting in the snow.

If the stress waves propagating in the snow are spherical, then the stress loading experienced along plane sections parallel to the snow surface may be determined from the equations:

$$\sigma_{zz} = \int_0^\infty \left(A\left(\Psi-\frac{q^2}{\Psi}\right)q + 2N\Psi q\right) J_0(qr)\, e^{-\Psi z} dq$$

(1)

$$\sigma_{zr} = 2N \int_0^\infty J_1(qr)\, q^2\, e^{-\Psi z} dq$$

(Johnson, 1978), where A and N are Lamè coefficients for snow, $\Psi^2 = q^2-\delta^2$, q being a parameter and δ the wave number. The cylindrical coordinate system used to describe the plane sections is shown in Figure 6.

With the aid of Equations (1) the outward traveling stress waves from a harmonically time varying source of unit amplitude in the snowpack will be examined. Solutions to harmonic inputs are used to elucidate the general vehavior of snow to stress wave loading, while eliminating the mathematical complexities associated with transient solutions. Solutions to nonharmonic inputs can be approximated by a combination of harmonic functions of a Fourier series or integral. Utilizing a cylindrical coordinate system the stresses are

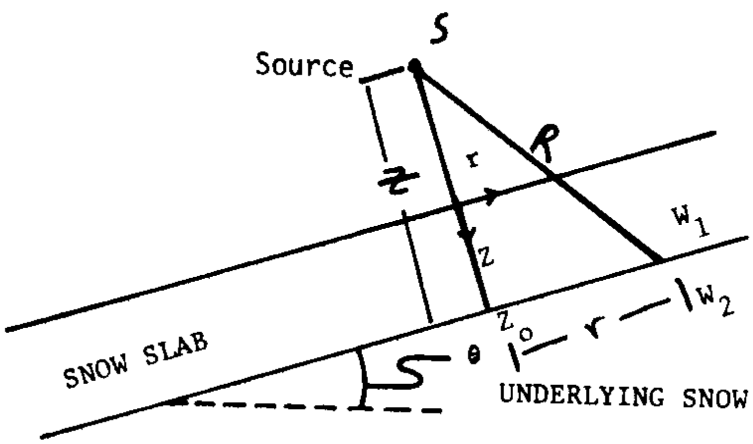

Figure 6. The orientation of the coordinate system for stress wave propagation in a snow slab.

calculated numerically along a plane at a distance z from the source and at various r values. Figure 7 shows $|\sigma_{zz}|$ with $\delta_1 = 60/m$ at z = 0.1 m, 1.0 m and 2.0 m. It is apparent that the maximum compressive stress along the plane at a given z value will be directly beneath the source. The compressive stress decreases from the maximum along the plane as r increases. As the z distance of the plane is increased, we find that $|\sigma_{zz}|$ decreases less rapidly with r than at smaller values of z. $|\sigma_{zr}|$, with $\delta_1 = 60/m$, is shown in Figure 7. $|\sigma_{zr}|$ is zero directly beneath the loading source, i.e., r = 0, and passes through a maximum as r increases. The rapidity of the decrease in $|\sigma_{zr}|$ as r continues to increase past the maximum shear stress is determined by the distance of the loaded plane from the loading source.

The stress wave interactions with snow discussed above are effects that must be considered when trying to determine how dynamic loads release snow slabs. The stress wave interactions may be suble at times, but field experience has shown them to be important.

B. A Theory for Snow Slab Failure Resulting from the Application of a Dynamic Load

Recent theories of snow slab failure place a high importance on the bonding strength between a snow slab and the underlying snow and the resulting shear capacity at the bed of the slab. Field observations tend to support the belief that snow slabs fail along a weakly bonded layer interface.

Snow slabs have been observed to fail under quite different types of dynamic loading sources. Cornice falls and explosives detonated on the snow surface form craters in the snow and are effective means of releasing snow

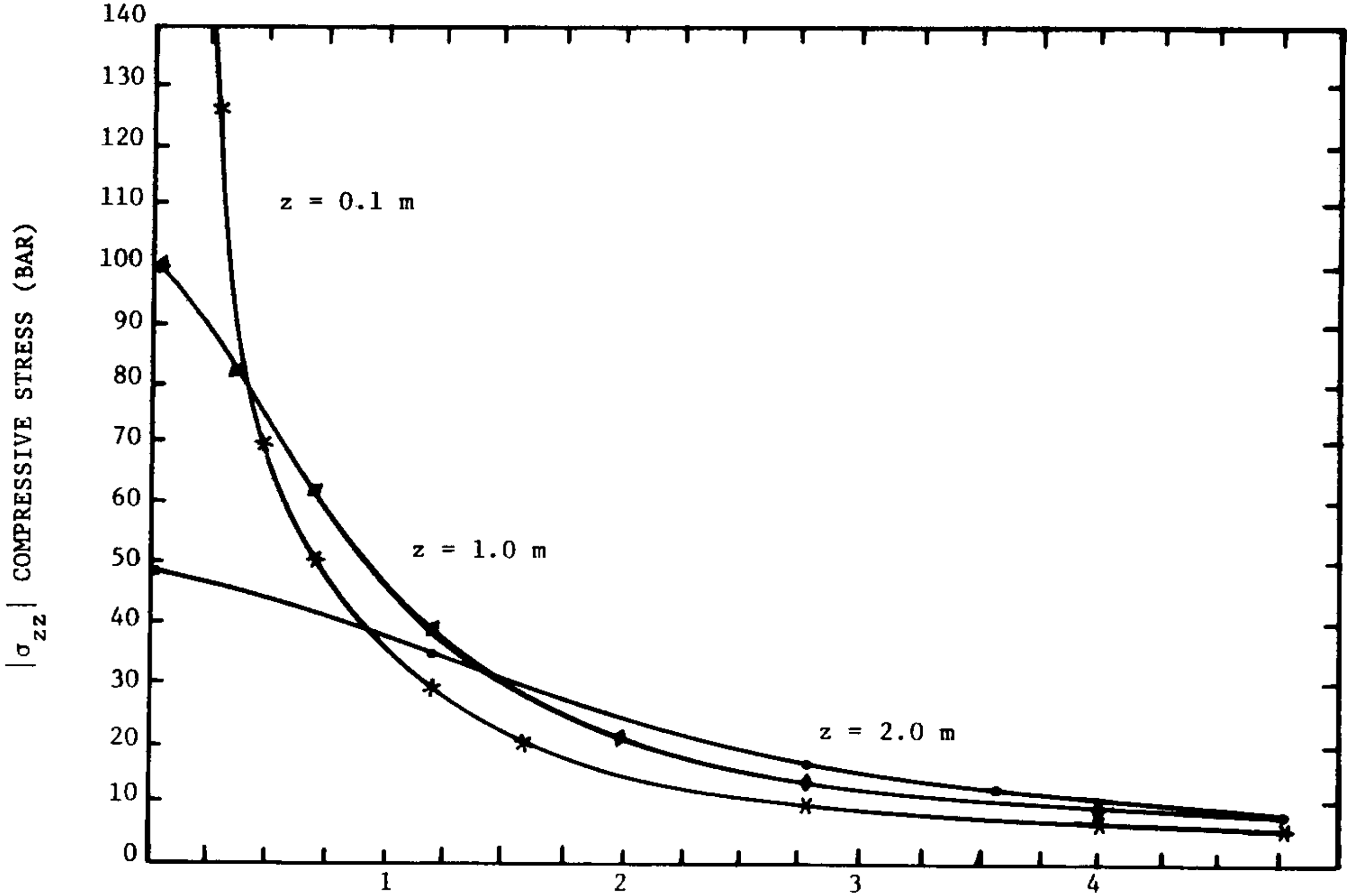

Figure 7.

Compressive stress magnitude on a plane layer in an infinite homogeneous snow medium resulting from spherical waves.

$\rho = 550\ kg/m^3$, $\delta_1 = 60\ /m$, $N = 8820$ bar, $A = 9650$ bar.

slabs. Sonic booms and explosives detonated above the snow surface are also effective at releasing slab avalanches but cause little or no cratering (LaChapelle, 1960; Martinelli, 1972; Mellor, 1973; Perla and Martinelli, 1976; Gubler, 1977). These observations suggest that the fractures in the crater area are not necessary to initiate slab avalanches. The effect of the crater region in a snow slope would be to remove some of the strength of the slope. A more important effect of the crater fractures is probably that they act as stress concentration points. If the tensile stresses in the crater region are such that the local fractures can grow, then larger tensile fractures may form across the snow slope. The effectiveness of crater fractures in causing snow slab failure depends on the tensile stresses set up in the snow slab by body forces and are related in a complex fashion to the basal shear support of the slab. It is the basal shear strength of the snow slab and the interaction with stress waves that impinge on the basal layer that probably determines the stability of the slab under dynamic loads.

It has been demonstrated that a spherical compressional wave sets up shear and compressive stresses along planar interfaces within the snowpack. If these stresses exceed the shear or compressive strength in a given layer, failure will occur in that layer and the shear capacity of the layer is reduced. If the shear capacity of the snow slab is reduced sufficiently, the body stresses of the slab will result in slab failure; this subsequent failure may be explained by any number of existing theories. The magnitudes of the shear and compressive stresses in a weakly bonded thin layer associated with an impinging shperical compression wave may be determined by applying the appropriate boundary conditions at the layer interface.

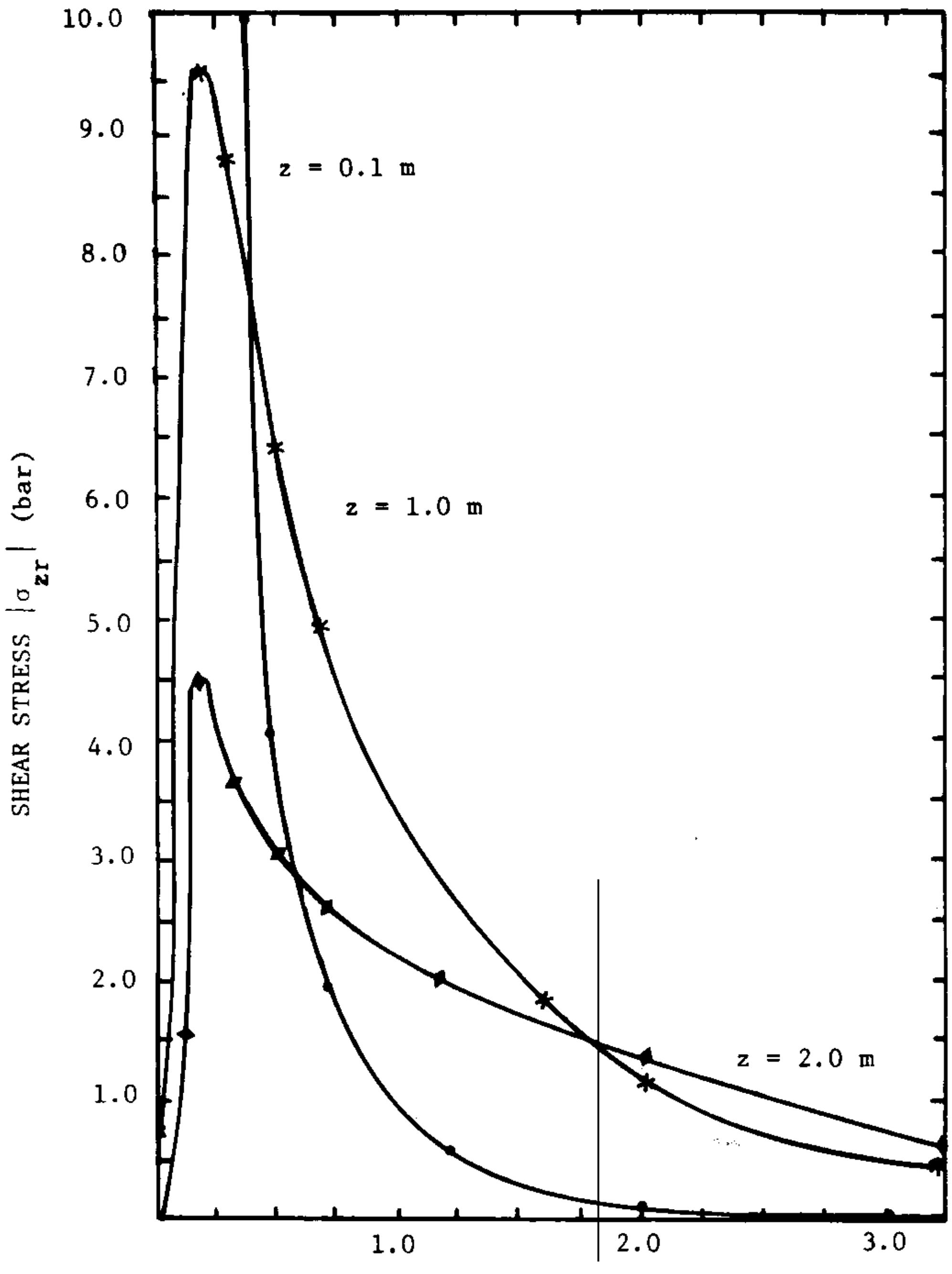

Figure 8.

Shear stress magnitude on a plane layer in an infinite homogeneous snow medium resulting from spherical waves. ρ = 500 kg/m^3, δ_1 =60/m, N =8820 bar, A = 9650 bar.

interface will experience lower stresses than for $W_1 = W_2$. In the natural snowpack the usual condition across a layer interface is for $W_1 < W_2$ so that stresses are generally greater at an interface than would be found in homogeneous snow.

The greatest reduction of shear capacity for a snow slab occurs when the largest possible area in an underlying weak layer fails. Figures 7 and 8 show that the stresses at a boundary differ depending on the z distance of the loading source from a plane boundary. As an example of the effect of source placement on the area of failure, we will assume that the shear strength and compressive strength in the basal layer between the snow slab and underlying snow are respectively 0.9 bar and 20 bar. The placement of a loading source 2.0 m above the interface will then result in the largest area of failure along the interface and will yield the most efficient use of the loading source (Figures 7 and 8). If the shear strength is 5 bar and compressive strength of snow in the basal layer is 50 bar, then a loading source should be 1.0 m above the layer to cause the maximum area of failure.

The stress wave interactions with a snow slab overlying a weakly bonded layer of snow may result in the following possible sequence to failure. A dynamic load will form a crater fracture region in the snow slab until the stress level drops below that required for producing tensile failure in the snow. The stress wave will continue to propagate through the snow slab, impinging on the weakly bonded layer beneath it. A failure region will spread along the basal layer of the slab, the area of failure determined by the magnitude of the stresses developed in the layer and the failure strength of the bonding snow. This failure region will strongly depend on the stresses transmitted to the slab, the height of the loading source above the basal plane, and the impedance mismatch between the slab and underlying snow. To achieve the maximum area of failure along the base of the snow slab, the position of the loading source should be a distance above the base of the snow slab such that the stresses developed in the basal layer exceed bonding strength over the largest area possible. The failure of bonding snow at the base of the slab will result in a loss of shear capacity at the bed and a redistribution of stress in the slab. If the loss of shear capacity is great enough, the snow slab will fail and this subsequent failure may be treated by existing theories.

Crater failure regions act as points of stress concentration and slightly weaken the slab. In a high percentage of slab releases, the crater region probably does not play an important role. If the tensile strength of a snow slab near the crown region does not differ greatly from the existing tensile stresses, a crater located close to the line of maximum tensile stress may result in failure. This failure would be reinforced as the shear capacity of the slab bed is reduced by the propagating stress wave. A more general occurrence is probably the reduction of shear capacity at a snow slab bed due to stress-wave induced failure with the resulting stress redistribution increasing tensile stresses to failure.

If the material properties of the snow slab are such that a large amount of the support of the slab is in the slab proper and not at the basal plane, e.g., hard slabs, cratering may be important in causing slab failure. In such instances craters should be formed in the crown and flank regions

and possibly in the stauchwall region to cut the slab from its support.

C. The Significance of Stress Wave Induced Slab Failure to Avalanche Control Methods

The model for stress wave induced slab failure can be utilized to explain observed avalanche control phenomina and to develop a more effective methodology for avalanche control. The important factors that determine the placement, size, and number of explosive charges necessary to cause slab failure as a consequence of the model are:

1. The compressional and shear strength of the basal layer supporting a snow slab;
2. The strength at the slab boundaries (crown, flank and stauchwall);
3. The body force loading on the basal layer and boundaries of the slab; and
4. The impedance mismatch between the slab and the underlying snow.

Each of the above factors are interrelated and must be considered to determine the most effective control technique. For a short slab most of the supporting strength is probably in the basal layer. If the body loading in the slab is such that the basal layer is close to failure, then a small explosive charge placed in the middle of the slab should cause failure. The charge should be placed so that the region of failure in the basal layer lies within the potential slab boundaries. If the body forces in the slab are not large enough to cause near failure in the basal layer, then consideration must be given to the bonding strength between the slab and underlying snow. Efficient use of an explosive would require it to be placed above the basal layer, the height determined by the conditions described in the previous section. The number of required charges and their spacing to release the slab depends on the area of basal failure caused by each explosive and the difference between slab body force loading and basal shear strength. As the difference between body force loading and shear strength increases, more explosives, spread over the slab and ignited simultaneously, are needed to initiate slab failure.

In hard snow slabs a large portion of the support may be in the slab proper. For extremely hard slabs most of the load bearing strength may be at the boundaries. In such instances a reduction of the shear capacity in the basal layer may not immediately affect the stability of the slab. To cause slab failure explosives should be placed along the slab boundaries (crown, flank, stauchwall) to reduce their strength and provide points of stress concentration from which fractures may propagate. Explosives should also be applied to the slab to reduce its shear capacity and increase the loading at the boundaries.

Avalanche control efforts have demonstrated that wet snow slab avalanches are not easily released by standard techniques. This results because the structure of wet slabs is uniform throughout the snowpack. There are no weakly bonded layers underlying the slab for an explosive to act on. The mechanical damage caused to the slab by the few explosives used in typical control procedures is too slight to cause failure. An additional difficulty is that the period of instability for wet slabs is limited and hard to predict. If a wet slab is significantly hazardous, it can be caused to fail while in a stable state by using a technique developed in Japan (Kobayashi, 1976). Explosive charges are placed across the slab in several lines from the stauchwall to the crown. The explosives are then ignited either sequentially from the stauchwall upward, or simultaneously to break up the slab (Kobayashi, 1976).

The present state of knowledge about the dynamic failure of snow and energy exchange between snow and explosives is too limited to develop quantitative control methods. To quantitatively determine the number, size and placement of explosives required to release a given slab, more theoretical and experimental work must be conducted.

D. Conclusions

A failure mechanism resulting from the application of a dynamic load, e.g., an explosive, is postulated utilizing a stress wave model for a sloping snow slab overlying a weakly bonded basal layer of snow. Calculation of the stresses in the basal layer demonstrate that stress waves may cause it to fail, resulting in a loss of shear capacity at the bed, a stress redistribution in the slab and slab failure.

The stress wave induced slab avalanche failure mechanism implies that the following are important consideration in efficient avalanche control:

1. Isolated explosive charges applied to snow slabs are effective avalanche triggers only when the slab is overlying a weakly bonded layer of snow.

2. The number and placement of explosive charges required to initiate slab failure depend on:

   a) The strength of the basal layer underlying the slab.

   b) The strength at the slab boundaries.

   c) The body force loading on the basal layer and boundaries of the slab.

   d) The impedance mismatch between the slab and underlying snow.

   e) The height of the charge above the basal layer.

3. The optimum location for an explosive charge is such that the region of failure in the basal layer lies within the slab boundaries. The largest shear capacity loss and subsequent stress redistribution in a slab will result when the charge is placed below the crown region toward the middle of the slab.

4. Wet snow slabs are not easily released using explosives due to their strongly sintered structure and limited period of instability. These slabs may be released while in a stable state by placing numerous charges throughout the slab and igniting them either sequentially or simultaneously as described by Kobayashi (1976).

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IV. CONCLUSIONS AND RECOMMENDATIONS FOR IMPLEMENTATION

A. Conclusions from Theoretical Studies

1. Forces on Barriers.

A parameter study using finite element techniques has led to empirical expressions for forces acting on a continuous barrier. Equations have been developed which are functions of parameters which can be obtained through field measurements. Tabulated values have been compiled for easy computation of barrier forces. These results can be used to determine maximum forces to be expected on a continuous barrier exposed to snow pressure on a slope, such as avalanche defense structures (supporting structures), snow fences, guide rails or retaining walls.

A more general extension of the finite element solution leads to a method which can be used to solve snow force problems for arbitrary barrier geometry. Examples have been developed for using this method to solve three practical problems: a pole or line barrier, a discontinuous barrier, and a cylindrical barrier. Barrier forces for these examples can be derived and backpressure zones determined.

2. Stress Wave Propagation in Snow

The theoretical results utilizing a fluid-saturated, elastic porous medium model to describe stress wave propagation in snow indicate that three waves occur, two dilatational waves and a shear wave. In homogeneous isotropic snow the propagation characteristics of the three waves are uncoupled from one another but involve coupled motion between the fluid and solid.

The stress wave model may be used to describe a failure mechanism for a sloping snow slab resulting from the application of a dynamic load, e.g., explosives. Stress wave interactions with a snow slab overlying a weakly bonded layer of snow may result in the following sequence to failure. A dynamic load will form a crater failure region, if stresses are large enough, and also produce stress waves in the slab. These stress waves then impinge on the weakly bonded layer beneath the snow slab. For spherical waves it is found that the compressive stress in the basal layer is a maximum beneath the loading source and decreases away from the source. Shear stresses are zero beneath the loading source, increase to a maximum, and then decrease as the distance from the source increases. The stress magnitude and distribution in the basal layer depends on the height of the loading source above the layer and the impedance difference between the slab and underlying snow. Failure will occur when generated stresses exceed snow bonding strength. The failure of bonding snow in the basal layer then results in a loss of shear capacity at the slab bed and a redistribution of stress in the slab. If the loss of shear capacity is great enough, the snow slab will fail at the slab boundaries, and this subsequent failure may be treated by existing theories.

B. Conclusions from Field Tests

1. Air bags

Air bags have a limited application for cornice removal at selected sites. Positioning of the bags is critical and may need readjustment as winter progresses. The bags have been found to be poorly effective for slope release of slab avalanches and are not deemed suitable for this purpose. Although rated bursting strength of dunnage bags is higher than calculated pressures required to break and lift a dense, strong snow beam, numerous practical cases of bag failure have pointed to their inherent weakness in this application. Most cases of failure can be related to uneven inflation, pinching by ice layers or other causes of localized stress concentration on the bag.

Bag inflation from compressed air bottles or compressors in a variety of sizes is possible. Rapid inflation requires a large compressor (80-125 cfm) and air lines at least 1" inside diameter. Remote control of valving is possible using electrically-operated solenoid valves, but these can experience problems from icing due to moisture carried by the air flow unless a suitable trap is provided.

2. Gas Exploders

The cannister-style gas exploders are functional for slope avalanche release in continental climates. They are most effective when deployed in an array of several canisters. They are unsatisfactory in the deeper snow cover of a maritime climate. The tire-style exploders communicate more energy to the snow cover and appear to be effective for deeper continental snow covers. Owing to the upward deflection of exploding gases from a raised platform, they do not perform well in very shallow snow. Their effectiveness has yet to be proven in a deep, maritime snow cover, but is thought to be limited on the basis of experiments to date.

A gas control unit permitting remote control charging and firing of the canisters has been developed and proven effective. It provides satisfactory reliability under winter field conditions with careful installation, a strict maintenance program and proper operation.

3. Gas Cannon

The gas cannon, providing an overhead explosive blast directed downward to the snow surface, has proven highly functional in a maritime climate and shows a high percentage of avalanche releases. The air burst principle circumvents the effect of a deep snow cover constraining the energy release from the exploder-type units located beneath the snow. The gas cannon has not yet been tested in a continental climate but is expected to be just as effective, if not more effective, there than in a maritime climate.

The principal limitation of the gas cannon is the requirement that it be suspended in the air above an avalanche release zone, thus making it useful only where natural supports, such as trees, are available or the terrain favors installation of support structures, such as poles or towers. In an area of deep snow accumulation, the cannon may need to be repositioned once or more times during a winter.

The gas cannon can be charged and fired by the same control unit used for the gas exploders.

4. Vibrators

Mechanical vibrators in the energy range of several horsepower have very limited effect for avalanche release under the test conditions described in Interim Reports 19.1 and 19.2. It is difficult to achieve useful coupling of mechanical energy from vibrator to snow. Original hopes of establishing mechanical resonance in bounded snow slabs were not realized. The air-driven vibrators required a larger flow rate of air than could be delivered by the available air lines and compressors. For effective operation, it is necessary to charge an on-site accumulator tank to high pressure and then discharge this directly to a vibrator through a solenoid-controlled dump valve.

5. Interface Modification

The use of plastic sheets to inhibit snow accumulation on steep slopes is highly effective in both continental and maritime climates. This method appears to be adpatable to both cornice and avalanche release zone sites. Snow accumulation is discharged most effectively from plastic lying on slopes above 35-40°. A large enough area must be covered to minimize burial of the plastic sheet by encroachment around the perimeter and the technique works best on convex slopes where space is available for snow discharge at the foot of the covered area.

A serious drawback to the use of large plastic sheets is the difficulty of anchoring them against destructive effects of the wind. The very strongest material must be used, and it must be thoroughly attached to well-anchored timbers around the entire perimeter. On complex terrain it is deemed advisable to cover individual plywood sheets with plastic and then attach these individually to prepared anchors set into the ground. The latter scheme has not been tried beyond a very preliminary test and needs further developmental work in the field.

6. Remote Control Systems

Several variations of the gas exploders, gas cannons and air bags can be operated by remote control. The gas control unit was designed to accomodate such control. Land lines are satisfactory for such control, but have to be installed to a rigorously high quality standard to insure reliability in an alpine environment. Power for control and valving at remote sites can be provided by sealed-type storage batteries of appropriate characteristics for the type of service desired. Remote control by radio is possible using a coded tone keying system than can easily be adapted to standard VHF communications systems.

C. Recommendations for implementation

1. Adopt interface modification as a primary means of suppressing avalanche formation on small paths. A further development program is needed to identify optimum modes of installation.

2. Adopt gas cannons for general artificial release of avalanche on small paths where terrain favors installation.

3. Adopt gas exploders only in continental climates and only in selected localities where the cannon cannot be used.

4. Adopt air bags only for highly selected cornice sites, use only heavy-duty bags and install rigorous safety valve systems to prevent over-inflation.

5. Do not explore further use of vibrators unless very high energy systems can be introduced.

These recommendations pertain to the control of small avalanche paths affecting mountains highways, the original target of research under this study. They do not apply to large avalanche paths, which under the present technology of avalanche control should be reserved for artillery or air cannon. Interface modification is given the primary recommendation for three reasons. Firstly, it promises to be the most generally effective of the methods tested. Secondly, it requires no moving parts nor any mechanical or electrical maintenance beyond the labor of initial installation and seasonal take-down, thus making it the best suited of the tested methods where manpower, and especially technically skilled manpower, is in short supply. Thirdly, the inhibition of snow accumulation is self-functioning, works continually, and requires no technical decisions about snow stability or the scheduling of control missions.

V. THE MAINTENANCE PROBLEM

The success of any avalanche control program is limited by the maintenance of the control equipment. This applies equally to structures like snowsheds or retaining barriers as it does to artificial release hardware like artillery or gas cannons. To address state highway departments on the subject of maintenance may have some flavor of carrying coal to Newcastle, for highway maintenance after all is a major function of every such department. But our experience to date with the introduction of innovative methods suggests that even in this milieu a discussion of equipment maintenance may be in order.

Equipment maintenance seems to be an accepted practice once it becomes an established custom. (Though we have yet to encounter a highway foreman who felt that repairs to his snowplows were speedy and thorough enough.) In the case of avalanche control work, for instance, it is accepted practice to clean, repair, transport and store under shelter a military howitzer or recoilless rifle used for this purpose. The need to do so is obvious and is accomodated each time a shooting mission is undertaken. The problem arises when something out of the ordinary routine has to be done. An excellent example of this came to light during the present research project.

About 20 years ago the Colorado Department of Highways retained the late Monty Atwater to examine avalanche problems in the vicinity of Red Mountain Pass and recommend means for dealing with them. One of the most active paths in this vicinity is the Blue Point slide just north of the Pass, where many avalanches reach the highway each year. This path is frequently loaded with wind-drifted snow transported across open slopes and deposited into a steep gulley topped by cornices. Atwater recommended a series of snow fences to the windward of this gulley that would catch the drifting snow before it reached the avalanche release zone. Such fences were constructed using standard snow fence material supported by steel posts and cables. The installation was soundly done and, according to highway personnel who remenbered it, proved effective in reducing avalanches from the Blue Point path.

When the Colorado part of the present research was undertaken, the Blue Point slide was quickly identified as an ideal test site and two of the alternate methods, air bags and vibrators, were tested here. The first thing the project crew found when they inspected this site was the remains of the Atwater snow fence system. Most of the steel posts still stood, but cables and snow fence elements had long since collapsed under two decades of storms, winds and snow settlement, reducing effectiveness as an avalanche prevention measure to zero. Appearances, as well as testimony of local highway personnel, spoke also of zero maintenance.

Here was an effective avalanche control system, installed at considerable expense and effort for design and construction, left to wither away into usefulness for lack of attention. Certainly, it was not a question here of dealing with complex or unfamiliar equipment. The maintenance required was of the simplest kind--annual inspection with tightening or replacement of cables, replacement of broken or damaged snow fence sections, reinforcing posts or anchors where these had proven weak. But even this was not done and over the years the snow fences fell into disrepair and were largely forgotton through changes of personnel in the local highway crews.

The reasons for such neglect are easy to see. Budgets are always tight, local crews often short-handed and the demands of routine snowplowing or road maintenance take priority over repairs to structures hardly visible from the highway and whose function is poorly understood. The repairs have to be made in the summer when the imperatives of avalanche protection are rapidly fading from memory. If these handicaps are coupled with suspicions about the effectiveness of a control system in the first place, the whole matter quickly reaches the bottom of the maintenance priority list and before long disappears from the list completely.

In recommending alternate avalanche control techniques developed under the present research contract, we are introducing methods of greater technical complexity than snow fences, some of them electro-mechanical systems demanding considerable care in their installation and use. The amount of maintenance required, in fact, has played an important part in ranking the order of the recommended methods, with interface modification heading the list not only because of high effectiveness but also because it is potentially the easiest to maintain given a proper initial installation. Given this great complexity, we wish to place the strongest possible emphasis on the maintenance question. None of these alternate methods is going to succeed beyond an ephemeral demonstration without an administrative and fiscal commitment to a systematic maintenance program by the executive levels of a highway department.

Technical details of installing, operating and maintaining the various avalanche control methods are given in the Operating Manual and need not be repeated here. There are, though, several general guidelines to maintenance which can usefully be emphasized at this point. These are based on hard experience during the four-year life of this research project.

A. Rodents

Alpine rodents, marmots in particular, have a voracious appetite for electrical insulation, rubber hose and the glue used to bond plywood laminations. They are not attracted, fortunately, to neoprene air bags and plastic pipe. Every inch of rubber hose and wiring that is not buried has to be shielded by metal. Even buried lines will be dug up by marmots if they lie near the surface. All signal cables, even those buried in the ground, should be of the type that has metal shielding, as well as electrical insulation. (Cables with 10-mil copper shields were used in this project.) Long runs of air line should be installed with steel or plastic pipe buried in the ground. Any rubber hose, buried or not, should be placed inside metal pipe or flexible conduit. Almost shielded is not good enough, as the research crew in Colorado discovered when a rabbit reached a few inches of exposed rubber gas line from an oxygen bottle and put a gas exploder system out of commission.

B. Lightning

Ridge-top locations are always vulnerable to lightning strikes. This is a big problem in Colorado in the summer, where afternoon thunderstorms are common. Lightning accompanying accasional winter thunderstorm activity in severely unstable air is possible in all climates. Electrical equipment has to be thoroughly shielded and grounded and should be removed from the field entirely whenever possible during the non-avalanche seasons. The possibility of electrical shocks transmitted through buried steel pipe also has to be considered, and for this reason plastic pipe may often be a better choice for air lines. A structure housing remote-control air bag equipment in Utah was put out of commission by a lightning strike in the summer of 1977.

C. Vandals

This is a growing problem with all kinds of field installation, and avalanche control equipment is not immune. Two air bags were stoken from a Colorado site in the short spring interval between snowmelt and equipment pickup. The Utah site had a power meter destroyed. Al element of the inter-fact modification test was stolen in Washington. There probably is no sure protection at all times, but the problem can be minimized by removing from the field and storing all portable equipment during the off-seasons.

D. The Enemy Within

Highway department personnel working on the mountain passes all need to be acquainted with the details of the avalanche control program and how the equipment is installed. While this may seem obvious to the point of triviality, the Colorado research crew found out otherwise when an over-enthusaistic operator of a road grader destroyed an air line to one of the air bag sites while cleaning ditches during a mid-winter period of fair weather.

The basic principle for maintenance of alternate method equipment should be to assume that if anything can go wrong, it will. Murphy's Law dominates in the alpine environment.

APPENDIX A

A listing of avalanche reports prepared by the University of Washington for the Washington State Highway Commission during the period 1971/77.

LaChapelle, E.R. *Avalanche Atlas: North Cascades Highway SR-20*. Washington State Highway Commission, Olympia, Washington, 1971. (Prepared under Agreement Y-1301)

LaChapelle, E.R. *Avalanches on the North Cascades Highway (SR-20), Summary Report*. Washington State Highway Commission, Olympia, Washington, 1971. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown and R.J. Evans. *Avalanche Studies (1971-1972)*. Report 8.3, Washington State Highway Commission, Olympia, Washington, 1972. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, T. Fox, D.M. McClung and L. Smith. *Avalanche Studies (1972-1973)*. Report 8.4, Washington State Highway Commission, Olympia, Washington, 1973. (Prepared under Agreement Y-1301)

LaChapelle, E.R. *Avalanche Atlas Supplement: North Cascades Highway SR-20*. Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, D.M. McClung, and M.B. Moore. *Avalanche Studies (1973-1974)*. Report 8.5, Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown and R.J. Evans. *Methods of Avalanche Control on Washington Mountain Highways, Summary Report 1970-74*. Report 8.6, Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R. *Avalanche Atlas, Cascade Passes: Part 1* (Chinook, Cayuse, White and Snoqualmie Passes). Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R. *Avalanche Atlas, Cascade Passes: Part 2* (Stevens Pass and Tumwater Canyon). Washington State Highway Commission, Olympia, Washington, 1975. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, J.B. Johnson, J.A. Langdon, M.B. Moore and P.L. Taylor. *Alternate Methods of Avalanche Control, Interim Report*. Report 19.1, Washington State Highway Commission, Olympia, Washington, 1975. (Prepared under Agreement Y-1637)

LaChapelle, E.R., R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett and P.L. Taylor. Central Avalanche Hazard Forecasting, Interim Report. Report 23.2, Washington State Highway Commission, Olympia, Washington, 1976. (Prepared under Agreement Y-1700)

LaChapelle, E.R., J.B. Johnson, J.A. Langdon, C.R. Morig, E.M. Sackett, and P.L. Taylor. Alternate Methods of Avalanche Control, Interim Report. Report 19.2, Washington State Highway Commission, Olympia, Washington, 1976. (Prepared under Agreement Y-1637)

LaChapelle, E.R. Alternate Methods of Avalanche Control, Executive Summary Report. Washington State Highway Commission, Olympia, Washington, 1977 (unpublished). (prepared under Agreement Y-1637)

LaChapelle, E.R., R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett and P.L. Taylor. Central Avalanche Hazard Forecasting, Final Report. Report 23.2, Washington State Highway Commission, Olympia, Washington, 1977. (Prepared under Agreement Y-1700)

LaChapelle, E.R., D.B. Bell, J.B. Johnson, R.W. Lindsay, E.M. Sackett, and P.L. Taylor. Alternate Methods of Avalanche Control, Final Report. Report 19.3, Washington State Highway Commission, Olympia, Washington, 1978. (Prepared under Agreement Y-1637)

LaChapelle, E.R., S.A. Ferguson, R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett, and P.L. Taylor. Central Avalanche Hazard Forecasting, Implementation Report. Report 23.3, Washington State Highway Commission, Olympia, Washington, 1978. (Prepared under Agreement Y-1700).

Inquiries regarding these reports may be addressed to:

Avalanches - Geophysics AK-50
University of Washington
Seattle, WA 98195