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AVALANCHE STUDIES (1971-1972)

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U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

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16. Abstract

An interim report of the second year of a three year study of avalanche hazards along Washington mountain highways is presented. Applicable snow, avalanche and weather data for 1971-72 are given. Also included are a theoretical treatment of the stress analysis of slab avalanches and a bibliography of snow clearing technology.

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The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Washington State Highway Commission, Department of Highways, or the Federal Highway Administration.

INTRODUCTION

This report covers the work performed by the University of Washington in connection with avalanche studies in the North Cascades. The research was performed the second year of a three year program in conjunction with the Washington State Highway Department (Research Project No. Y1301) and included the period from September 1971 to July 1972. The first year of the study provided a field reconnaissance of avalanche conditions on the North Cascades Highway (SR-20)[1]. In the second year of the project, diversified activities were carried out by the investigators. These are reported here.

Dr. E. R. LaChapelle was on leave at the Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, in the Winter Quarter. While in Japan a complete bibliography of snow clearing methods was compiled, and the local avalanche problems studied. The first part of this report is a discussion of the avalanche problems. The written portion is supported by a movie film. The bibliography on snow clearing methods is included as an Appendix at the end of this report.

In order to gain some quantitative impression of avalanche dimensions and mechanics, Dr. Brown and Dr. Evans prepared a study of the state of stress in fallen snow and subsequent mechanics of slab avalanching. Dr. LaChapelle added material which provided correlations of the theory with observed avalanching. A complete paper was published, and the result of this inquiry[2] is included in the second part of this report.

Important mechanical parameters of the snow are required for the engineering application of the theory. These strength, glide and creep properties are being collected at test sites in the North Cascades. The third part of this report is concerned with the data obtained and the apparatus. The information is not complete, and this aspect of the report is of an interim character. Refinement of the apparatus and the resulting data collection will be continued into the third year of the study. This work is being undertaken by Mr. D. McClung and supervised by three investigators.

The final part of the report consists of winter observations at Washington Pass which Mr. L. Miller organized. This was supervised by Dr. LaChapelle.

PART 1.

(a) Snow and Avalanche Technology in Japan

The following report summarizes collateral information concerning current snow research and avalanche control practices in Japan. These observations were collected during a tour of Japanese institutions and avalanche sites by E. R. LaChapelle during the period January-March 1972. Emphasis here is placed on those observations most directly pertinent to research on avalanches in the North Cascades being carried out under the present contract.

Snow Research Activities

The Japanese Disaster Prevention Institute maintains snow research stations at Nakaoka and Shin-jo in the Japanese Alps on the Island of Honshu. Both of these stations are engaged in a wide spectrum of applied research relating to avalanche control, snow damage, and problems of snow removal from buildings, streets and highways. By way of background, it can be noted that those parts of the Japanese Alps facing the Sea of Japan are subjected to very heavy winter snowfall at low altitudes, including sea level. Large quantities of snow can arrive in a single storm, usually heavy, wet snow deposited at temperatures close to the freezing point. Many wet snow avalanches are engendered by these snowfalls, which also present formidable difficulties for traffic movement and the general routine of winter life.

The following research projects at the Nagaoka and Shin-jo Stations are especially pertinent.

Roof Snow Removal:

Heavy snow accumulations often cause structural damage to roofs and buildings in the Japanese Alps. Extensive tests are now underway on various methods of removing the snow from roofs. Most of these involve snow melting. Injection of hot water into snow at the roof peaks is one method. Another is circulation of hot water in pipes immediately under the roof. Special attention is given to design of eaves so that a cold zone does not develop along the roof edge and generate an ice trap. Model roofs of various angles and composition have been constructed at Shin-jo to ascertain the optimum conditions for snow melt.

Snow Settlement:

The well known damaging effects of settlement in a deep snow cover on exposed structures is being systematically tested at Nagaoka by observing the effects of snow on horizontal bars of various shapes, sizes and materials. Tests in a cold laboratory are also underway to determine the zone of influence within the snow cover of buried structures.

Laser Snow Depth Gauge:

The Nagaoka Station has developed a successful laser snow depth gauge which automatically transmits an accurate measure of snow depth to a recorder on interrogation. The laser beam and sensor are shifted by mechanically operated mirrors to scan for and detect the snow surface. The present design is suitable for research purposed but probably is too large and complex for convenient installation at remote sites away from power mains. The basic principle of the gauge can seemingly be adapted to smaller and more portable versions.

Snow Glide Observations:

Especially pertinent to avalanche research is the ingenious methodology developed at Nagaoka to study glide or the movement of the snow cover over the ground. Glide has a significant effect on vegetation and is often related to avalanche formation in wet snow conditions. A research area at Nagaoka has been prepared on a convenient hillside with a tunnel giving access underneath the ground surface at mid-slope. In the roof of the tunnel a glass port has been installed flush with the ground surface. A direct view of the base of the snow cover is thus possible. Character of the snow crystals, including debris, and the glide motion itself can all be directly observed. A time-lapse motion picture camera has been used to record variations in glide velocity. The study has produced useful insights into the influence of weather patterns and snow thickness on glide motion. It has also identified a period of rapidly accelerated glide prior to the onset of wet snow avalanching on the ground surface.

Snow Melting in Streets:

A convenient combination of warm snowfalls and the availability of warm water from numerous hot springs in the coastal regions of the Japanese Alps has led to an unusual method of removing large snowfalls from city streets. A sprinkler system for distribution of the warm water has been installed down the center of major thoroughfares. As soon as snowfall begins, these sprinklers are turned on and the melted snow is carried away by gutters. Plates 7C and 7D illustrate an operational installation of this system. The Shin-jo Station presently is testing various combinations of sprinklers, spacing and water temperature on a short section of experimental highway to ascertain the optimum method for snow melting. It should be noted that this method is useful only in climates where air temperature commonly rises above freezing after snowfalls; otherwise, a sheet of ice could quickly build up on the streets.

Snow Capacity of Culverts:

Snow plowing activities plus natural and artificial melting place a heavy load of water and slush in the culverts in this climate. The Shin-jo Station has constructed an artificial section of culvert with variable dimensions and input of snow and water. Tests are being made to determine the optimum shape and size of culvert to carry off expected storm loads.

The Japanese National Railways maintains a snow and avalanche research station at Shiozawa. Current research projects of interest include:

Free Water Content Meter:

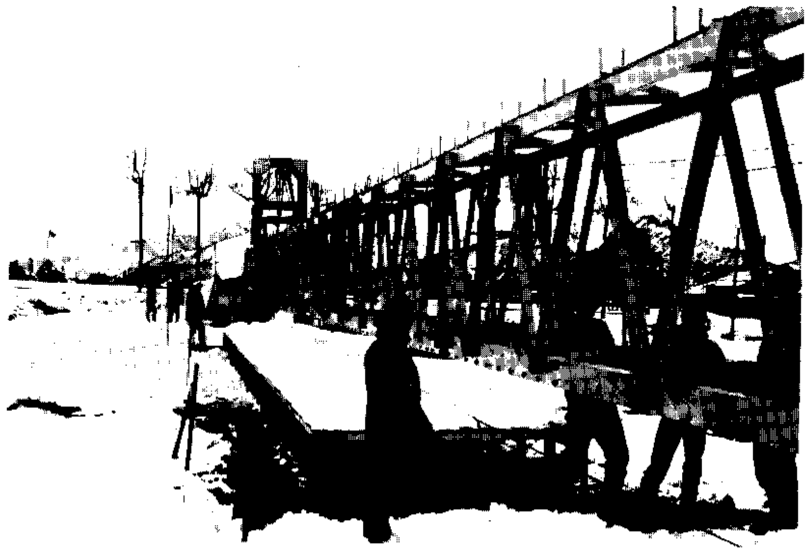
A modified and improved version of the Ambach metood for determining liquid water content of wet snow has been developed. This method depends on the dielectric effects of free water on a capacitor. The improved version samples a large snow volume and utilizes advanced electronics.

High Speed Plow Tests:

To date, the famous JNR Hikari high speed train system has been constructed only in the southern part of the country where winter snowfall is not a problem. Looking forward to eventual extension of such a system to the northern regions, the JNR has begun a series of tests on the design of snow plows intended to operate at speeds up to 150 miles per hour. A scale model test is underway at Shiozawa. A large steel frame (Plate 1a) guides the travel of a cable-propelled model plow through a layer of snow, seen in this Plate just behind the standing figure. Forces exerted on the model plow (Plate 1b) are sensed by strain gauges and sent by radio telemetry to a recorder. A wide variety of plow shapes is now being tested with this equipment to provide design data for a full scale test. (Our 16 mm film on Japanese snow work includes footage of this test in operation.)

Snow Roof Tests:

An alternate method of operating a high speed train in snow country is to cover the track with a continuous snowshed. Various shapes, styles and materials of roofs for this purpose are being tested at Shiozawa with emphasis on developing a design which will allow snow to slide off spontaneously and minimize the need for heavy supporting walls.



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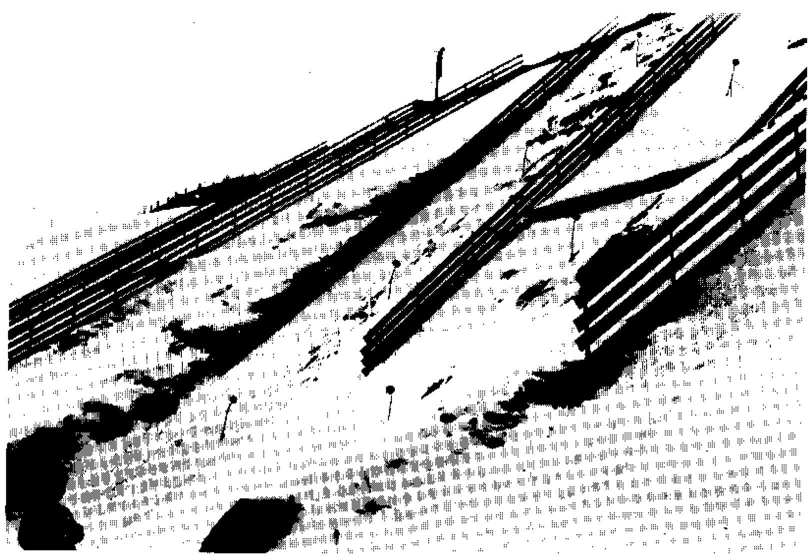

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Plate 1

The Japanese Ministry of Forests operates a snow research station at Kamabuchi. Emphasis here is on examining the creep and glide characteristics of the snow cover in relation to effects on vegetation. An ambitious test of the effects of exposure (compass orientation) of a slope on glide is underway in an artificial basin carved out of a hillside to form half a bowl with slope varying through 180°. The slopes in this basin are instrumented to measure both creep and glide of the snow. Nearby another section of the hillside has been modified to provide plane slopes of varying inclination and surface roughness (Plate 1c). The willingness to move a substantial amount of earth to establish uniform and controlled test slopes is a noteworthy aspect of this study.

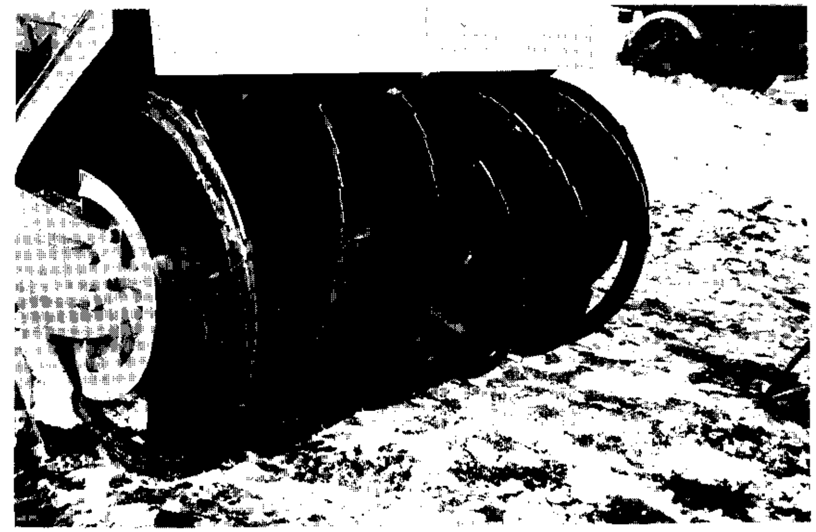
The Institute of Low Temperature Science, Hokkaido University, operates an avalanche research station at Toikanbetsu in Northern Hokkaido. This is a region where wet snow glide avalanches predominate in the spring. A current study program is addressed to the problem of determining the details of snow mechanics involved in creep deformation of the snow cover. An instrumental scheme has been devised to measure strain ellipses in the snow without introducing foreign elements in the snow except at the actual moment of measurement.

Snow Removal Methods

Although the visits to scientific institutions in Japan were not aimed at investigating snow removal methods, there were numerous opportunities to observe this during the winter and to collect some useful information.

The larger snow plows seen in Japan, both push plows and rotaries, were generally related to familiar types known in this country. Push plows with wings and throwing blades (e.g. Plates 3c and 3d) were common. There seems to be little opportunity on the narrow and crowded mountain roads of Japan for such plows to be operated at sufficiently high speeds for effective throwing

a



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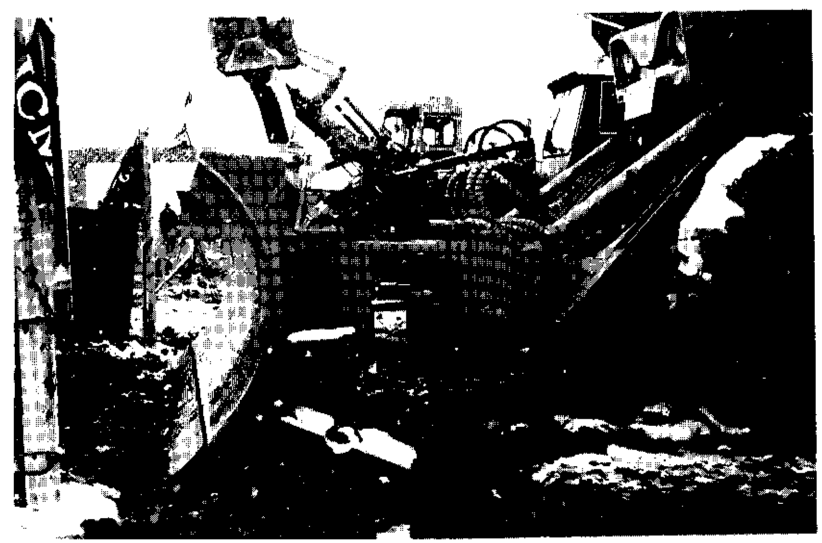

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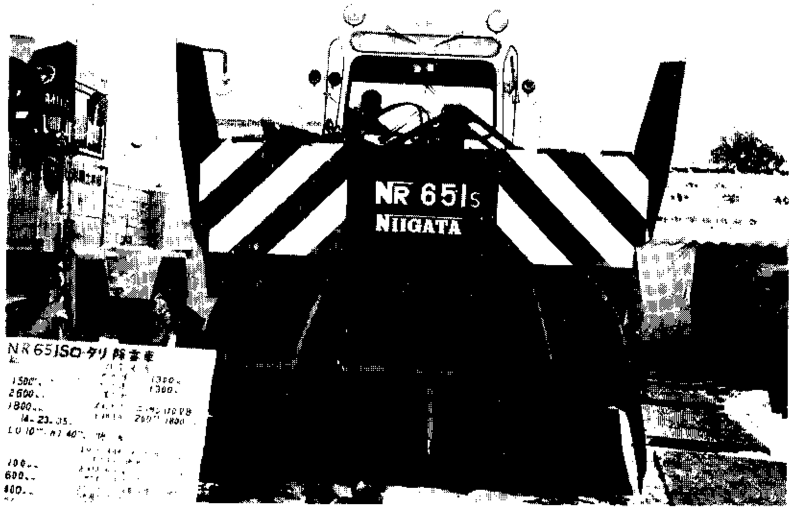
Plate 2



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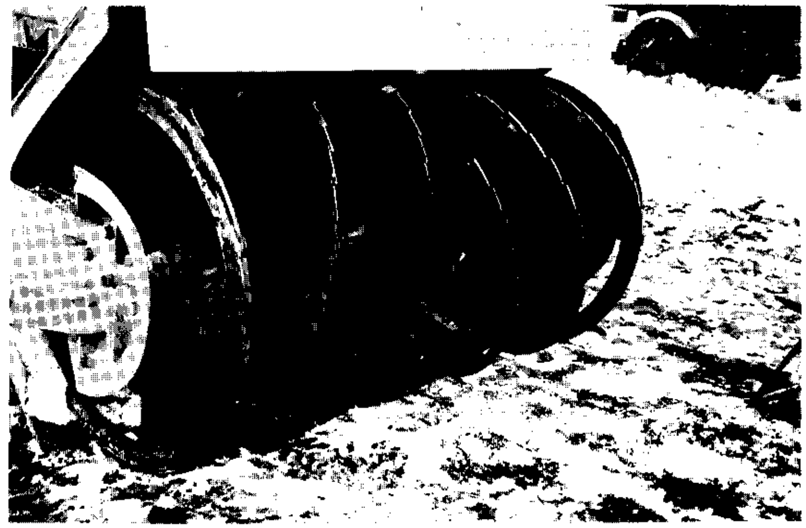

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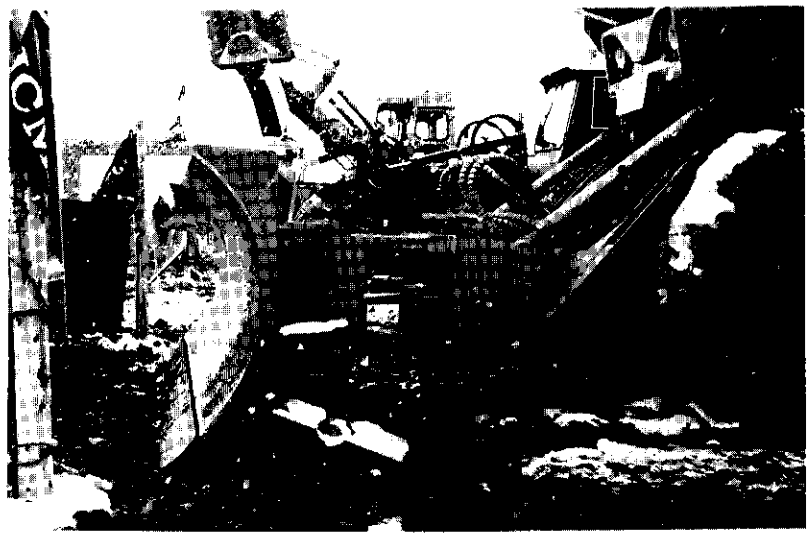

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Plate 2

a

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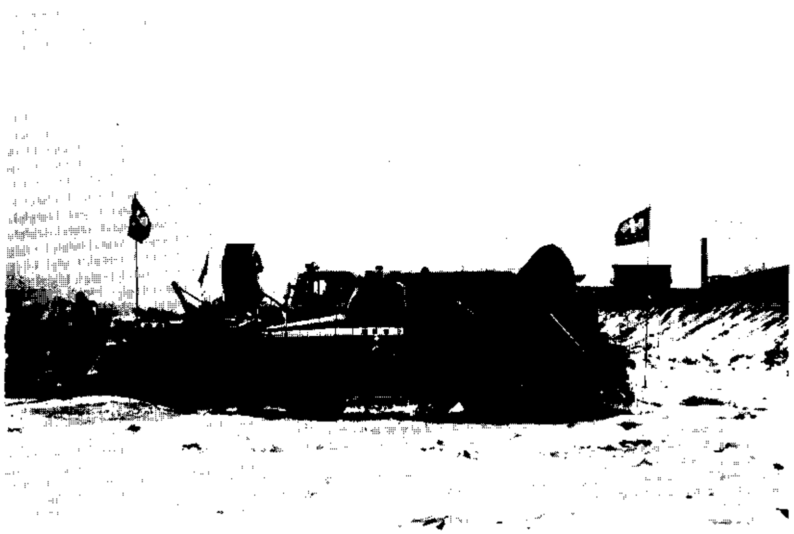

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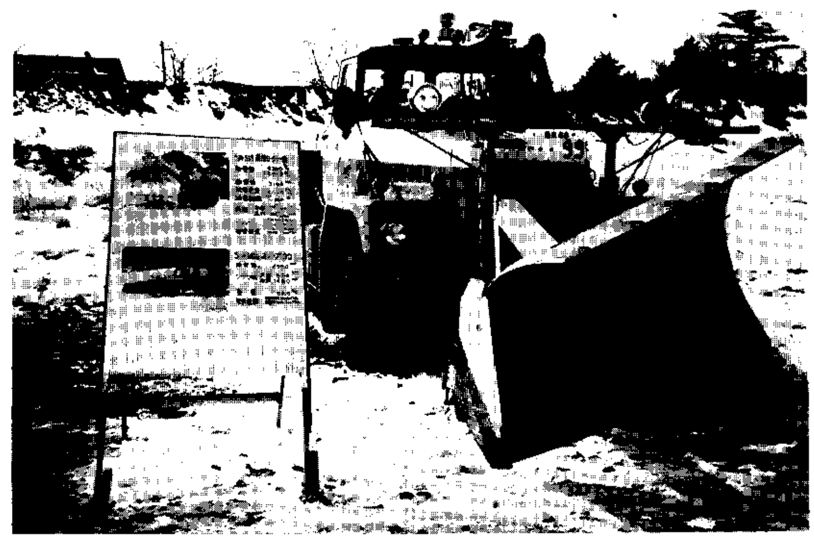

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Plate 3

action. Most such plows observed at work on the highways in fact were operated at much slower speeds. A less familiar type was two variations of large end-loaders. One variation was a straight push plow (Plates 2d and 3b, plus righthand unit in Plate 2c). More unusual was the other variation (not illustrated) in which a rotary package complete with power plant was hung on the front of an end loader.

Only one example of our familiar sno-go type of rotary was seen. Most large rotary plows in Japan are based on the Swiss Rolba design (marketed by Snowblast in U.S. A.). Plates 2a and 2b illustrate heavy-duty modifications of the Rolba system utilizing solid plates instead of open reels to gain additional strength and durability. These large machines appear to be comparable to the Snowblast machine in power and performance. A distinctly different type of rotary plow is the lefthand unit in Plate 2c. This asymmetric design intended for clearing highways in deep snow country utilizes a single rotating blade as combination disaggregator and blower, a design long used on railway snow plows.

The most distinctive Japanese snow plows are the smaller models intended for hand operation by a man walking alongside or at the rear. Several types of these were observed in operation, some of them substantially larger than any hand-guided plows we are familiar with and obviously powered by substantial engines. An example of this type of machine is shown in Plate 3a. Smaller hand operated plows of the garden tractor variety are also common. Another type of small machine is a hand guided push plow resembling a miniature caterpillar tractor which is used for clearing city streets and parking lots.

Extensive use is still made of hand labor to clear snow in Northern Honshu and in Hokkaido. For this purpose a small, hand propelled push plow shaped like a scoop is widely used. Such plows seem more common than snow shovels in many parts of Japan. Observations of these plows in use suggest that they are an efficient means of clearing snow from sidewalks, driveways and around buildings where powered machinery normally is not used. They could well be adopted in this country for similar purposes where snow shovels are commonly and often inefficiently used.

Avalanche Defenses

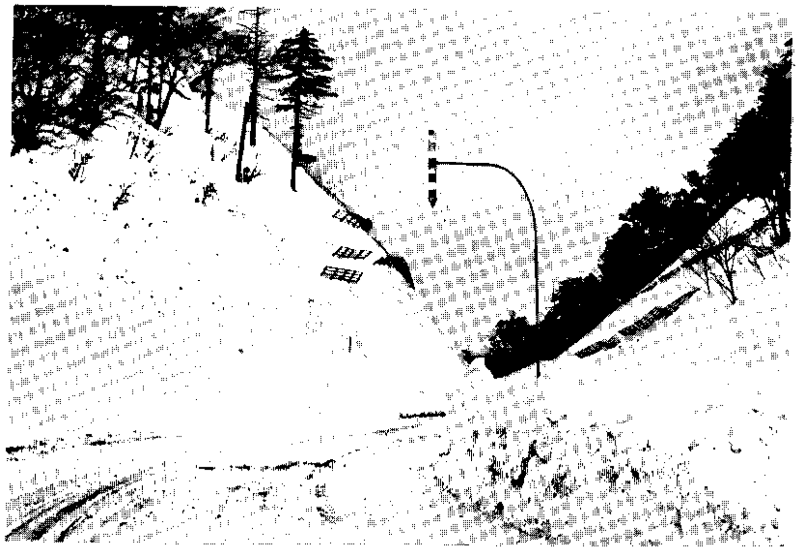
A combination of mountainous terrain, heavy snowfalls, and a dense railway and highway network leads to a considerable avalanche hazard to transportation routes in the northern part of Japan. To a very large extent the serious avalanching is associated with wet snow, either freshly deposited or warmed by rains. Many of the avalanche paths threatening rail and highways are relatively short and many, especially in the Japanese Alps, originate in dense timber or brush covered slopes. Large, open slopes involving dry slab avalanches do occur in the higher reaches of the Alps and in the higher mountains of Hokkaido, but these generally are not associated with direct hazards to communities or traffic. Where rail or highways do pass thourgh the bigger avalanche zones, the danger is usually averted by tunneling. Tunnels, in fact, abound everywhere in Japan, and their excavation is undertaken in places where in our own country they would be eschewed on account of cost. (A Japanese engineer, who looked through a copy of the Avalanche Atlas for the North Cascade Highway, remarked that in Japan they would never even consider building a highway in such a high avalanche hazard zone as Washington Pass-- they would tunnel under it.) Avalanche defense systems are widely used and snow sheds are common. Diversion walls and barriers are also frequently used. Most of the defense systems (supporting structures of one kind or another designed to inhibit avalanche release) are on relatively short slopes, in some cases little more than road cuts or embankments. Artificial release of avalanches as a control measure is little used, in large part due to lack of available military weapons but also to the prevalence of wet snow avalanching, which is less susceptible to reliable artillery or explosive control than dry snow. In some parts of the Japanese Alps a technique is used to dynamite and release the entire snow cover prior to onset of spring melt and a wet slide cycle, but this is limited to relatively small slopes due to the time and effort required to prepare and install the dynamite charges.

The technology of avalanche defense structures in Japan shows evidence of a ready willingness to experiment with fresh ideas and materials. In several places, new structures were explained as being strictly experimental and had in fact not yet stood up to the test of a major avalanche. Most of the defense systems are of recent construction, but there is one rather extensive system of defense for a railroad line in the Japanese Alps which was built over 50 years ago. This system consists of a series of snow sheds, diversion walls and barriers, all of heavy masonry construction. Early European techniques apparently were the basis for this design, but the Japanese construction was carried to considerably greater length and effectiveness than was usual for that period prior to the foundation of a formal science of avalanche defense.

Some specific aspects of modern Japanese avalanche defense systems are discussed below:

Supporting Structures:

Most modern systems of supporting structures follow closely the principles set forth in the Swiss Guidelines. Some of the bridges on smaller slopes are rather light and anchored by uphill tension tables, like those in the cutbanks in Plate 4a. In areas of heavier snowfall, the downhill compression braces following customary Swiss design are used (Plate 4b). Sometimes special soil and foundation problems require extensive concrete footings and braces (Plate 4c). These general patterns, predominantly bridges rather than rakes, are found in



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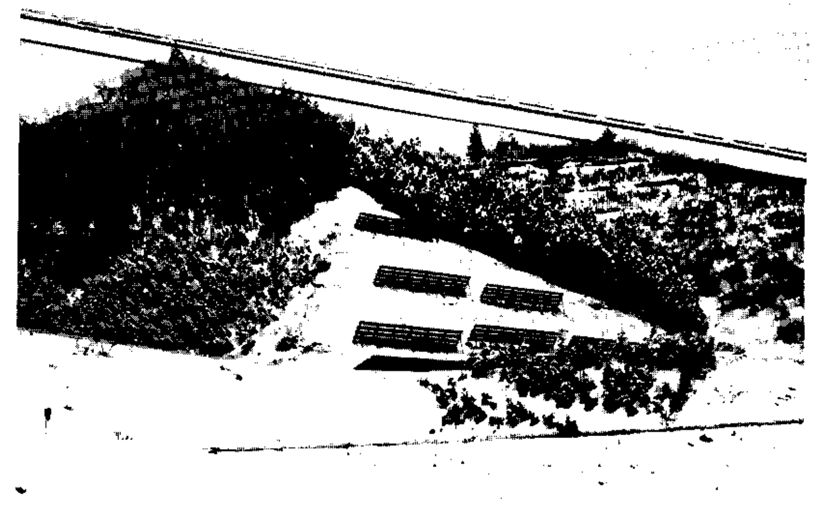

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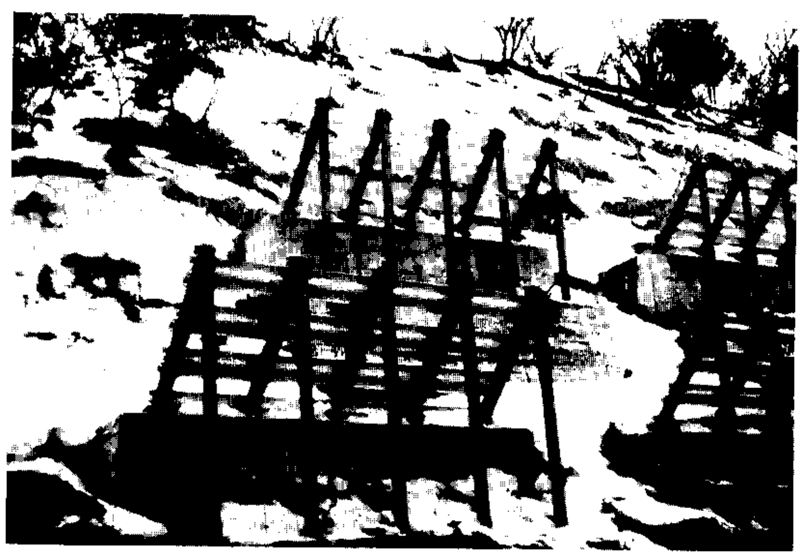

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d

Plate 4

most defense systems that were observed. To a lesser degree, snow jacks (Plate 4d) are also used along road banks. The spacing in this illustration indicates the jacks are aimed at anchoring wet snow to the ground; they would be largely ineffective against soft slab release. In some localities of the Japanese Alps, individual supporting structures are located in gulleys among thick timber stands where avalanche release would not ordinarily be expected.

An incidental item of interest is the market pole in the foreground of Plate 4a (also in the middle distance). The arrow points to the road margin as a guide for snow plows and is equipped with reflectors for easy visibility at night. Markers of this type are used extensively on the highways of Hokkaido. They are removed in the spring.

Snow Sheds:

Snow sheds are extensively used, and the structural details vary widely according to snow conditions and size of the avalanche path. A useful innovation is the tunnel-liner type of shed (Plate 5a) used to eliminate nuisance sluffs in deep road cuts. Steel, concrete, and combinations of these are used variously according to expected impact forces and economic considerations at the site (Plates 5b, 5c, 5d).

Some unique experimental designs of snow sheds are presently being tested. The shed shown in Plates 6a and 6b was just constructed and had not yet sustained a major avalanche impact. Concrete is used for the uphill abutment where most of the impact force would be expected, while the rest of the shed is made up of steel arches to conserve material and costs. This shed probably will be effective against smaller avalanches, but may well be damaged by very large, high-velocity ones (only the former kind normally fall at this site). A still more unusual design is the one located on the east side of Nakayama Pass in Hokkaido (Plate 6c). The cantilevered snow shed was built to avoid a serious

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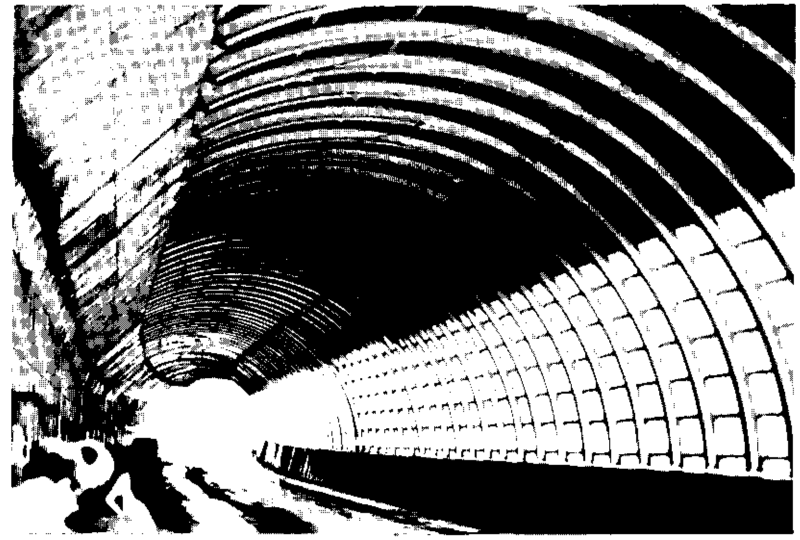
Plate 5

a



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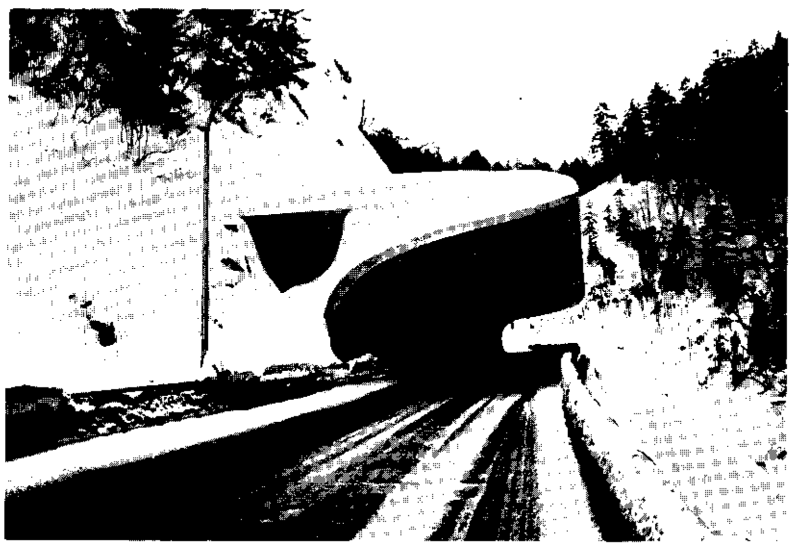

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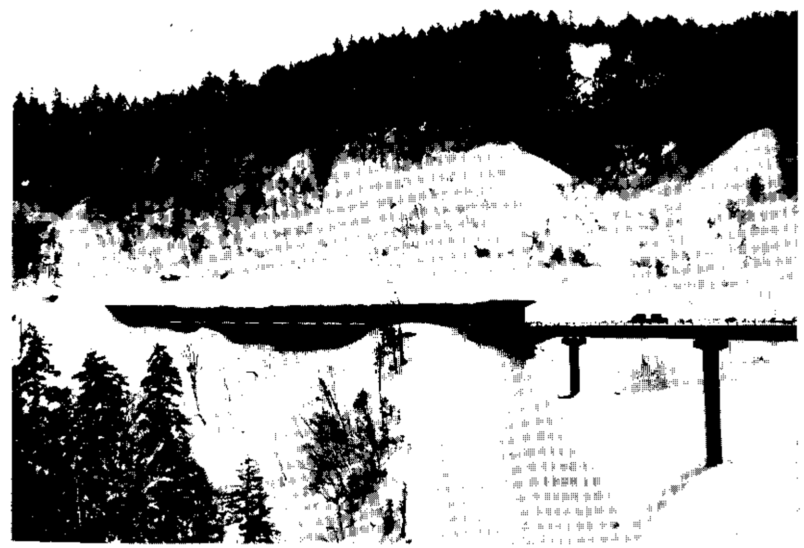

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Plate 6

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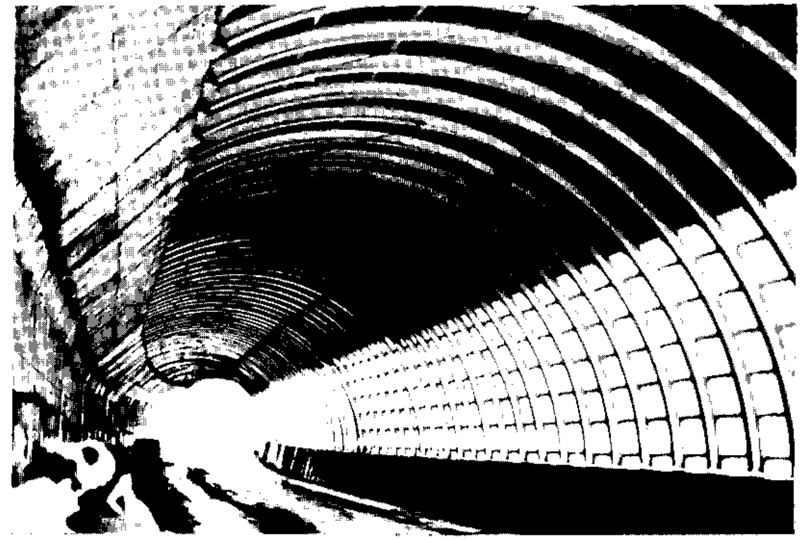

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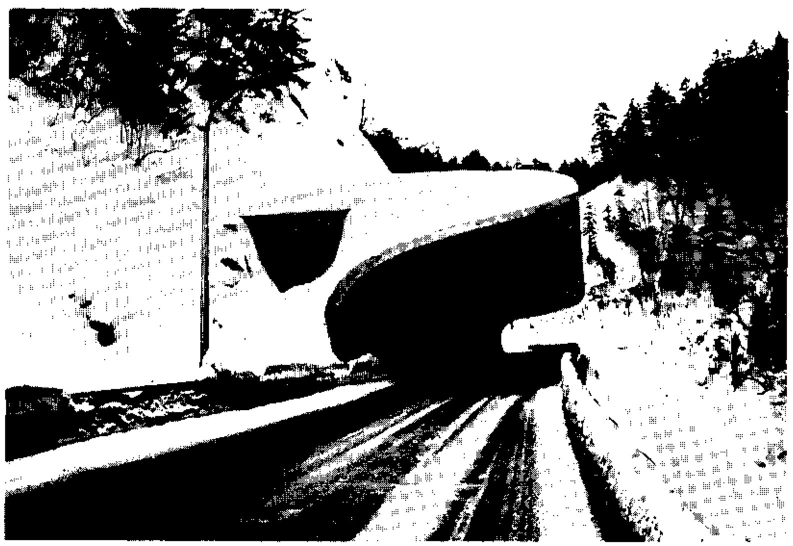

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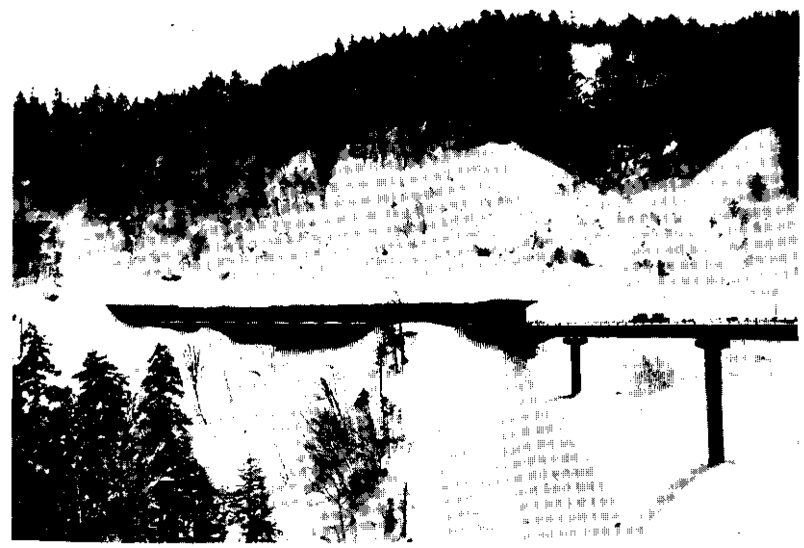

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Plate 6

foundation problem on the downhill side of the road. This one also has yet to pass the test of a severe avalanche. Plate 6d illustrates an elegant solution to a combined problem of poor road foundation and a short avalanche slope at one end of a highway bridge.

Avalanche Dams:

The frequent occurrence of wet snow avalanches invites the use of avalanche barriers or dams, which are much more effective against wet snow sliding along the ground than against high velocity dry snow accompanied by a dust cloud. Such structures in Japan are usually constructed of masonry or reinforced concrete at the foot of narrow gulleys where wet snow avalanches occur at least annually. Two examples are shown in Plates 7a and 7b. The one in Plate 7b is of recent construction. The holes allow discharge of flood water during spring run-off. This is an exceptionally massive dam at the foot of a rather long gulley -- it has not yet sustained a full-load test from a major avalanche.

By way of collateral information, the rip-rap in the foreground of Plate 7a is a common pattern in Japan. The elements are pre-cast of concrete. This rip-rap faces the approach to a snow shed.

Snow Fences:

Though not usually associated with avalanche control directly, snow fences are widely used for the customary purpose of snow drift management along highways and railways. The most common type is made of netting suspended from poles, an economical arrangement which can readily be erected in the fall and taken down each spring. A variation used in parts of Honshu utilizes rice straw mats instead of nets. A more permanent type used in the heavier snow zones consists of perforated steel panels which can be raised by sliding them up steel supporting poles to adjust to accumulating snow.

a

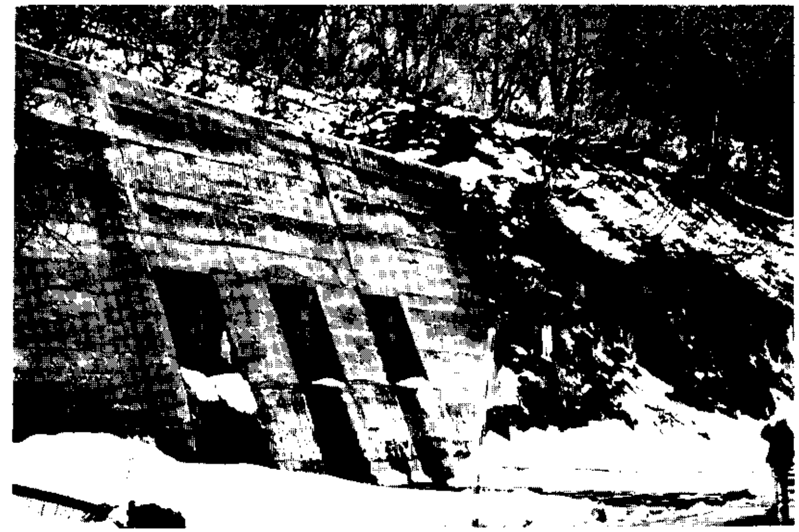

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Plate 7

PART 2

The Mechanics of Slab Avalanching and the State of Stress in Fallen Snow

A recent paper on snow slab failure[3] provides an avalanche model falling into four parts:

a) Shear failure at the snow-ground or snow-snow interface

b) Tensile failure at the slab top

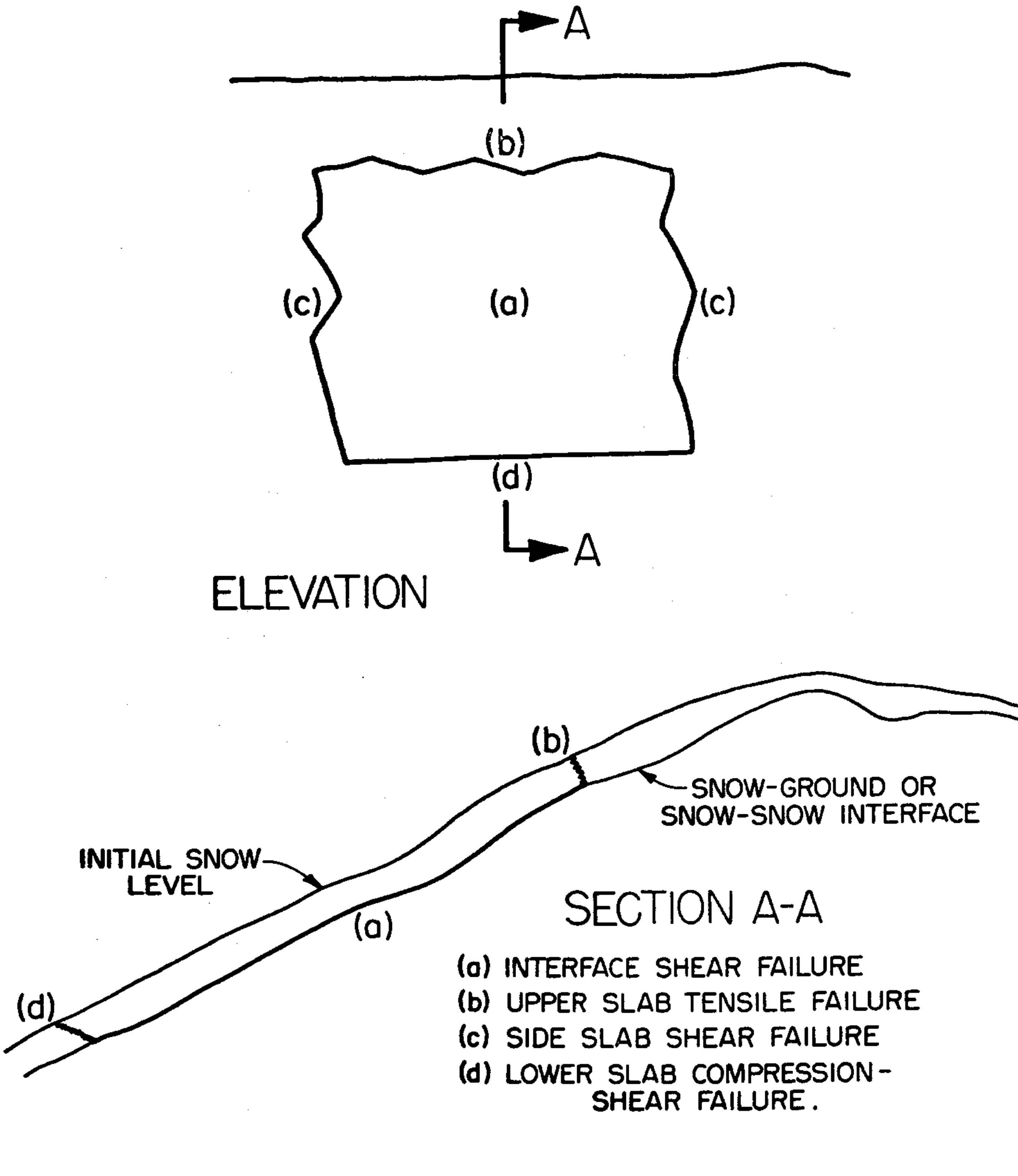
c) Shear failure at the slab sides

d) Compression failure at the slab bottom

These regions are indicated in Fig. 1 The physical reasons for the snow-ground or snow-snow interface shear failure have been dealt with[3]; the subsequent behavior is a consequence of this initial shear degeneration. Unfortunately, the above models could not be developed into a complete theory because no adequate way of predicting the stress distribution in the snow slab prior to avalanching appeared to be available. Therefore, only order of magnitude arguments were used to examine the consequences of the model. In spite of this restriction, the results proved encouraging.

In this paper a method of incremental analysis developed for accreting bodies is used to determine the initial state of stress in fallen snow;[4] it thus corresponds most closely in nature to conditions for soft slab avalanches originating in new fallen snow. The basic anlaysis is for uniform cover of a plane surface of constant slope, but the effect of curvature is examined by considering uniform accretion on a spherical surface. Non-uniform coverage is also investigated.

The shear stresses over a part of the interface are then released, and the subsequent forms of failure at the top, sides and bottom described. The bottom failure can be due to buckling or fracture[5]. Both modes are examined.



Slab Avalanche Failure Modes

FIG. 1

The consequences of the theory are slab dimensions (length and breadth) in terms of the thickness, slope, snow density and mechanical properties.

These dimensions are consistent with observed slab behavior and suggest that the Perla-LaChapelle approach is valid.

One concept of metamorphosis involves a shear strength degeneration along a layer. This layer may be located at the ground-snow interface,at an interface between new and old snow or at some other surface in the snow thickness. The cause of the metamorphosis may be crystal metamorphism, e.g. the development of depth hoar, or some completely different phenomenon such as lubrication of the interface by percolating meltwater. The origin of metamorphosis is not, in fact, germane to the arguments of this paper and the term will be used to describe any shear degeneration.

IDEALIZATION

The varied physical conditions of snow and avalanche terrain have to be idealized in order that an analysis can be generated. Here we consider initially an infinite, uniform, rigid surface of angle θ on which snow is continuously deposited to a depth t. In nature this surface may be either the ground or an old snow surface. It is referred to here as the ground for convenience. The coordinate x_1 is on the snow-ground interface, and x_2 is the normal so that the snow surface is $x_2 = t$. These matters are illustrated in Fig. 2. The snow density as deposited is $\rho(x_2)$, the modulus of elasticity E, Poisson's ratio ν(λ and μ are the equivalent Lamê constants). The stresses in the deposited snow are $\sigma_{ij}(x_1,x_2)$. Metamorphosis over a region $-D \leq x_1 \leq D$ changes this stress state to $\Sigma_{ij}(x_1,x_2)$ where

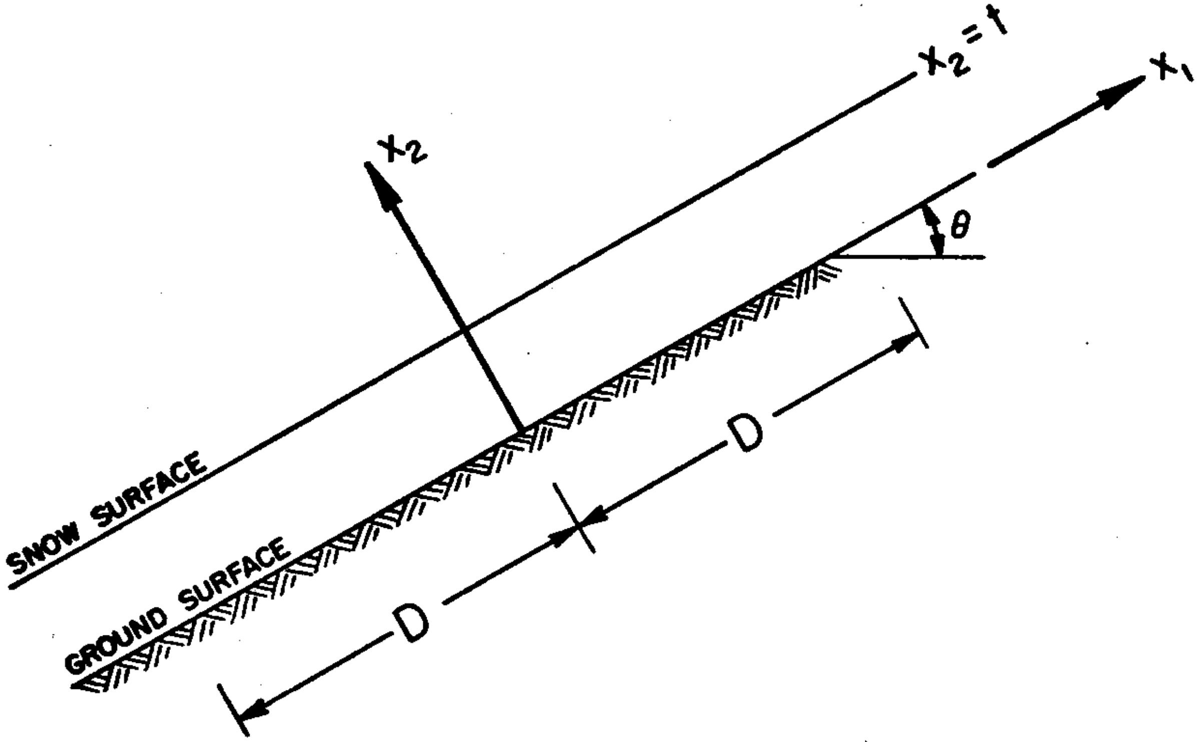
$$\Sigma_{ij}(x_1,x_2) = \sigma_{ij}(x_1,x_2) + \tau_{ij}(x_1,x_2) \tag{1}$$

when $\sigma_{12}(x_2=0)$ is smaller than the new shear strength.

τ_{ij} is the state of stress associated with the reduction of shear capacity at the metamorphosed region to a value below that of the initial shear stress.

When metamorphosis occurs above the interface, a distance t' below the surface (t' <t), then t' should replace t in all subsequent analysis.

The strengths of the snow in tension, compression and shear are Σ_1, Σ_2 and Σ_3 respectively. Complete failure of the snow slab is manifested by an avalanche of breadth 2B. The length is assumed to be bounded by $x_1 = \pm D$. The snow is assumed to behave linearly elastically and the ground to be rigid. σ_{ij} is first described, and then the effect of the change on the interface is evaluated in order that Σ_{ij} can be compared to snow strengths Σ_1, Σ_2, and Σ_3.



Idealized Plane Geometry

FIG. 2

THE INITIAL STATE OF STRESS

It is first assumed that snow is deposited uniformly to a final depth, t, on a rigid infinitely extending uniform slope (Fig. 2). At some time in this accretion process, snow is at a depth α as shown in Fig. 3. An increment of thickness $\Delta\alpha$, density $\rho(\alpha)$ is added. Initially interest is in the incremental stresses, $\Delta\sigma_{ij}$, at $x_2<\alpha$ due to this addition. The analysis follows that of Brown and Goodman,[4] 1963.

The incremental loading at $x_2=\alpha$ is separated into normal and shear parts as shown in Fig. 3. The incremental boundary conditions are, for normal loading,

$$\begin{aligned} x_2 = \alpha; \quad & \Delta\sigma_{22} = -\rho\Delta\alpha \cos\theta \\ & \Delta\sigma_{12} = 0 \\ x_2 = 0; \quad & \Delta u_1 = \Delta u_2 = 0 \end{aligned} \tag{2}$$

and, for shear loading,

$$\begin{aligned} x_2 = \alpha; \quad & \Delta\sigma_{22} = 0 \\ & \Delta\sigma_{12} = -\rho\Delta\alpha \sin\theta \\ x_2 = 0; \quad & \Delta u_1 = \Delta u_2 = 0. \end{aligned} \tag{3}$$

Considering the normal loading case, the infinite extent of the region requires that

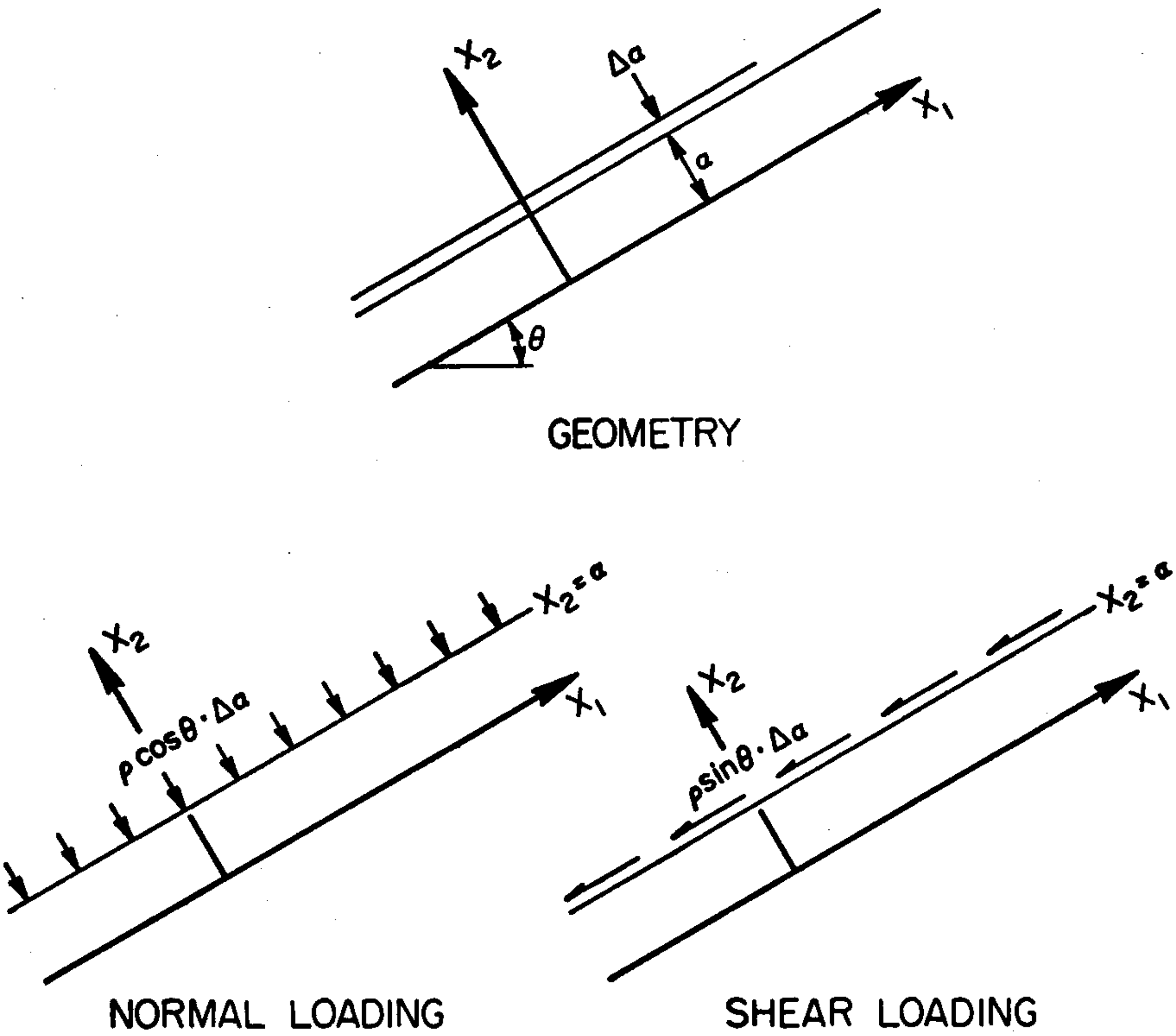
$$\Delta\varepsilon_{11} = \Delta\varepsilon_{33} = 0. \tag{4}$$

Using the constitutive law

$$\Delta\sigma_{ij} = \lambda\Delta\varepsilon_{kk}\,\delta_{ij} + 2\mu\Delta\varepsilon_{ij} \tag{5}$$

the state of stress is bound to be

$$\begin{aligned} \frac{1}{k}\Delta\sigma_{11} = \frac{1}{k}\Delta\sigma_{33} = \Delta\sigma_{22} = -\rho\Delta\alpha\cos\theta \\ \Delta\sigma_{ij} = 0, \quad i \neq j \end{aligned} \tag{6}$$



Geometry and Incremental Loading Conditions

Fig.3

where

$$k = \frac{\lambda}{\lambda + 2\mu} = \frac{\nu}{1-\nu} \,. \tag{7}$$

The solution for the increment of shear loading is

$$\Delta\sigma_{12} = -\rho\Delta\,\alpha \sin\,\theta \tag{8}$$

$$\Delta\sigma_{ij} = 0, \qquad i \neq 1,\ j \neq 2$$

Since the snow is added from $\alpha = 0$ to $\alpha = t$, the final stress state is obtained by summing these incremental stresses. Analytically this is done by shrinking $\Delta\,\alpha$ to the limit and integrating so that

$$\sigma_{ij}(x_i) = \int_{x_2}^{t} d\sigma_{ij}(\alpha). \tag{9}$$

For uniform snow density (9) with (6) and (8) gives

$$\begin{aligned} \sigma_{11} &= \sigma_{33} = \frac{-\nu}{1-\nu}\,\rho\,\cos\,\theta\,(t-x_2) \\ \sigma_{22} &= -\rho\,\cos\,\theta\,(t-x_2) \\ \sigma_{12} &= -\rho\,\sin\,\theta\,(t-x_2). \end{aligned} \tag{10}$$

It should be noted that the results of (10) may be obtained directly by treating the weight as a body force applied to the entire thickness. Such is not generally the case for such accretion problems however, as may be shown for the subsequent analysis where some consequences of relaxing the assumptions on geometry and density are considered.

a) Variation of Snow Density.

The density of the deposited snow may vary with the depth. Such a variation can be expressed by

$$\rho(\alpha) = \sum_{i=0}^{\infty} \rho_i\,\alpha^i \tag{11}$$

This leads to

$$\sigma_{11} = \sigma_{33} = \frac{-\nu}{1-\nu} \cos\theta \sum_{i=0}^{\infty} \frac{\rho_i}{i+1} (t^{i+1} - x_2^{\,i+1})$$

$$\sigma_{22} = -\cos\theta \sum_{i=0}^{\infty} \frac{\rho_i}{i+1} (t^{i+1} - x_2^{\,i+1}) \tag{12}$$

$$\sigma_{12} = -\sin\theta \sum_{i=0}^{\infty} \frac{\rho_i}{i+1} (t^{i+1} - x_2^{\,i+1})$$

where (10) is the solution for $i=0$. The density variation due to consolidation by itself does not affect the initial state solution. However, such an effect would mean that λ and μ depend on α in the incremental constitutive law, which would then modify the form of (12).

b) Curvature of the Ground Surface

This is examined by extending the previous analysis to the case where the ground surface is spherical. In order to examine the effect of curvature on the initial stress state radial loading only is taken into account.

The perfectly flat geometry previously discussed can be modified to the convex or concave spherical shapes of Fig. 4. The rigid surface is at r_o and the snow deposit of thickness $\Delta\alpha$ is at α. r_o, α and r, the generic position, are surfaces of concentric spheres. The requirement of (4) becomes

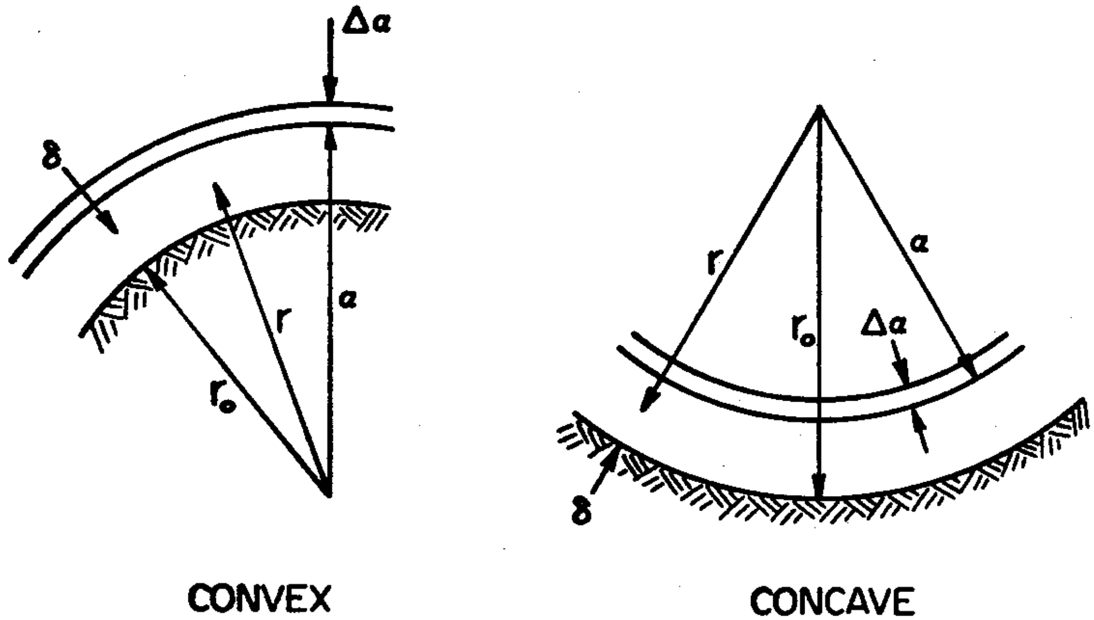
$$\Delta u_\theta = \Delta u_\phi = 0 \tag{13}$$

in spherical coordinates, and only Δu_r exists. These conditions provide point symmetry and increment of radial displacement, Δu_r, is governed by the Lamé equation of elasticity

$$\left(\Delta u_{r,r} + \frac{2\Delta u_r}{r}\right)_{,r} = 0 \,. \tag{14}$$

This has a solution

$$\Delta u_r = Br + \frac{C}{r^2} \,. \tag{15}$$



Spherical Ground Geometry & Incremental Conditions

FIG 4

The incremental boundary conditions are

$$r = r_o ; \quad \Delta u_r = 0 \tag{16}$$

$$r = \alpha \quad ; \quad \Delta \sigma_{rr} = - \rho \Delta \alpha$$

where

$$\Delta \sigma_{rr} = (3 \lambda + 2 \mu) B - \frac{4 C \mu}{r^3} . \tag{17}$$

The incremental solution is then

$$\Delta u_r = \frac{\rho \alpha^3 r}{(3\lambda+2\mu)\alpha^3 + 4\mu r_o^3} \left\{ \left(\frac{r_o}{r}\right)^3 - 1 \right\} \Delta \alpha$$

$$\Delta \sigma_{rr} = \frac{-\rho \alpha^3}{(3\lambda+2\mu)\alpha^3 + 4\mu r_o^3} \left\{ 3\lambda + 2\mu + 4\mu \left(\frac{r_o}{r}\right)^3 \right\} \Delta \alpha \tag{18}$$

$$\Delta \sigma_{\theta\theta} = \Delta \sigma_{\phi\phi} = \frac{-\rho \alpha^3}{(3\lambda+2\mu)\alpha^3 + 4\mu r_o^3} \left\{ 3\lambda + 2\mu - 2\mu \left(\frac{r_o}{r}\right)^3 \right\} \Delta \alpha .$$

Final stresses are found by integration, i.e.

$$\sigma_{ij} = \int_r^{r_o \pm t} d\sigma_{ij}(\alpha) \tag{19}$$

where in the above, and also subsequently, the upper sign refers to the convex shape and the lower sign to the concave. Stresses are

$$\sigma_{rr} = -P \left\{ 3\lambda + 2\mu + 4\mu \left(\frac{1}{q}\right)^3 \right\} \tag{20}$$

$$\sigma_{\theta\theta} = \sigma_{\phi\phi} = -P \left\{ 3\lambda + 2\mu - 2\mu \left(\frac{1}{q}\right)^3 \right\}$$

where

$$P = \frac{\rho r_o}{3(3\lambda+2\mu)} \left\{ 3(1 \pm p - q) - G \left[\frac{1}{2} \text{Ln} \frac{(G+1\pm p)^2 (G^2 - Gq + q^2)}{(G^2 - G\langle 1 \pm p\rangle + \langle 1 \pm p\rangle^2)(G+q)^2} \right. \right.$$

$$\left. \left. + \sqrt{3} \ \text{Tan}^{-1} \frac{2(1 \pm p) - G}{\sqrt{3}\ G} - \sqrt{3} \ \text{Tan}^{-1} \frac{2q - G}{\sqrt{3}\ G} \right] \right\} \tag{21}$$

and

$$G^3 = \frac{4\mu}{3\lambda+2\mu} = \frac{2(1-2\nu)}{1+\nu}, \; p = {}^{t}/r_o, \; q = {}^{r}/r_o.$$

Of particular interest is the ratio $\frac{\sigma_{\theta\theta}}{\sigma_{rr}}$ for small curvature. This may be found by substituting

$$r = r_o \pm \delta \tag{22}$$

into (20) and expanding. Retaining only terms linear in $\frac{\delta}{r_o}$ there results

$$K = \frac{\sigma_{\theta\theta}}{\sigma_{rr}} = \frac{\nu}{1-\nu} \pm \frac{(1+\nu)(1-2\nu)}{(1-\nu)^2} \cdot \frac{\delta}{r_o}. \tag{23}$$

The ratio given by (10) is thus corrected for curvature. As opposed to the flat case, the value of K varies with position in the snow. At $\delta = 0$, $K = k$; this value increases with distance from the interface for convex shapes and decreases for concave shapes. However, the sensitivity in ranges of $\frac{\delta}{r_o}$ of interest is negligible compared to the quality of idealization already posed.

c) Non-Uniform Snow Deposition

This is investigated by considering snow deposition which is uniform in time but which increases linearly with x_1 so that the final depth, t, is given by

$$t = t \;\; + A\frac{x_1}{D}.$$

The incremental loading is again separated into normal and tangential parts, and it is assumed that A is small enough so that the upper surface may be considered to remain essentially parallel to the x_1 axis.

The problem formulation is identical to that of (2) and (3) with $\rho(1+A\frac{x_1}{D})\Delta\,\alpha$ replacing $\rho\Delta\,\alpha$ as the incremental load. Solution of the elasticity problems leads to

$$\begin{aligned}
\Delta\sigma_{11} &= \frac{-\nu}{1-\nu}\ \rho(1+A\ \frac{x_1}{D})\cos\theta\Delta\alpha \\
\Delta\sigma_{22} &= -\rho(1+A\ \frac{x_1}{D})\cos\ \theta\Delta\alpha \\
\Delta\sigma_{12} &= 0
\end{aligned} \tag{24}$$

for normal loading and

$$\begin{aligned}
\Delta\sigma_{11} &= \{\frac{-2x_2}{1-\nu}+\nu(1+\nu)(x_2-\alpha)\}\ \frac{A}{D}\rho\sin\theta\Delta\alpha \\
\Delta\sigma_{22} &= (x_2-\alpha)\ \frac{A}{D}\rho\sin\theta\Delta\alpha \\
\Delta\sigma_{12} &= -(1+\frac{A}{D}x_1)\ \frac{A}{D}\rho\sin\theta\Delta\alpha
\end{aligned} \tag{25}$$

for shear loading.

The final state is determined by integration, and is

$$\begin{aligned}
\sigma_{11} &= \frac{-\nu}{1-\nu}\ \rho\cos\theta(1+\frac{A}{D}x_1)(t-x_2)\ - \\
&\quad \frac{A}{D}\rho\sin\ \theta\{\frac{2}{1-\nu}(t-x_2)x_2+\frac{\nu(1+\nu)}{2}(t-x_2)^2\} \\
\sigma_{22} &= -\rho\ \cos\ \theta(1+\frac{A}{D}x_1)(t-x_2)-\frac{A\rho\ \sin\theta}{2D}\ (t-x_2)^2 \\
\sigma_{12} &= \rho\ \sin\ \theta(1+\frac{A}{D}x_1)(t-x_2).
\end{aligned} \tag{26}$$

It may be seen from (26) that σ_{11} and σ_{22} contain correction terms in addition to replacing ρ in (10) by $\rho(1+A\frac{x_1}{D})$. These corrections increase the compressive initial stress. The correction is small for typical avalanche dimensions since $A\ \frac{x_1}{D}$ will be of order unity and $A\frac{x_2}{D}$ will be small compared with unity.

The ratio σ_{11}/σ_{22} is given by

$$K = \sigma_{11}/\sigma_{22} = \frac{\frac{\nu}{1-\nu}\left\{1+\frac{(1-\nu)A\tan\theta}{\nu(1+A\frac{x_1}{D})}\left(\frac{2x_2}{(1-\nu)D}+\frac{\nu(1+\nu)}{2D}(t-x_2)\right)\right\}}{1+\frac{A\tan\theta(t-x_2)}{2D(1+A\frac{x_1}{D})}} \tag{27}$$

$$\simeq \frac{\nu}{1-\nu}\left\{1+\frac{A\tan\theta}{1+A\frac{x_1}{D}}\left(\frac{2}{\nu}\frac{x_2}{D}+\frac{\nu^2}{2}\frac{(t-x_2)}{D}\right)\right\} \tag{28}$$

It follows from (28) that K varies along the length and through the thickness of the avalanche. For example, $K \simeq k$ at the interface ($x_2=0$) and for $\nu=\frac{1}{4}$, $\theta=30°$, and $D/t=8$ has a maximum value of $1.57\ k$ at $x_1=-D$, $x_2=t$.

SLAB FAILURE

Knowledge of the initial state of stress allows failure conditions to be determined by calculating the additional stress induced by the reduction of the shear strength over some area of the interface. Exact three dimensional solutions based on linear isotropic elasticity are not available; even three dimensional numerical solutions are presently intractible. Accepted values for Σ_1, Σ_2, Σ_3 suggest the following order of failure: top tensile fracture, side shear fracture and bottom compressive failure. Analyses are carried out assuming a reduction to zero of the shear strength over a metamorphosed basal rectangular region ($-D \leq x_1 \leq D$, $-B \leq x_3 \leq B$) and considering each of these failure modes chronologically.

a) Upper Tensile Slab Fracture

The interface metamorphosis in the region $-D \leq x \leq D$ of Fig. 2 alters the snow stresses to Σ_{ij} as in equation (1). For zero shear capacity at the interface τ_{ij} is obtained by considering the stresses caused by shears at $x_2=0$, $-D \leq x_1 \leq D$ given by the negative of σ_{12} $(x_2=0)$ in equation (10).(See Fig. 5). The boundary conditions are

$$\begin{aligned}
&x_2 = t; \quad \tau_{22} = \tau_{12} = 0 \\
&x_2 = 0; \quad u_2 = 0 \\
&x_2 = 0, \ -D \leq x_1 \leq D; \ \tau_{12} = \rho \sin \theta t \\
&x_2 = 0, \ x_1 > D, \ x_1 < -D; \quad u_1 = 0 \ .
\end{aligned} \tag{29}$$

Because of the stress singularities at $x_1 = \pm D$, we concentrate our attention on the average tensile failure features of the top slab (Fig. 1). From the evidence of Perla and LaChapelle[3] and Sommerfeld[6], a brittle failure representation of the form

$$\int_0^t \Sigma_{11} \ (x_1 = D, \ x_2) \ dx_2 = \Sigma_1 t \tag{30}$$

may be employed. The components of Σ_{11} (Equation 1) are $\sigma_{11}(x=D, \ x_2)$ and $\tau_{11}(x=D, \ x_2)$.

The second component cannot be determined analytically at $x_1 = D$, but from statics and arguments of symmetry about $x_1 = 0$.

$$\int_0^t \tau_{11}(x_1 = D, \ x_2) \ dx_2 = \int_0^D \tau_{12} \ (x_1, \ x_2 = 0) \ dx_1 . \tag{31}$$

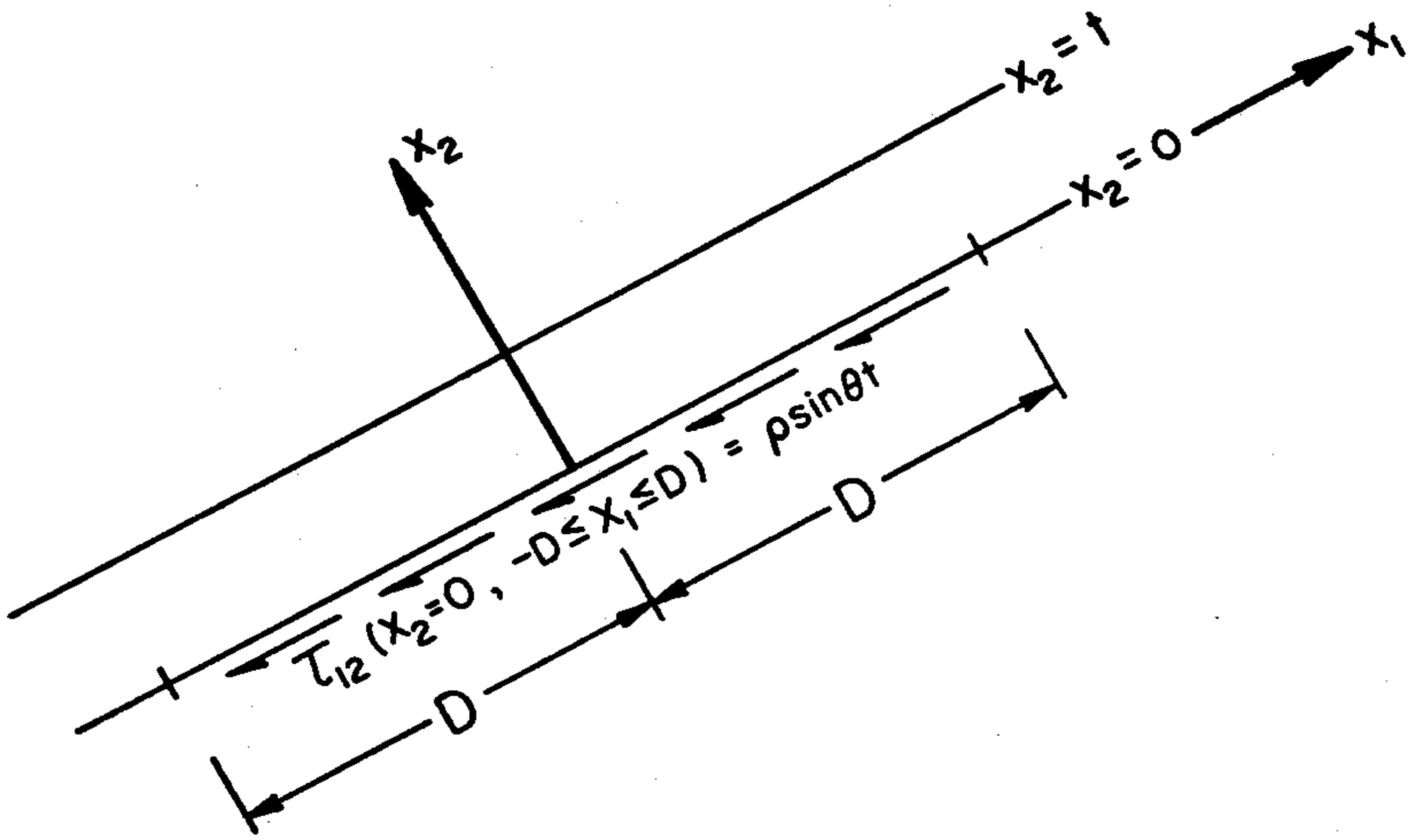
Hence in (30)

$$\frac{-\nu}{1-\nu} \rho \cos \theta \ \frac{t^2}{2} + \rho \ \sin \theta t D = \Sigma_1 t \tag{32}$$

and the dimensional ratio

$$\frac{D}{t} = \frac{\Sigma_1}{\rho} \ \frac{1}{t \ \sin\theta} + \frac{\nu}{1-\nu} \ \frac{1}{2} \cot \theta . \tag{33}$$

This important ratio depends on the snow properties Σ_1, ρ and ν, the ground slope, θ, and the snow thickness, t. The tensile strength of snow, Σ_1, is



Conditions for τ_{ij}

FIG.5

dependent in part on snow density, ρ. Values of the ratio $\Sigma_{1/\rho}$ vary from 3.4 meters for fine grained old snow to 6 meters for coarse grained old snow[5].

θ is usually in the range of 30° to 45°.

Poisson's ratio, ν, seems to be ill-defined but values from 0.1 to 0.4 are reported. Regardless of the values chosen, the second term of the right hand of (33) is dominated by the first. Fig. 6 shows a plot for computing D/t for various values of θ, ν and $\Sigma_{1/\rho}$.

σ_{11} is zero at the surface, $x_2=t$, for all shapes of surface. As stated above, the solution for τ_{11} is intractable at $x_1= D$ because of a singularity at $x_2= 0$. However,

$$\tau_{11} = \rho \sin \theta D \tag{34}$$

is an excellent representation (see Discussion and Conclusions). This means that the tensile stress will be greatest at the upper surface, and incipient tensile failure in the upper slab will be indicated by surface cracking on $x_2 = t$ along the region about $x_1 = D$.

b) Side Shear Fracture

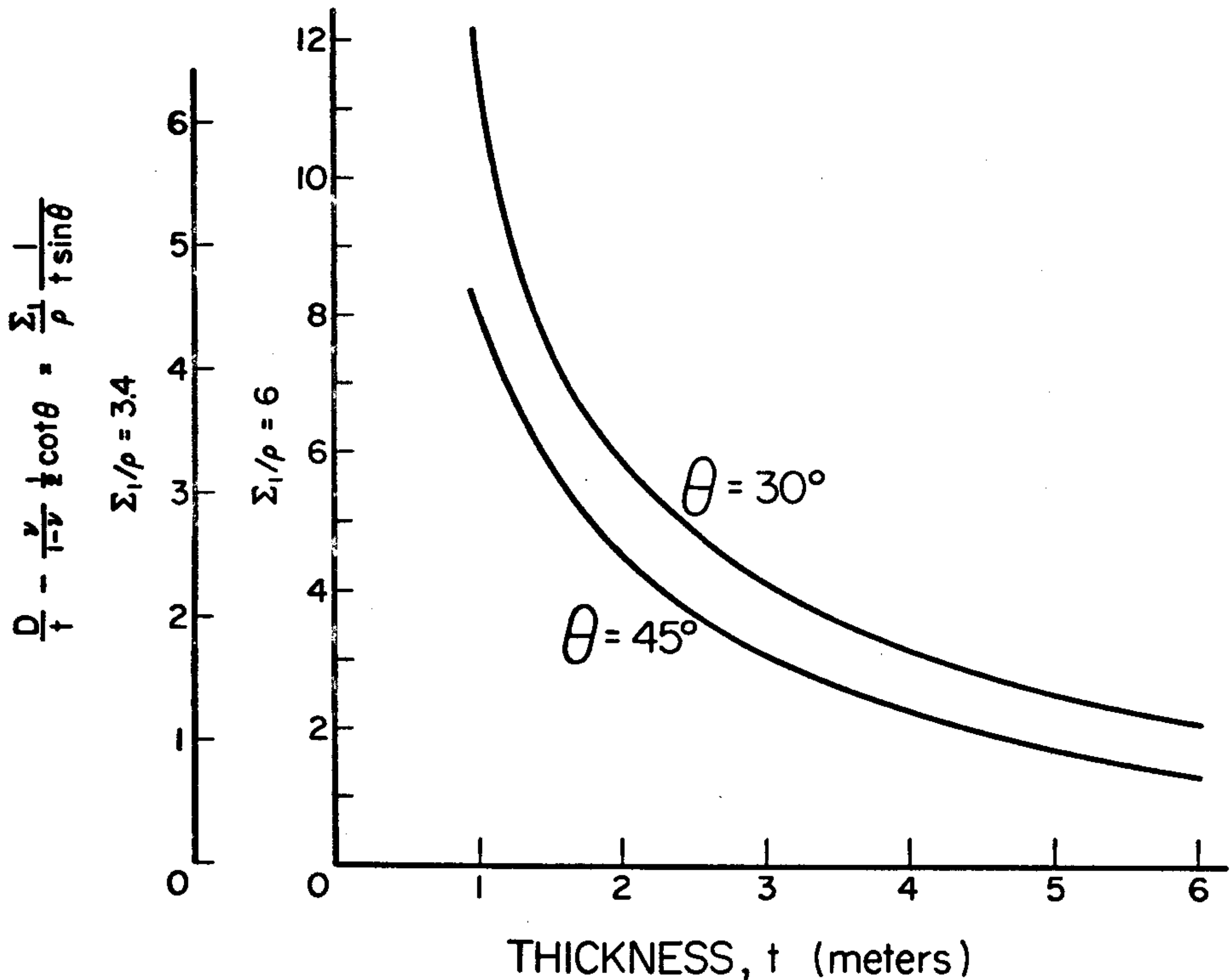
Tensile fracture along the line $x_1= D$ causes a force of magnitude $2\,\Sigma_1 tB$, where 2B is the length of tensile failure in the x_3 direction, to be accommodated in shear over the region $0< x_2 <t$, $x_3 = B$ and $-B$, and in compression over $0 <x_2 <t$, $x_1 = -D$. An upper bound on shear stress is obtained by assuming that the force is taken exclusively in shear until the full shear capacity is mobilized. Then

$$4\, \Sigma_3\, Dt = 2\, B\, t\, \Sigma_1 \tag{35}$$

and

$$\frac{B}{t} = \frac{2\Sigma_3}{\Sigma_1}\,\frac{D}{t}\,. \tag{36}$$

In most materials $\frac{\Sigma_3}{\Sigma_1} \simeq \frac{1}{2}$. Interpretation of the tests[7]



	$\frac{\nu}{1-2}\ \frac{1}{2}\ \cot\theta$	
	$\theta = 30°$	$\theta = 45°$
$\nu = 0.1$	0.097	0.055
$\nu = 0.25$	0.291	0.166
$\nu = 0.4$	0.582	0.333

Data for Computing $\frac{D}{t}$ Ratio

FIG 6

suggests a value of $\frac{2}{3}$. If any of the force $2\,\Sigma_1 tB$ released by the tensile failure failure is accommodated with the bottom slab compression region, then $\frac{B}{t}$ in (37) will be increased. Thus, we would expect under all circumstances

$$B \geqslant D \tag{37}$$

c) Bottom Slab Compression Failure

Failure on three sides of the slab results in high compression at the lower slab, $x_1 = -D$. Two modes of failure are possible and both have been reported[5], buckling of the slab over $x_1 \geqslant -D$ and compression failure at $x_1 = -D$. The latter is more common for catastrophic slab failure leading to avalanche release. Buckling is usually associated with slower deformation accompanying glide of the snow cover over the ground.

A possible buckling configuration is shown in Fig. 7, the problem being equivalent to that of a beam under the action of an end load and a distributed axial load. An approximate solution by Rayleigh's method has been found.[8]

In Fig. 7 the coordinates have been changed so that

$$\Psi = x_1 + D \tag{38}$$

$$\omega = x_2 . \tag{39}$$

The deflected shape is

$$\omega = \omega(\Psi) \tag{40}$$

which must satisfy the conditions

$$\omega = 0,\ \frac{d\omega}{d\Psi} = 0 \tag{41}$$

at $\Psi = 0$ and for $\Psi \geqslant L$.

The axial loading is $\rho \sin \theta t(2D - L)$ at $\Psi = L$ which describes the accumulated tangential forces over $\Psi \geqslant L$ and a spread axial loading $\rho \sin \theta t$ over $0 \leqslant \Psi \leqslant L$. An assumed shape that satisfies (41) is suggests a value of $\frac{2}{3}$. If any of the force $2\Sigma_1 tB$ released by the tensile failure failure is accommodated with the bottom slab compression region, then $\frac{B}{t}$ in (37) will be increased. Thus, we would expect under all circumstances

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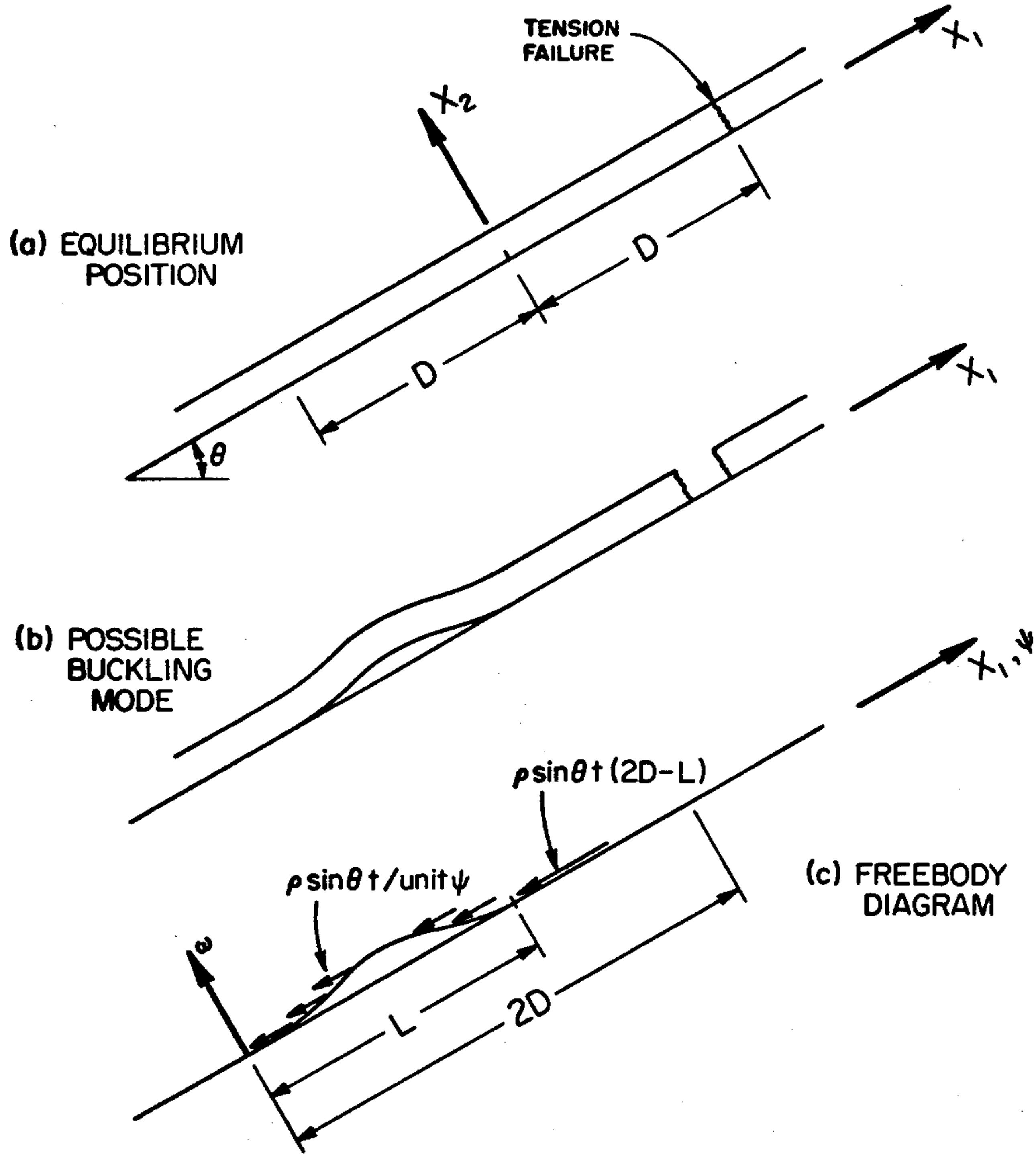


Snow Slab Buckling Configuration

FIG 7

$$\omega = A(1- \cos \frac{2\pi\Psi}{L}) \tag{42}$$

which, when applied to the Rayleigh quotient, gives an upper bound

$$\rho \sin \theta tL \leq \frac{\pi^2 Et^3}{3(1-\nu^2)L^2} \left(2\frac{D}{L} - \frac{1}{2}\right)^{-1}. \tag{43}$$

A stationary value of $\rho \sin \theta tL$ occurs at

$$L = 2D, \tag{44}$$

that is the whole slab will buckle rather than a portion $L < 2D$. In this case

$$2 \rho \sin \theta tD \leq \frac{\pi^2 Et^3}{6(1-\nu^2)D^2}. \tag{45}$$

(45) gives snow properties ρ, ν and E for buckling given the geometry θ and t and the results of equation (33).

For compression at the bottom of the slab

$$2 \rho \sin \theta tD = \Sigma_2 t. \tag{46}$$

Therefore, from (45) buckling will occur when

$$\frac{\beta Et^3}{(1-\nu^2)D^2} < \Sigma_2 t \tag{47}$$

where β is the numerical value that insures an equality in equation(45), i.e.

$$\beta \leq \frac{\pi^2}{6}. \tag{48}$$

From (33) we may write

$$\frac{D}{t} < \frac{\Sigma_1}{\rho} \frac{1}{t \sin \theta} \tag{49}$$

and this together with (47) gives

$$\beta t^2 \sin \theta < \Sigma_2 \frac{(1-\nu^2)}{\rho^2 E} \Sigma_1{}^2. \tag{50}$$

Therefore,

$$t_{crit} < \sqrt{\frac{\Sigma_2}{E}} \frac{\Sigma_1}{\rho} \sqrt{\frac{(1-\nu^2)}{\beta} \frac{1}{\sin \theta}}. \tag{51}$$

The previous argument indicates an insensitivity to the value of β . Improvements may be obtained by a better description of $\omega(\Psi)$. In particular, the boundary condition $\frac{d\omega}{d\Psi}(\Psi=L) = 0$ is unrealistic when $L=2D$. Then the boundary condition

$$\frac{d^2\omega}{d\Psi^2}(\Psi=L) = 0 \tag{52}$$

is appropriate; this corresponds to zero moment at the top surface. The function

$$\omega = A\left(\Psi^2 - \frac{5}{3L}\Psi^3 + \frac{2}{3L} = \Psi^4\right) \tag{53}$$

satisfies (52) and gives a value of $\beta \approx 1.18$.

As previously discussed, $\frac{\Sigma_1}{\rho}$, varies from 3.4 to 6 meters. The ratio $\frac{E}{\Sigma_2}$ is of the order of 1000. This means that for elastic buckling the thickness must be less than about 35 cm.

Shear failure will occur at the base if

$$\Sigma_2 > \frac{1}{2}\Sigma_3 \tag{54}$$

and in this case a 45° slip plane will originate at $x_1 = -D$.

DISCUSSION AND CONCLUSIONS

The previous stress calculations were based on certain assumptions which merit further discussion. The condition of equation (4) is valid for an infinitely extending slab, but is an approximation for finite slabs. Provided the displacement vector at $x_2 = 0$ remains zero throughout the accretion, (4) still provides a very close description of the actually occurring strains. This may be understood by considering the work of Goodier[9] who dealt with a very similar problem and showed, by use of St. Venant's principle, that ε_{11} and ε_{33} would be non-zero only in the region close to the edges of the slab.

Also important is the effect on the initial state of the viscous behavior of the snow. In fact, the state of stress given by (10)may be extended to the linear viscoelastic problem[10] so that σ_{12} and σ_{22} will be as shown while σ_{11} and σ_{33} will only change through the dependence on time of Poisson's Ratio.

The significant point with regard to the initial stress state is that it is closely estimated by (10) and that the initial stress σ_{11} is compressive and increasing with snow depth.

Exact solutions for the state of stress after metamorphosis are not possible in the present model in view of the singularities at $x_1 = \pm D$. In order to justify the use of averaged stress values, a finite element analysis for the elasticity problem of (29) was carried out. The results showed that, except in the neighborhood of the points $x_1 = \pm D$, $x_2 = 0$, the stresses were essentially uniform and in addition that the average of τ_{11} over t increased uniformly from $x_1 = 0$ to $x_1 = D$ and then died away in a distance of approximately 2t beyond $x_1 = D$. Such analysis justifies the approach of Section IV in determining the avalanche conditions. For a finite width slab, the dimensional ratio D/t is underestimated by (33) since no contribution from the shear along the sides is taken into account.

On the basis of the considerations of mechanics in previous sections, certain conclusions can be drawn with regard to slab avalanche release. The dimensional quantities D and B provide limiting dimensions for the avalanche slab. A lower bound on the length, $2D$, necessary for top tensile fracture is given by (33) and is shown in Fig. 6. This length, which depends on snow thickness, properties and slope, is the extent of up slope metamorphosis necessary for superficial cracking to occur at the top of the potential slab avalanche. The initial state of stress is one of compression, and because this compression increases with depth, it is to be expected that the tensile cracks will initiate at the surface of the slab.

The lateral extent of the tensile crack is expected to correspond approximately to the breadth of the metamorphosed region. The preceding analysis provides a lower bound, but not an upper bound, to the breadth of any subsequent avalanche. If the breadth of the metamorphised region is less than $2D$, then no side shear and avalanching will occur. The assumptions made concerning the shear transmittal in the derivation of equation (37) are extreme. Any accommodation,by compressive stress at the bottom,of the force released when the top cracks,will require $B > D$ for side shear failure.

The conclusion that B must exceed D for slab avalanche release is consistent with observations. Snow slabs wider than they are long are observed, sometimes the width greatly exceeds the length. Slabs longer than wide have not been observed. Table 1 shows a compilation of $^B/D$ values for observed avalanches. For the values in the table

$$2.5 < {}^B/D < 10.7$$

with an average figure of 4.7. These observations conform to the theory, particularly since there is no theoretical upper bound to slab avalanche width. They do suggest that bottom compression plays a considerable role in determining the minimum width for side shear failure. This is confirmed by an observation near Silverton, Colorado, (December 1971) of an area where a slab avalanche had occurred/ which showed that a zone of highly compressed snow existed just below the bottom. It should be noted that the values in Table 1 are for fallen slab avalanches rather than states where just top tensile and side shear failure has occurred.

Complete failure by slab avalanching requires failure at the bottom, and as shown this will in general be by shear-compression rather than by buckling. If avalanching does not occur immediately after side shear failure, then only a change in snow properties can result in subsequent avalanching for the same snow layer. Observations indicate that slabs which fracture but do not fall normally stabilize in place and fail to generate avalanches. On a non-uniform slope, the viscoelastic character of the snow will cause amplification of any initial irregularity in conjunction with glide. What is probably the result of such deformation is shown in Plate 8. Although immediate avalanching may not occur, such uplift would seem to be a danger indicator. The condition in Plate 8. was accompanied by a separation of some two meters in the tension zone. Such "glide cracks" are common in isothermal snow.

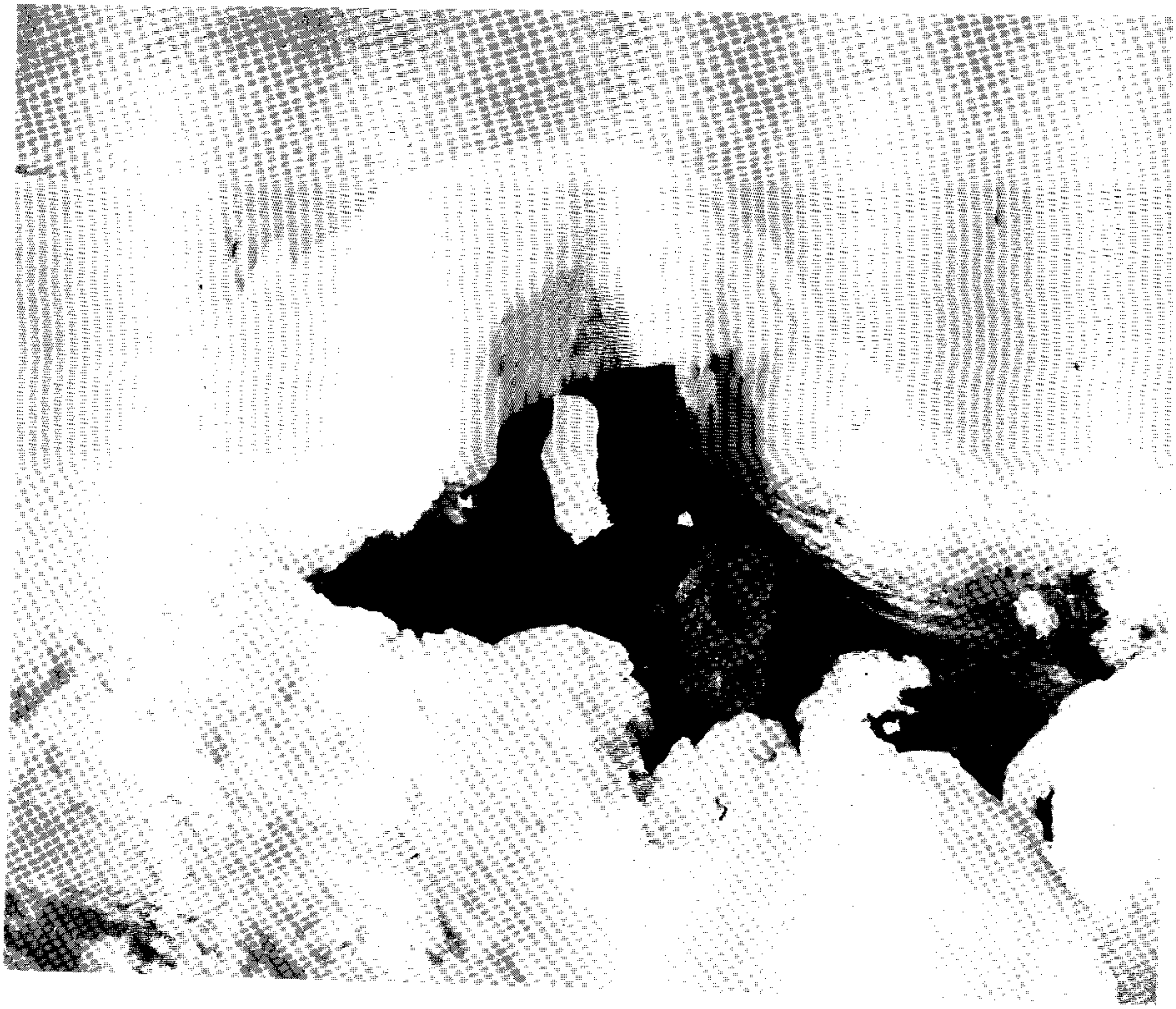


Plate 8

Possible Creep Buckling Mode

TABLE 1.

Observed Values of $^{B}/D$ in Actual Avalanches

B	2D	$^{B}/D$
20	8	5.0
13.5	8	3.4
10	6	3.3
13	8	3.2
9	2.5	7.2
9	8	2.3
14	11	2.5
20	9	4.4
16	7	4.6
18	6	6.0
10	4	5.0
2.5	2	2.5
10.5	4	5.3
9.5	3	6.3
19	12	3.2
7	3	4.7
4.3	2.5	3.4
2	1.6	2.5
10	7	2.9
5	3	3.3
2.8	2	2.8
8	1.5	10.7
4	1.8	4.4
7	3.5	4.0
3	0.7	8.6
5.5	2	5.5

Sources for the dimensions in this Table are photographs, principally from copies of "Schnee und Lawinen in den Schweizer Alpen," published annually by the Swiss Federal Institute for Snow and Avalanche Research and the collection of E. R. LaChapelle.

PART 3.

Mechanical Parameters of Snow

Snow Glide.

Snow glide is the movement of the entire snow cover over the ground. During the winter of 1971-72 measurements of snow glide were conducted at ten different sites in the Cascades. The sites were selected to sample varied compass bearings and ground-surface vegetation conditions. Five of the sites were in the Stevens Pass area, and the remaining five were in the vicinity of Cascade Field Station and Mt. Baker ski area.

The basic method of measuring the glide is by recording the time-history of the motion of a metal glide shoe placed on the ground before the first snowfall. Results showed that throughout the winter one to two feet of glide is to be expected depending on compass bearing and vegetation pattern. In general, south and west facing slopes showed more glide than north facing slopes. Timbered or brushy slopes yielded less glide than smooth or grassy slopes.

Figure 8 shows typical glide data collected at sites #2 and #3 at Mt. Baker. Site #2 is a south facing slope in timber while site #3 is a south facing slope with small brush and some grass. These data are quite typical of other data collected at Mt. Baker.

In general, the highest glide velocities were obtained at the beginning of the winter with a steady decline throughout the winter. The high veloci in early winter may be attributed to a lubrication of the snow-ground interface by melting snow at the bottom of the snowpack due to escape of heat stored in the ground during the summer and fall.

Another prominent feature of the snow glide data is the presence of strong peaks during periods of rainfall in late winter. These peaks appeared to be more pronounced for smooth slopes than for timbered or brushy slopes.

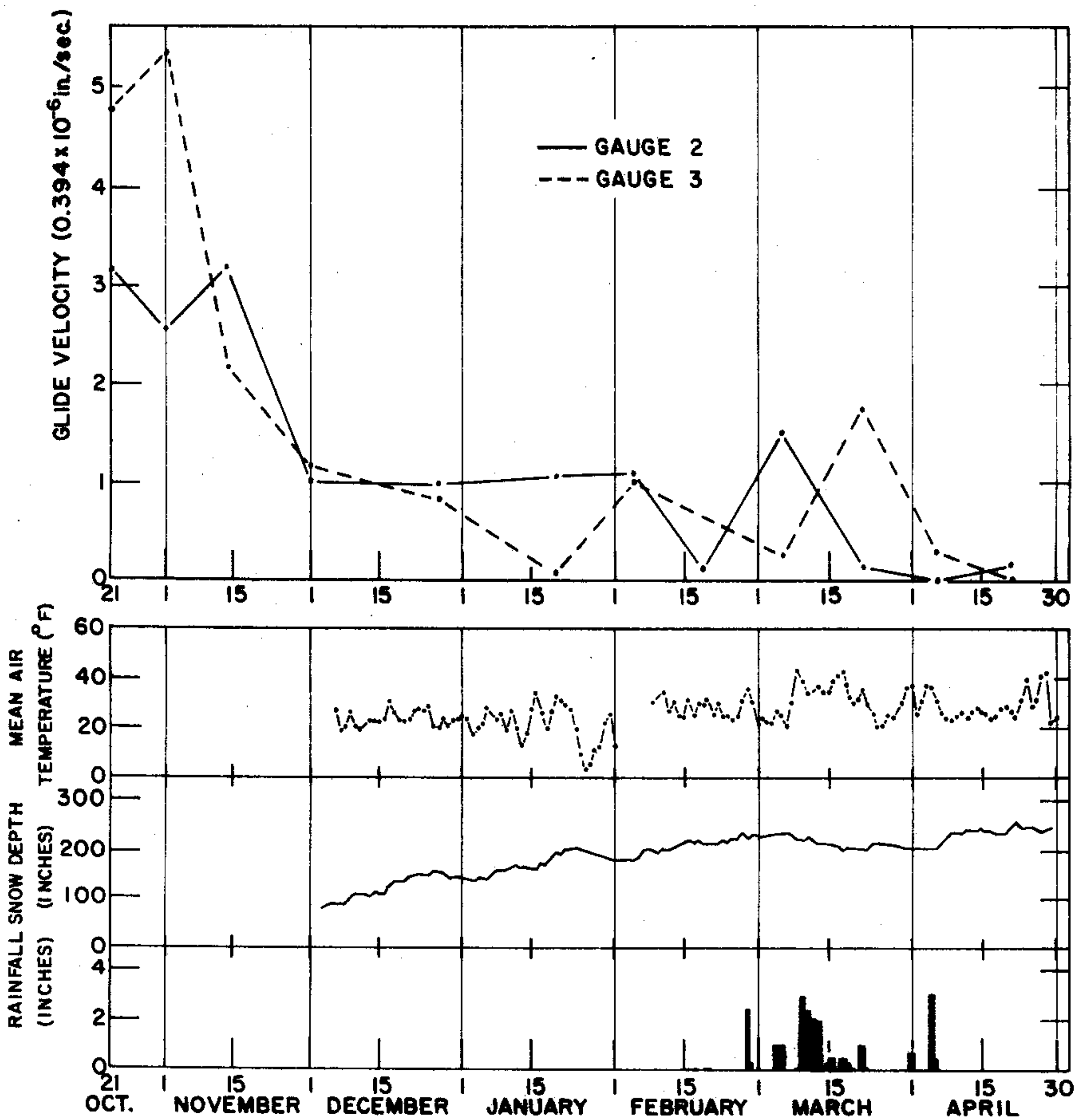


Fig. 8- Typical Glide and Meteorological Data from Sites Near Cascade Field Station, 1971-1972.

This effect may be an important consideration for the design of avalanche defenses in the North Cascades. Since rainfall usually comes in late winter when the snow depths are large, it is to be expected that stresses on defenses due to glide may be large during this period.

Snow Creep.

Snow creep is the result of shear deformation and settlement in the interior of the snow pack. Creep measurments were carried out throughout the spring of 1972 on the same slopes that glide measurements were made at Stevens Pass and Mt. Baker. This enabled a comparison of the rate of shear deformation and settlement within the snow pack with the rate of glide over the ground.

The method used in the creep experiments was an examination of the deformation of vertical sawdust columns placed in the snow pack. The duration of the experiments was typically two months.

The experiments showed that the velocity due to shear deformation was of the same order of magnitude as the velocity due to glide during the experiments. Settlement is more difficult to assess by this method since the results are complicated by ablation of the snow at the surface. Accordingly, snow settlement experiments are planned for the winter of 1972-73 to complement the sawdust column experiments. These experiments should together yield a solid quantitative definition of the creep processes in the snow pack for the Cascades.

Since velocities due to creep deformation in the snow pack are of the same order of magnitude as glide velocities, it is apparent that for avalanche defense design the stresses due to snow creep as well as for snow glide must be taken into account. This result is also evident from the work of Swiss engineers concerned with defenses.

Measurements of Snow Strength

An important input to understanding the stability of snow slabs with regard to slab avalanches is the failure strength of the snow. Accordingly, in-situ measurements of the strength of the snow were made at Cascade Field Station near Mt. Baker during the 1971-72 winter.

These measurements were attempted by a new method which utilized large tilting tables. The great advantage of the method is that it enables large samples of snow to be used. This feature is deemed to be essential to reduce the large scatter in the data gained by previous methods.

The warm character of the 1971-72 winter presented unexpected problems with the experiments which were rectified by the end of the season. In addition, it was evident that a slight modification was needed to enable sampling of the lowest density snow.

The data taken during the 1971-72 season show less scatter than previous in-situ measurements, thus perhaps indicating that the basic method is adequate. The number of data points obtained and the lack of data in the important low density range seem to indicate a need for more experiments before a definite appraisal of snow strength can be made, however. Accordingly, another series of experiments is planned for the winter of 1972-73.

PART 4.

1971-1972 Snow Report on the North Cascades

The 1971-1972 winter was, along the North Cascades Highway as well as throughout the Washington Cascades, a severe one with respect to the large amounts of snowfall and the great amount of avalanche activity which took place. The charts on the following pages summarize the observed weather and slide activity for this winter on the section of SR-20 between Washington Pass and Early Winters.

Figures 9 and 10 show the 24 hour maximum and minimum temperatures which were observed at three places along the highway. Daily temperature observations were made at Early Winters (elevation 2200 feet), about three miles west of Mazama at the mouth of the Early Winters Canyon. Temperature observations were also made at Cutthroat Creek (elevation 4000 feet) at the times when the observer was present. In addition, a thermograph was in operation at Washington Pass (elevation 5500 feet), from which daily maximum and minimum temperatures have been extracted and are produced in Figure 10.

The record at Early Winters exhibits a wide range of temperatures. There were many sub-zero days as well as many in which above freezing temperatures were recorded.

Although the intermittent Cutthroat Creek record appears to show less amplitude of diurnal temperature fluctuations, a day by day examination reveals that corresponding temperature observations at the Early Winters Station were usually quite comparable in magnitude and range. (The observations at Cutthroat Creek usually were made during storm periods when cloudiness may have prevented radiative heating and cooling from playing a large role in widening the daily temperature range.) However, a fairly large number of above freezing temperatures were reported at the 4000 foot station.

FIGURE 9.

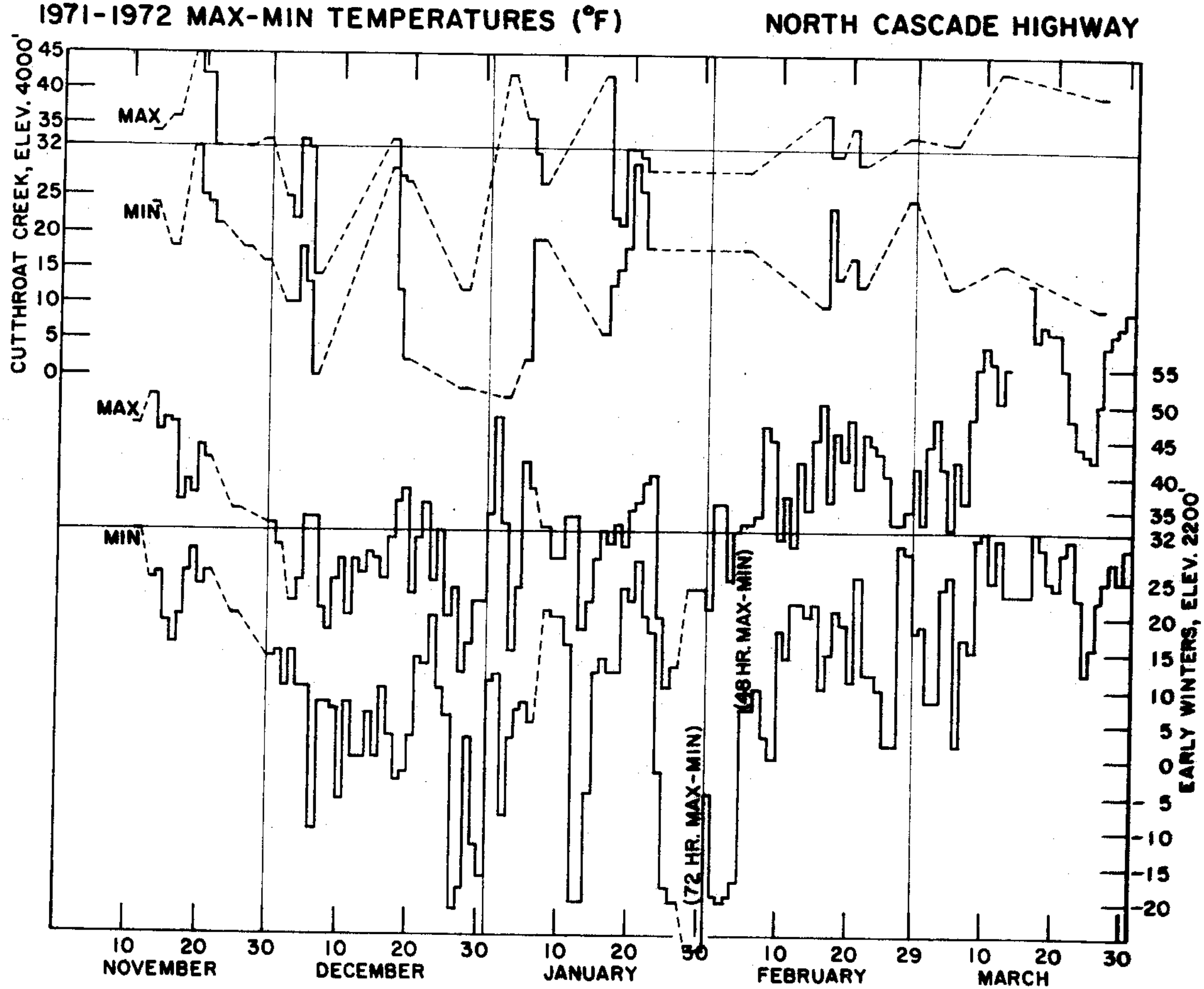
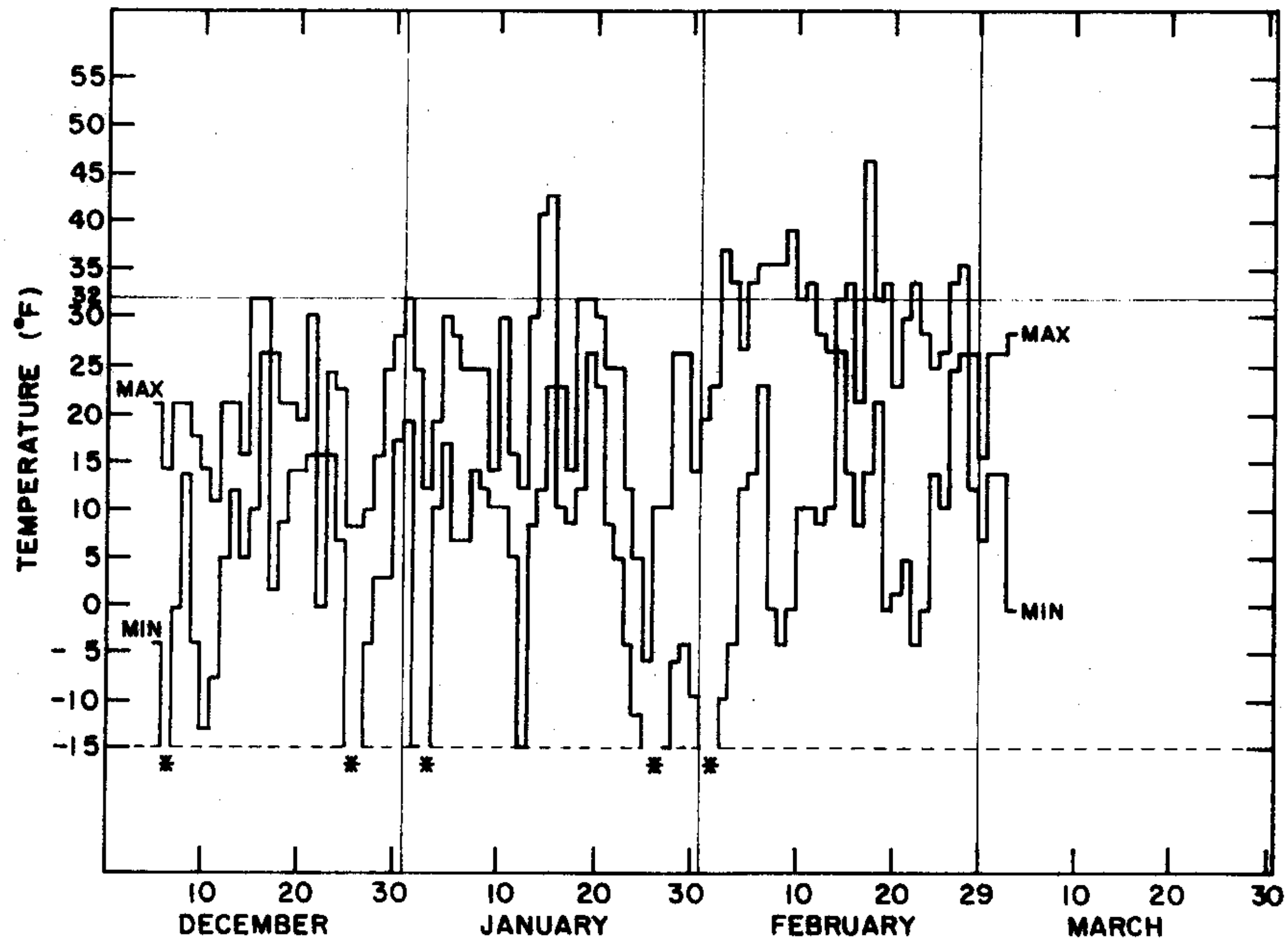

1971-1972 MAX-MIN TEMPERATURES (°F)
NORTH CASCADE HIGHWAY
CUTTHROAT CREEK, ELEV. 4000'
EARLY WINTERS, ELEV. 2200'
MAX
MIN
MAX
MIN
(72 HR. MAX-MIN)
(48 HR. MAX-MIN)
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH

FIGURE 10.

1971-1972 MAX-MIN TEMPERATURES WASHINGTON PASS



*TEMPERATURES BELOW -15°F WERE NOT RECORDED.

The Washington Pass record shows on the whole slightly lower maximum temperatures with a fewer number above freezing than the two lower stations. The minimum temperature at Washington Pass often dipped below the -15° F. limit of the thermograph chart.

Figures 11 and 12 show snow depth information for the 1971-72 winter. When studying these charts, it should be considered that measurements of snow depth often were taken on different days, and the interpolated values of snow depth (which are indicated by the lines on the chart connecting observations) may not accurately represent the daily values for use in comparing the different elevations.

Inasmuch as observations were made nearly every day at 2200 feet, the variations in that record, especially sharp rises, may help in interpreting the intermittent data at the higher levels. Of course, when it snowed at upper levels but rained below,as happened often in February and March, the 2200 foot record cannot be considered representative of the variations at some of the higher levels.

Figures 11 and 12 show that, very generally, snow depth at all levels increased fairly steadily from November until the middle of January, and fluctuated around these mid-January depths through most of February. Maximum depths at 4000 feet and below were reached as a result of the storms of late February and early March, after which rain was apparently responsible for a steady decrease in snow depth at these levels.

The snow depth record showed a systematic increase with increase in elevation as the snowpack began to grow in November. This type of variation with elevation continued to be displayed from the middle of December to the middle of February below 4500 feet. But from 4500 feet to 5500 feet the values were roughly comparable during that period. (In fact, the 4500 foot snow depths

FIGURE 11.

CUTTHROAT CREEK TO EARLY WINTERS TOTAL SNOW DEPTH

NORTH CASCADE HIGHWAY

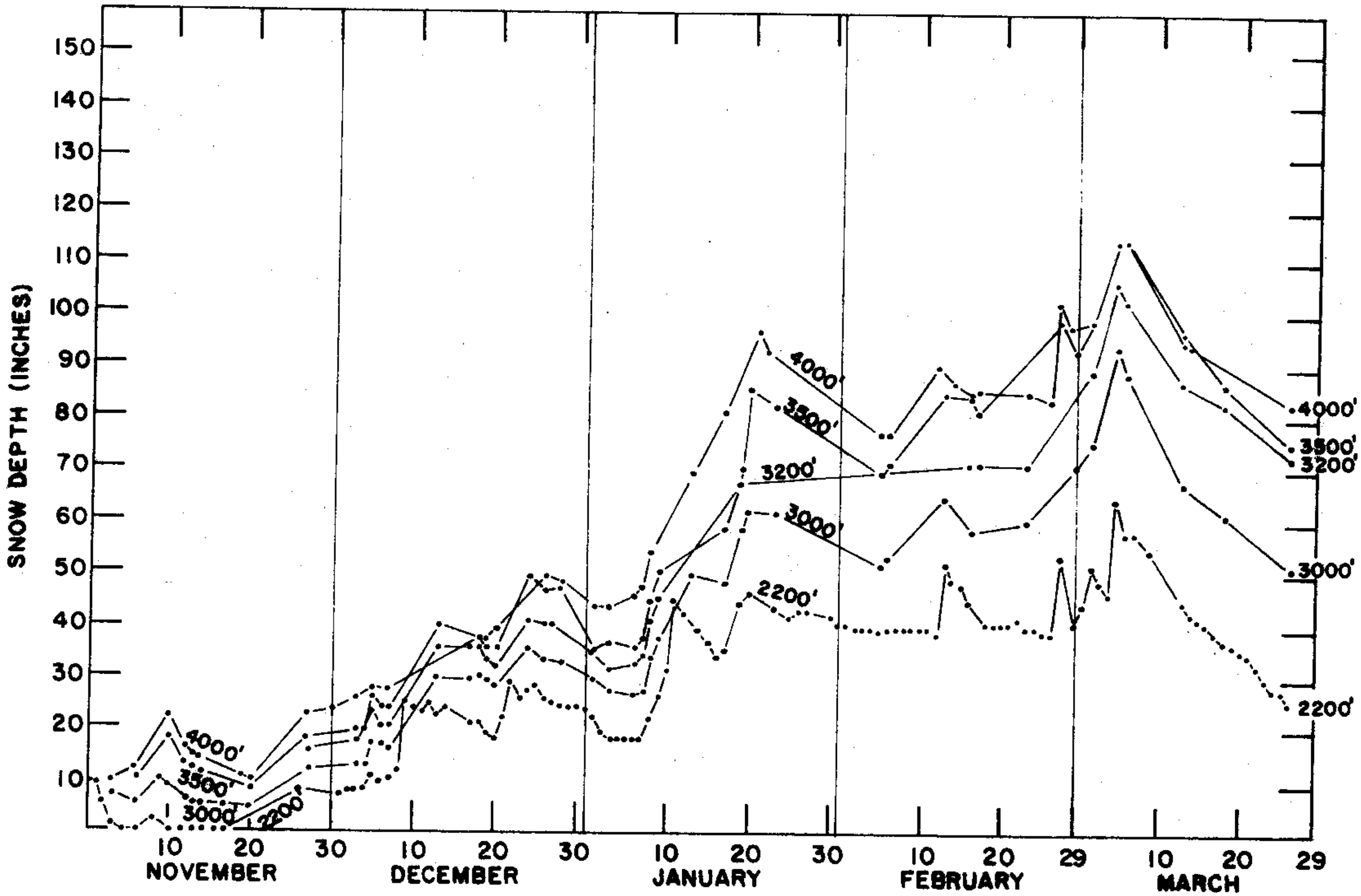
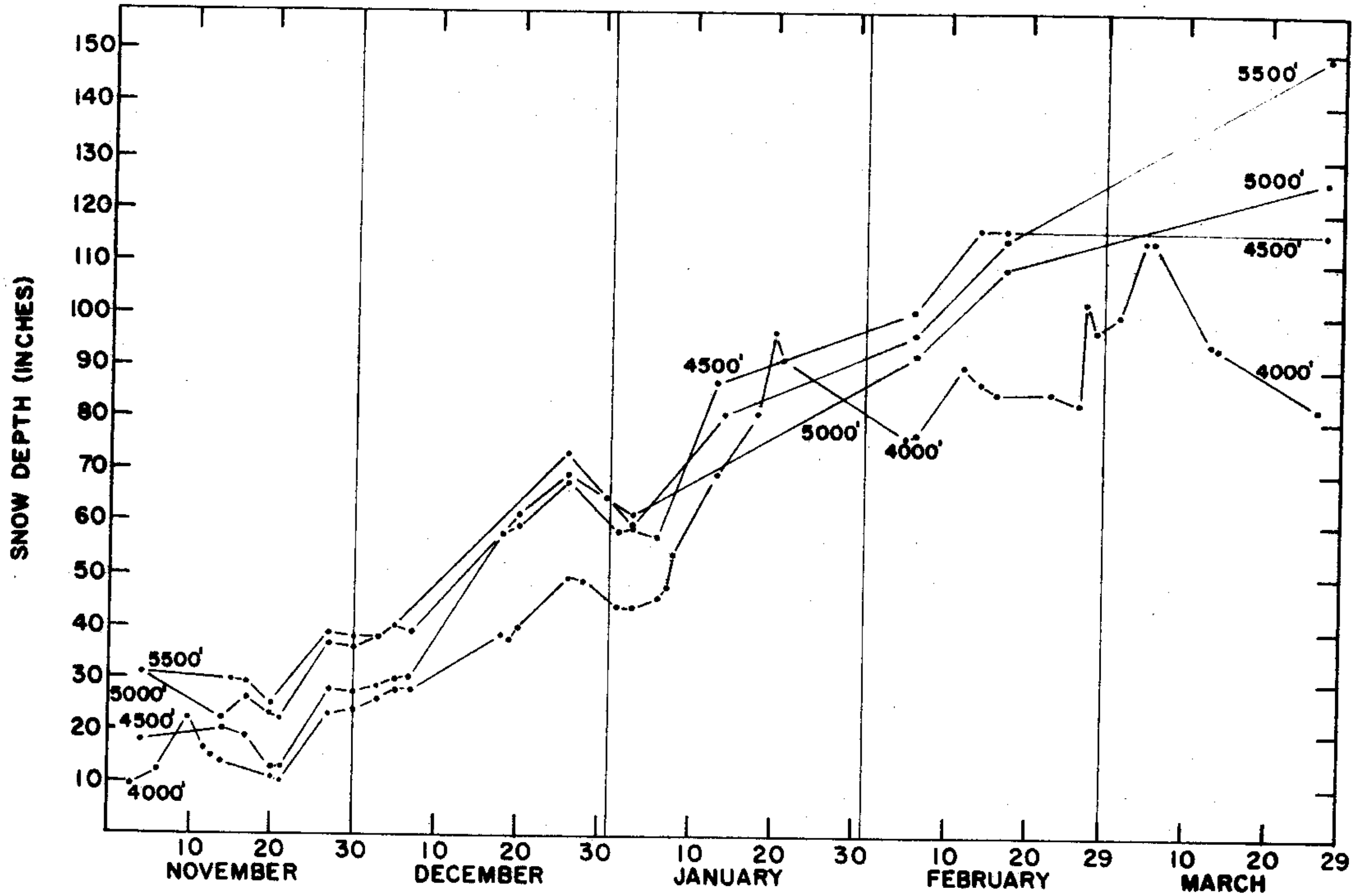


FIGURE 12.

WASHINGTON PASS TO CUTTHROAT CREEK
TOTAL SNOW DEPTH

NORTH CASCADE HIGHWAY



were usually a little greater.) By the end of March, however, the systematic increase with elevation had re-established itself at these levels.

Figure 13 shows the new (24 hour) snowfall record taken at Early Winters. This may roughly indicate what was happening at higher levels, except in February and March when rain predominated at this level.

Twenty four hour snowfalls greater than 12 inches occurred several times throughout the winter even at this low elevation. It may be noticed in comparing this chart with Figures 14, 15, and 16 that those intensive 24 hour snowfalls correspond in many cases to the major slide cycles.

Figure 14 shows the winter's slide activity along four different sections of the North Cascades Highway. It can be seen that along Delancy Ridge, Cutthroat Ridge, and Liberty Bell Mountain slide cycles are often concurrent. These cycles coincide generally with the major cycles throughout the Washington Cascades this past winter, especially the January 11, January 20, and March 5 cycles. The Diablo Gorge slides seemed generally unrelated in time to those on the east side.

Figures 15 and 16 show the record of activity for the individual slide paths along Delancy Ridge, Cutthroat Ridge, and Liberty Bell Mountain. The record shows the slides which were observed to have taken place and also indicates the slides which later investigation showed were probable but which could not be recorded because of hazard at the time to further travel along the road.

The slide activity along Delancy Ridge was considerable throughout the winter, although on only three days did any of these slides deposit snow on the road.

By comparison, the Cutthroat Ridge and Liberty Bell slides were more active, and a greater percentage of them ran into the road. In fact, the

FIGURE 13.

EARLY WINTERS DAILY SNOWFALL RECORD (2200' ELEVATION) NORTH CASCADE HIGHWAY

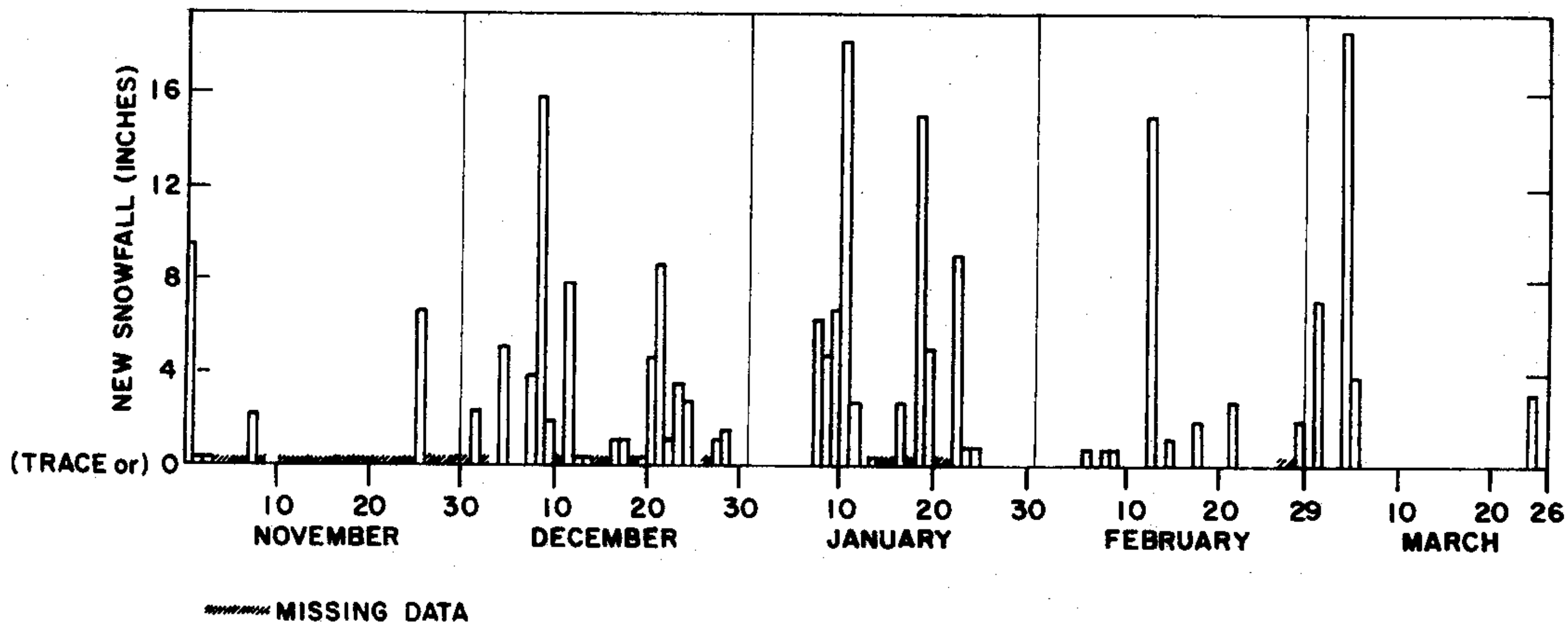
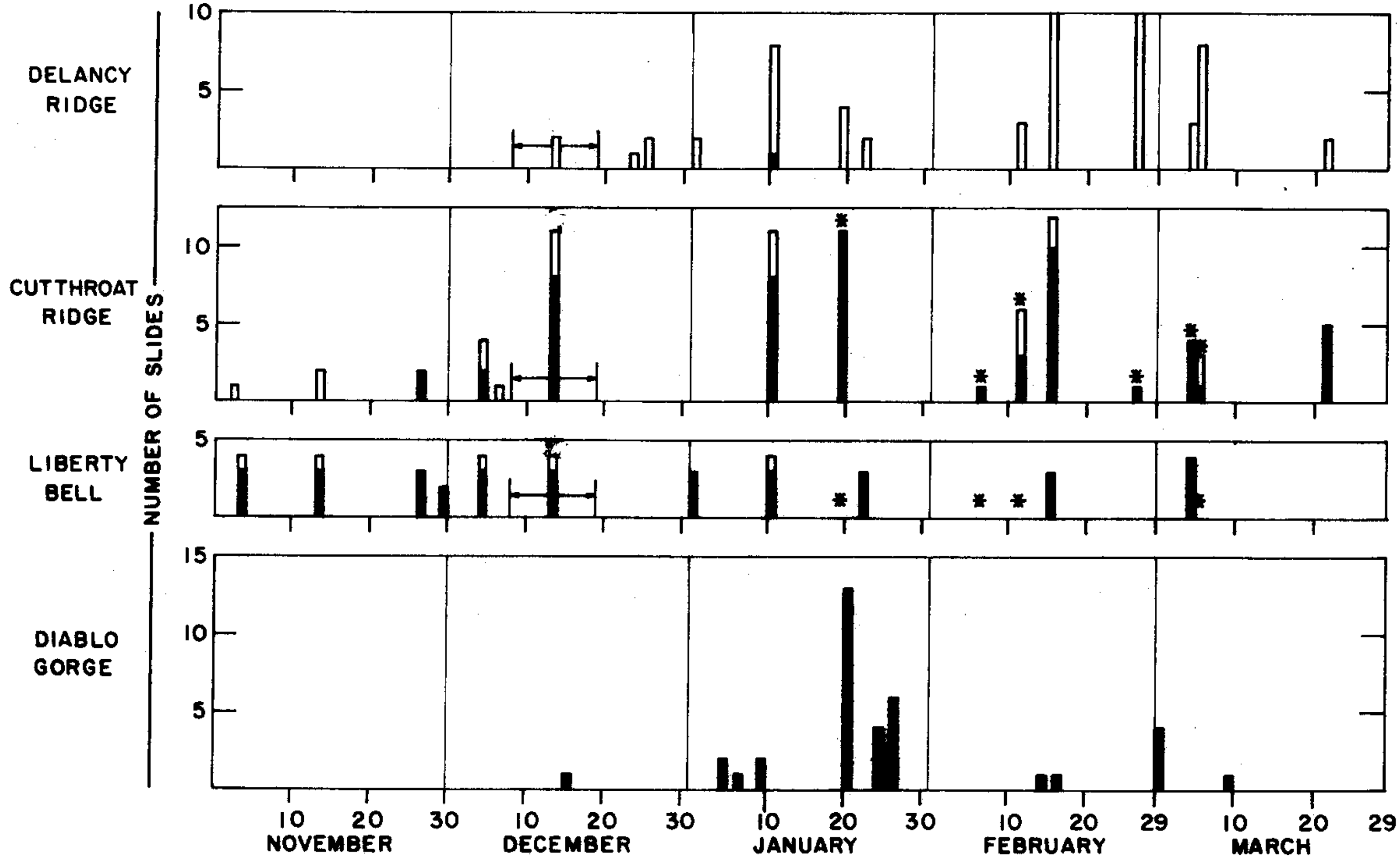


FIGURE 14.

OBSERVED AVALANCHES-WINTER OF 1971-1972 — NORTH CASCADE HIGHWAY



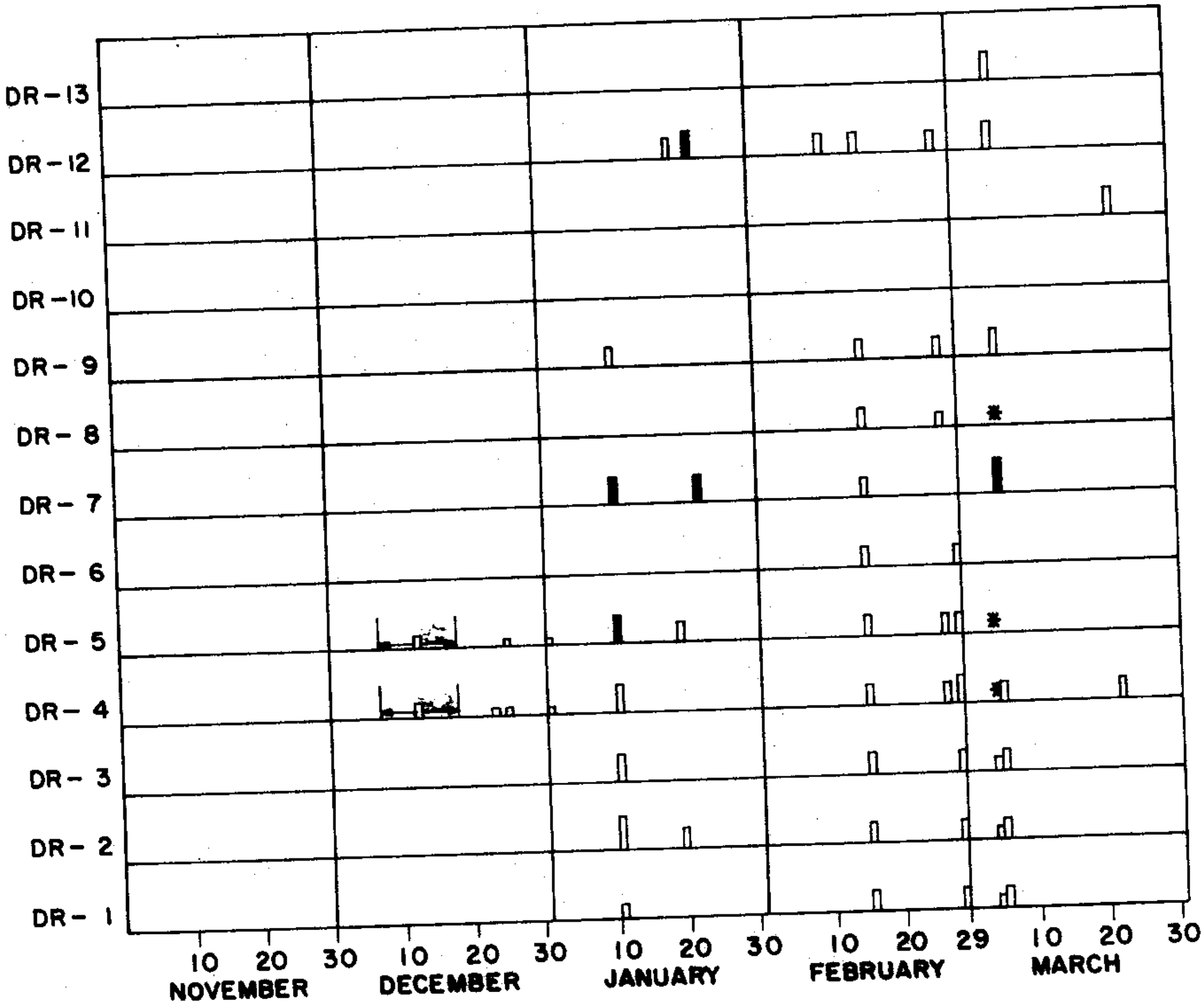
■ Observed slides in or across the road
□ Observed slides not reaching the road

* Indicates other slides may have occurred which were not observed

☆ These slides occurred sometime between 8 Dec. and 19 Dec., possibly in two separate cycles

FIGURE 15.

NORTH CASCADE HIGHWAY
DELANCY RIDGE SLIDE RELEASE LOG
1971-1972



SIZE

▫ sluff

▯ small

▯ medium

▯ large

▯ maximum

▯ Observed slide, not reaching road

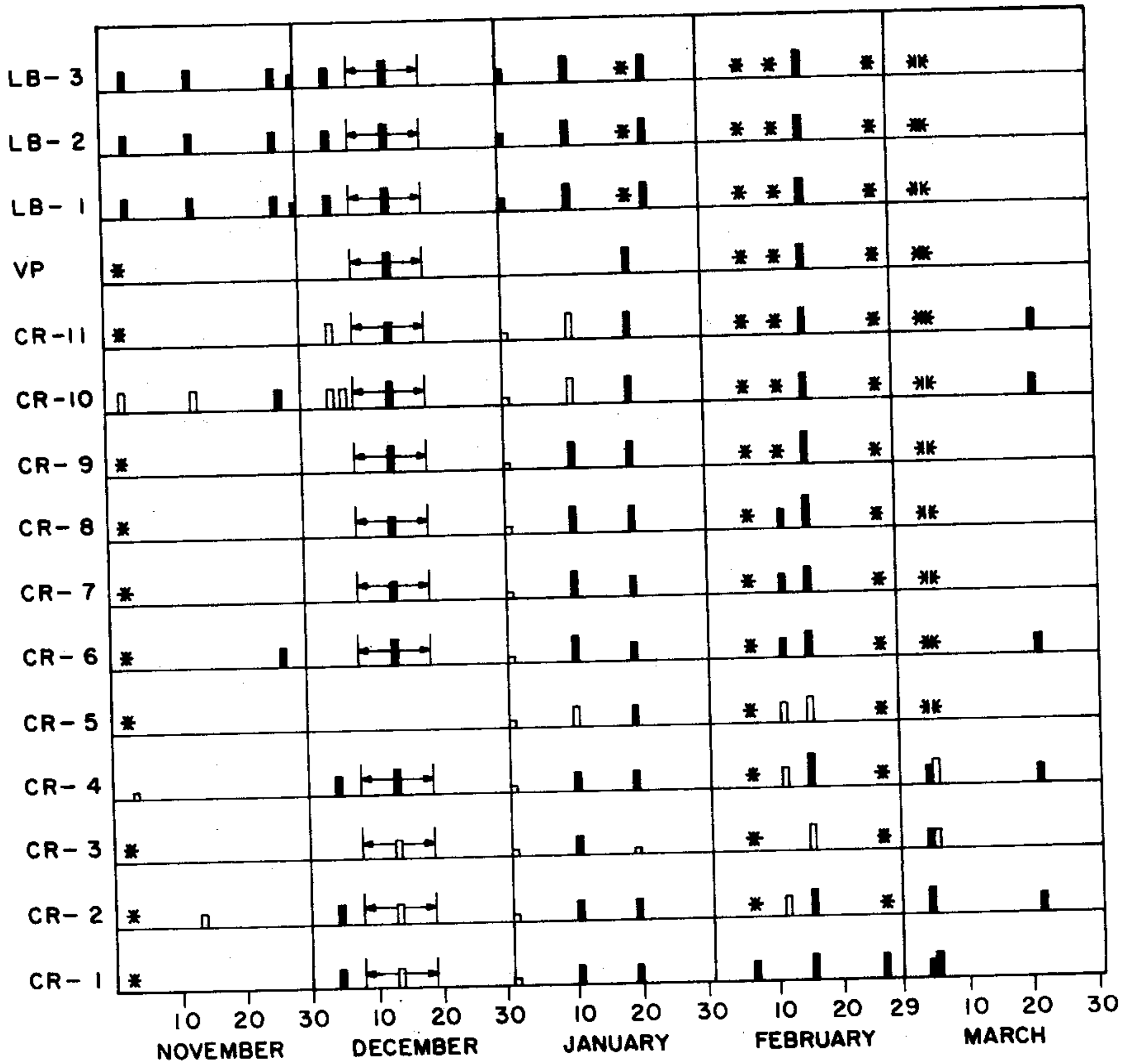
▮ Observed slide, in or across road

* Slide not observed, but thought probable

Slides released sometime between 8 December and 19 December were possibly in two separate cycles.

FIGURE 16.

NORTH CASCADE HIGHWAY
LIBERTY BELL & CUTTHROAT RIDGE SLIDE RELEASE LOG
1971 - 1972



SIZE

▫ sluff

▯ small

▯ medium

▯ large

▯ maximum

▯ Observed slide, not reaching road

▮ Observed slide, in or across road

* Slide not observed, but thought probable

Slides released sometime between 8 December and 19 December were possibly in two separate cycles.

Liberty Bell slides came into the road each time they were observed to have been released, usually all three in the same storm

Table II and Figure 17 summarize the activity of each active slide path between Early Winters and Washington Pass for the winter 1971-72. Most of the Cutthroat Ridge slides and the first three Liberty Bell slides were quite active and often in the road. (Liberty Bell #3 was in the road at least 12 times, with more unrecorded slides likely to have occurred. Often this slide continued down the slope to cross the lower portion of the switchback of the highway as well.)

The winter of 1971-72 was of exceptional severity throughout the Cascades. The above illustrations thus serve as good examples of the kind of activity to be dealt with along the North Cascades Highway.

TABLE II.

NORTH CASCADES HIGHWAY - EARLY WINTERS TO WASHINGTON PASS SLIDE PATH ACTIVITY

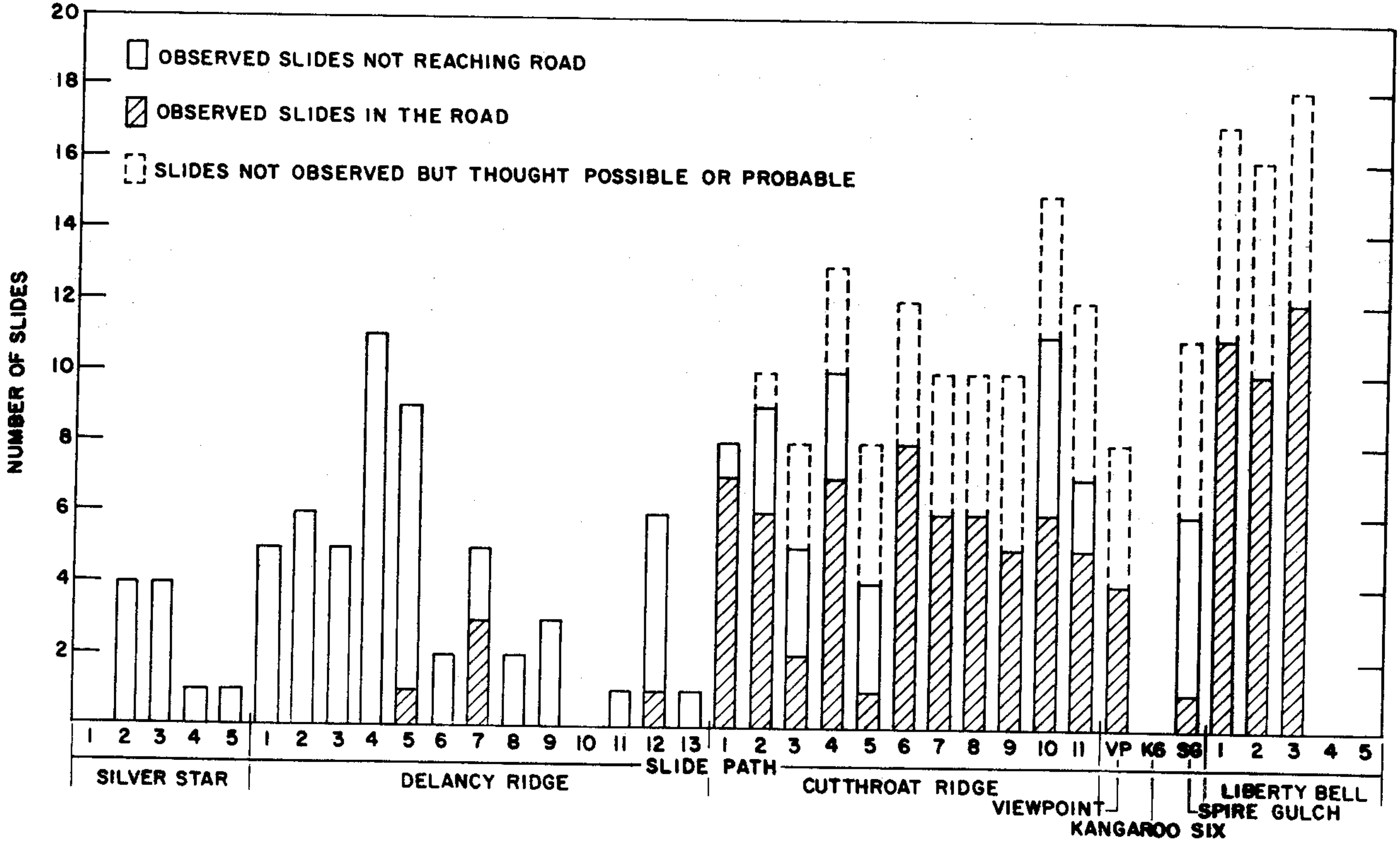
Winter of 1971-72

Slide Path			Number recorded	Number in road	Percent of recorded slides in road
Silver Star		#1	0	0	0
"	"	2	4	0	0
"	"	3	4	0	0
"	"	4	1	0	0
"	"	5	1	0	0
Delancy Ridge		#1	5	0	0
"	"	2	6	0	0
"	"	3	5	0	0
"	"	4	11	0	0
"	"	5	9	1	11
"	"	6	2	0	0
"	"	7	5	3	60
"	"	8	2	0	0
"	"	9	3	0	0
"	"	10	0	0	0
"	"	11	1	0	0
"	"	12	6	1	17
"	"	13	1	0	0
Cutthroat Ridge					
"	"	#1	8	7	88
"	"	2	9	6	67
"	"	3	5	2	40
"	"	4	10	7	70
"	"	5	4	1	25
"	"	6	8	8	100
"	"	7	6	6	100
"	"	8	6	6	100
"	"	9	5	5	100
"	"	10	11	6	55
"	"	11	7	5	71
View Point			4	4	100
Spire Gulch			6	1	17
Liberty Bell		#1	11	11	100
"	"	2	10	10	100
"	"	3	12	12	100

FIGURE 17.

EARLY WINTERS TO WASHINGTON PASS
SLIDE PATH ACTIVITY, WINTER OF 1971-1972

NORTH CASCADE HIGHWAY



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