AVALANCHE FORECASTING—A MODERN SYNTHESIS

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ABSTRACT

Avalanches are generated by structural weaknesses in the snow cover. Some of these weaknesses can be observed and measured by investigating snow stratigraphy in pits or with instruments. This method offers reliable data from direct observation, but it is time-consuming. It is most effective when forecasting climax avalanches caused by snow metamorphism or a sequence of snowfalls.

Many avalanches fall during or immediately after a single storm. Time usually does not permit stratigraphic investigation, which is difficult in fresh snow. These direct-action avalanches can be forecast by an analysis of meteorological factors prevailing during the period of snow deposition. This indirect evidence is less reliable, but can be more easily obtained and often is the only forecasting guide available.

The accuracy of such forecasts is checked by practical field tests for the existence of tensile stresses leading to slab avalanche formation. Tests are made by disrupting the snow in potential slab zones with skis, with explosives, or with artillery fire, according to the character of the snow and accessibility of the test zone.

In practice, these methods are combined, weight being given to one or another according to circumstances largely determined by climate. This determination is illustrated by examples from different climate zones in the western United States.

RÉSUMÉ

Les avalanches sont la conséquence d'une faiblesse structurale. On peut observer et mesurer cette faiblesse par des instruments ou par un examen de la stratigraphie dans un puits. Cette méthode est très efficace pour la prévision des avalanches évolutives (climax avalanches) qui résultent de la métamorphose de la neige ou d'une séquence de chutes de neige. Mais le procédé est onéreux.

Un grand nombre d'avalanches tombent pendant ou immédiatement après une chute de neige. Un examen stratigraphique dans la neige fraîche est difficile et exige trop de temps. Ces avalanches immédiates (direct action avalanches) peuvent être prévues par une analyse des facteurs météorologiques agissant pendant la chute de neige cependant sans la sûreté de la méthode directe.

La précision de telles prévisions est étudiée, par des expériences dans la nature (field tests). Dans des zones potentielles de formation d'avalanches de plaque de neige la couche de neige est brisée par des skieurs, par des charges explosives ou par du feu d'artillerie selon le caractère de la neige et l'accessibilité de la zone.

Dans la pratique ces méthodes sont combinées, en préférant l'une ou l'autre selon les circonstances locales et climatiques. On démontre cette variation par des exemples pris dans des zones climatiques différentes de la partie ouest des États-Unis.

DEFINITION OF TERMS

Avalanche forecast: Either an *evaluation* of current avalanche conditions or a *prognostication* of future ones, the latter depending on mountain weather forecasts.

Climax avalanche: This type falls as the result of internal structural weaknesses within the snow cover which may develop over long periods of time. It may be triggered by a new snowfall, but involves snow layers at the release point deposited by more than one storm.

Direct-action avalanche: This type falls during or within 24 hours after a storm, and involves only the snow of that storm at the release point.

Hard slab: The constituent snow of a slab avalanche with a high degree of internal cohesion. Sliding snow usually remains in chunks or blocks.

Soft slab: The constituent snow of a slab avalanche with a low degree of internal cohesion. The sliding snow breaks up into an amorphous mass and may resemble loose snow.

Introduction

Avalanches are caused by structural instability in the snow cover. The concept of an *avalanche forecast* is predicated on the assumption that this instability can be recognized and interpreted. Recognition may be based on *direct observation* (snow pits, test instruments), or it may be based on *indirect evidence* (meteorological records). Interpretation in terms of possible avalanche release is largely empirical, being based on general knowledge accumulated by the forecasting profession plus personal experience of the forecaster with a given area or climate zone. Though today the basis exists for a good theoretical understanding of the physics and mechanics of the snow cover which leads to an informed interpretation of conditions causing snow avalanches, operational practice in day-to-day forecasting nevertheless still depends on the subjective element of personal experience. The interacting mechanical forces involved in avalanche release, together with the physical processes which determine them, are far too complex to allow a timely, exact, analytical or numerical evaluation.

An avalanche forecast may assess instability with considerable accuracy for a given area, but it cannot foretell the exact time of avalanche release on a given slope. More precisely, it is a *hazard* forecast which evaluates or foresees the *probability* of avalanche release, natural or artificial.

This paper attempts to state systematically the principles applied today in forecasting avalanche hazard, and to relate the variations of these to variations in climate. Winter avalanche situations only are considered; the forecasting of spring avalanches is reserved for a separate and later treatment.

Forecasting from direct evidence

The condition of snow stability is most readily inferred from direct examination of snow cover structure. The techniques of such observations have been highly developed over the past thirty years, particularly in Switzerland. The standard techniques of snow pit investigation and the use of such instruments as the ram penetrometer (Haefeli rammsonde) have served as the basis for snow studies in such diverse applications as snow road compaction and assessment of annual accumulation on polar ice caps. Today their application to avalanche forecasting, the original reason for their development, is also widespread.

According to the concepts developed in this paper, *snow structure observations are primarily applicable to forecasting climax avalanches.* Such avalanches frequently, but not necessarily, originate as hard slabs. Unstable conditions which develop slowly (such as depth hoar formation), or those depending on a sequence of snowfalls or other meteorological events, allow sufficient time for pit excavations and for instrument studies of changing snow properties. The structural conditions leading to climax avalanches usually can be detected well in advance of the actual avalanche release. These may illustrate a currently unstable snow cover, or, more commonly, one which will become unstable when overloaded by additional snow accumulation.

Certain relations of snow stresses and strength properties are amenable to quantitative analysis (Roch, 1956). Such analysis provides criteria for estimating avalanche hazard, but solves only a part of the complex mechanical problem of avalanche release. In forecasting avalanches from structural observations, everyday practice depends on the empirical comparison of existing snow structure patterns with those known to produce avalanching. (Fracture line observations are the most fruitful source of the latter). This empirical approach has been explicitly adopted where climate and snow conditions are appropriate (Vrba and Urbanek, 1957).

Structural characteristics of the snow cover ultimately are a product of the meteorological environment. If the physical processes of weather influence on snow deposition and metamorphism are clearly understood, it should be theoretically possible to predict snow cover structure from a sufficiently detailed weather history. In practice this is done in general terms, but not with sufficient precison for reliable comparison with avalanche-producing structure patterns. Again, empirical experience and the observer's familiarity with local climate play an important role. An attempt to formulate a basis for quantitatively predicting the important structural feature of depth hoar formation has met with only partial success (Giddings and LaChapelle, 1962).

Where the climate causes climax avalanching to predominate, snow structure analysis provides good forecasting accuracy in the hands of a forecaster whose experience can be developed only by a substantial investment of time and training. Structural analysis loses its effectiveness in those climates which minimize climax avalanching.

Forecasting from indirect evidence

Soft slab avalanches usually run in newly-fallen snow (direct-action avalanches), often involve only the surface snow layer, and may fall over extensive areas of mountainside with only limited reference to wind direction. The avalanche hazard may develop rapidly in a few hours during intense storms, with the new snow sliding off a stable snow cover which does not become involved except where it is swept away by large surface avalanches already in motion. Rapid hazard development and the difficulty of measuring strength properties in newly-fallen snow preclude a meaningful examination of snow structure. Indirect evidence of instability must be sought instead.

Direct-action, soft slab avalanches are forecast primarily form meteorological evidence. Empirical experience has taught that there are a number of contributory weather factors which determine the stability of newly-fallen snow. Forecasting methods have been developed which depend on the sometimes subjective weighing of these contributory factors (U.S. Forest Service, 1961). Eight are recognized as a regular part of forecasting procedures: wind velocity, air temperature, snowfall intensity, precipitation intensity, and new snow depth, crystal type, density and settlement. Other factors appear to be involved as well, such as the degree of riming on falling snow crystals, but satisfactory criteria for their evaluation have not been established. Precipitation intensity has a dominant influence in many situations of hazard development (Atwater, 1952). The depth and surface condition of the existing snow cover are also considered in estimating the hazard from soft slabs.

Avalanche forecasting by meteorological analysis also produces good results in favorable climates and in the hands of an experienced forecaster, who again must be trained at some length. This method alone does not give information about hidden structural weaknesses which may give rise to climax avalanches.

Stability tests in the field

It is the view of avalanche forecasters in the United States that the application of these two basic methods of forecasting, singly or in combination according to climate, does not furnish sufficiently accurate information upon which sound operational decisions can be based. Maintaining a high degree of public safety in ski areas or on highways requires a higher degree of certainty about snow conditions than can be achieved by formal forecasting procedures in the present state of the art. To improve this certainty, the hazard evaluation is *tested in the field.*

The basic criterion of snow instability adopted for these tests is the existence of *tensile stress* in potential slab layers. Though the mechanical conditions determining this stress may be complex, its existence, and its approximate magnitude, are readily indicated by the manner in which cracks form when snow is disturbed on an inclined surface. The propagation of fracturing in snow away from the point of disturbance, whether an avalanche is released or not, shows the existence of tensile stress. Extent and and distance of the fracturing shows its relative magnitude. Practical experience has taught that there is a high degree of correlation between snow which so exhibits tension and the formation of slab avalanches. The recognition of this fracturing under tensile stress can readily be taught to untrained personnel. In fact, skill in this aspect of avalanche forecasting is acquired much more readily than that required to interpret snow structure and weather conditions.

The test for tensile stress is most readily applied to soft slabs, where the passage of a ski usually provides sufficient disruptive force to initiate fracturing. Correlation between stress evidence and soft slab avalanching is high, just in those circumstances where structural evidence of instability is difficult to obtain. Field-testing for stresses in soft slabs thus provides the direct evidence to supplement that gained indirectly by meteorological observations. Such testing customarily is done on short, steep *test slopes* whose slope angle and exposure imitate those of the large and more dangerous avalanche paths. Stringent safety precautions are observed to reduce the possibility of accident in case of avalanche release.

Field-testing of hard slabs requires a more vigorous disruptive force. Explosives are usually required to obtain a more satisfactory test. The results sometimes are less clearly related to general snow stability, but valuable information still is gained to supplement structural observations. It has become accepted practice in the United States to use artillery as well as hand-placed charges for this purpose. Gunfire thus is sometimes deliberately used to test stability as well as to eliminate known hazard conditions. Where circumstances permit, soft slabs as well as hard slab conditions are also tested in this fashion. In both cases, test by artillery offers the advantage of rapid access to distant or dangerous slopes. It is useful only during good visibility, when the results (fracturing as well as avalanche release) can be closely observed. The judicious interpretation of results from test skiing or exploratory artillery fire depends on accurate records of avalanche occurrence, for slopes which earlier have been relieved of their burden of snow will react differently than those which have not.

The synthesis and its relation to climate

Avalanche forecasting today is a practical synthesis, based on both direct and indirect evidence of snow stability which may be further checked by field tests. The fact of this synthesis has been recognized in the design of modern avalanche forecasting and control methods (Schaerer, 1962). On the other hand, there have been occasions when misinterpretation of forecasting principles has led to wrong observation methods for a particular climate. The latter is especially true of forecasting from indirect evidence, when the limitations of this method have not been recognized, or its application has been too formalistic. Difficulties also arise when overemphasis is placed on structural investigation to the point of excluding consideration of winter storm characteristics.

The relative weight which should be given to these methods of avalanche forecasting is largely determined by climate. Diverse examples of this determination are found in the mountain regions of the western United States, which extend over nearly 15° of latitude and encompass both maritime and continental climates. Roch (1949) recognized three major snow and avalanche zones in the western United States: High Alpine, Middle Alpine and Coastal Alpine. These broadly correspond to areas 3, 4 and 1, respectively, in figure 1. The subsequent compilation of data from these areas on snow cover and avalanche characteristics furnishes the following examples of the relation between climate and forecasting methods.

The Pacific Coast

Mountain altitudes are generally under 2 500 meters except in parts of the Sierra Nevada Range, precipitation is heavy, and winter temperatures mild. Annual snowfall varies from 15 to 25 meters, large quantities may fall in a single storm, and snowfall intensities as high as 30 cm per hour have been observed. Snow covers are deep and often very firmly consolidated. Direct-action soft slab avalanches are common. Rain may fall at any time during the winter, and a significant cause of major avalanching is rain which immediately follows a deep fall of new snow. Avalanches which slide off a rain-generated ice layer in the snow cover are also frequently seen. High storm winds and extensive rime formation are encountered above timberline (1 500-2 500 meters). Lower layers of the snow cover achieve ram resistances of several hundred kilograms by mid or late winter. The ram penetrometer thus is useful for collecting snow structure data only in the upper snow layers.

Forecasting of both dry soft slabs and rain-induced avalanching is predominantly based on weather observations. Air temperature telemetry from mountain tops is considered an essential forecasting aid, for it warns of the onset of thaw or rain accompanying a warm front. The principal concern about snow structure is for ice layers which may provide a good sliding surface.

Lower temperatures at altitudes above 3 000 meters in the Sierra Nevada Range modify these conditions in spite of the low latitude.

The Coastal Transition Zone

This zone encompasses some eastern parts of the coast ranges (not shown separately in fig. 1), the Blue Mountains of Oregon, and Northern Idaho and northwestern Montana. The winter climate is drier and colder than along the Pacific Coast, but snowfall is still moderately heavy. Snow covers tend to be stable and direct-action avalanches predominate, but climax avalanches occasionally fall. Winter rain is much rarer than in the coastal mountains. Forecasting depends mainly on the analysis of weather factors.

The Rocky Mountains

This zone includes much of Colorado, and parts of Wyoming and Montana. Altitude range is 2 500 to 4 000 meters, annual snowfall generally less than 8 meters, and very low winter temperatures are common. Timberline is around 3 200 meters in Colorado. High winds are frequent, both during snow storms and in fair weather. In all but sheltered valleys, snow drifting is extensive. Depth hoar formation is almost universal throughout this region. Heavy snowfalls are rare, but very deep wind drifts may accumulate in a few hours. Principle avalanche type is a hard, wind-drifted slab sliding off poorly consolidated snow or depth hoar. Avalanching is markedly confined to lee slopes. Slab avalanches may originate in surprisingly thick stands of trees below timberline.

Similar, though less cold and severely continental, climate is found in southern Utah. A peculiar precipitation pattern there brings maximum snowfall in the autumn and spring, but very little in mid-winter. Depth hoar formation is extensive.

Avalanche forecasting depends heavily on observations of structural weaknesses in the snow cover. Comprehensive studies on the relation of snow structure to avalanche formation in the Colorado Front Range have demonstrated that in this climate ram profiles furnish an accurate picture of snow cover stability (Borland, 1952-1960). Recording anemometers are also essential, for, given a weak existing snow structure, the immediate cause of most hazard is the deposition of hard slabs by wind.

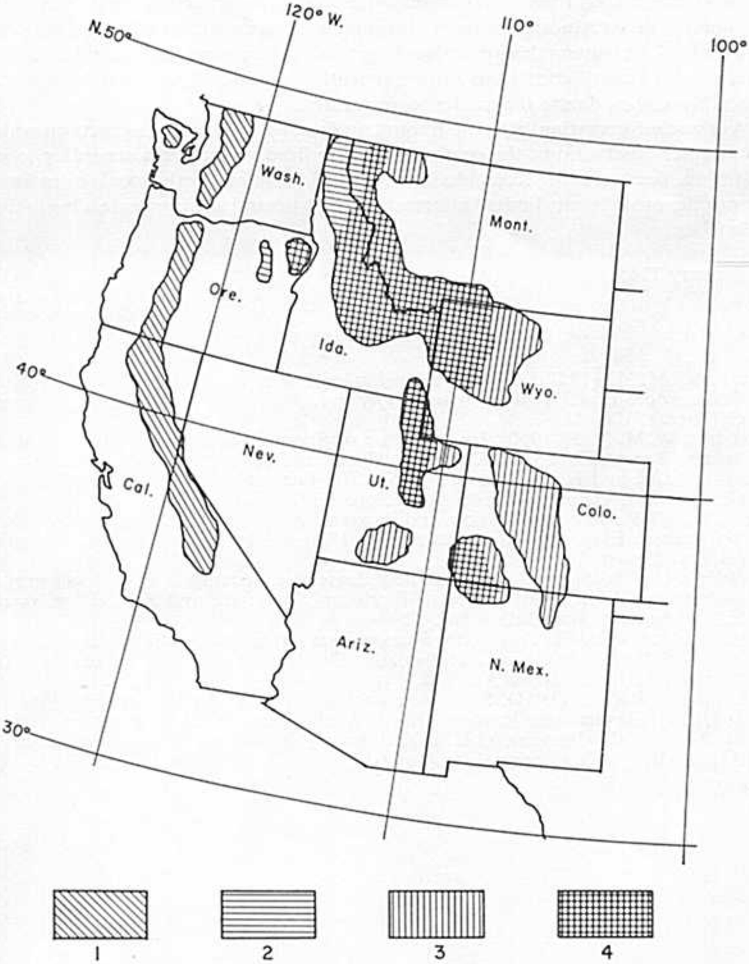

Fig. 1—Predominate avalanche types and applicable forecastng methods in the mountainous areas of the western United States. 1) Generally deep and stable snow covers. Extensive surface avalanching, with possibility of melt or rain throughout the winter. Avalanching forecasting by meteorological observations. 2) Often stable snow covers, extensive surface avalanching, melt or rain rare in mid-winter months. Forecasting largely by meteorological observations. 3) Shallow, unstable snow covers with depth hoar formation common and climax, hard slab avalanches frequent. Forecasting largelyby snow structure analysis. 4) Conditions of 2) and 3) may overlap, with one or the other usually predominating in a given winter. Forecasting actively combines meteorological and snow structure observations.

The Intermountain Zone

This zone is located in Utah, Idaho, Southwestern Colorado, and Western Wyoming, between the Rocky Mountains and the Coast Ranges. Altitudes vary from 2 000 to 3 000 meters. Annual snowfall averages 7.5 to 15 meters, temperatures are mild compared with the Rocky Mountains, but mid-winter thaws or rain are rare. Wind storms are distinctly less frequent and less intense than in the high Rockies. Snow cover stability varies widely from season to season. Soft slab, direct-action avalanches are very common, while structural weaknesses leading to climax avalanche formation occur in about half of the winters. Major avalanching tends to be extensive, rather than confined to lee slopes. Hazard conditions form frequently, but do not persist as long as in the Rocky Mountains due to the milder temperatures.

Avalanche forecasting in the Intermountain Zone depends on both structural evidence and weather observations, the emphasis shifting from year to year according to snow conditions. Because snow accumulation is deep and soft, ram resistance is often low and ram profiles provide only limited information on structural weaknesses leading to climax avalanches.

January 1965.

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