TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ALTERNATE METHODS OF AVALANCHE CONTROL - INTERIM REPORT		5. Report Date July 1976 6. Performing Organization Code
7. Author(s) E.R. LaChapelle, J.B. Johnson, J.A. Langdon, C.R. Morig, and P.L. Taylor		8. Performing Organization Report No.
9. Performing Organization Name and Address Geophysics Program and Department of Civil Engineering University of Washington Seattle, Washington 98195		10. Work Unit No. 11. Contract or Grant No. Y-1637
12. Sponsoring Agency Name and Address Washington State Highway Commission Department of Highways, Highway Administration Bldg. Olympia, Washington 98504		13. Type of Report and Period Covered INTERIM August 1975 - July 1976 14. Sponsoring Agency Code

15. Supplementary Notes

Cooperation with US Department of Transportation, Federal Highway Administration

16. Abstract

A collection of reports resulting from the second year's study. Reports are entitled:

1. Air Bag System by E.R. LaChapelle, C.R. Morig and P.L. Taylor
2. Gas Exploder System by E.R. LaChapelle, C.R. Morig, and P.L. Taylor
3. Vibrator Tests by E.R. LaChapelle, C.R. Morig and P.L. Taylor
4. Mechanical Resonance of Snow by J.B. Johnson
5. Interface Modification Field Tests by E. R. LaChapelle
6. Approximate Solutions for the Interruption of the Creep and Glide of a Snowpack by Rigid Structures by J.A. Langdon

17. Key Words	18. Distribution Statement
Avalanche, Snow, Weather, Creep, Glide	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	95	

Form DOT F 1700.7 (8-69)
HWY FORM 341-004 6/72

ALTERNATE METHODS OF AVALANCHE CONTROL

by E. R. LaChapelle and
J.B. Johnson, J.A, Langdon, C.R. Morig, E.M. Sackett, and P.L. Taylor

INTERIM REPORT

Research Project Y-1637 Phase 2

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Prepared for
Washington State Highway Commission
Department of Highways
in cooperation with
US Department of Transportation
Federal Highway Administration

July 1976

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Chapter I

AIR BAG SYSTEM

by E. R. LaChapelle, C. R. Morig, and P. L. Taylor

1. General Comments

In spite of a light avalanche winter in both Washington and Colorado, some useful advances were made in understanding the application of inflatable air bags to avalanche control. The growing body of experience with this system at the Cascades and San Juan Mountain Passes, plus the newly-added site in Utah, has led to the following interim conclusions:

a) Problems experienced the first year with non-inflation and eventual rupture of some bags in a multiple bag array have not been repeated. The bag failures apparently were due to the placement of new bags which had never been inflated and the subsequent accumulation of a very heavy and hard snow cover which insured the bags were compressed completely flat without an opportunity to begin inflating over their whole area. Experience with the problem and the avoidance of excessive inflation pressures has also helped. As a further protective measure, pressure relief valves set at 15 psi are now routinely installed on each bag at the point of air hose entry. Some pre-inflation prior to snow cover accumulation is also thought to be beneficial.

b) Several different kinds of hose or pipe for air lines have been tested to determine which is the most effective and economical. Standard general-purpose pressure hose rated at 300 psi appears to be durable and effective but is costly in the larger diameters required for efficient inflation and deflation. Nylon garden hose is reasonable in cost, easy to install and safe to use at the inflation pressures currently utilized, but does not have a stiff enough wall to resist collapse under the pressure of a deep snow cover. Polyethylene pipe rated at 120 psi is economical even in larger sizes and adequate for most installations. It is stiffer than hose and cannot be bent around sharp corners, but plastic elbows are available to accommodate sharp bends. On the basis of experience to date, polyethylene pipe is recommended for future installations of air bag systems. A short length of flexible hose should be provided for connection to each bag to accommodate flexing during inflation.

Rapid and efficient inflation definitely requires a minimum air line size of one inch internal diameter. Smaller sizes may be used for short runs up to 200 feet, but the minimum size should be 1/2 inch. Owing to the very small pressure differential during deflation, any hose smaller than this requires an inconveniently long deflation time even for short runs.

c) Air bags used for cornice removal definitely need to be placed in multiple arrays which cover the shifts in optimum bag position accompanying the seasonal changes in cornice configuration with build-up of the winter snow cover. Details concerning experience with this problem are discussed in the specific test summaries below.

d) The common effect of air bag inflation is first to fracture the snow and then to tilt up a large slab consisting of the entire snow cover. This effect is clearly seen in Figure 1. On the basis of experience to date, most bag-initiated avalanches have been secondary to the actual snow rupture. Falling cornices, snow dislodged in sluffs, or toppling of the lifted segment of snow cover have actually triggered the release of slab avalanches. We have little evidence to date that the initial snow rupture over an inflating bag is propagated as a slab avalanche fracture line. There are too few tests of air bag releases on slopes to draw definite conclusions at this time. Emphasis on further tests for slope release is needed to determine whether in fact the air bags are effective agents for directly initiating slab avalanches. If they should prove not to be, this will have important implications for the basic understanding of avalanche release mechanisms, for it would imply that dynamic loading is an essential requirement for artificial release.

2. Tests in the Washington Cascades

2.1 Snoqualmie Pass, East Snowshed Avalanche Path E4

a) Installation

Two 4x9' rubber dunnage bags (ShopKwik) were installed on the NW side of the release zone. Exact location, the consensus of highway and research field people, was along the most probable fracture line between two groups of trees (Figure 2). Slope angle was about 42°; elevation, about 3600'; and aspect, SW.

Bags were placed side-by-side. Anchoring on the slope was provided by 3/4" water pipe running through rubber loops glued to the top of each bag. The pipe was anchored by 1/4" wire rope attached to tree trunks above. Two cable lines were strung per bag with "Y" attachments to

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

Figure 2. Air bag site at the East Side Snowshed avalanche release zone, Snoqualmie Pass, Washington. The broken snow is a result of bag inflation during a test on 1/8/76.

distribute the force along the pipe.

Air flow to each bag was provided by 100' of 3/4" plastic water hose which descended the fall line. Hose was attached to wire rope anchor cable at about 30' intervals by nylon rope Prussik knots, "O" rings, and wire rope clips. Care was needed during installation to prevent collapse of water hose at bends in the line. Additional Prussik knots and wire wraps were used for this purpose.

Nitrogen gas for bag inflation was provided by M size bottles (122 cu. ft., 1900 psi) through a pressure regulator and a manifold constructed of water piping. The manifold had a manual valve for each bag and a common dump valve. Loose plastic covers over the regulator and the manifold were sufficient weather protection.

Initial installation was completed October 26, 1975.

b) Operation

Both air bags were inflated simultaneously from one nitrogen bottle in about two minutes at 20 psi delivery pressure. Back-pressure was zero psi at the end of full inflation. Bags inflated together during both control missions.

The installation was maintenance-free throughout the winter. The pressure regulator was removed and operation discontinued on April 21, 1976.

c) Results

Snow had a tendency to slide off bags in early winter. Coverage on the bags occurred once the snowpack surrounded them.

The expanding bags acted on the snowpack in similiar fashion for both control missions. Snow fractured above the bags and a slab, about 18" thick, was lifted and tilted downslope. In the first instance, six " of new, soft snow slid from the tilted snow table onto the slope. In the second instance, a boot push sent the entire slab of wet, heavy snow onto the slope.

Snow avalanche release occurred by air bag, explosive handcharge, or ski check on the first control mission. Further evaluation of air bag results was hampered by urgency to control the slope and open the road to traffic. Undisturbed snow surface was observed between bags and fracture line. Release during the second control mission was by handcharge. Snow fractured about 20' below bags on both missions at the convex slope of 50-55° angle above the cliffs.

d) Discussion of Results

Two air bags inflating together, side-by-side, may enhance the formation of a tilted table of snow with added loading of surface snow layers below the fracture line.

More positive avalanche results from inflating air bags might occur by locating bags on the transitional area above cliffs. This area is steeper and below the anchoring effects of the tree groups. It was thought at the beginning of the season that snow of any significant depth would not remain on the cliff breakover area for control purposes.

2.2 Stevens Pass, Bobby's Chute, Stevens Pass Sno-Country Ski Area

a) Installation

Four rubber dunnage bags were installed, two 4x6' bags on the cornice prone ridgeline, and one 4x9' bag and one 4x8' bag on a slope of about 50° angle. Elevation of installation was about 5750'. Aspect was N for cornice bags, NW for slope bags. Exact location for cornice bags was adjacent to windward slots in trees, allowing for greatest snow transport and cornice buildup. Bags on slope were placed where handcharging normally produced best results and where the most probable fracture line exists.

All bags were anchored using 3/4" diameter water pipe inserted through rubber loops cold-patched to the bag or lashed by polypropylene rope to grommeted holes in upper edge of bag. The piping was secured by 1/4" wire rope and rope clips to trees on ridgeline, two lines per bag. The cable was strung in "Y" sections to distribute force along pipe. Cornice bags were separated by about 10"; slope bags were placed side-by-side. Plastic sheeting was wrapped around the bags, taped closed on sides, and left open at bottom.

A single 1/2" diameter rubber air hose ran to both cornice bags, another to both slope bags, with a "T" installed between each pair of bags. Hose from the slope bags ran straight uphill to the ridgeline. From there it paralleled hose from cornice bags to the top terminal of 7th Heaven chairlift. On the steep slopes and long traverses wire rope cable was strung beside hoses and anchored to trees. The hoses were attached to this cable at 10-30' intervals with nylon rope Prussik knots, "O" rings, and wire rope clips.

Inflation gas was provided by M size nitrogen bottles (122 cu. ft., 1900 psi) through a pressure regulator and a manifold hand-valved to

direct gas flow to cornice and/or slope bags. Bottles and auxiliary equipment were protected from the weather inside the chairlift building.

b) Operation

Initial checkout of the system occurred on December 17, 1975, with about 2 1/2' of snow in Bobby's Chute. One cornice and one slope bag inflated. Additional hoses were layed two days later with one hose attached to each bag. The 3/4" diameter plastic water hose was strung half-way along the ridge for slope bag #2. A four-hose manifold was installed on December 23. Valves were opened so all bags would inflate simultaneously. Pressure regulator was preset for 20 psi delivery pressure. A sheet with operating procedure and visual observations to be taken by control crew was posted above the manifold and patrol leaders were informed that the system was ready for their use.. The system was functional from this date.

Hose constrictions plagued slope bag #2 early on. Two sections of coiled garden hose collapsed by snow pressure were discovered below the chairlift terminal on January 29. At slope bag #2, the 1/2" air hose, which for purposes of low profile to snow glide forces ran directly from an elbow fitting on the bag underneath 3/4" water pipe anchor to ridgeline, was pinched between the ground and water pipe. Also, at or near full inflation, the air hose became folded back on itself as the elbow rose with the bag and the pipe anchor remained close to ground. Rotation of the elbow for side entrance to the bag and addition of a small section of air hose remedied these two problems at bag #2. The first inflation of this bag later in the winter probably contributed to air hose difficulties by subjecting hardware to the full weight of the snowpack.

Full inflation of air bags took two bottles of nitrogen gas. Bottle change-over required additional and not always available effort from busy control crews. For this reason, a compressor was installed January 29, 1976, at the top lift house of 7th Heaven chairlift. Included were an electric timer (60 minutes maximum pump time), a solenoid-operated valve for dumping air after bag inflation, and a relief valve set at 9 1/2 psi maximum pressure in the system. With no overriding snow, all air bags inflated hard at 4 psi manifold pressure with 20 minutes compressor pumping. Timer was set for 30 minutes pump time initially so that the dump valve might be open and bags deflating when control crew handcharged slope and cornice areas.

The system operated maintenance-free through most of February and March, 1976. On the March 24 test, slope air bag #2 (Acme Steel 4x7') would not inflate when given full compressor output. Air was heard leaking within upper left corner of bag near air inlet. The left side of bag was found distorted and folded under itself. Old snow was pushed up against this side of the bag. Speculation is that slope bag #1, which was inflating and deflating faster than bag #2, broke a snow slab tilted on the March 20 test as it deflated. The broken slab pushed against side of the bag #2 before it was completely deflated. Also observed on March 24 were grommets and anchor rope torn free of about 2' of top center edge of bag #2. The plastic cover was torn from pipe anchor in this area also. A large void space was found above the bag, a light covering of new, loose snow on bag surface. The slab broken free on the March 20 inflation appeared intact and contacted lower section of bag directly below damaged area. A more durable protective covering around air bags is recommended for next season.

Handcharges of 2 3/4 pounds of 85% gelatin dynamite were thrown near bags on slope and cornice on some 23 control missions. The bags were unaffected.

The compressor was removed and operation discontinued on April 24, 1976.

c) Results

Cornice air bags repeatedly released cornice chunks after only a few minutes of inflation and kept corniced area small above them. Bags were located ideally for the beginning of the season at ground breakover. Later on cornices built out above bags thereby reducing their effectiveness. Cornice bag #4 was raised on December 19. Slab avalanche release by cornice chunks was not readily apparent. Snow buildup on the icy cliff below the bags was thin. Routine handcharging restricted full testing of the cornice air bag potential. On March 20, however, a possible one foot deep slab was released by a cornice fall in the transition area below cliffs and air bags. Poor visibility in the blowing snow of enveloping storm made confirmation difficult before handcharging was undertaken.

Inflating slope air bags fractured snow atop them and lifted snow to cause sluffing of loose surface layers. On January 29, slope bag #2 fractured 3 1/2' of dense, hard snow with less than 10 psi manifold pressure. Confirmed slab avalanche releases by slope bags occurred on March

19 and 20. Bags released a soft slab avalanche with one foot fracture on March 19 covering 70% of release zone and sliding to transitional region of track. On March 20 a tilted table of snow, about 2 1/2' thick, was formed by both bags inflating, which slid off the bottom side of bags onto slope. This slab caused a soft slab avalanche with one foot fracture depth extending about 10' laterally from bag #2. To fully inflate slope bags under this snowload with the compressor, air flow was turned off to cornice bags at 35 minutes pump time and pressure relief valve was stopped so manifold pressure could build to 14 psi with additional 20 minutes pumping. A handcharge then released snow above the bags and removed surface evidence at bag site. Angle of the tilted table was 70°.

Snow depth above the slope bags on March 20 was 135 to 285 centimeters when probed perpendicular to slope surface.

d) Discussion of Results

The potential for air bags to release cornices in Washington was demonstrated. Plastic covering seemed to aid snow removal on bags and reduce inflation times. The extent of cornice release needed to induce slope avalanches seems greater than shown by bag deployment this season. Routine handcharging restricted extensive investigation of cornice bag potential. Additional deployment of bags with greater separation along ridgline seems a logical step to gaining needed information on cornice fall triggering of slab avalanches in this chute. The slope air bags inflated routinely, cracking the snow surface, showing potential to release avalanches by tensile fracture. Unfortunately difficulty was experienced with inflation of slope air bag #2. This bag was in a key position to cause the greatest tensile disturbance to snowpack. Deployment of more air bags along most probable fracture line seems necessary to disclose full potential of tensile fracture inducement of snow avalanches in a Washington snowpack. Full air bag inflations then may not be necessary for slope avalanches to occur.

The formation of a wedge of snow by slope bags when inflated together and to full size is of interest for its possible loading of the slab below tensile fracture region. Timing of bag inflations might be less critical during periods of rapid change in avalanche hazard if loading were induced. More dense snow may be moved during periods of low hazard keeping volumes of avalanching snow smaller and running distances shorter on the average.

The void space found at slope bag #2 on March 20 indicates a possible need for alternate inflations of staggered bags along fracture line from storm to storm, especially if tilted table principle is used or a large disturbance of snowpack to induce avalanches.

A means of completely inflating air bags in about 5 minutes is needed for including air bag tests in routine control missions.

2.3 Snoqualmie Pass, Wac Bluff, Alpental Ski Area

a) Installation.

Three air bags, a 4x7' and two 4x6', were installed on Wac Bluff on two small chutes at an elevation of about 4480' and NW aspect. Exact location, a consensus of ski area control and field research people, was one of two possible sites along the bluff with the highest frequency of avalanche occurrence. The site was selected for its proximity to AC electrical power for the compressor motor.

Bags were anchored by 3/4" water pipe lashed through grommeted holes in bag edge with plastic rope or inserted through rubber loops glued to bag upper edge. Pipe was suspended on the slope by 1/4" wire rope, two lines per bag.

Air to bags was supplied by 3/4" plastic garden hose which was secured along the slope with 1/4" wire rope, rope clips, "O" rings, and nylon Prussik knots.

The air compressor was installed at the ridgeline above bags. The compressor, motor, and manifold were housed in a wooden weather-proof box which was lashed to the side of a tree and suspended from a limb. One thousand feet of power cable was strung along the snow from the site to a power house at the top terminal of Chair #1. The power line was protected from snow creep on steep slope by lashing it to accompanying 1/4" wire rope anchored to trees.

Initial installation was completed on December 4, 1975.

b) Operation.

Initial checkout of air bag system occurred on December 4, 1975. Bags inflated about 1 1/2' thick in about six minutes. A pressure relief valve was installed on December 18 and bags inflated fully in 12 minutes, to 9 1/2 psi manifold pressure in 33 minutes. A solenoid operated dump valve was installed on manifold on December 31. Bags were inflated with the compressor door closed to check for overheating on a warm day. Interior of

compressor box was cool. Switches were set to run compressor from power house. This allowed bags to inflate without delay to Wac Bluff control operations and the opening of Chair #1.

On about January 9, 1976, a series of events was initiated which led to damage of the compressor. On that morning the compressor motor circuit breaker was thrown on at the power house by a patrolman assigned the Wac Bluff control route. The patrolman was reassigned another control route, forgetting about air bag operation. On about January 10, another patrolman on Wac Bluff control route noticed the compressor breaker switch on in the powerhouse, and found the breaker off at the compressor site. He threw the switch on, smelt burning material, and turned the switch off. Examination of the compressor on January 12 disclosed the oil plug holes open, the fly wheel frozen, and the drive belt broken. The box was removed on January 13. Further investigation showed the plastic oil plugs had melted. Probably the compressor ran on January 9 until the interior of the box heated to melt the plastic oil plugs and drain the lubricant from the compressor, at which time the electric motor was overloaded and the circuit breaker opened at the compressor site. In retrospect, a timer installed at the powerhouse or at the compressor would have protected the equipment during use by control crews.

Additional information from a former patrolman with extensive control experience at Alpental disclosed Wac Bluff chutes to be low frequency sliders. Because the Bobby's Chute air bag installation looked so promising and lacked a very simple, quick means for inflating bags, it was decided to forgo further tests at Alpental Wac Bluff and transfer the compressor to Stevens Pass Sno-Country.

c) Results

Air bags were inflated on at least two occasions with a stable snowpack. Snow on all bags cracked in about two minutes inflation time, 1 1/2' of dense, hard snow and virtually zero system pressure. Snow slid from the NE bag which was installed parallel to the slope, while snow remained on bags which were installed horizontally on the slope.

d) Discussion of Results

The ease of fracturing 1 1/2' of snowpack with air bags showed potential to disturb snow. Placement of bags parallel to the slope surface seems preferred to a horizontal position for loading shallow snowpack below the fracture area. The quick, complete removal of snow on the bag parallel to

the slope surface seems preferred to a horizontal position for loading shallow snowpack below the fracture area. The quick, complete removal of snow on the bag parallel to slope surface disclosed a possible advantage of low cohesive plastic covering. Local fracturing of the snowpack above the bags showed a need for careful placement of sufficient numbers of air bags along the most probable release zone in shallow snowpack.

The 3/4" plastic garden hose operated successfully in about two feet of snowpack.

3. Tests in the Colorado San Juan Mountains

Four air bags were installed along the Blue Point cornice just north of Red Mountain Pass, the same site used for similar tests the previous winter. The same bags were used and the air hose installation differed from 1974/75 only in having an added solenoid valve for remote switching of the 1/2" air line between the air bags and the vibrator which was located on the Blue Point slide path just below the cornices. The character of this site is shown in Figures 1, 2 and 3 of Report 19.1 for the year 1974-75. Installation was completed in late October prior to the onset of winter snows. The distribution air lines between manifold and bags were re-positioned and covered with armor wherever exposed above ground as protection against hungry rodents. The nylon/neoprene air bags themselves fortunately do not seem to be attractive to marmots and no problems have been experienced with bag damage.

As in the previous winter, bag inflation was accomplished with a trailer-mounted compressor furnishing 90 psi air from the highway through approximately 600' of 1/2" air hose. Full inflation of all four bags normally took three to four minutes. No difficulties were experienced with bag inflation during the 1975/76 winter.

Two years of experience with air bags at this cornice site have confirmed that this is a simple and efficient means of removing cornices (and often initiating avalanches on the slope below), but that bag location is critically dependent on the time of season and the character of the winter. During the first winter the bags were placed well over the lee edge of the ridge where they were expected to push off the cornice overhang. This worked well early in the winter, but as the snow cover thickened the main body of the cornices tended to form higher and farther back toward the ridge crest until eventually the bags became ineffective and had to be

re-positioned. In 1975/76 the bags were installed farther back and away from the lee edge at the start of the winter. The cornices formed later during this second winter and tended to build up well out on the lee of the ridge where the new bag position was less effective. Again the bags had to be relocated (early January), this time in the opposite direction to the previous winter. It is obvious that for optimum efficiency, bags ought to be located in both places simultaneously. Figure 3 shows a sequence of photos taken during an early-season test inflation when the bags were still in their rearward and less effective position. The basic air bag action of cracking the snow cover and levering up large slabs can be clearly seen.

A new test site was established just south of Red Mountain Pass for the winter of 1975/76. This was at the lower release point of the Silver Ledge Mine avalanche which regularly falls onto the highway. It was chosen as a small and accessible test site to determine the effectiveness of air bags for direct release of avalanches by initiating slab fracturing. Two bags were placed at the normal fracture line of this release point, which is well-known from frequent artillery control of the Silver Ledge path. Figure 4 illustrates this test site as seen from the highway through a telephoto lens. This photograph was taken on March 23 when a test inflation was carried out during stable snow conditions, leading to rupture and displacement of the snow cover above each bag.

The air line to the Silver Ledge Mine site consisted of about 600' of 1" flexible polyethylene pipe rated at 125 psi. The lower end of this pipe was terminated at a readily accessible signpost along the highway where it could be connected to the same trailer-mounted compressor used at the Blue Point site. With 90 psi delivery pressure, full bag inflation was achieved in 90 seconds, with fracturing of the snow cover beginning in less than half this time.

The Silver Ledge tests were unfortunately abbreviated when the air line was lost for seven weeks. Through cooperation with the local Highway Maintenance Crew the air line was installed by burying it in a ditch for part of its run along the highway. During a prolonged period of fair weather in January some road maintenance was done which included cleaning out the ditches. In the course of this work, part of the air line was destroyed and was not replaced until early March.

A summary of the Red Mountain Pass air bag tests is given in the chronological list in section 5 of this Chapter.

Figure 3. Sequence of photos showing fracturing and tilting of snow cover during air bag inflation at Blue Point cornice site, Red Mountain Pass, Colorado.

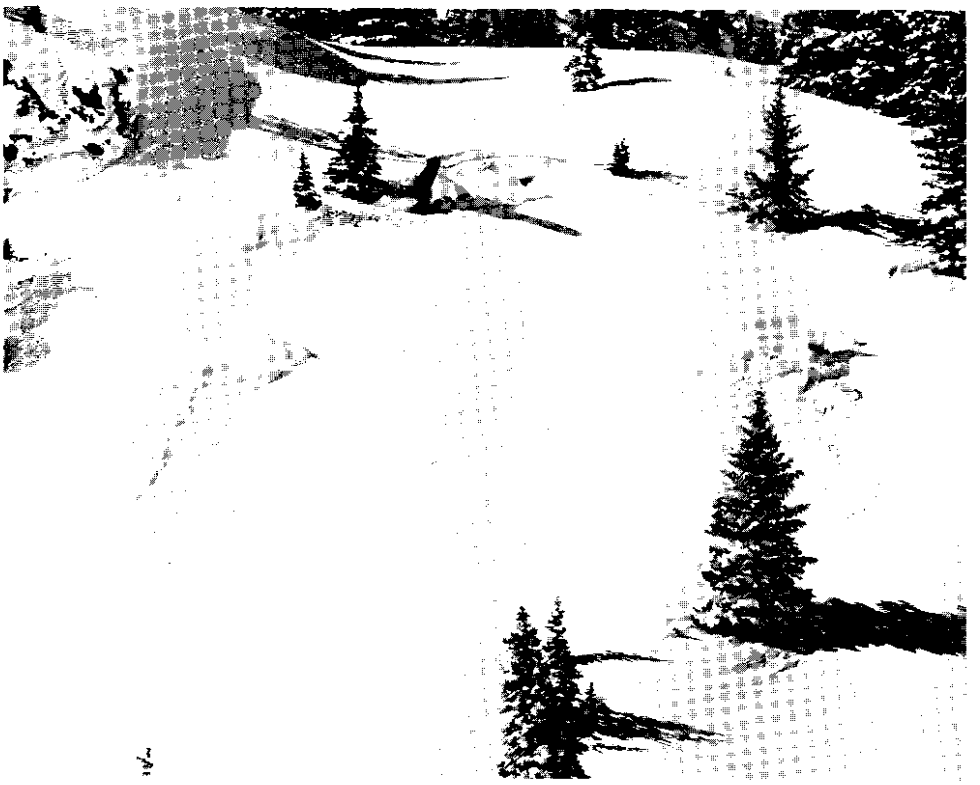


Figure 4. Air bag site at the Silver Ledge Mine Avalanche Path, Red Mountain Pass. Inflation test in stable snow on 3/23/76.

4. Tests in the Wasatch Mountains, Alta, Utah

Through the interest and cooperation of the U.S. Forest Service, an experimental air bag installation was made on an active slide path affecting the Little Cottonwood Canyon Highway between the ski resorts of Alta and Snowbird. A single 4x9' bag was placed in the release zone of the West Hellgate avalanche path, close to the top of Cardiff Peak where a USFS weather telemetry station offered equipment housing and access to a commercial power line. This site presented an opportunity to test the air bag technique in still another climate and to develop and test a radio-controlled inflation system. An air bag and the design and construction of the control electronics were provided by this project, with the Wasatch National Forest providing the compressor, air hose, radio system and installation.

Owing to installation delays unrelated to this project, the operational system was not completed until late in the winter. Nevertheless, one successful test with an avalanche release was accomplished in April. Bengt R. Sandahl, U.S. Forest Service Snow Ranger at Alta, who supervised the installation, furnished the following report:

> This air pillow installation is at an altitude of approximately ten thousand feet facing the Southwest with a slope angle of about 38°. During storms out of the West-Northwest with high winds, this slope loads quite heavily and becomes a threat to the highway below.
>
> The air pillow is inflated from a weather site building atop Cardiff Peak some 200' away. This was installed the last week in March. It was expected that April would be a period of heavy snowfall and would provide a good period for tests. This did not prove to be so since there was very little snow that month.
>
> However, a storm did come in on April 26 with strong northwest winds that deposited 10" of snow at temperatures of 9° ranging up to a high of 39°. On April 27 I went to a point on the highway where I had a clear view of the site and with my hand-set radio sent a tone to the receiver and control box in the weather building. The first indication I had of anything happening was the light atop the weather tower turned on, indicating that the air compressor inside the building was running. After seven minutes time through my binoculars I could see snow sliding over a line of rocks just below the air pillow. As this snow landed on the slope below, a fracture occurred in about two-thirds of the bowl causing an avalanche that ran three quarters of the distance down the slide path.
>
> On the following morning, I climbed to the site to measure the fracture and found it to be from 7" to 11" deep. The snow ran on a light suncrust layer.

> I found this to be a very successful test and am looking forward to further testing next winter. There are a few items I have to change on this setup such as a larger compressor and larger line going to the air pillow plus a different anchoring system for the air pillow.

This air bag system was installed with a 3/8" air hose, which proved to be too small, for the slow inflation from the small compressor was further delayed and the deflation rate was severely inhibited. As discussed above in section 1, the use of a 1" air line is recommended even for short distances to facilitate rapid inflation and deflation.

This test installation was especially useful to the Alternate Methods project for it afforded a test of coded, radio-controlled signalling method which can have wider applications for remotely controlling air bags, gas exploders and other avalanche control devices. The system shown in the block diagram of Figure 5 utilizes a coded tone sent over a standard Forest Service VHF communications radio on the highway to initiate the remote automatic inflation process. The coded audio tone is generated in a small portable control box which is placed next to the radio microphone and keyed along with the radio for at least 3 seconds.

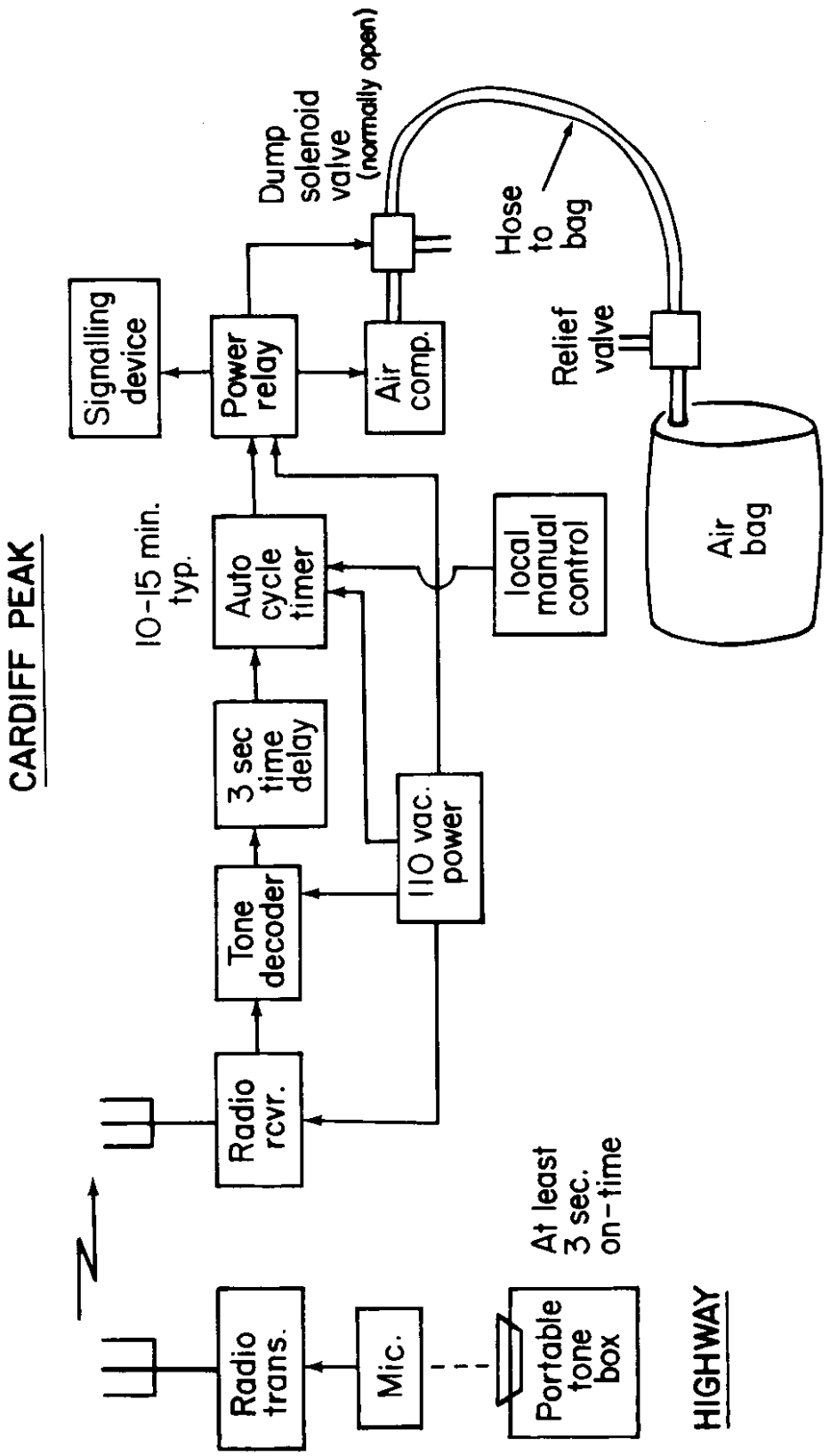
This signal is received at the remote site, decoded, and starts an automatic cycle timer which turns on the air compressor through the power relay. At the same time, the dump solenoid valve is closed, and an outside light is turned on as a signal to the operator that the cycle is underway. The compressor then fills the bag, which is protected from over-inflation by the pressure relief valve.

When the cycle timer runs out, the air compressor and the outside light are turned off and the dump solenoid valve returns to the normally open position, allowing the air bag to deflate. In a few seconds the cycle timer automatically resets.

The system is designed to accommodate a cycle time up to 30 minutes in length, and an air compressor up to 2 hp size, allowing flexibility in equipment selection, and in the size and number of bags to be used at a particular site.

The control system proved entirely satisfactory. It can readily be adapted to any short-wave radio communication system and the degree of security can be adjusted at the time of design by selecting the appropriate degree of complexity for the tone coding system. The same control principle can also be used over land lines or commercial telephones. Further

Figure 5. Block diagram of the air bag control system designed for the U.S. Forest Service at Alta, Utah.



technical details can be furnished on request to users who may wish to install a similar remote control system.

5. Chronological List of Tests

5.1 Wac Bluff, Alpental Ski Area, Snoqualmie Pass, Washington

12/4/75	Three air bags installed at test site. Bags inflated about 1 1/2' thick in about six minutes with compressor.
12/18/75	All bags fully inflated in 12 minutes after pressure relief valve installed. Snow cracked above bags in two minutes and slid from NE bag. Snowpack stable, release not expected.
12/31/75	All bags fully inflated. About 1 1/2' of hard, refrozen snow cracked above bags in minutes. Air dump valve installed. Compressor ran cool with box door closed. Breaker switches set so compressor could be turned on at power house atop Chair #1.
1/9/76 +/-	Compressor breaker turned on at power house. No observations at air bag site reported.
1/10/76 +/-	Circuit breaker at compressor box turned on. Burning material smelled. Breaker turned off.

5.2 East Snowshed Avalanche Path E4, Snoqualmie Pass, Washington

1/5/76	Air bag system checked by cracking nitrogen bottle valve. No back-pressure observed on low pressure gauge of regulator.
1/8/76	Both bags inflated simultaneously. Snow cracked above bags. 18" slab was lifted and tilted. Surface layer of about 6" depth slid from slab. Stabilized on slope. Handcharging released SS-AO-2-O with 1' fracture line running about 20' below bags. Snow slid from below thumpers and near air bags in morning.
2/16/76	Both bags inflated simultaneously. Snow surface cracked above bags and 24" slab lifted and tilted. Handcharge released SS-AE-4-O with 1' fracture line running about 20' below air bags. Footpush sent snow table off bags downhill.

5.3 Bobby's Chute, Stevens Pass Sno-Country Ski Area, Stevens Pass, Washington

12/17/75	System checkout with nitrogen bottles. One cornice and one slope bag inflated. Cornice chunk 2-3' diameter released. Snow fractured on top of slope bag #1 and slid down slope. Fracture line 2 1/2' thick and 3' above bag. Snowpack stable, release not expected.
12/29/75	System checkout with air hose to each bag. Both cornice bags and slope bag #1 inflated in four to five minutes. Handcharge released avalanche with 6" fracture. Dump valve leaks.
1/17/76	System checkout. Both cornice bags and slope bag #1 inflated. Slope bag #2 would not inflate with 38 psi on regulator pressure gauge. Snowpack stable, release not expected.

1/29/76	System check with compressor installed and hose repaired for slope bag #2. All bags inflated. Cracks formed above slope bag #2 in 3 1/2' of dense, refrozen snow. Snowpack stable, release not expected.
2/4/76	System checkout with timer on compressor motor. Slope bag #2 inflated slowly. Hose constriction found at bag at full inflation.
2/5/76	System checkout after hose alteration at slope bag #2. All bags inflated hard with 20 minutes pumping--4 psi manifold pressure. No snow cover of bags.
2/12/76	All bags inflated. Small cornice chunks released. Two inch sluff from slope bag #1. Slope handcharged, SS-AE-2-0, less than 1/2' fracture. Snow surface cracking above slope bag #2 after handcharging, about 20 minutes pump time.
2/18/76	All bags inflated. Cornice chunks released and slid to bottom of track. Slope bag #1 lifted snow 2' with sluffing of surface layer. Cracks visible above slope leased SS-AE-2-0, 2' fracture.
2/25/76	All bags inflated. Cornice chunks released. Slope bags lifted snow about 12-16" causing sluffing. Hand-charging near slope bags released SS-AE-2-0, 1' fracture.
2/28/76	Bags inflated. Cornice chunks released and caused sluffing. Slope bags released small surface slide. Handcharge released SS-AE-2-0 with fracture depth less than 1/2'. Protective skiiing on 2/27/76 kept avalanche hazard low.
3/19/76	All bags inflated. Large cornice chunks released and ran to lower track. Slope bags released SS-AO-2-0 with 1' fracture covering 70% area and sliding to transition area.
3/20/76	All bags inflated. Small cornice chunks released. Possible small avalanche caused by falling chunks. Storming with blowing snow, visibility poor. Slope bags fracture snow upslope and lifted slab which slid onto slope causing local avalanche, 1' fracture and 10' feet wide. 55 minute pump time. 14 psig manifold pressure. $70^{o} <$ of repose for snow wedge. Handcharge released SS-AE-2-0 covering 50% of slide path.
3/24/76	All bags except slope bag #2 inflated. Small cornice chunks released. Slope bag #1 raised slab 1 1/2' high. Leak inside slope bag #2. Grommets torn at top center of bag. Wedge of snow formed 3/20/76 still intact and contacting bag at lower center. Plastic cover torn. Handcharge released SS-AE-2-0, 1' fracture.
4/15/76	All bags except slope bag #2 inflated in 30 minutes. Handcharge released SS-AE-2-0 with 1' fracture.

5.4 Silver Ledge Mine, Red Mountain Pass, Colorado.

12/11/75	Test reported but not logged--no avalanche released, no details.
1/7/76	Large blocks lifted, cracking limited to 2 m x 4 m area of bag. Small loose-snow sluff ran 10'.
1/15/76 to 3/9/76	System disabled by air line destruction by snowplow.
3/23/76	1030. Broken to overcast sky, +3°C, calm wind, stable snow, 30 cm crust, 90-second fill, considerable lifting of the snow cover over entire bag, no slide activity.

5.5 Blue Point Cornice site, Red Mountain Pass, Colorado.

1/7/76	The first cornice of the year is finally present but very small. Only a very small portion of the center of #1 released any snow. This did release a medium soft slab avalanche into the road. Fracture depth was 50 cm.
2/11/76	1100-1700 AM test. Large portions of the cornice released over bags 2,3,4. Soft slab running to ground released under #2. North side of #2 did not clean out??? Used handcharge of explosives to release entire left (south) side of path. Medium soft slab running to ground crossed road. Entire length of highway under Blue Point covered 2-3 m deep.
2/20/76	1000 at Blue Point. Weather: temp. -12.5 °C, wind 5-10 m/s 360°, overcast and snowing. Fill air bags 4 minutes, released several small chunks but no material on slope below.
3/3/76	1000. 3-minute fill with chunks of cornice to road.
3/23/76	1045. 3-minute fill, small chunks to road, #2,3 clean of snow after test, #4 still covered.

Chapter II

GAS EXPLODER SYSTEM

By E. R. LaChapelle, C. R. Morig, and P. L. Taylor

1. General Comments

Although a good number of operational tests with corresponding technical development occurred in 1975/76, the scarcity of unstable avalanche conditions in both the Cascades and San Juans limited the opportunities for checking actual avalanche releases. Details of the gas metering and firing system and the steel canisters ("thumpers") have been described in Report 19.1 for the first test winter (1974-75) and will not be repeated here. Experience to date has added the following observations and conclusions to those of the previous year.

a) Available explosive energy from the steel canisters (thumpers) continues to be insufficient for Cascade snow conditions. The tire configuration of gas exploder tested in Colorado appears to offer considerably greater energy and this form will be used in Cascades tests for the third winter.

b) The basic design of the control system has been proven by two winters of tests and sources of difficulties largely eliminated by the end of the second winter. The gas mixer unit (welding torch handle) can develop carbon deposits which interfere with proper balance of the gas mixtures. This problem was experienced in Washington but not in Colorado. Pre-season cleaning and maintenance apparently will prevent this problem. A flow meter of the proper gas flow range is needed to insure accurate balancing of gas flow to multiple exploders working from a single control unit. Different batteries were used in the gas exploder control boxes the second winter because of the abnormally high stand losses experienced the previous season with the original Globe Gel-Cell CC 1245 - 1 A. These batteries were all of the same batch and were returned to the factory for evaluation. They were found to be defective and were replaced with new batteries of type GC 1245 - 1 B, which gave normal service. A small voltmeter was installed in the control box to monitor battery voltage during local control, and to provide confidence during the winter that the new batteries were doing the job.

c) Partial burial and ties to deadmen are satisfactory anchoring measures for the canisters in soil, but there has been some difficulty

in preserving their orientation when they sit on the surface of bedrock. A modified chain or cable bridle as an anchor is needed in these circumstances.

d) At Red Mountain Pass a total of eleven tests were conducted at the Longfellow site without any avalanche release. Even in a light avalanche winter this is unusual, because the most energetic gas exploders were located at this site, a known avalanche release zone. There is reason to suspect that the frequent and energetic firing of the system may have had a distinctly stabilizing effect on the snow and thus served as avalanche prevention. Tests with this frequency of firing have not been possible on the Willow Swamp (Red Mountain Pass) and East Side Snowshed (Snoqualmie Pass) sites owing to the necessity of traffic interruption as a safety measure.

2. Tests in the Washington Cascades

2.1 Snoqualmie Pass, East Snowshed Avalanche Path E4.

a) Installation

Three thumpers were installed on SE side of the release zone at elevation of about 3600', SW aspect. Exact location, the consensus of highway and research field people, was along the most probable fracture line above cliff area, a distance of about 140'. The canisters were separated by about 35' and anchored by 1/4" wire rope threaded through holes in the base plates. The wire rope was bolted to 3/4" expansion bolts in bed rock. A 1/4" guy wire also ran from an eyebolt on side of each thumper uphill to rebar in bedrock. Canister bases were tilted 25-35° downslope from horizontal and backfilled beneath with rock.

Exploder gas feed was provided by 3/8" rubber air hose from the control box in a shelter on the ridgeline. A manifold was located on a shallow slope midway to the canisters. Branch lines were extended out and down the fall line to the canister sites. The lines were buried on traverses and secured to adjoining 1/4" cable with anchoring fixtures on steep sections of the slope.

Oxygen and acetylene gases were supplied from welding tanks located beneath the shelter through pressure regulators to the control box with standard welding hose.

Initial installation was completed on November 20, 1975.

b) Operation

Snow was blown from thumper lids and a good detonation heard on initial checkout of system November 20, 1975. (Figure 1)

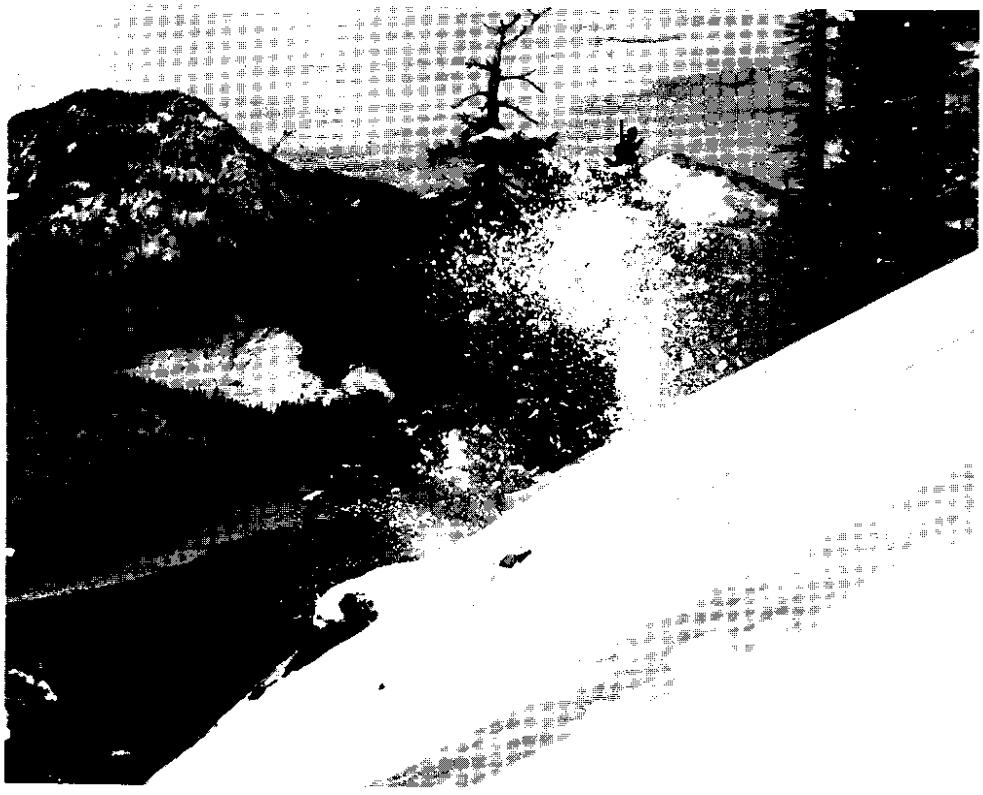


Figure 1. Test of gas exploder (thumper) operation in shallow snow cover at East Side Snowshed site on Snoqualmie Pass, Washington, 11/20/75.

Some difficulty was experienced with detonation during first control missions in early January 1976. Oxy-acetylene ratio was found to be highly variable before and after 10 minute fill cycles, but steady during repeated flame tests. Regulator delivery pressures were steady. Partial blockage of welding handle (mixer) valves was disclosed, possibly by carbon deposits. Two contributory factors were: (1) this tool was used last year without cleaning before installation, and (2) a reduced gas flow rate was introduced during repeated flame tests this year. A new welding torch handle was installed with full volume gas flow on flame test. Installation ran maintenance-free through seven firings for rest of season, although flame test showed slightly oxygen rich ratio on last test firing. Periodic monitoring of oxy-acetylene ratio seems important for optimum energy generation.

Remote firing of system with trigger box from East Snowshed was maintenance-free throughout winter. Installation of trigger box and check-out occurred on January 19. The thumpers were fired remotely on three control missions--two with confirmed detonations at release zone.

The thumper anchoring with cables to steep bed rock needed some additional maintenance through the winter. The 1/4" wire rope guys from eyebolt in canister to rebar in bed rock uphill worked very well. The 1/4" wire rope around base plate, however, was replaced with 1/2" stock to withstand the strong rebound action of canister during detonation in a shallow snowpack. A six-foot long steel channel iron was bolted to bottom of each base plate to prevent the thumpers from topling sideways. At the final test firing on April 21 with little or no snow about canisters, two thumpers were observed to topple upslope as they were catapulted the full length of anchor cables into the air by their lids. It seems that a broad based, free floating platform of sufficient mass to lower the center of gravity is needed to support thumper canisters on steep slopes of bed rock where they cannot be attached to buried deadmen.

The canister angles increased to about 38° near end of winter and the middle thumper lid jammed open. Snowcreep or repositioning of rock support under the canister base with repeated firing may have pushed the base uphill.

The thumper with the longest hose from the manifold seemed to have the same audible response as other units during firing, but a slightly weaker impact on snow. Flow rate measurements should be made for optimum distribution of gas flow to each canister.

The hose installation was maintenance-free through the winter.

All in all, the thumpers fired satisfactorily in a shallow Cascade snowpack. The tally is eight confirmed firings out of 11 tests with two misfires and one unconfirmed firing from remote location.

The pressure regulators and control box were removed and operations discontinued on April 21, 1976.

c) Results

Six of 11 test firings occurred with unstable snow conditions. The breakdown of thumper results is two firings with sluffs from thumper (one a possible), one firing with poor visibility and results unconfirmed, one firing remote with results unconfirmed, one firing with no avalanche, and one misfire under unstable snow conditions.

Snow above the thumper lids was blown into the air during most detonations. Snowpack accumulation was less than three feet above lids, and generally observed to be about 1 1/2' deep. Lids acted, in most cases, on soft, new snow which fell into the hole above them during the recent storm period. Wind transport played a minor role in densification and filling the holes above the thumpers at this avalanche path. On January 6, 1976, a six inch void space was observed around the middle thumper after firing. This may have occurred from downward diversion of explosive flame by lip of the lid.

Fractures occurred just below the thumper line on January 6, 12, and 15 from handcharging. Fractures were observed from natural release just above the thumper line on January 9 and 15.

d) Discussion of Results

The basic operation of the gas exploder system seems sound for the Washington snowpack. There remains a question about the necessary coupling of explosive energy to the snow, and the size and distribution of point detonations to induce avalanches in Washington snowpack.

The thumpers seemed to expend considerable energy in recoil during detonation. In a deeper snowpack, thumper action may have been more effective.

The location of thumpers seemed good for avalanche inducement, i.e., along the most probable fracture line.

Lateral dispersion of explosive energy from a point source seems important in a shallow snowpack, especially where there might be a great difference in densities of old and newly fallen snow. The method of coupling

explosive power should also accept the presence of voids in dense, old snow generated from past disturbances. These voids are not necessarily filled between avalanche cycles as was observed at slope bag #2, Stevens Pass on March 20, 1976. Perhaps two rows of gas exploders should be installed along the most probable fracture line, staggered vertically, and fired, one row at a time, on alternate storm cycles to improve coupling to the snowpack.

3. Tests in the Colorado San Juan Mountains

Tests near Red Mountain Pass were conducted at two separate sites. One site, the Willow Swamp Slide, was occupied as a test site the previous year. It is a medium-size avalanche path which discharges slides across a switchback section of U.S. 550 just north of the Pass. The second site was a new one for 1975/76, located about 1/4-mile away from the highway next to the Longfellow Mine and in the vicinity of the San Juan Avalanche Project research area for snow and weather observations. This latter path did not affect the highway, permitting tests at more frequent intervals because traffic control and provision of snow plows were not required.

The Willow Swamp test site was occupied the first year by an array of four steel canister "thumpers" distributed across the release zone at the head of a shallow basin. The same basic configuration was used in the second winter, but the line of thumpers was moved a short distance uphill and closer to the ridge crest. Experience the first year had indicated that this would place the thumper line closer to the most common fracture line. As before, the canisters were partially buried in the ground and anchored to deadmen buried beneath them. Two modifications were made to the canisters. The rim around the lid was cut away to allow the exploding gases to blow outward instead of being deflected downward, a change which appears to have increased the efficiency of the unit in disrupting snow. A gas distribution manifold was also installed within the canister in the form of a coiled and perforated copper tubing. Open air tests indicated that this did seem to improve the gas mixing and explosive force of the canister, but there is no conclusive evidence that the efficiency was increased under the snow. General experience with the various forms of exploders (see below) does show that better performance can be expected when a manifold is used to equalize gas distribution through an exploder, so for this reason the adoption of the manifold in the canister seems advisable.

Except for some minor difficulties with the control unit batteries prior to their replacement, the Willow Swamp system operated normally through the winter. When the batteries were changed on 1/12/76, the oxygen tank was found to be drained and was replaced by a spare. There appears to have been a slow, high-pressure leak in the tank valve, reduction valve or fittings. A careful test for leaks at time of installation obviously is required for these gas exploder systems. Performance and avalanche record for this test site is summarized in section 4, below, under test chronology.

The Longfellow site was used to test two different configurations of gas exploders which were a distinct departure from the canister design. Both of these are described in Report 19.1 for the first winter of tests (1974-75) under Alternate Exploder Configurations. One is a steel pipe with discharge ports along the side covered by flaps of heavy rubber belting. (Figure 2) The other is a large truck tire bolted to a split rim on one side, leaving the other side free to permit discharge of the gases when an explosive mixture is ignited inside the tire. Figure 3 shows the operating principle of this latter configuration.

The steel pipe proved to operate satisfactorily and did not suffer the structural weaknesses found in its aluminum predecessor the previous winter. Because no avalanches were released at the Longfellow site through a second winter, its efficacy in triggering unstable snow slabs still remains to be proved. Its overall effectiveness for disrupting snow appears inferior to that of the tire.

The tire continues to be the most promising gas exploder design for energetic disruption of snow. In part this is due to the larger volume available for charging with the exploding gas mixture than is in the canisters. There also seems to be an additional impulse imparted to the snow from elastic recoil of the tire. This recoil also presents a problem in anchoring the tire, for it literally leaps into the air on detonation. Initially the tire was installed at the Longfellow site by anchoring it to bolts in a concrete pad intended as a deadman. On the first test firing on 10/16/75, the tire leaped six feet into the air and tore the anchor bolts out of the concrete. A modified installation then tied the tire to a slack steel cable which allowed it to move upward but prevented it from being carried away entirely by sliding snow. Further redesign of the manifold is required to properly accommodate this violent motion. Figure 4 shows the

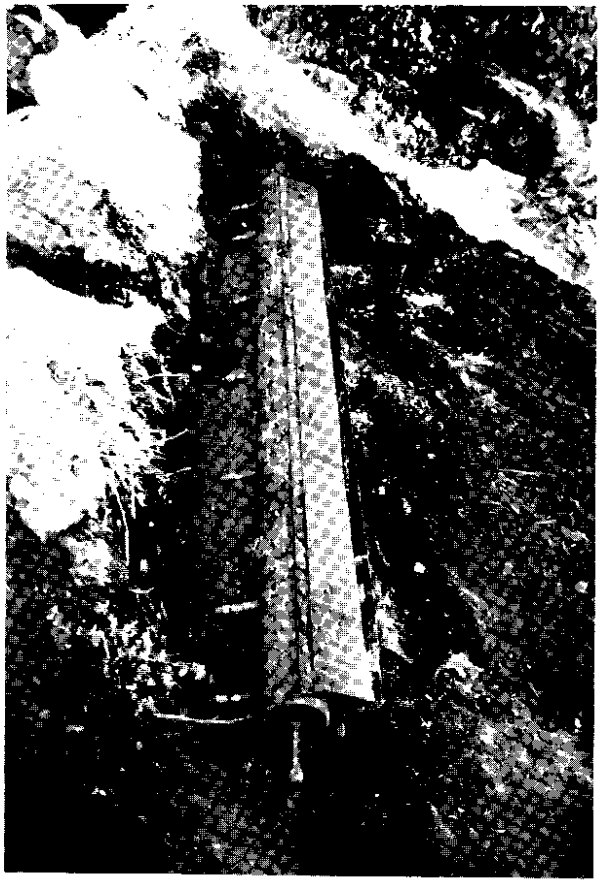


Figure 2. Steel pipe gas exploder installed at release zone of Longfellow site near Red Moutain Pass. Manifold feed pipes are visible on the left and the rubber belting flap covers the exhaust ports on the right.

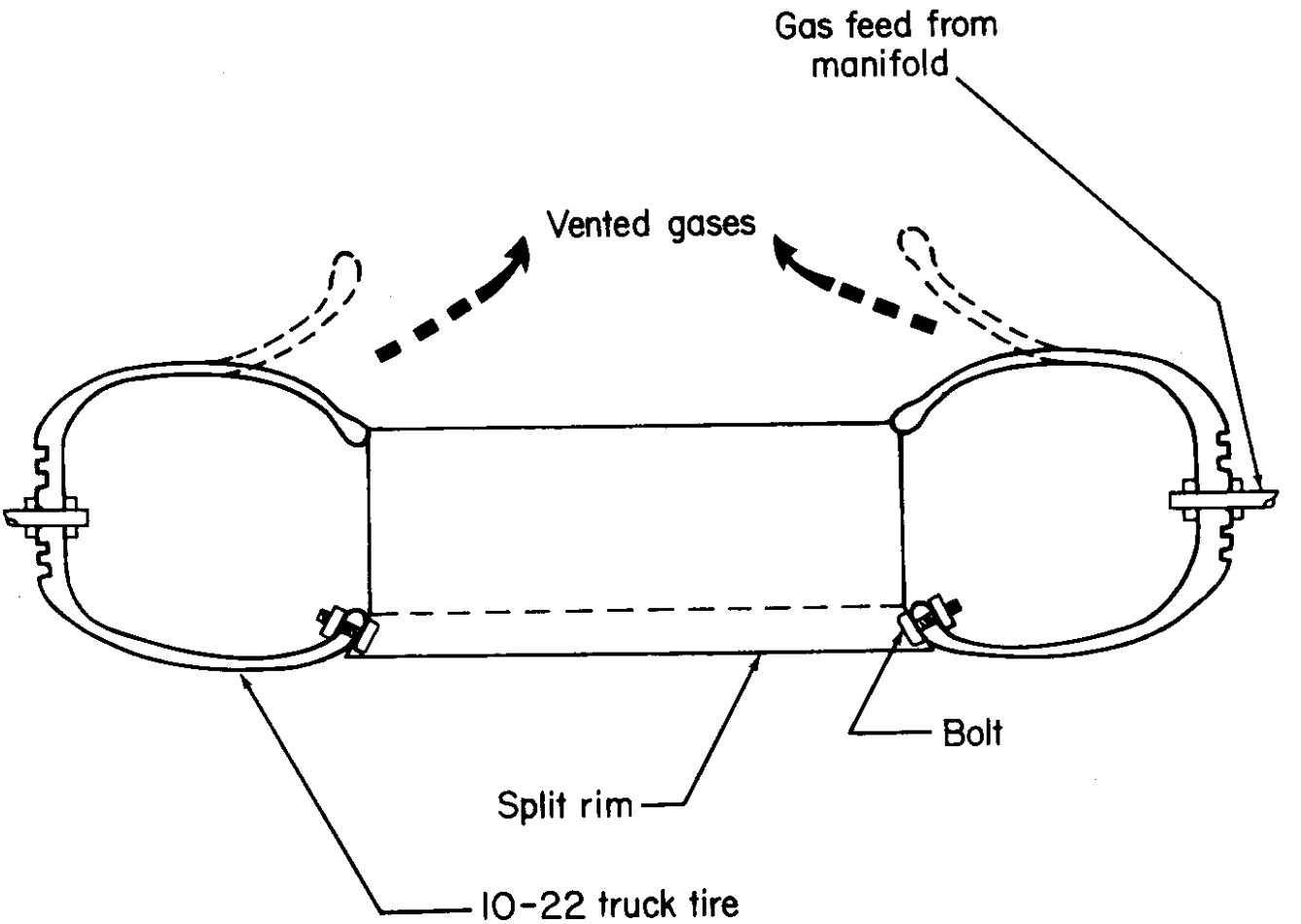


Figure 3. Configuration of the tire gas exploder used at the Longfellow test site, Red Mountain Pass, Colorado, during the 1975/76 winter test season. Not shown are the cable tie points for anchors welded to the inside of the rim. An improved version for use in 1976/77 will use an inner manifold feeding the gas through the rim wall.

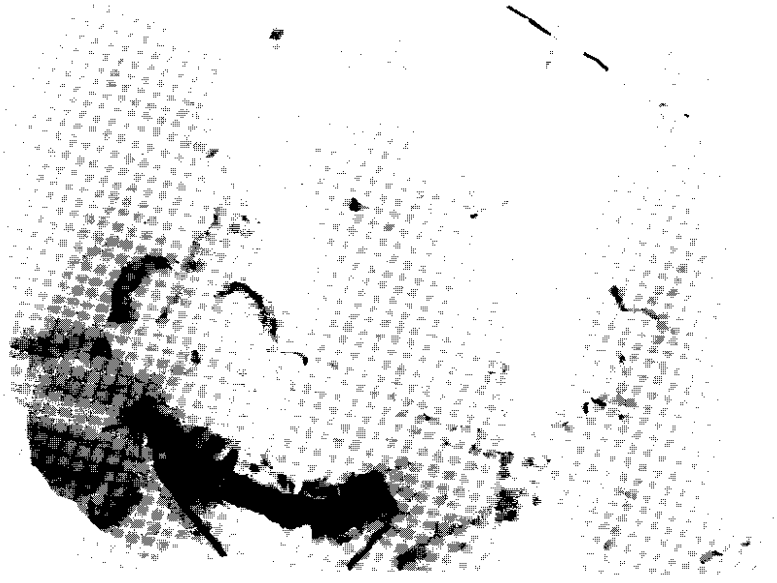


Figure 4. Tire gas exploder at Longfellow site, Red Mountain Pass. Excavation of 2/26/76, showing the region of disturbed snow above the tire following a test firing.

large volume of broken snow surrounding the tire when it was excavated for inspection on 2/26/76. The tire exploder will be adapted to several sites for the 1976/77 tests, including a larger version for use in the Cascades.

No difficulties were experienced with the control system and remote firing during the eleven tests conducted during the winter. Further details are found in section 4, below, under test chronology.

4. Chronological List of Tests

4.1 East Snowshed Avalanche Path E4, Snoqualmie Pass, Washington

11/20/75	System fired. Good detonation heard. Snow blown from thumper lids. Snowpack stable, release not expected.
1/5/76	Attempted to fire system. Flame test revealed deficient oxygen. Snowpack moderately stable. Control terminated.
1/6/76	System fired. Good detonation heard. Snow blown from thumper lids. Small sluff from SE thumper. Hand-charging released SS-AE-2-0, 6" fracture, to mid-track. Flame tests showed variance in oxy-acetylene ratio before and after thumper firing.
1/12/76	Attempted to fire system. Flame test showed correct oxy-acetylene ratio before mission, but highly variable ratio after mission. Handcharging released SS-AE-2-0, 8" fracture, to mid-track.
1/15/76	System fired after new welding torch housing installed and gas flow rates increased to maximum for torch tip. Snow-pack stable, release not expected. SE thumper found on side with cable wrap around base loose.
1/19/76	System fired with trigger box at East Snowshed. Short fill time. Snowpack stable, release not expected. Thumper anchoring beefed up.
2/16/76	System fired with trigger box at East Snowshed. Good detonation heard at release zone. Storming, visibility poor. Possible sluffing from two thumpers. Snow appears undisturbed above NW thumper. Handcharge released SS-AE-4-0, 1' fracture, to lower part of track.
2/17/76	System fired with trigger box at East Snowshed. Good detonation heard at release zone. No avalanche release. Handcharging released SS-AE-3-0 to mid-track.
2/17/76	System fired with trigger box at East Snowshed. No detonation heard or moving snow observed at East Snowshed. Lid of middle thumper found jammed open upon inspection of site at a later date.
4/7/76	System fired. Good detonation heard. Thumper lids above snow. Snowpack stable, release not expected. Lids on SE and middle thumpers jammed open. Thumpers tilted more downhill. $38^{o} <$ measured on NW thumper lid.

4/21/76	System fired. Good detonation heard. Thumper lids above snow. Flame test showed slightly oxygen rich ratio. Snowpack stable, release not expected. SE and middle thumpers tipped on side uphill during explosion.

4.2 Willow Swamp Slide Path, Red Mountain Pass, Colorado

11/20/75	Installation test, no avalanche conditions. 1015 hrs. 6-minute fill with very strong detonation, no slide. A flame was visible for about 1 m around the #4 thumper.
1/7/76	8-minute fill, no apparent detonation. Remote circuit checks good. Upper batteries must be low.
2/5/76	8-minute fill, good slide into road.
2/20/76	8-minute fill with detonation, no release confirmed, poor visibility.
3/3/76	8-minute fill, small soft slab avalanche released.
3/23/76	8-minute fill, detonation, no activity. Snow cracked above.

4.3 Longfellow Mine Slide Path, Red Mountain Pass, Colorado

11/20/75	Installation test, no avalanche conditions. 0950 hrs. 5-minute fill and detonation, no slide. Could hear small thud at detonation. Tire left a visible hole in snow. Steel pipe was not heard nor seen to have detonated.
1/7/76	8-minute fill, tire detonated but no apparent detonation of steel pipe.
1/16/76	Checked out Longfellow control box. Tested the system twice with 7 and 8 minute fills. Detonation OK and the tire and steel pipe were both heard to detonate. Steel pipe is really buried in snow. Batteries OK.
1/26/76	Test Longfellow, 8-minute fill, detonation, no slide.
2/5/76	8-minute fill, detonation, no slide.
2/6/76	8-minute fill, detonation, no slide.
2/9/76	8-minute fill, detonation, no activity.
2/20/76	8-minute fill, detonation, no release.
2/26/76	Test reported with no avalanche, but not logged.
3/3/76	8-minute, detonation, no activity
3/4/76	8-minute fill, detonation, no activity.

Chapter III

VIBRATOR TESTS

by E. R. LaChapelle, C. R. Morig and P. L. Taylor

1. General Comments

Part of this research project, Alternate Methods of Avalanche Control, 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. Ongoing work on this topic is discussed separately in this report in Chapter 4. In the meantime, some empirical field tests have been started during the second year of the project to develop experience in the design and operation of high-energy vibrators and to find out whether, in principle, unstable snow can be induced to avalanche by mechanical vibration. 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 has shown that seriously unstable snow can be triggered into avalanching by very small signals, including, traditionally, the sound of a human voice. A serious investigation of this question is an important part of the Alternate Methods study. This Chapter discusses the results from a winter of field experiments.

Three test devices were constructed, all using compressed air for power. Details of these devices and their performance in individual tests are described below. In brief, 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 smaller vibrator unit constructed on the principle of a rotating eccentric weight was mounted on a small sled for positioning on the snow surface at various sites at the Alpental Ski Area near Snoqualmie 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 smaller fabricated unit about 2-4 horsepower. The main problem in designing a test like this 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. If the cavities are small, snow deformation from creep and settlement is slow to close them and subsequent tests begin in a decoupled state. Our experience to date suggests that the grid-style of vibrating unit (Figure 1) 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 (Figure 3) appears to retain better contact, for settlement quickly brings the snow to rest on the platform surface and coupling is restored. Oscillation of the platform parallel to the snow cover also provides transmission of shear forces with minimum cavitation. A next step in tests for the coming winter will be to explore further the use of platforms, including the application of vibration perpendicular to the platform plane.

The winter of 1975/76 provided few opportunities for tests in highly unstable snow at all sites. Some tests were run with known stable snow when there was little expectation of avalanche release. One avalanche release with a vibrator was achieved at Red Mountain Pass on 2/6/76. This was a small, soft slab avalanche running in a shallow snow pack on a depth hoar layer near the ground. On two occasions an air-bag induced cornice fall triggered avalanches on this same slope after the vibrator had failed to do so. Thus, we have demonstrated to date that vibrators can in principle release avalanches under favorable conditions, but the test scope so far is not adequate to determine if vibrators can serve as a reliable release tool under a variety of snow conditions. We doubt that the present designs discussed here would be adequate. Improved designs will be tested further in 1976/77.

2. Tests in the Washington Cascades

2.1 Stevens Pass, Cutbank on Little Windy Avalanche Path

a) Construction and Preliminary Tests

The driving unit for this vibrator assembly was a commercial unit called a "Vibrolator" which is attached to railroad cars to aid the free flow of loose materials such as gravel when the car is emptied. Its operation depends on an air motor to rotate a heavy eccentric weight. The vibrolator was welded to a 2" angle iron and bolted to a grid of 8' long, 4" wide aluminum angle "L" pieces. The grid consisted of four elements in parallel, anchored by two cross elements. Two diagonals of aluminum channel

Figure 1. Vibrolator attached to heavy aluminum frame for use as vibrator test unit at Little Windy cutbank near Stevens Pass, Washington.

Figure 2. Jackhammer-driven vibrator used for tests at Red Mountain Pass, Colorado. The plywood platform is oscillated in a direction parallel to the jackhammer and steel frame.

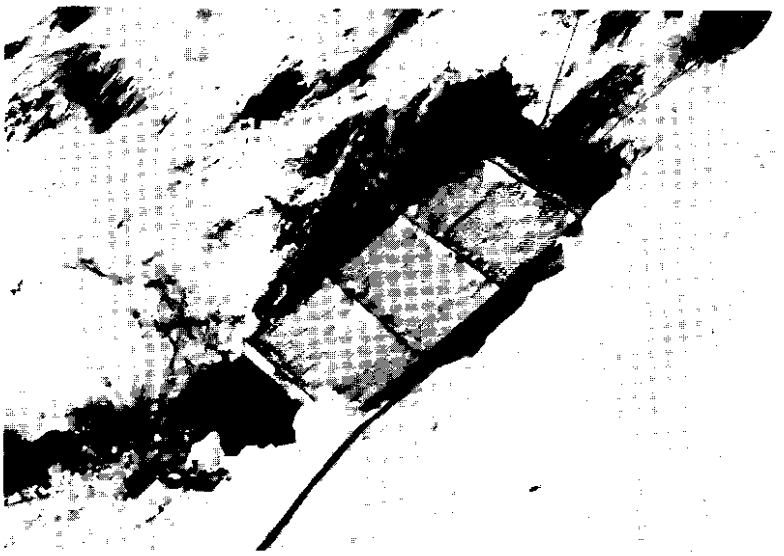


Figure 3. The vibrator unit in Figure 2 shown installed at the Blue Point release zone near Red Mountain Pass, Colorado.

were attached to give the grid system rotational rigidity. Total weight of the unit was about 300 pounds. Total surface area parallel to the snow was about 1350 square inches. Surface area for transferring lateral vibrational energy was about the same as that normal to the snow. This device is illustrated in Figure 1.

Gas delivery to the vibrolator was supplied directly from extra large sized (60 cu. ft., 1900 psi) nitrogen cylinders through high pessure fittings with a 150 psi pressure valve for safety. First tests were run with a secondary high pressure valve for additional pressure drop. It was found, however, that the high pressure valve on the gas cylinder could be easily adjusted manually to give the 100 psi operating pressure for the vibrolator.

Preliminary tests run at Snoqualmie Pass on January 27, 1976, showed the vibrator to be supported adequately in wet, dense snow on the level and on a steep incline with the four parallel grids cross-slope. Vibrations could be felt in the snowpack about 10' away from the vibrating grid.

The unit ran for at least 20 seconds on a single tank of nitrogen at 100 psi.

b) Installation

The vibrator was installed at Stevens Pass on the cutbank of Little Windy avalanche path, a slope of 45-50° angle at about 3800' elevation and N aspect. The four parallel elements of grid were oriented cross-slope about 20' below the breakover.

The grid system was supported by two lines of 1/2" wire rope anchored to trees upslope.

Nitrogen gas was supplied to the vibrator from the highway. High pressure bottles were mounted on a rack in a State Highway Maintenance vehicle. A short section of 1/2" air hose extended from high pressure fittings on a bottle to a high pressure quick-coupling fitting attached to a vertical 4x4 post beside the road, away from the snowplow run. A 1/2" air hose ran from the post uphill through a wide "U" turn toward the vibrolator. An accompanying 1/4" wire rope supported the hose against snow forces. An inline oil recepticle kept the vibrolator lubricated. Oil resistant hydraulic hose ran from this recepticle to the vibrolator unit itself.

Installation was completed on March 5, 1976.

c) Operation

The vibrator was audible from the road. A puff of oil, silhouetted by afternoon sun, heralded its opening lines.

The vibrator ran six times in March and April without maintenance.

The pressure gauge froze on the March 11 test and the relief valve "popped" several times. The gauge was thawed and operated maintenance-free for the next four tests.

d) Results

Three of the six tests were conducted in possible unstable snow conditions. About 8" of new snow settled in place in a small area on March 11 test. This settlement may have occurred around the vibrolator motor which protruded above the grid. The snow surface remained undisturbed on the March 12 and 23 tests. No confirmation of slope stability was available.

Inspection on April 23 showed 1/2" void space in the snow up- and downslope of horizontal members of the grid, and about 1" void space by the side members.

e) Discussion of Results

The vibrolator unit ran well in the snowpack.

It appears that the vibrator oscillation developed a void space around itself in the snowpack. The coupling of energy from the grid to snowpack in this situation is unknown. A more positive form of coupling to the snow is obviously required.

2.2 Snoqualmie Pass, Disposal Ridge, Alpental Ski Area

a) Construction and Preliminary Tests

A portable rotating eccentric weight driven by an air motor was bolted to two parallel 6' aluminum channels and covered with a plywood box. The unit was run from a Scott portable air bottle (about 30 cu. ft., 2000 psi) through a pressure regulator and 1/2" air hose for two minutes at 20 psi.

Tests on the lab floor showed the unit could vibrate a man across the floor with about 25 psi air pressure using the largest eccentric weights on the wheel. Another test was performed with the vibrator unit supported by 1/4" wire rope cable midway between the building wall and a pillar, a distance of 25'. A 4-6" oscillation was observed in the cable at about 15 psi operating pressure. The pillar hummed.

b) Installation

The portable vibrator was installed on Disposal Ridge at about 5200' level, S exposure. Location was the consensus of ski area and research

field people. Cable was strung from tree to tree across slope, a distance of about 100'. The hose ran uphill to the regulator and the Scott air bottle.

c) Operation

The vibrator unit checkout occurred on March 10, 1976. The vibrator ran taking 50 psi to show any visible shaking going on.

The unit operated on March 11 and 12, trouble free.

The vibrator was moved to a steep narrow chute on March 12 for remaining tests. The Scott air bottle was found empty by a patrol on the last test attempt. The bottle may have leaked or been "tested" by a skier.

The unit was removed on May 6 as rocky terrain was appearing in chute.

d) Results

One of three tests was conducted under unstable snow conditions. The March 11 test showed 80 psi pressure was needed to get visible shaking of vibrator box with 6" of new snow. No disturbance was observed in snow around vibrator. A handcharge released a 2" slab of soft wind slab below vibrator.

d) Discussion of Results

The unit operated satisfactorily beyond the design limits for eccentric weight and RPM of centrifugal force. Limits were exceeded to get visible oscillation in snow.

The portable vibrator might be coupled through a secondary unit such as a suspended cable to create sufficient disturbance in the snowpack.

3. Tests in the Colorado San Juan Mountains

The site chosen for vibrator tests at Red Mountain Pass was the Blue Point slide path. This is a small, but highly active and accessible slide path which already was the site of air bag tests on the adjacent cornice. Only a short extension of the existing air line was required to power the vibrator. Extra circuits were also available in the electrical cable which ran parallel to the air line and continued on to provide control circuitry for the Willow Swamp gas exploder site to the north. A set of solenoid valves was installed which permitted the air line to be switched between air bags and vibrator by remote control from the highway below (compressor site). The normal test routine was to operate the vibrator first to effect a slope avalanche release, and then to inflate the air bags to dump the cornices onto the same slope. On three occassions the cornice fall initiated

avalanching after the vibrator had failed to do so.

The basic vibrator design provided a platform of plywood mounted parallel to and flush with the ground surface at the normal fracture line of the Blue Point slide. Four horizontal cleats of 1" angle iron were bolted across this platform. The drive mechanism underneath was arranged to oscillate the platform parallel to the slope in the direction of the fall line. This drive mechanism consisted of a heavy steel frame in two separate parts which were free to move in respect to one another. A large, heavy jackhammer (tamping hammer) was mounted between the two parts of the frame. The part supporting the jackhammer body was anchored to bedrock, while the part driven by the hammer blows was bolted to the platform. A heavy rubber cushion between the two parts provided elastic recoil of the platform. Figure 2 illustrates the construction of this unit and Figure 3 shows it mounted on the Blue Point path, the drive mechanism occupying a space excavated into the ground.

Initial attempts to couple the jackhammer energy to the bedrock and then to the snow proved ineffective. The configuration described above was then adopted. Pre-season tests showed that the 700+' of 1/2" air hose from highway to the site offered so much flow resistance that an adequate supply of air could not be delivered for proper jackhammer operation. A 10.7 cubic-foot accumulator tank was then ordered and was received in time for installation in mid-December. When air flow from the compressor at the highway was switched to the vibrator site, it charged this accumulator tank. An additional solenoid dump valve was used to discharge the accumulated compessed air into the jackhammer. This provided vigorous and effective jackhammer operation for 15-20 seconds, more than adequate to test the effects of vibration on unstable snow.

Once some initial control circuitry problems had been remedied, the final configuration of the Blue Point vibrator described here functioned without mishap for the rest of the winter. A total of six test runs were made which are summarized below in the chronological listing.

4. Chronological List of Tests

4.1 Cutbank on Little Windy Avalanche Path, Stevens Pass, Washington

3/5/76	Vibrator installation completed. System tested. Vibrator audible from road. Snowpack stable, no release expected.
3/11/76	Vibrator ran. Snow settled in small area, possibly around vibrolator motor.

3/12/76	Vibrator ran. Snow surface appeared undisturbed.
3/23/76	Vibrator ran. Snow surface appeared undisturbed.
4/8/76	Vibrator ran. Snowpack stable, no release expected.
4/22/76	Vibrator ran. Snow surface appeared undisturbed.

4.2 Disposal Ridge, Alpental Ski Area, Washington

3/10/76	Vibrator installed and ran. Snowpack stable, no release expected.
3/11/76	Vibrator ran. Wood housing seen vibrating above snow. Hand-charge released SS-AE-2.
3/12/76	Vibrator relocated on narrow chute and ran. Snowpack stable, no release expected. Snow attenuation measurements taken.

4.3 Blue Point Avalanche Path, Red Mountain Pass, Colorado

1/8/76	Tested the vibrator. Everything works OK. The vibrator showed several cracks around the platform. No releases were observed.
2/6/76	Accumulator filled to 80 psi. Good release from vibrator, avalanche ran into road, 2 m deep and 10 m wide.
2/11/76	Insufficient snow cover over vibrator, but tested anyway. 80 psi in accumulator. Good vibration.
2/20/76	1030--filled accumulator to 70-80 psi in 6 minutes. Vibration OK, no avalanche release.
3/3/76	Vibrator run from 70 psi in accumulator, no release.
3/23/76	Snow stable, no avalanche expected. Vibrator ran from 80 psi in accumulator, no release.

CHAPTER IV

MECHANICAL RESONANCE OF SNOW

By Jerome B. Johnson

Introduction

Snow is a two-phase material consisting of a snow (ice) framework with air and water vapor occupying the voids within the frame. It exhibits modes of vibration of entrapped air in addition to vibration of the framework. The two-phase nature of snow requires the solution of the equations of motion and continuity for waves traveling in the snow frame and waves traveling in the voids.

If, as a first approximation, the snow frame were considered to be elastic with a loss associated with wave transmission, then the equation of motion would be (in one dimension) $-\frac{\partial \sigma}{\partial x} = \rho 1 \frac{\partial V_1}{\partial t} + S(V_1 - V_2)$. The pressure waves in the air voids, if the compression takes place isothermally, would be governed by the equation of notion.

$$-\frac{\partial P}{\partial x} = \rho_2 \frac{\partial V_1}{\partial t} + S(V_2 - V_1)$$

The equations of continuity being:

$$-\frac{\partial \sigma}{\partial t} = K_1 \frac{\partial V}{\partial x} - \frac{1-h}{h} \frac{\partial P}{\partial t}$$

$$-\frac{\partial P}{\partial t} = hPo \frac{\partial V_2}{\partial x}$$

Where

σ = The stress in the snow frame.

P = The excess pressure in the voids.

Po = Total equilibrium pressure of the air.

V_1 = Mean velocity of the snow material at X.

V_2 = Mean velocity of the air at X.

ρ_1 = Density of snow material as mass of snow per unit volume of porous material.

P_2 = Density of air, i.e., mass of air content per unit volume of porous material, it is h times the density of free air.

h = Porosity.

s = Coupling coefficient between the air and snow frame dependent on the structure, air flow resistance and flexibility of the snow.

K_1 = Modulus of simple longitudinal expansion to be taken complex for attentuation Re(K1) = K + 4/3M where K is the bulk modulus and M is the rigidity modulous.

For an unbounded medium, the solution of the above four equations results in two waves at any given frequency, which are present in both the air and snow frame.

In acoustics the properties which define the acoustical behavior of a medium are W its wave impedance and δ the propagation constant, where W is the impedance of an unlimited medium and must be independent of position. The impedance is defined as the quotient of pressure to particle velocity at position X. $Z(X) = P(x)/V(x) = R + iX$

R is the resistive term and X is the reactive term. The propagation constant is defined as $\delta = \beta + i\alpha$ where β is the wave number and α is the attenuation constant.

Impedance is a measure of the energy of a pressure wave that is reflected or transmitted at a boundary between two media. If the impedance at a boundary is large, then little of the incident wave is transmitted across the boundary and most of the energy is reflected. The attenuation constant is a measure of the energy lost per unit distance by a wave as it travels through the media. Energy of a stress wave traveling through snow is lost by varius mechanisms labeled internal friction. The major mechanisms for dissipating energy are possibly intergranular friction and viscous losses associated with air passage in the voids. The internal losses can be a function of

frequency, amplitude and often in the past history of a sample. Few reliable measurements of attenuation in snow have been made. It appears that attenuation is of order 0.5 meter $^{-1}$ varying with snow type, density and airflow resistance.

Field Experiments

The field experiments were carried out at the Blue Glacier, Olympic Mountains, in the summer and the Mt. Baker Field Station, Cascade Mountains, this past winter. Two measurements were made on every sample: airflow resistance of the sample and the acoustical impedance of the sample.

Method of Measuring Acoustical Impedance

The acoustical impedance of samples was measured using a constant length impedance tube. A diagram of the impedance tube is shown in Figure 1. A specimen of snow closes the end of the tube. For measurements to determine resonance of samples, the snow sample is backed by a massive steel piston. The sound waves are produced by a moving coil loudspeaker. The resulting waves impinge on the specimen as plan waves. The steady sound field in the tube is explored using a moving probe microphone consisting of a small diameter tube, P, attached to an external microphone and which is moved the length of the main tube. The position of the microphone is accurately measured using a metal scale graduated in milimeters.

A sound field is set up in the impedance tube as the result of wave interference to yield successive maxima and minima. The probe microphone observes the sound pressure at varying distances from the surface of the sample. The impedance is determine from $Z = R + iX$

Resistance $$\frac{R}{\rho c} = \frac{\sinh(2\pi\alpha_\ell)}{\cosh(2\pi\alpha_\ell) + \cos(2\pi\beta_\ell)}$$

Reactance $$\frac{X}{\rho c} = \frac{\sin(2\pi\beta_\ell)}{\cosh(2\pi\alpha_\ell) + \cos(2\pi\beta_\ell)}$$

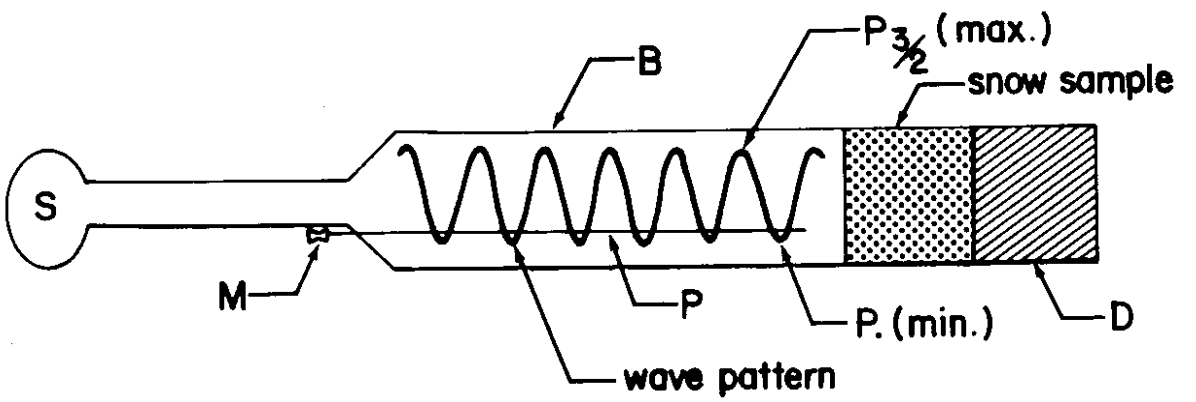


Figure 1. Constant length impedance tube.

D = massive piston
B = seamless tube
P = probe tube
M = microphone
S = sound source

where $\beta_\ell = N - \frac{2\,D\,min^{(n)}}{\lambda}$ and

$$\alpha_\ell = \frac{1}{\pi}\,\mathrm{Tanh}^{-1}\left|\frac{|P\,min^{(n)}| + |P\,min^{(n+1)}|}{2\,|P\,max^{(n+\frac{1}{2})}|\,\cosh(\frac{\delta n}{4})}\right| + \delta\,dmax^{(n+\frac{1}{2})}$$

N is an integer identifying successive minima, $dmin^{(n)}$ is the distance to the nth minima and $dmax^{(n+\frac{1}{2})}$ is the distance to the following maxima. δ is the attenuation associated with the impedance tube.

Air Flow Resistance Measurement

Because snow is a porous medium the propagation of sound through it is strongly influenced by its porosity, shape, and distribution of the pores. Low intensity sound waves are primarily propagated through the snow by the vibration of air in the pores. It is thus necessary to know the resistance of snow to air flow to determine the sound propagating characteristics of a particular snow sample and how it varies with density.

The resistance of porous material to stational air flow is given by Darcy's Law $\frac{\Delta P}{L} = \Sigma V$ where ΔP is the pressure difference across the sample, L is the length of the sample, Σ is the flow resistance in gm./cm.^{3}-s and V is the linear velocity of air flow through the sample.

Air flow resistance was measured using an analytic balance and timer as in Figure 2. A pressure difference is set up across the sample by placing a weight on the scale. The time of travel is measured electronically.

$$\Delta P = \frac{\text{weight}}{\text{area of cylinder}}$$

$$V = \frac{\text{rise of cylinder during fall}}{\text{time of fall}}$$

As can be seen in Figure 3 Σ increases with density. The scatter of values indicates that flow resistance is not only dependant on density but also on the internal structure of the snow.

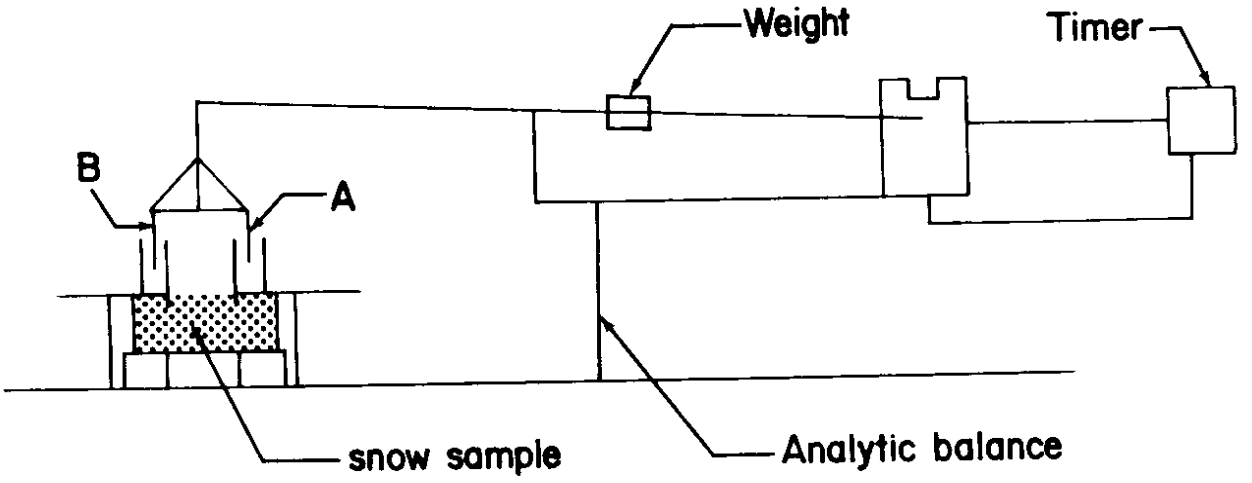


Figure 2.

A = kerosene seal
B = cylinder

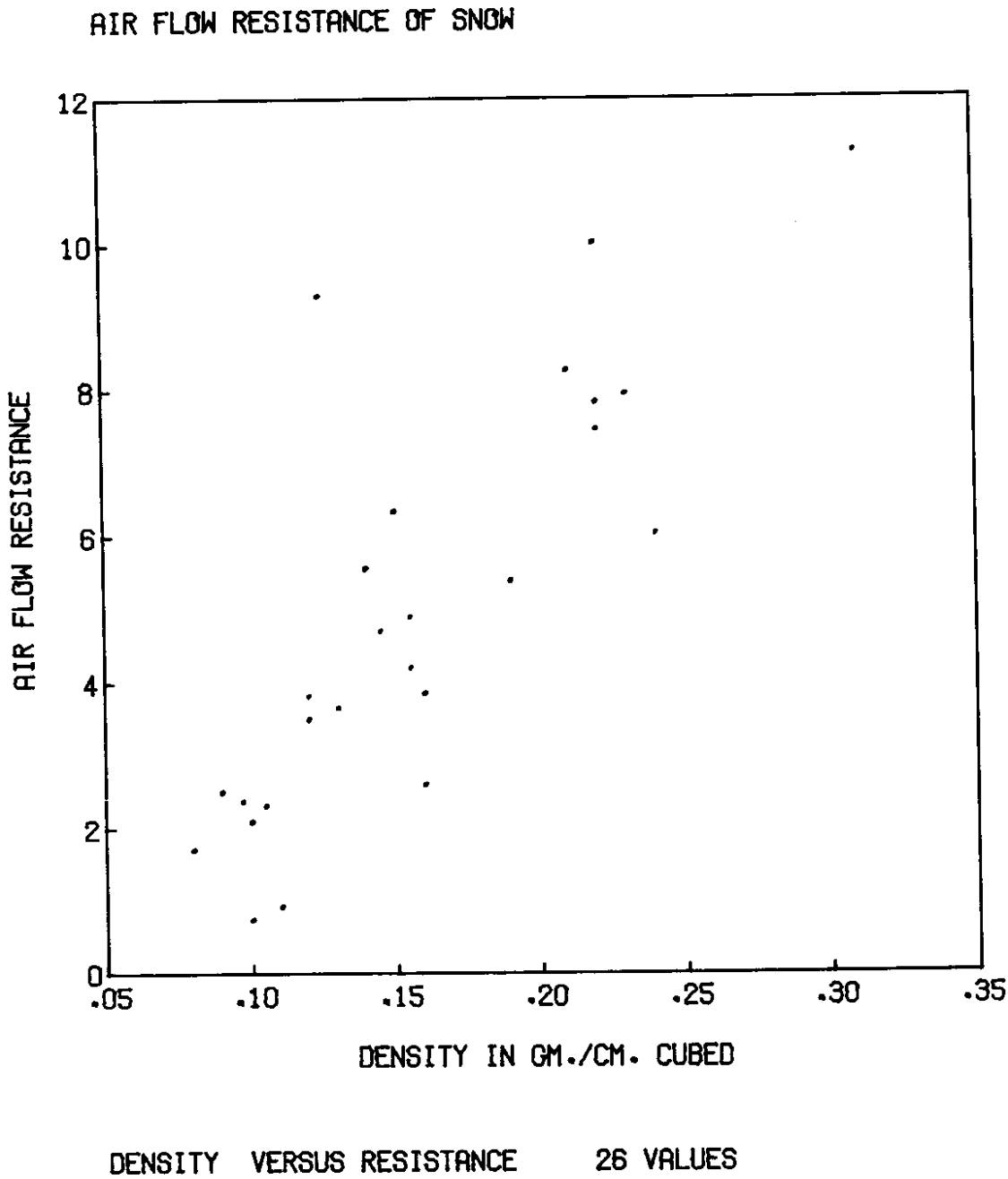


Figure 3. Air flow resistance of snow gm/cm^3-sec. vs. snow density.

Mechanical Resonance

The resonance frequencies of snow are determined by many parameters. The viscoelastic parameters, vibrational properties and internal friction of snow and the vibrational properties and energy loss of the air in the voids change both with frequency and temperature resulting in a complicated dependence of the resonant frequency, on temperature, geometry, internal structure and snow density. A measure of resonance is the absorption of sound by the snow where the absorption is defined as

$$a_o = 1 - \left| \frac{Z-\rho c}{Z-\rho c} \right|$$

Z is the specific impedance of the snow and ρc is the characteristics (wave impedance of air). Peaks in the absorption curve correspond to the maximum energy input which is a result of the snow resonating. Figure 4 shows the absorption curves of samples of various lengths at constant density and temperature. These curves show several peaks that vary with the sample length. The variation in the absorption peaks seems to indicate a complex trend, occurring at lower frequencies for larger samples. Experiments were also conducted on samples of constant length but of varying density. Figure 5 indicates that the absorption decreases with increasing density of snow. No conclusions can be gathered about the effect of density change on resonance as the frequency range examined seems to be too limited. It is apparent that experiments need to be conducted in the frequency range below 300Hz to better determine the resonance characteristics of the snow.

Application

The preliminary results of this past winter suggest that low frequencies are required to resonate snow samples larger that 6cm. Thickness of soft slabs in the Cascades normally ranges from 10cm to 2m or more, which implies

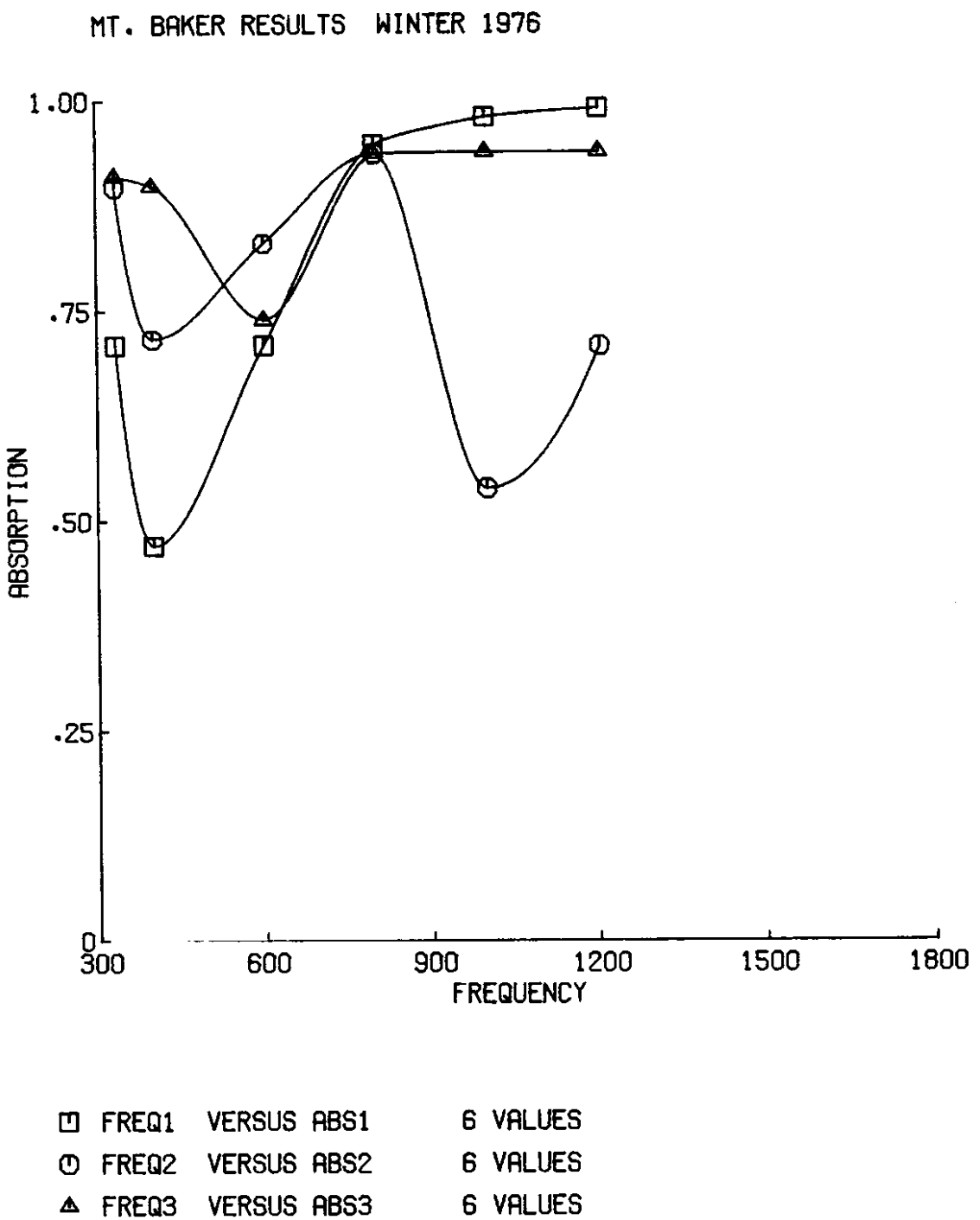


Figure 4.

Relationship of absorption to sample length. Freq. 1, ℓ = 4 cm) Freq. 2, ℓ =8 cm; Freq. 3, ℓ = 12 cm. Density = .23 gm/cm^3 Σ = 8 gm/cm^3-sec.

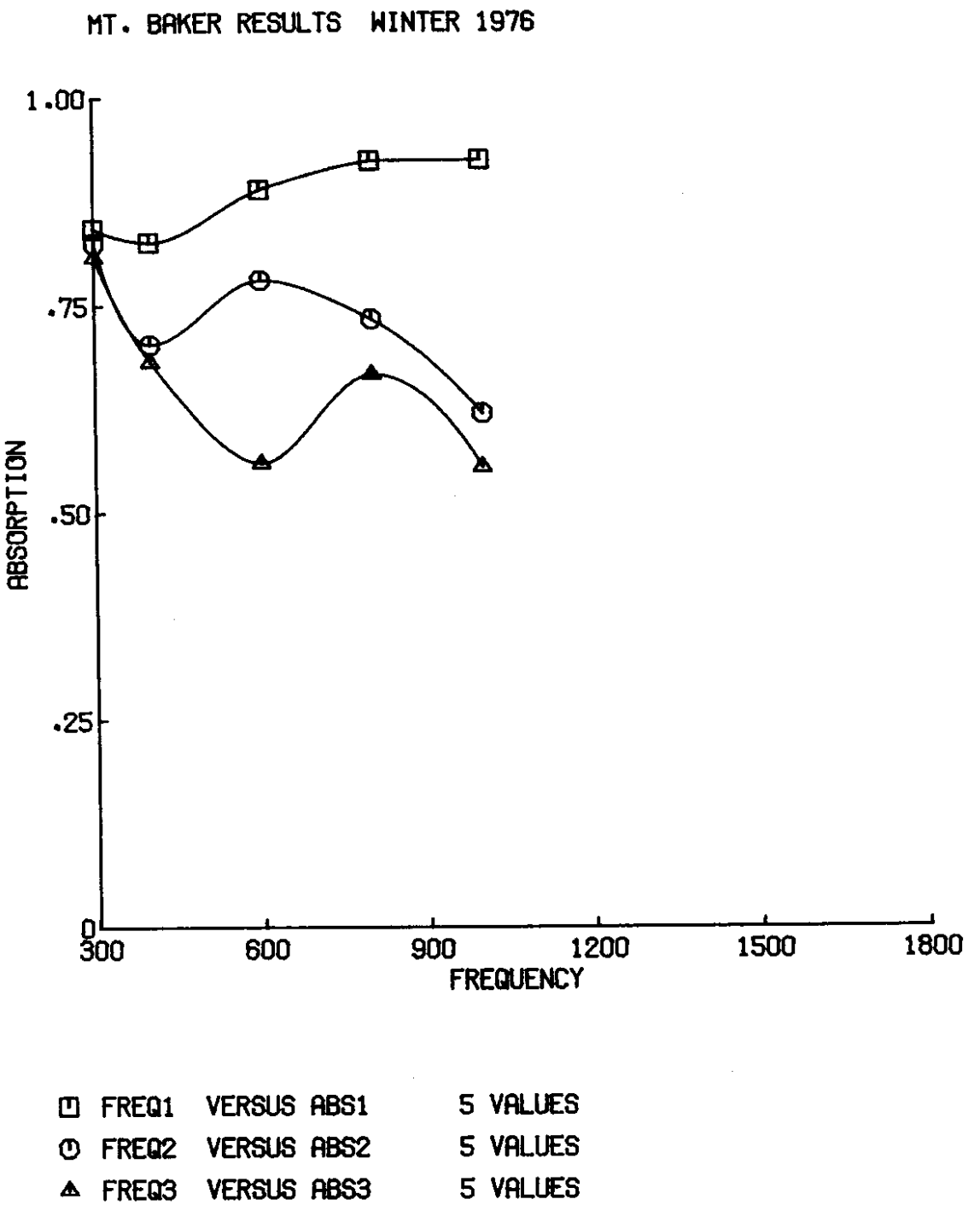


Figure 5

A comparison of absorption to sample density.

Freq. 1, density = .14 gm/cm^3, Σ = 1.6 gm/cm^3-sec;

Freq. 2, density = .26 gm/cm^3, Σ = 7.9 gm/cm^3-sec;

Freq. 3, density = .32 gm/cm^3, Σ = 11.3 gm/cm^3-sec.

that frequencies well below 400Hz would be most likely to set up resonance in these snow slabs. The vibrating mechanism would have to set up longitudinal waves in the snow if geometrical resonance of a snow slab is to be the result.

Conclusions

Initial conclusions can be made as to the effect of changing density and length of snow samples on wave propagating in the samples. Lengthening snow samples of constant density cause a change in the absorption and seem to lower the resonant frequency of the sample. Increases in density lowers the absorption of the sound for a given frequency in a sample. The experiments show a need to increase the range of frequencies and snow types examined. It is the attenuation and strength of the snow which determine the energy input required to cause failure of a snow slab. Attentuation of pressure waves in snow need to be examined in more detail to determine if the energy requirements of inducing resonance are reasonable.

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Chapter V

INTERFACE MODIFICATION FIELD TESTS

by E. R. LaChapelle

During the first winter of this project, some experiments were conducted to see if plastic sheets placed on the ground would encourage sluffing of snow on steep slopes and thus inhibit avalanche development. This was found to be the case with small areas (2 x 3 meters) until the surrounding snow built to a depth sufficient to anchor the snow on the plastic and allow it to accumulate. Even after the plastic was covered, accelerated glide of the snow cover persisted throughout the winter.

These experiments were repeated the second winter, using larger sheets of plastic (polyethylene and reinforced polythylene) in both black and white. Again, serious difficulties were experienced in anchoring the plastic sheets to the mountain side in the face of high winds. One test site lost the plastic entirely, a second was damaged early in the winter, and only one survived until eventually buried by the accumulating snow. But the same effects were found the second winter: snow simply will not adhere to this material on steep slopes until the surrounding snow gets deep enough to provide an anchor, and in this case with larger sheets the required snow depth for anchoring was greater. On the basis of evidence so far obtained in the cold, dry-snow climate of Colorado, it appears that a sufficiently large area of mountainside covered with polyethylene sheet would remain snow-free most of the winter. The interface modification technique thus offers considerable promise as an avalanche control measure from the technical standpoint. There are some severe practical difficulties, however, in the problem of anchoring the sheets, as well as durability, and questions of labor costs, if they are removed and re-installed each year or summer, and esthetic and ecological problems, if they are left in place.

Two areas of the Longfellow site release zone adjacent to the gas exploder installations (see Chapter II) were used to test the effects of plastic sheets. One of these sheets was white plastic, 8 x 33 meters in extent and oriented with the long axis in the fall line; second one was similar except that it was black. The white sheet pictured in Figure 1 was the only one to survive the early-winter winds. A third site was at the

Figure 1. White polyethylene plastic sheet installed in release zone of Longfellow Avalanche Path, Red Mountain Pass, Colorado.

Rockwell slide, a short, steep path overhanging the highway just south of Red Mountain Pass. An early installation at this site was lost to wind and a replacement could not be installed before too much new snow had already accumulated. The basic tie-down technique made use of standard plastic anchor points (plastic loop and ball) at frequent intervals along the edges. The 8 x 33 m sheets on the Longfellow site, for instance, were each anchored with 24 stakes and tie points. The stakes were 1' (30 cm) long pieces of 3/8" (1 cm) rebar. It is thought that adequate anchoring may require attachment to continuous supports such as rods or poles along the sheet edges, as well as anchors in the middle.

The following excerpts from the San Juan Avalanche Project work log summarizes the 1975/76 experience with the plastic sheet experiment.

10/17/75	Layed one roll of white plastic to the north of steel pipe installation at Longfellow site. Sheet measured 20' x 100'. Plastic was layed in vertical position down the fall line. Each roll requires 24 1' stakes.
10/30/75	Three men installed black plastic at Longfellow site, just below and to the left of the steel pipe installation. The exposure is SW.
10/31/75	Gathered materials for installing 40' x 100' sheet of plastic. The Rockwall was chosen as the site with help of Sid Krunenberg, Colorado Department of Highways.
11/10/75	Repair black plastic at Longfellow. The wind is lifting upper right corner and tearing it loose from anchor. Need some system to keep the edges flat.
11/18/75	Repair black plastic on Longfellow, three men, twelve man hours. The wind has torn loose the upper 2/3 of the installation.
11/20/75	Took photos of plastic: Black-light covering of snow over entire surface; White - clear.
11/26/75	Checked Longfellow plastic, both clear. Snow has released over entire sheet, both pieces.
12/9/75	Checked AM sites from road. Black plastic destroyed by wind. White OK with upper 3/4 clear.
12/16/75	Attempted to install new plastic at Rockwall site. Blasted slope with explosives but was unable to release anything. Snow cover from wind was about 70 cm deep. (Rockwall test aborted at this point.)
12/17/76	Longfellow: white plastic covered, small opening visible right corner, but could not see plastic.
1/7/76	Longfellow: white plastic covered, small opening visible upper right corner, but could not see plastic.

1/16/76	The white plastic was barely visible in the upper right corner. The snow is about 2 meters deep away from the sheet.
1/26/76	Plastic-slight crack visible in upper right corner.

The log entries unfortunately make no further mention of the plastic experiment for the rest of the season.

Chapter VI

APPROXIMATE SOLUTIONS FOR THE INTERRUPTION OF THE CREEP AND GLIDE OF A SNOWPACK BY RIGID STRUCTURES

by James A. Langdon

Abstract

A survey of solution methods useful in the design of avalanche defense structures is presented. Recently developed finite element solutions are compared with each other and with earlier developed approximate analytical solutions which are currently used for avalanche defense design in the Swiss Alps. In addition, a general finite element solution method is presented which can be used to solve problems of arbitrary barrier geometry. The method is illustrated by solving three practical problems: a pole or line barrier, a discontinuous barrier, and a cylindrical barrier. Values of barrier forces are given and backpressure zones are illustrated. The element is a triangular prism extending the full depth of the snowpack. Only normal loading at the barrier is considered. Design implications and suggestions for refining the element and conducting experimental research are made.

Notation

A	S/h or relative stagnation depth
C	force intensity coefficient for continuous barriers
C_o	C when $A = 0$
C_1	component of C due to creep and glide divided by $\sin \alpha$
C_2	component of C_1 due to difference in constitutive laws
C_3	force coefficient for arbitrary barrier
e_{xz}	xz shear strain rate
e_z	z direction strain rate
E	Viscous modulus analogy of young's modulus (effective for plane strain)
E_o	E at the snow-ground interface
f	force intensity exerted on a continuous barrier
F	force exerted on an arbitrary barrier
g	gravitational acceleration
h	snow thickness measured perpendicular to the slope
S	stagnation depth
U_o, V_o	velocity components at snow-ground interface as shown in Figure 1
U_1, V_1	velocity components at surface as shown in Figure 1
x	upslope direction
y	cross slope direction
z	direction perpendicular to slope and zero at surface
α	slope angle in degrees
β	glide modulus
ν	viscous Poisson analog (effective for plane strain)
ν'	actual viscous Poisson analog

ρ	snow density
σ_x	normal stress in the x direction
σ_y	normal stress in the y direction
σ_z	normal stress in the z direction
τ_{xz}	xz shear stress
τ_{xy}	xy shear stress
ψ	gliding function - the ratio of f with glide to f with no glide

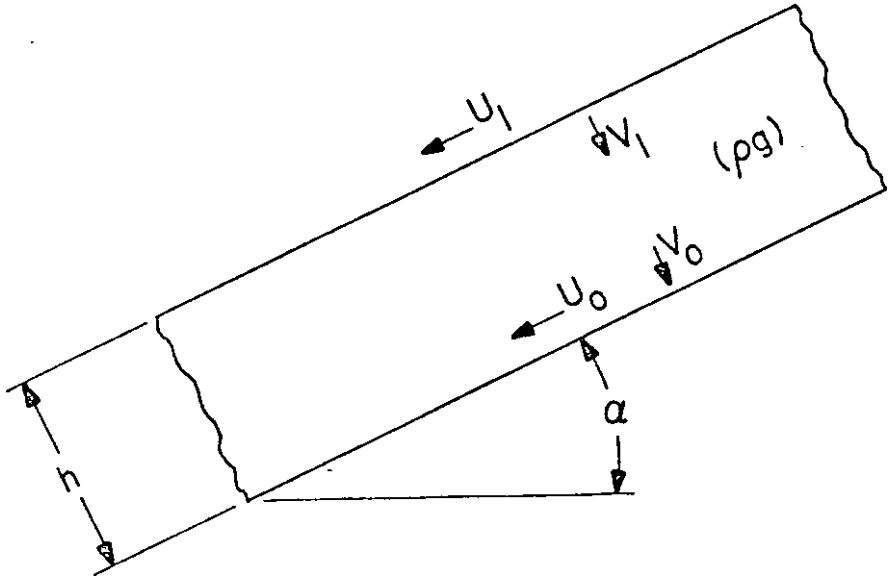


Figure 1. Neutral zone parameters.

Introduction

Two processes, creep and glide, contribute to the slow downslope motion of a snowpack. Creep is the internal deformation within the snowpack; glide is the slip of the entire snowpack over the ground. Interruption of these processes on an inclined slope by rigid structures such as avalanche defenses, trees, power line towers, ski-lift pylons, and buildings causes forces to be exerted upon these structures.

Avalanche defense structures or barriers are of primary interest here. These include masonary and earth terraces as well as supporting structures. Over 1200 running kilometers of these structures exist in the Swiss Alps today. Construction and maintenance costs have become significant and their magnitude warrents a refinement in design of static defense structures.

Design of these structures is presently based upon the work of Haefeli (1939) and Bucher (1948). Their formulations for snow pressure exerted on a barrier employ approximate analytical solutions and require several assumptions to be made about the snow behavior.

Recent interest in the design of barriers has led to significant contributions in the refinement of the problem by the use of finite element numerical methods. Although numerical solutions are approximate, they are more general requiring fewer assumptions than the solutions obtained by Haefeli and Bucher. McClung (1973) suggested that the deep wet snow conditions of the Cascade Mountains of the western United States warrent the use of a finite element method. He was the first to use the method and solved several snow pressure problems for continuous barriers using a standard two dimensional plane strainrate finite element program. Langdon (1975), extending McClung's work, performed a parameter study and established

empirical relationships between barrier forces, snow properties and site conditions. Brown and Evans (1974) developed a one dimensional element for continuous barriers extending the full depth of the snowpack.

Brown and Evans assumed that the velocity profile at any position in the snowpack in linear, that is that sections initially plane remain plane during deformation. Such motion has been observed in the neutral zone; that is the zone where equilibrium exists between the body forces acting downslope and the glide restraint acting upslope. Brown, Evans and McClung (1972) suggested two constitutive laws to explain this observed behavior. These are: (1) an inhomogeneous law in which the viscous modulus varies linearly with depth, or (2) a nonlinear isotropic law in which the viscous modulus is proportional to the bulk stress. Subsequently, these laws are referred to as law (1) and law (2), respectively. Presently there is no experimental evidence available to prefer one law over the other. Haefeli had suggested the inhomogeneous law and used it in his formulation.

The creep behavior of the snow is assumed to be steady and quasi-static. An analogy thus exists between the velocity and the displacement of an elastic solid and problems may be solved using solution methods of the theory of elasticity. In general, numerical solution schemes such as the finite element method are required. The finite element method allows settlement considerations to be incorporated as a viscous analog of Poisson's ratio.

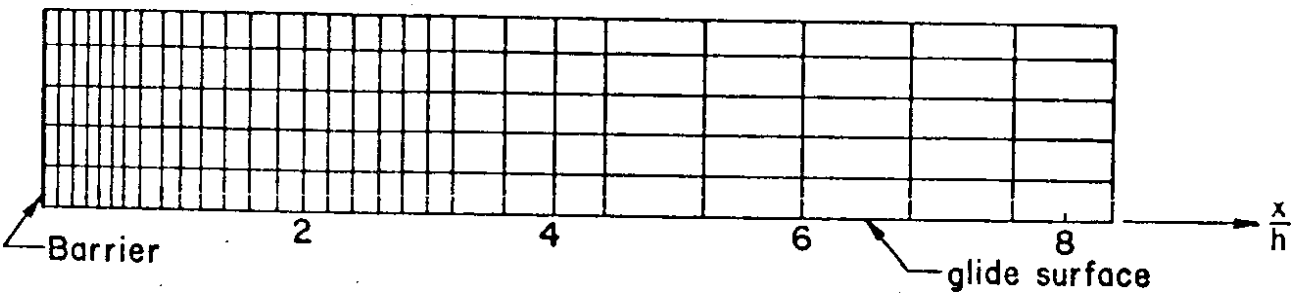
General Assumptions

The following assumptions are applicable to problems throughout the remainder of this paper unless otherwise noted.

1. The snow thickness is assumed constant.
2. The snow density is assumed constant throughout the snowpack.
3. The glide law is linear; that is, the restraining traction due to glide is proportional to glide velocity.
4. The glide modulus is constant along the glide surface.
5. The viscous analog of Poisson's ratio equals the elastic Poisson's ratio and is constant throughout the snowpack.
6. Continuous barriers are perpendicular to the gradient of the slope (i.e., the fall line).
7. The boundary condition on the barrier face is the slip condition; that is, the face of the snow is traction free in the direction perpendicular to the slope.
8. The creep rate is assumed to be proportional to the glide rate so the stagnation depth does not fluctuate with time.

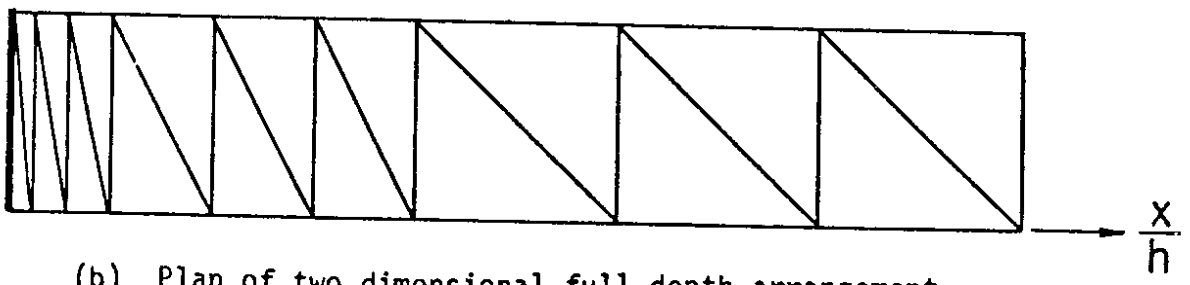
Continuous Barrier Solutions

Langdon used a standard plane strain elastic finite element program to obtain solutions for many continuous barrier problems. This method allows the boundary condition at the barrier to be arbitrary. A smooth barrier can be modeled with the slip boundary condition. A rough barrier can be modeled with a fixed boundary condition or an intermediate boundary condition (i.e., traction is related to velocity). Solutions for law (1) are

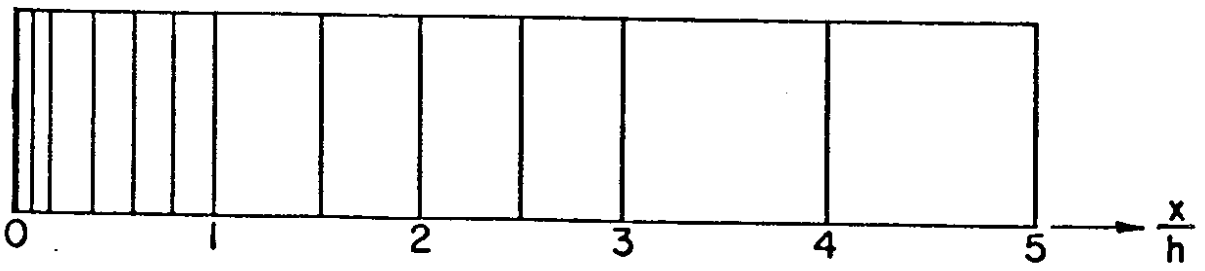


(a) Elevation of two dimensional arrangement.

same scale as (c)



(b) Plan of two dimensional full depth arrangement.



(c) Elevation of one dimensional full depth arrangement.

Figure 2. Element arrangements for continuous barriers.

not difficult since the viscous moduli are predetermined for each element. Law (2) solutions were obtained using an iterative procedure. The element arrangement is shown in Figure 2a. Langdon included variations in ν, A and α for both constitutive laws. Appendix C shows how A may be expressed in terms of the moduli β and E. The effect of variations in ρg and h were determined analytically.

An expression for force intensity acting on the barrier is

$$f = \rho g h^2 C$$

where

$$C = \tfrac{1}{2}\nu \cos \alpha + C_1 \sin \alpha$$

The empirical expression for C_1 fits computed values within 5%. The term $\tfrac{1}{2}\nu \cos \alpha$ is due to the static pressure and was deduced by Brown, Evans and LaChapelle (1972). Values of C_1 for the slip boundary condition are 10 to 15 percent higher than for the fixed condition.

In general it was found that plane sections do not necessarily remain plane except at the barrier and in the neutral zone. This is consistent with the observations of Frutiger (1967). However, this deviation is relatively small (about 10 percent) and is significant only over a short distance near the barrier. This behavior was noted for both constitutive laws.

The solution scheme developed by Brown and Evans provides an efficient and accurate solution method for predicting snow pressure and glide behavior for many problems. It is computationally efficient in that the number of degrees of freedom is significantly reduced. The assumption that plane sections remain plane does not seem to cause significant error. However, many problems cannot be accurately solved because of two limitations.

First, problems with tangential boundary conditions at the barrier cannot be considered because the element stiffness matrix is derived without considering stresses in the z direction. These stresses should be included to obtain accurate solutions for problems with fixed or intermediate boundary conditions.

Second, law (2) problems cannot be accurately solved. Brown and Evans obtained law (2) solutions by averaging the bulk stress over the entire element to obtain new moduli in an iterative scheme. The stresses σ_z and components of σ_x and σ_y are assumed to vary linearly with depth and are superimposed as static pressures. However, Langdon demonstrated that σ_z was up to 70 percent larger than predicted by the superimposed static pressure. The larger than predicted z stresses cause larger bulk stresses and larger viscous moduli than predicted by the Brown-Evans scheme. This effect is magnified in the iteration procedure. In addition, the viscous moduli do not vary linearly with depth as assumed in the one dimensional solution scheme. For these reasons the one dimensional scheme does not give accurate results for law (2) or a nonlinear glide law. Attempted problems using law (2) gave values for C_2 of about one-half those predicted using the two dimensional solution. This error is about 10 to 15 percent for a slope of 45 degrees.

Results of 16 one dimensional problems are compared with the two dimensional empirical expression for C_1 in Figure 3. The element arrangement used is shown in Figure 2c. Values of C_1 are as much as 8 percent higher and an average of 4 percent higher than the one dimensional solution. The actual two dimensional results are, on average, only 2 percent higher than the one dimensional results. Glide behavior and the pressure distribution are nearly identical to that of the two dimensional solution if the value for C_1 is adjusted a few percent.

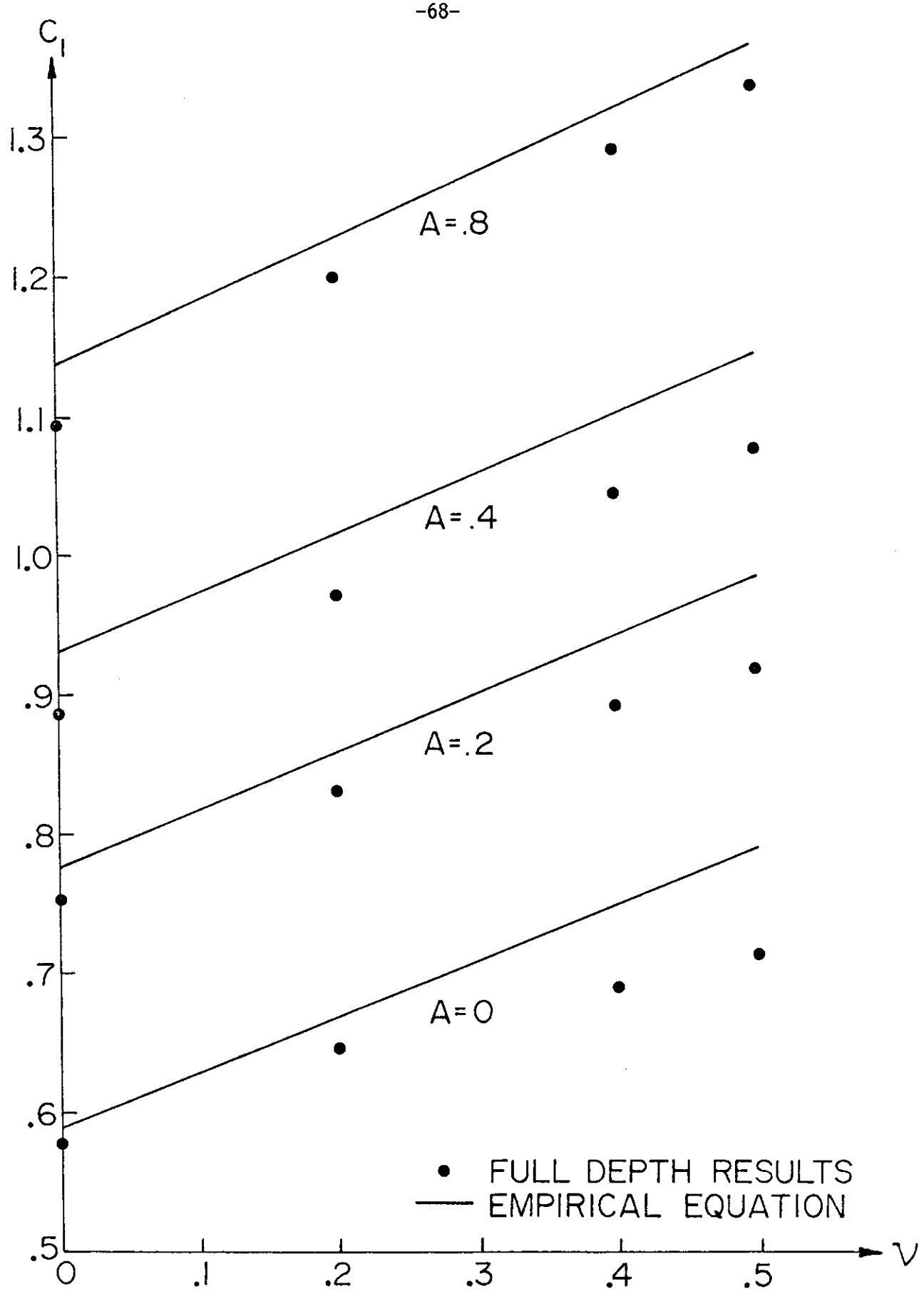


Figure 3. Comparison of empirical and full depth solutions.

The existing Swiss Guidelines for avalanche defense construction are the most comprehensive guidelines in use. Since they are based to a large extent on the following analytical formulations, these formulations are compared with the empirical equation representing the numerical results.

Ignoring static pressure and assuming $V_0 = 0$, Haefeli's expressions for force intensity can be reformulated as:

$$f = \rho g h^2 C_1 \sin \alpha$$

$$\text{where } C_1 = \frac{2}{3} \frac{\sqrt{1 + 3A}}{1 - \nu}$$

Haefeli assumed that plane sections stayed plane and used constitutive law (1), a linear glide law and a slip boundary condition at the barrier. The above assumptions are the same as those used for the full depth finite element scheme. Haefeli also made three assumptions that are not necessary in the finite element solution schemes. First, values of the stagnation depth of the neutral zone were used throughout the backpressure zone. Second, values of neutral zone settlement were used throughout the backpressure zone. Third, the glide velocity profile was assumed to be parabolic. These last three assumptions generally disagree with results obtained using the finite element solution schemes.

Haefeli's formulation gives values of C_1 that are greater than the empirical values for law (1). Since the finite element solution schemes are more general and require fewer assumptions, they should be considered a refinement of Haefeli's work.

Bucher's formulation applies only to the case of $A = 0$ and assumes incompressibility. However, it contains a term to account for variations in snow type. For old compact snow this can be expressed as $C_1 = 1$ which is greater than empirical C_1 for all cases of zero glide for law (1). Bucher assumed a realistic, assymptotic, glide velocity profile. Figure 4 compares C_1 values

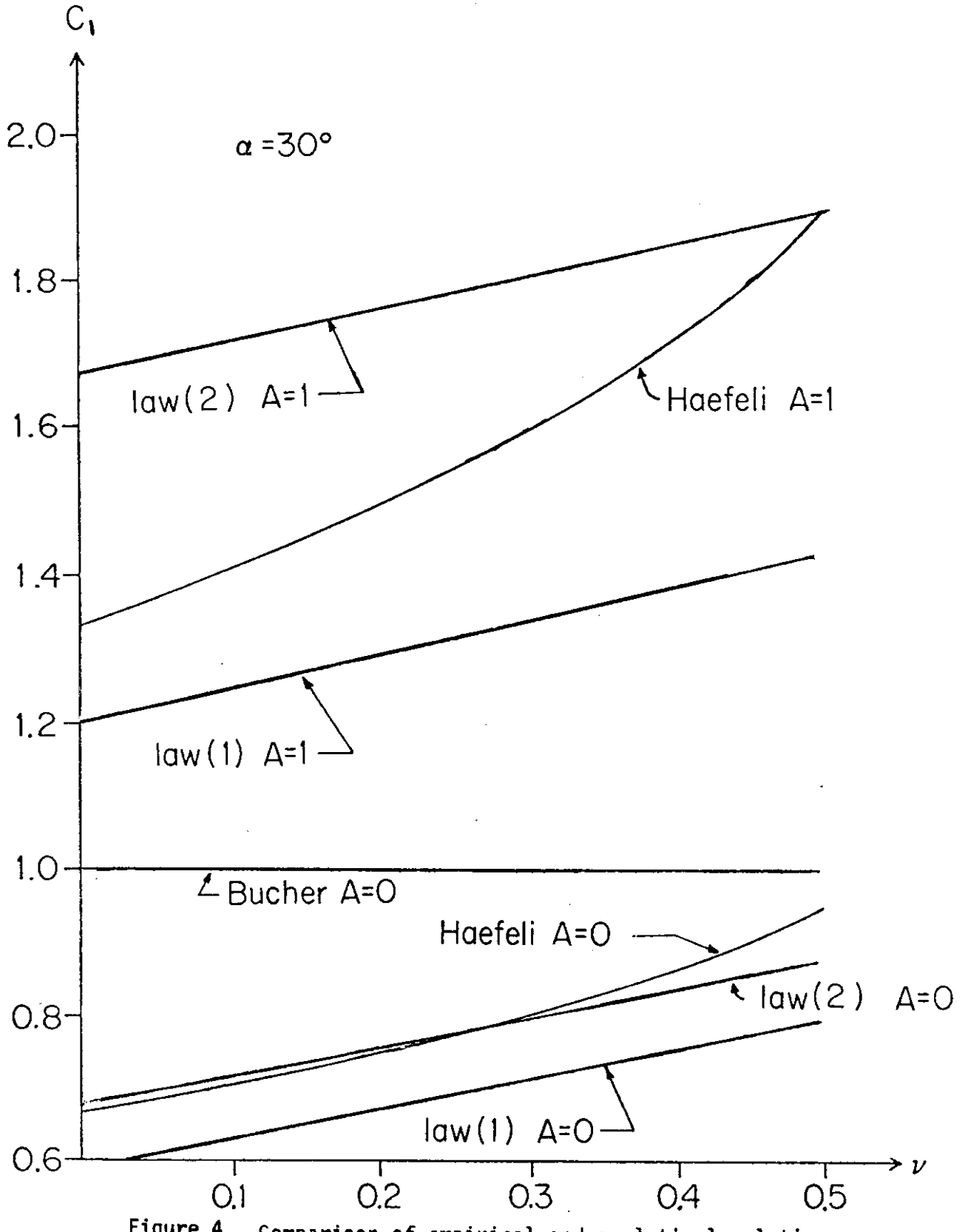


Figure 4. Comparison of empirical and analytical solutions

for Haefeli's, Bucher's and the empirical for a slope angle of 30 degrees. Values of C_1 are given for both constitutive laws.

A good way to compare the effect of gliding of the solution methods was used by de Quervain and Figilister to compare formulations of Haefeli, Roch and de Quervain, all of which neglect compressibility considerations. De Quervain and Figilister define a term, gliding function, ψ, which equals the force intensity divided by the force intensity with no gliding. Haefeli's formulation gives

$$\psi_H = \sqrt{1 + 3A.}$$

while Roch's formulation gives

$$\psi_R = (A + 1) \cos \left[\frac{\pi}{2}\left(1 - \sqrt{\frac{1}{A + 1}}\right)\right],$$

and de Quervain's formulation yields

$$\psi_Q = 2\sqrt{1 + A} - 1.$$

The empirical formulation for law (1) results in

$$\psi_L = 1 + A\,\frac{1 - .4A - .07\nu}{.592 + .4\nu}$$

The formulations of de Quervain and Roch are reformulations, with glide considerations, of Bucher's expression with various assumptions on viscosity and pressure distributions. Figure 5 compares these expressions with the empirical expression for the cases of $\nu = 0$ and $\nu = .5$.

A static pressure term should be added to Haefeli's and Bucher's formulations. The static pressure is an elastic pressure and exists even when there is no creep. Haefeli recognizes this fact and states that it needs to be added. Bucher recommends that the barriers be spaced according to their backpressure zone thereby eliminating the static pressure.

However, most of the static pressure appears in a short distance (about 1.5 h) down slope from a barrier. This has been demonstrated using the two dimensional solution scheme. The backpressure zone is at least 3h for continuous barriers so the static pressure term does contribute to the total force intensity.

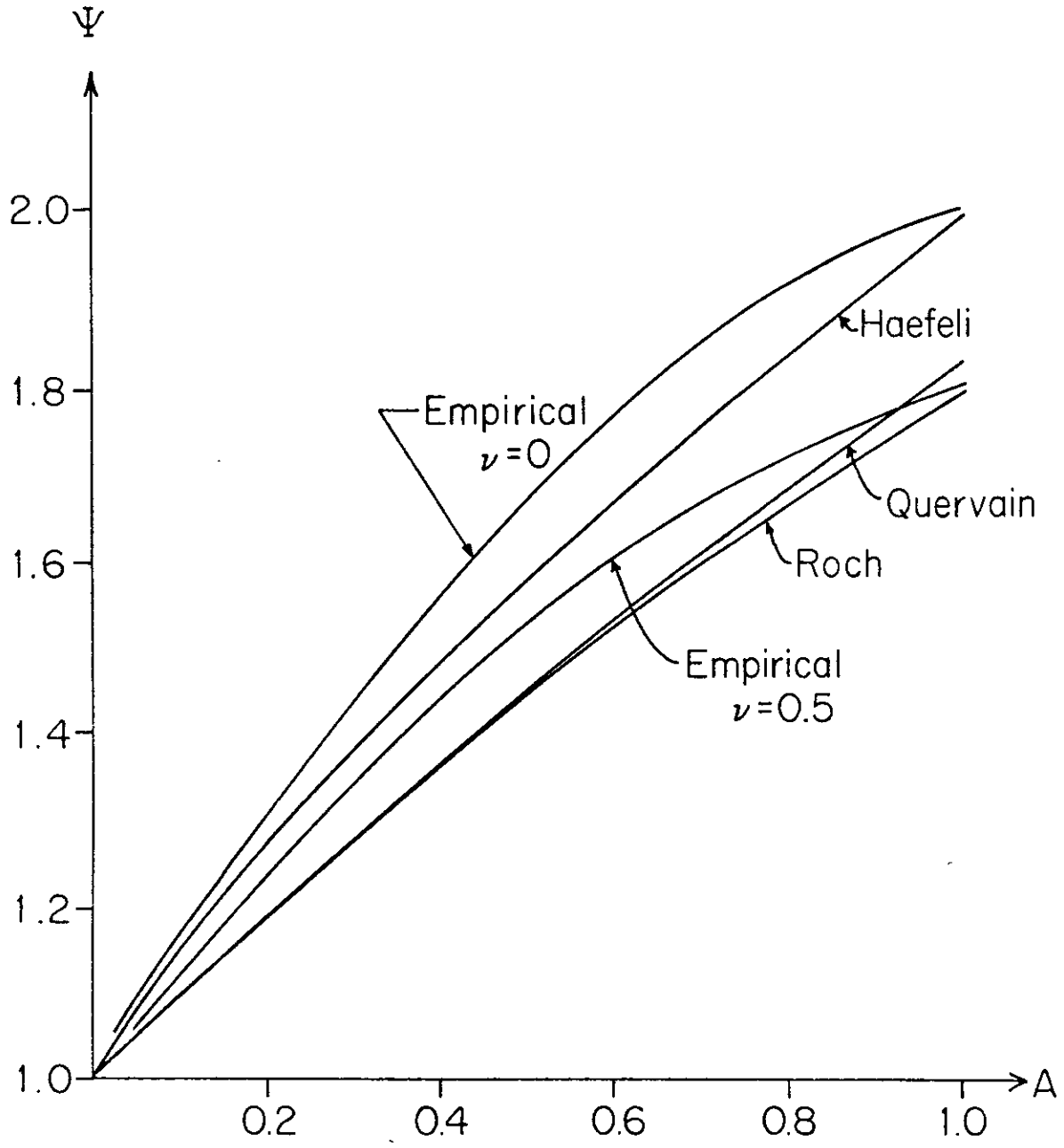


Figure 5. Comparison of gliding functions.

General Solution Method for Barriers of Arbitrary Geometry.

Brown and Evans (1974) suggested the development of a scheme using a parallel piped full depth element to solve three dimensional problems. The stiffness matrix developed here is for the pentahedral element shown in Figure 6. The element is triangular prism parallel to the z axis and has constant thickness h. The displacement field is such that any section perpendicular to the z axis is in a constant state of strain and that strains vary linearly in the z direction. Area coordinates can be used and significantly simplify stiffness matrix calculations (Zienkeiwicz, 1971). The stiffness matrix is given in Appendix A. Its calculation is lengthy but straightforward.

This element conforms reasonably well with snowpack kinematics and reasonably well to arbitrary barrier geometry. Since z stresses are neglected as in the one dimensional full depth element, accurate solutions are limited to law (1) and the slip boundary condition. A FORTRAN computer program taking advantage of matrix symmetry and bandwidth considerations is used to solve specific problems.

In order to test the program several continuous barrier problems were solved. The results were nearly identical with those using the one dimensional full depth element. The maximum difference in forceintensity for these cases was less than 2 percent.

Pole Barriers (Line Barriers)

A pole barrier is a line barrier normal to the slope. Figure 7 shows the 120 element arrangement that was used for pole barrier problems. It is necessary to have very small elements near the pole. Arrangements with larger elements gave larger forces and smaller velocities. Most x direction

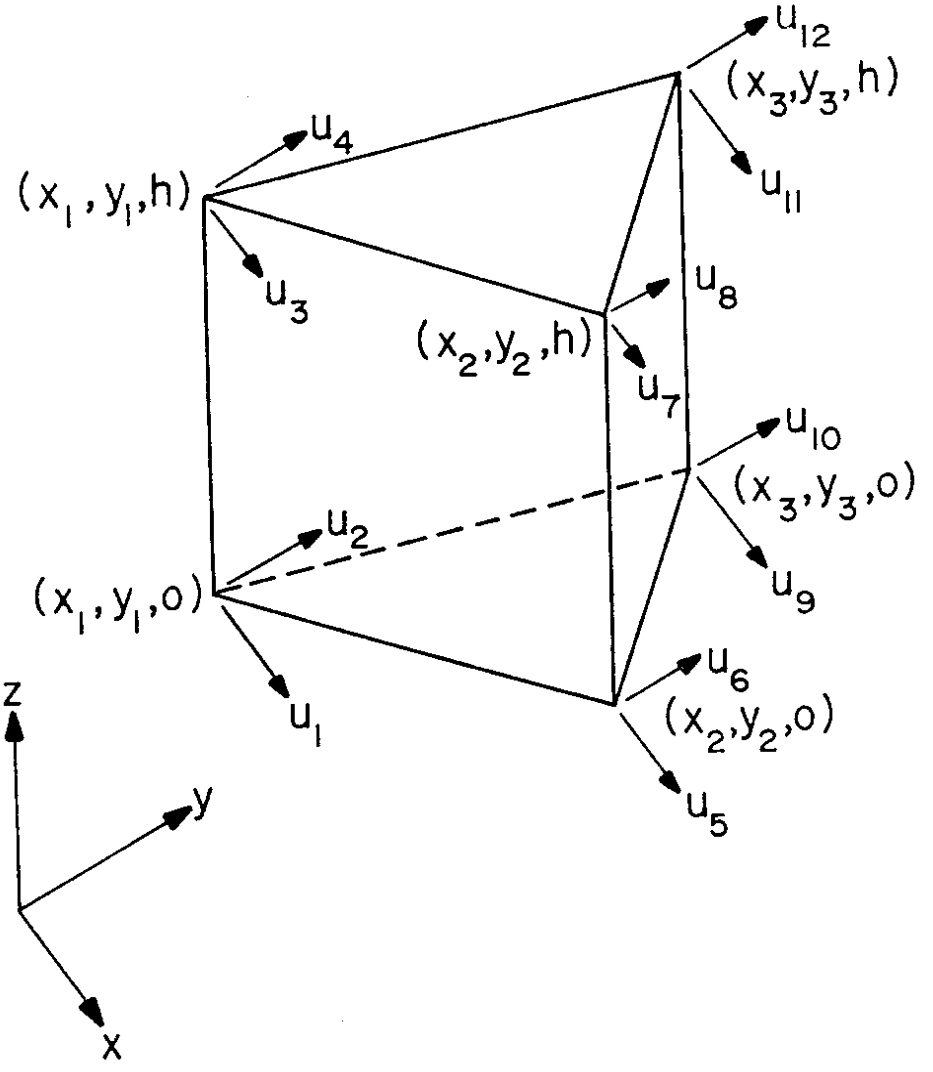


Figure 6. General solution method element.

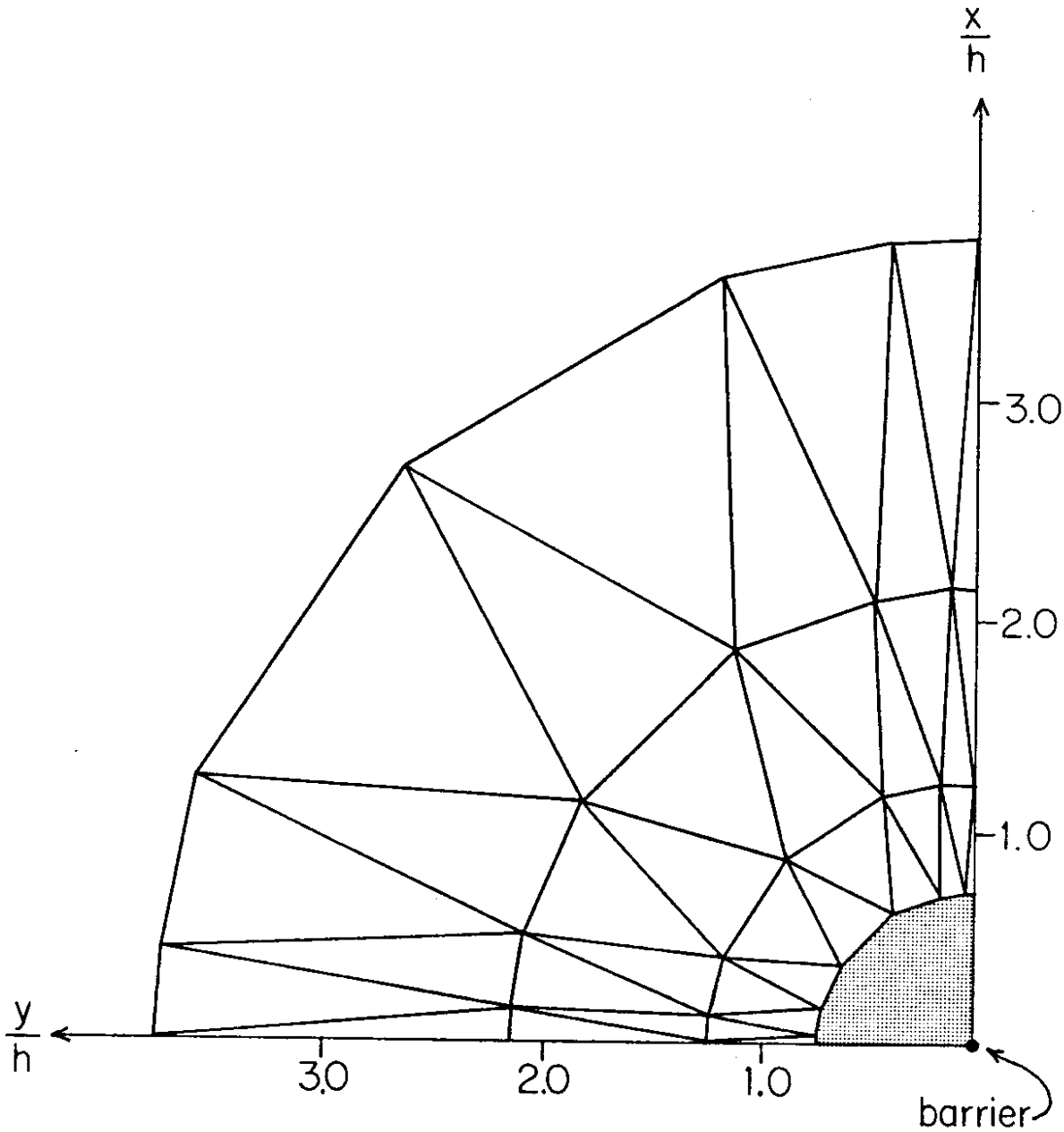


Figure 7. Element arrangement for pole barriers. Shaded area contains 81 similar elements diminishing in size.

velocity components from the arrangement of Figure 7 varied less than 3 percent from those of an arrangement with 86 elements. Since real poles will be of finite size, it is felt that further refinement is not warranted.

The element arrangement takes advantage of symmetry and antisymmetry. The boundary condition at the pole is zero velocity in both directions. The boundary conditions along both axis are zero y velocity and zero x traction. This boundary condition at the y axis arises as follows: Although the entire problem is not antisymmetric it may be thought of as the sum of two problems, (1) the uniform creep and glide and (2) a superimposed line force at the pole to make the total velocity there zero. The x traction and y velocity for case (1) are zero everywhere, while case (2) is antisymmetric about the y axis and hence the x traction and y velocity are zero at the y axis for this case. Thus the entire problem may be solved considering the quarterspace and using boundary conditions of symmetry about the x axis and antisymmetry about the y axis. The other boundary can be traction free or have zero y velocity since it is within the neutral zone. The condition of zero y velocity requires less computation time.

A parameter study varying A and ν for law (1) results in the following empirical equation for barrier force:

$$F = \rho g h^3 C_3 \sin \alpha \tag{1}$$

$$\text{where } C_3 = .252 + .107\nu' + .267\nu' A + .692A - .040A^2 \tag{2}$$

$$\nu' = \frac{\nu}{1 + \nu} = \text{actual Poisson's ratio effect}$$

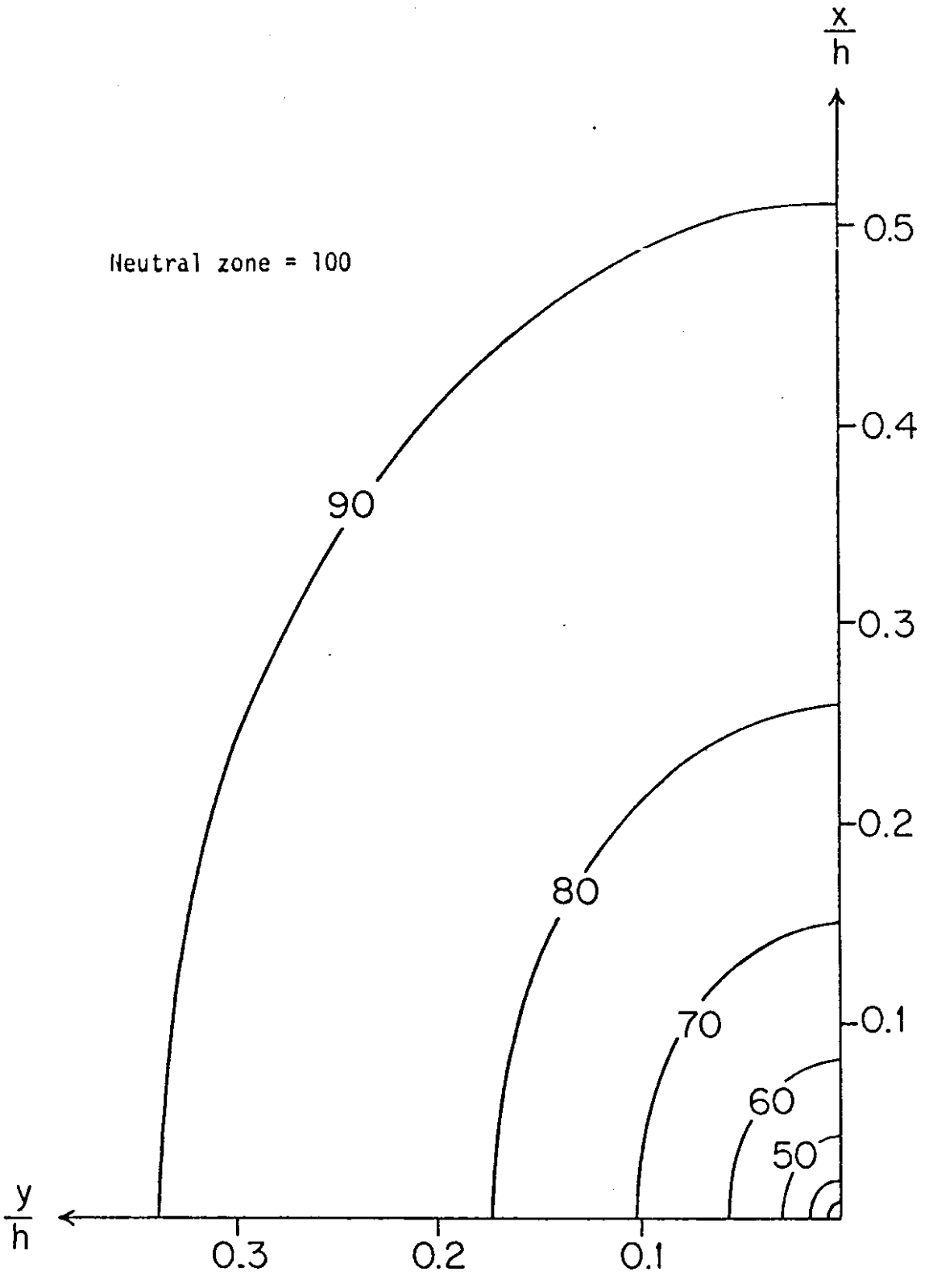


Figure 8. Approximate contours of x velocities and τ_{xz} for pole barrier where $A = \nu = .2$

This force approximately equals the force acting on a continuous barrier over a length of one half the snow depth. Equation (2) is accurate to one percent for all cases studied in the range between $0 \leq A \leq .8$ and $0 \leq \nu' \leq .375$.

The glide and surface velocities in the x direction as well as τ_{xz} can be closely approximated by ellipses as shown in Figure 8. This figure might be considered a contour map of velocities or shear stresses. The relief is then a deep elliptical depression with zero elevation at the barrier and with convex slopes gradually reaching neutral zone elevation. A cross section of this depression along the x or y axis can no longer be represented by a simple exponential equation as in the case of a continuous barrier. The usefulness of a complex empirical equation is questionable, so none is given. In Appendix B it is shown that the barrier force is equal to the volume of this depression times the glide modulus. The extent of the backpressure zone in the x direction is considerably less than it is for a continuous barrier. The 90 percent contour for $A = .2$ and $\nu = .2$ for the pole barrier is at $x = .51h$. For the continuous barrier it is at $x = 1.80h$. This smaller backpressure zone is attributable to the interruption of glide in both the positive and negative directions along both the x and y axis instead of just along the positive x axis as in the case of the continuous barrier. Some difference is due to the different nature of U. The excentricity of the ellipses is nearly independent of A and increases with increasing ν. If an ellipse is represented by: $\frac{x^2}{b^2} + y^2 = m^2$, then b varies nearly linearly from about 1.4 to 1.7 as ν varries from 0 to .6. Values for m increase with both ν and A.

Velocity components in the y direction and τ_{yz} are small and do not warrant a quantitative discussion. For the quadrant in Figure 8, Y velocity components are positive upslope of the pole as expected.

Cylindrical Barriers

Two cylindrical barrier problems were solved using an element arrangement similar to that used for the pole barrier problems. The snow was assumed to stick to the barriers on all sides so that symmetry and antisymmetry boundary conditions could be used. In reality, the snow usually separates from the barrier on the downslope side so these boundary conditions are not realistic. Results were obtained for two cylinder diameters, .02h and .06h. Such dimensions might correspond to trees; and in 4 m deep snow the diameters corresponding to the above data are 8 and 24 cm, respectively. The velocities and τ_{xz} can be approximated by ellipses as before. The eccentricity is no longer constant near the barrier and the backpressure zone increases with increasing barrier size. For the case $A = .2$, $\nu = .2$ values of C_3 in equation (1) are .62 and .82 for diameters of .02h and .06h, respectively.

Pole Barriers Restrained at Only One Point

Two cases of this problem were studied for the specific conditions $A = .2$, $\nu = .2$. The first case, the restraint at the snow-ground interface, might be considered an approximation to a very short obstacle interrupting the creep and glide. The second case, the restraint near the snow surface, might be considered a special pole barrier free to move at the ground and hinged at the surface. Values of C_3 for these cases ($A = \nu = .2$) are .064 and .117, respectively, or 15 and 28 percent of C_3 for a completely rigid pole barrier. The first case enhances avalanche formation by increasing xz shear stresses up to 30 percent. The second case reduces shear stresses, especially near the barrier, but its backpressure zone is smaller

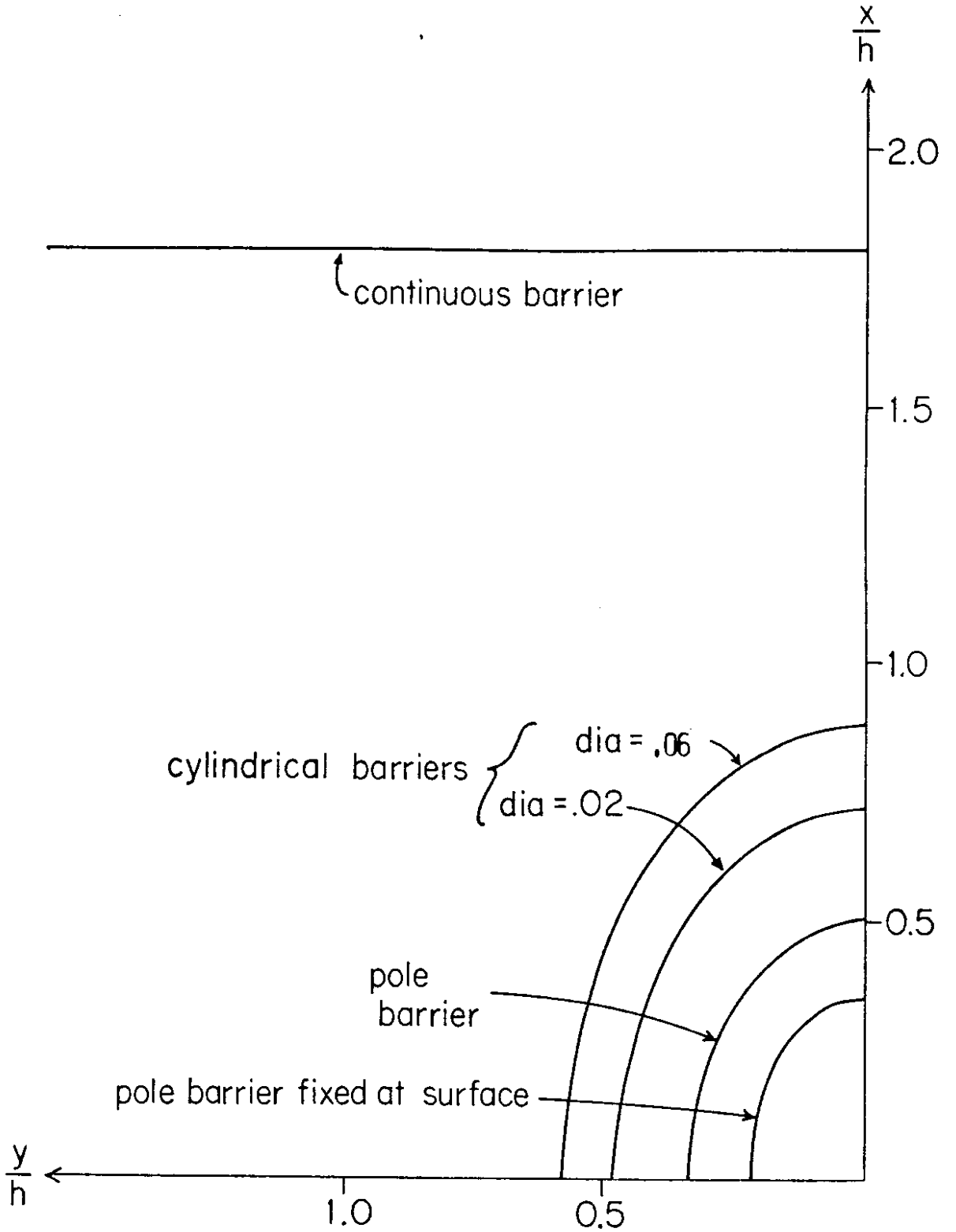


Figure 9. Approximate 90 percent contours for various barriers where A = ν = .2.

than that of the completely rigid pole barrier. Figure 9 compares the 90 percent of the neutral zone values for several types of problems.

Discontinuous or Semi-Infinite Barriers

An approximate solution to this problem was obtained by using the element arrangement shown in Figure 10; it contains 181 elements. Symmetry cannot be used because of the velocity discontinuity across the barrier. All surfaces are traction free except the upslope side of the barrier which is fixed in the x direction and the boundary at $y = 2h$ which is fixed in the y direction. These are realistic boundary conditions which allow a separation between the snow and the barrier on the downslope side of the barrier.

The value of C_3 was found to be 2.18 for $A = \nu = .2$. Force intensity was extremely large near the end of the barrier with an average value of over 30Q for the first .01h along the barrier and an average of 1.6Q over the first h along the barrier (Q is the force intensity, neglecting static pressure, for the same creep and glide conditions on a continuous barrier). Figure 11 illustrates this behavior. Figure 12 shown the 80 and 90 percent neutral zone value contours.

Design Implications

The formulations for snow pressure by Haefeli and Bucher appear to be conservative for law (1) but conservative for law (2) only in some cases. Since the constitutive law is not presently known conclusions would be premature.

The static pressure does contribute to snow pressure and should be added to the creep and glide pressure. The spacing of barriers on a slope has little or no effect on the static pressure. Snow pressure may be

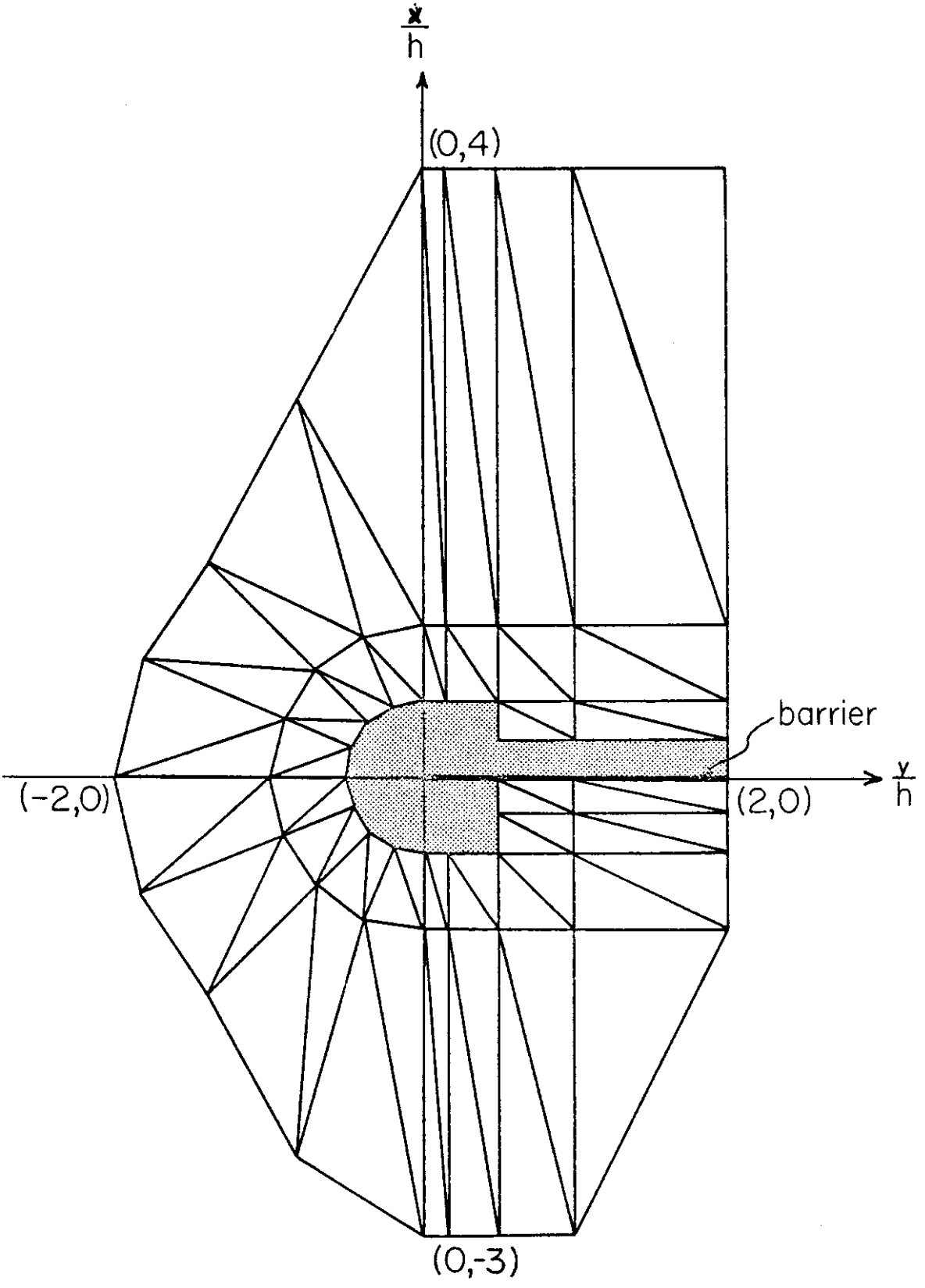


Figure 10. Arrangement used for discontinuous barrier. Shaded area contains 105 similar elements diminishing in size.

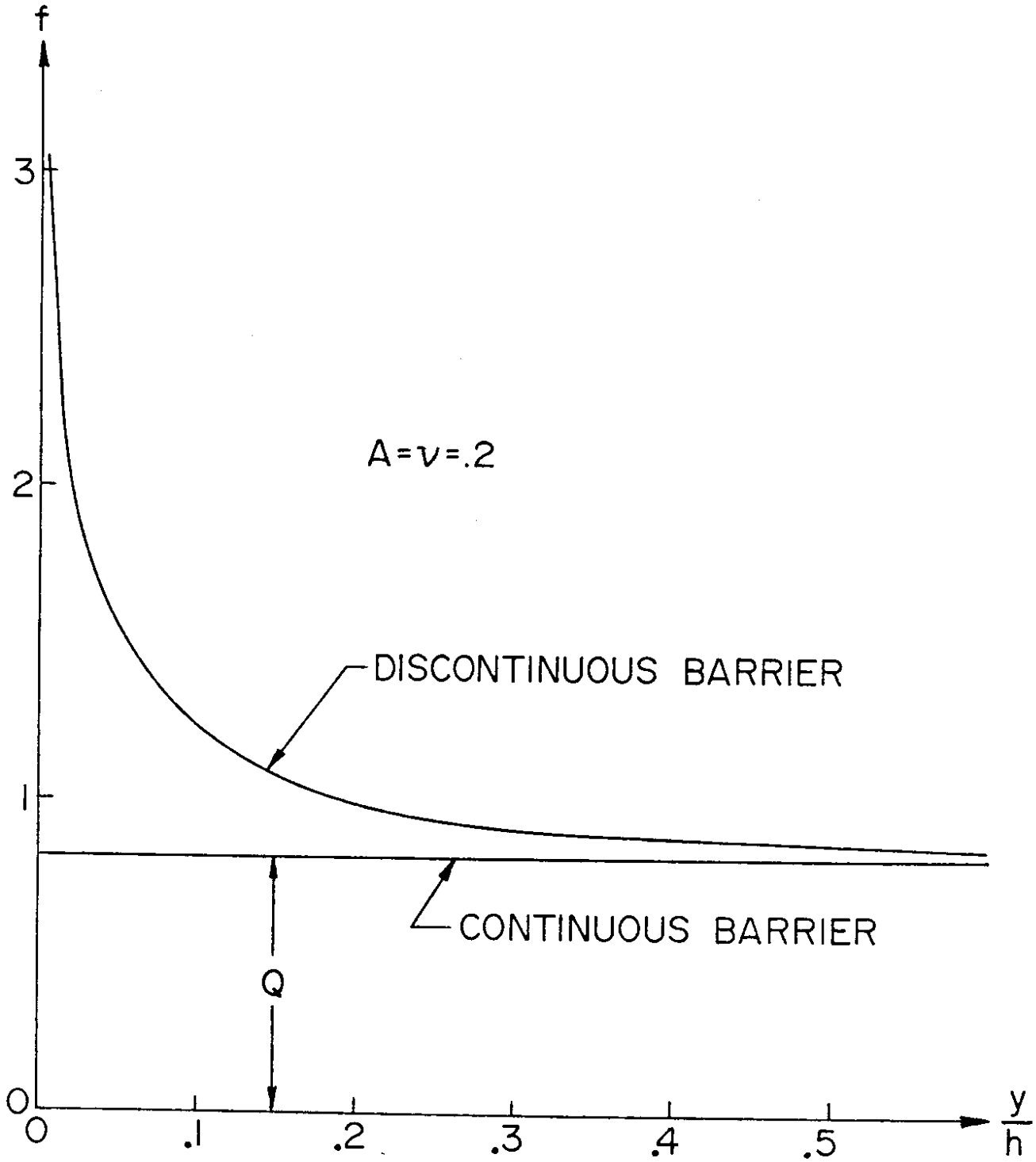


Figure 11. Force intensity near the end of a discontinuous barrier.

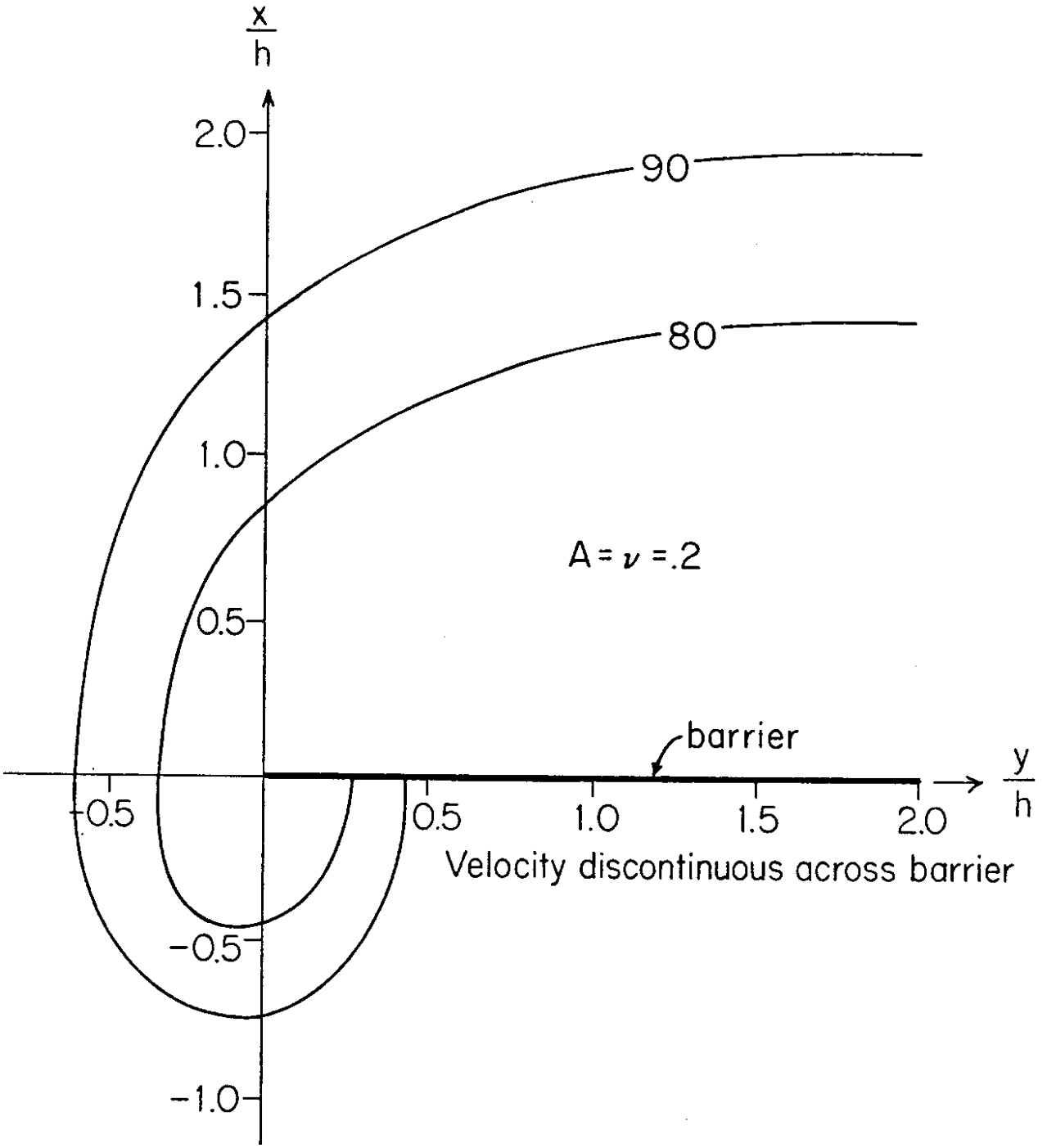


Figure 12. Contours of 80 and 90 percent near the end of a discontinuous barrier.

reduced by reducing glide, by artificially increasing the glide surface roughness such as introducing additional vegetation, building small terraces, or closely spaced minature barriers.

Periods of maximum snow pressure in general do not coincide with the worst avalanche conditions. De Quervain and Figilister state that snow pressure analysis should be for conditions of maximum glide in April, May or June. Conceivably, in the Cascades rain can occur at anytime and cause the snowpack to be isothermal and glide to occur. Maximum pressure can then occur in February or March when the snow depth may be greater. Inversely, worst avalanche conditions can occur with zero glide, when the backpressure zone is smallest. Barrier spacing should be based on zero glide conditions.

The assumption that the creep rate is proportional to the glide rate is probably not correct. McClung's creep measurements that are the basis for the constitutive laws, are over a time period of several months. His glide data show several large fluctuations over the same period. Since different mechanisms are involved in creep than glide, one cannot expect the creep rate to always be proportional to the glide rate. Because of these short-term variations, the short-term stagnation depth can be significantly larger than its average value. This implies significantly larger pressures than predicted using the average stagnation depth. This uncertainty can be predicted by artificially increasing the glide surface roughness so that glide becomes insignificant. Further study is needed here.

The question of which barrier type is best cannot presently be answered. Based on the postulate that the "best" barrier is the one that provides the largest ratio of backpressure zone to barrier force, then the continuous barriers are about 50 percent better than the pole barriers and the cylindrical barriers are nearly as good as the continuous barrier.

A continuous barrier hinged on top and free at the bottom for A = .2 is nearly twice as good as a continuous barrier but its construction and operation are difficult to imagine. Based on the assumption that barrier spacing will be based on a minimum avalanche dimension, the pole barrier will probably prove to be superior.

The methods presently developed can also be used to advantage in controlling avalanches by predicting enhanced avalanche formation. As an example, the presence of a short obstacle significantly increases shear stresses. Another example is that of avalanche fracturing which can be forced to occur along a given line by artificially increasing the glide below the desired fracture line or decreasing the glide above the desired fracture line. The methods of analysis presented here can give quantitative insight into such cases.

Research Suggestions

Additional experimental measurements are needed. Experimental snow pressure measurements tabulated by de Quervain and Figilister and Mathews and MacKay (1975) are difficult to compare with the solution methods presented. Most measurements are for barriers of finite length. Measurements are for zero glide and show considerable scatter. If a value of $\nu' = .3$ and the slip boundary condition are assumed then experimental values of de Quervain and Figilister tend to be a little lower than those predicted.

Future experimental measurements should be designed to measure neutral zone compressibility, the glide velocity profile and creep rates as well as the pressure distributions at the barrier. Creep velocity needs to be measured on a short time scale to determine how the stagnation depth fluctuates on a short time scale. Such measurements should aid in determining an accurate model for the glide and constitutive laws.

The limitations of the general solution method presented can be overcome with a more general element having three additional degrees of freedom in the z direction at each of the upper nodes. Such an element, once developed and included in a solution scheme, should provide solutions to problems of law (2), the nonlinear glide law, and the fixed boundary condition. The fixed boundary condition problem seems to be the more important one since snow pressures are generally less for this case.

Failure theories applicable to snow within avalanche defense networks need to be developed. Solution schemes presently developed predict stresses needed for these theories.

Many of the three dimensional problems in this study need more thorough study. The problems presented are primarily intended as examples. There are no doubt many other barrier types and barrier arrangements that could be profitably studied.

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APPENDIX A

STIFFNESS AND GLIDE MATRICES FOR GENERAL SOLUTION METHOD

Element Stiffness Matrix (see figure 6)

$$K = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix}$$

where

$$K_{ij} = Q \begin{bmatrix} 3\,b_j\,b_i + 3\,a_j\,a_i\,a + R & 3\,a_j\,b_i\,\nu + 3\,b_j\,a_i\,a & b_j\,b_i + a_j\,a_i\,a + R & a_j\,b_i\,\nu + b_j\,a_i\,a \\ 3\,b_j\,a_i\,\nu + 3\,a_j\,b_i\,a & 3\,a_j\,a_i + 3\,b_j\,b_i\,a + R & b_j\,a_i\,\nu + a_j\,b_i\,a & a_j\,a_i + b_j\,b_i + R \\ b_j\,b_i + a_j\,a_i\,a + R & a_j\,b_i\,\nu + b_j\,a_i\,a & b_j\,b_i + a_j\,a_i\,a + R & a_j\,b_i\,\nu + b_j\,a_i\,a \\ b_j\,a_i\,\nu + a_j\,b_i\,a & a_j\,a_i + b_j\,b_i\,a + R & b_j\,a_i\,\nu + a_j\,b_i\,a & a_j\,a_i + b_j\,b_i\,a + R \end{bmatrix}$$

$Q = \frac{EH}{48\,A}$ $\qquad R = 2c$ if $i \neq j$ $\qquad a = \frac{(1-\nu')}{2}$

$c = \frac{A^2 a}{H^2}$ $\qquad R = 4c$ if $i = j$ $\qquad \nu = \frac{\nu'}{1-(\nu')^2}$

$a_1 = x_3 - x_2$ $\qquad b_1 = y_2 - y_3$ $\qquad E = \frac{E'}{1-(\nu')^2}$

$a_2 = x_1 - x_3$ $\qquad b_2 = y_3 - y_1$ $\qquad \nu'$ = real poisson effect

$a_3 = x_2 - x_1$ $\qquad b_3 = y_1 - y_2$ $\qquad E'$ = real viscous modulus at snow-ground interface

$A = \frac{1}{2}(a_3 b_2 - a_2 b_3)$

H = snow height

K is found as follows:

$$K = \int_{Vol} b^T K b \, dVol$$

where

$$b^T = \frac{Q_1}{2A} \begin{bmatrix} b_1 & 0 & a_1 & -\gamma_1 & 0 \\ 0 & a_1 & b_1 & 0 & -\gamma_1 \\ cb_1 & 0 & ca_1 & \gamma_1 & 0 \\ 0 & ca_1 & cb_1 & 0 & \gamma_1 \\ b_2 & 0 & a_2 & -\gamma_2 & 0 \\ 0 & a_2 & b_2 & 0 & -\gamma_2 \\ cb_2 & 0 & ca_2 & \gamma_2 & 0 \\ 0 & ca_2 & cb_2 & 0 & \gamma_2 \\ b_3 & 0 & a_3 & -\gamma_3 & 0 \\ 0 & a_3 & b_3 & 0 & -\gamma_3 \\ cb_3 & 0 & ca_3 & \gamma_3 & 0 \\ 0 & ca_3 & cb_3 & 0 & \gamma_3 \end{bmatrix}$$

$$K = EQ_1 \begin{bmatrix} 1 & \nu & 0 & 0 & 0 \\ \nu & 1 & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & a \end{bmatrix}$$

$$e = \frac{1}{Q_1 H}$$

$$Q_1 = 1 - \frac{z}{H}$$

$$Q_2 = \frac{z}{H}$$

$$c = \frac{Q_2}{Q_1}$$

$$C_1 = x_2 y_3 - x_3 y_2$$

$$C_2 = x_3 y_1 - x_1 y_3$$

$$C_3 = x_1 y_2 - x_2 y_1$$

$$\gamma_1 = e(a_1 x + b_1 y + C_1)$$

$$\gamma_2 = e(a_2 x + b_2 y + C_2)$$

$$\gamma_3 = e(a_3 x + b_3 y + C_3)$$

Glide Stiffness Matrix

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix}$$

where

$$G_{ij} = \frac{\beta A}{12} \begin{bmatrix} d & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$d = 2$ if $i = j$

$d = 1$ if $i \neq j$

β = glide modulus

G is found as follows:

$$G = \int_{A_b} b^T K b \, dA_b$$

where A_b is the area of the bottom face in figure 9.

$$b = Q_1 H \left[\begin{array}{c|c|c|c|c|c|c|c|c|c|c|c} \gamma_1 & 0 & \gamma_2 & 0 & \gamma_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & \gamma_1 & 0 & \gamma_2 & 0 & \gamma_3 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

$$K = \beta \left[\begin{array}{c|c} 1 & 0 \\ \hline 0 & 1 \end{array}\right]$$

APPENDIX B

GLIDE VELOCITY - BARRIER FORCE RELATIONSHIP

Consider the rectangular region of snow bounded in the x direction by a and -a and bounded in the y direction by b and -b. The boundary is in the neutral zone and a barrier lies within the boundary. Overall equilibrium in the x direction requires that the x direction component of snow weight plus the barrier force plus the glide force be zero or

$$4ab\rho g \sin \alpha + f - \beta \int_{-a}^{a} \int_{-b}^{b} u dx dy = 0$$

from equation (C1)

$$\rho g h \sin \alpha = U_0 \beta$$

manipulation yields

$$f = \beta \int_{-a}^{a} \int_{-b}^{b} (U_0 - U) dy dx$$

This equation may be interpreted graphically. If U is plotted three dimensionally as a function of x and y then the barrier force is β times the volume between the surface defined by U and the plane $U = U_0$.

APPENDIX C

NEUTRAL ZONE RELATIONSHIPS

From the definition of neutral zone

$$U_0\beta = \rho g h \sin \alpha \tag{C1}$$

and from equilibrium

$$\tau_{xz} = U_0\beta z/h \tag{C2}$$

The definition of Stagnation depth is equivalent to

$$S = \frac{U_0 h}{U_1 - U_0} \tag{C3}$$

From the definition of strain

$$e_{xz} = \frac{1}{2}(U_1 - U_0)/h \tag{C4}$$

and

$$e_z = (V_1 - V_0)/h \tag{C5}$$

The stress strain rate relations are

$$\frac{E}{2(1 + \nu)} = \frac{\tau_{xz}}{e_{xz}} \tag{C6}$$

$$\sigma_x = \frac{E\nu e_z}{1 - \nu^2} \tag{C7}$$

The consitutive law requires $E = E_0 z/h$ (C8)

Manipulation of (C2), (C3), (C4) and (C6) gives

$$A = S/h = E_0/[2h\beta(1 + \nu)] \tag{C9}$$

which is useful in parameter studies because it reduces the two parameters β and E to one similitude parameter A. The static pressure is

$$\sigma_x = \nu z \rho g \cos \alpha \tag{C10}$$

Manipulation of (C1), (C2), (C3), (C5), (C7), (C8), (C9) and (C10) yields,

$$\nu = 1 - 2 \frac{(V_1 - V_0)}{(U_1 - U_0)} \tan \alpha \tag{C11}$$

which is useful in calculating ν from field measurements.