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SNOW AVALANCHES: A REVIEW OF CURRENT RESEARCH AND APPLICATIONS

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ABSTRACT. Snow avalanches have long been an active area of applied glaciology. Empirical and traditional methods of forecasting and controlling avalanches are gradually giving way to the application of modern science and engineering. There are four areas of this science where progress is being made through active interaction among scientists, engineers, and practical men. The artificial release of avalanches as a control measure has seen a large body of research regarding effects of explosives on snow but still is handicapped by inadequate basic knowledge about avalanche release mechanisms. There is currently a surge of interest in testing numerical methods of avalanche forecasting and several sophisticated statistical techniques have been introduced, but operational forecasting still depends largely on empirical experience. The pressure of development on alpine lands has brought to the fore a number of problems associated with mapping avalanches, determining their return intervals and deducing their behavior from both observations of terrain and vegetation and calculating their behavior from theory. The ability to predict the characteristics of moving avalanches is advancing through a combination of theoretical insights and field observations, but is inhibited by the difficulty of the latter.

RÉSUMÉ. *Avalanche de neige: un état de la recherche actuelle et de ses applications.* Les avalanches de neige ont longtemps été un secteur actif de la glaciologie appliquée. Des méthodes empiriques et traditionnelles de prévision et de contrôle des avalanches ont progressivement ouvert la voie à l'application de la science et des techniques de génie civil modernes. Il y a quatre domaines de cette science où des progrès sont en cours grâce à d'actifs échanges entre les savants, les ingénieurs et les praticiens. Le déclenchement artificiel des avalanches comme mesure de contrôle a suscité un volume important de recherches sur les effets des explosifs sur la neige, mais reste handicapé par le manque de connaissances de base sur les mécanismes du déclenchement des avalanches. Il y eu récemment un regain d'intérêt pour l'essai des méthodes numériques pour la prévision des avalanches et plusieurs techniques statistiques sophistiquées ont été introduites, mais la prévision opérationnelle dépend encore largement de l'expérience empirique. La pression du développement des régions alpines a mis en avant nombre de problèmes liés à la cartographie des avalanches, à la détermination de leur fréquence, à la prévision de leur comportement à partir des observations du terrain et de la végétation et de calculs théoriques. La possibilité de prévoir les caractéristiques des avalanches en mouvement est en progrès grâce à une combinaison de vues théoriques et d'observations de terrain, mais elle est génée par la difficulté de ces dernières.

ZUSAMMENFASSUNG. *Schneelawinen: Eine Übersicht laufender Untersuchungen und Massnahmen.* Schneelawinen waren lange ein Forschungsobjekt der angewandten Glaziologie. Empirische und traditionelle Methoden der Vorhersage und Überwachung von Lawinen werden jedoch schrittweise von der Anwendung moderner wissenschaftlicher und ingenieurtechnischer Verfahren abgelöst. Es gibt vier Bereiche in diesem Forschungszweig, wo durch das aktive Zusammenwirken zwischen Wissenschaftlern, Ingenieuren und Praktikern Fortschritte erzielt wurden. Die künstliche Auslösung von Lawinen als Vorbeugungsmassnahme hat zu intensiven Untersuchungen über die Wirkung von Sprengstoffen auf Schnee geführt, leidet aber immer noch unter dem Mangel an Grundkenntnissen über den Mechanismus der Lawinenauslösung. Derzeit lässt sich starkes Interesse an der Erprobung numerischer Methoden für die Lawinenvorhersage beobachten und einige ausgeklügelte statistische Rechenverfahren wurden eingeführt; doch muss sich die praktische Vorhersage immer noch auf die Erfahrung im Felde stützen. Die Entwicklung in Gebirgsländern hat eine Reihe von Problemen aufgeworfen, die sich auf die Kartierung von Lawinen, auf die Bestimmung ihrer Häufigkeit und auf die Erklärung ihres Verhaltens sowohl aus Beobachtungen des Geländes und der Vegetation wie aus der theoretischen Berechnung beziehen. Die Möglichkeit der Vorhersage der Charakteristiken abgehender Lawinen erhöht sich durch eine Kombination von theoretischen Einsichten mit Feldbeobachtungen, wird jedoch durch die Schwierigkeit der letzteren gehemmt.

INTRODUCTION

In concept if not in name, snow avalanches have long represented one of the most active areas of applied glaciology, for they create broad problems in safety and property protection throughout the inhabited alpine regions of the world. Traditional knowledge and empirical experience have for centuries served as guides for construction, agriculture, and winter alpine travel in face of the threat from snow avalanches. More recently the search for systematic protection and control measures has brought together efforts of scientific research and engineering applications from several disciplines. These efforts continue to be strongly supplemented by empirical experience, especially in the area of avalanche forecasting.

The treatment of snow avalanches in the literature is extensive but widely scattered in scientific and engineering journals, government reports and research papers. Most of the relevant literature is found in English, French, German, Russian and Japanese. There are few comprehensive summaries and no textbooks which deal exclusively with avalanches. The classic introduction to the subject is the well-known work of Seligman (1936), dated in some respects in the light of the subsequent 40 years of research but still rich with valuable insights. A succinct, semi-popular overview with a well-balanced treatment was prepared by [Bucher and others] ([1940]). The most comprehensive recent review of the subject is that by Mellor (1968), who gave a valuable summary of the literature to that date, covering snow properties, avalanche formation, forecasting and control measures with added emphasis on snow mechanics. Most recently, Perla and Martinelli (1976) have compiled a practical manual of forecasting and control which touches on many relevant aspects of avalanche science. For a more restricted overview of the engineering and practical problems of avalanche defense construction, the compilation by Castelberg and others (1972) is especially informative.

This present review is not intended to be comprehensive. Rather, it addresses only those areas of current research which are related to the most pressing problems of application and hence stand especially clear as examples of applied glaciology in the field of avalanche science. One area of interest which clearly fits this category is omitted in the following discussion, the creep and glide of the snow cover and engineering problems related to the consequent snow forces. This topic is reviewed separately in the present Symposium. The four areas of concern here are the artificial release of avalanches, numerical methods of avalanche forecasting, avalanche mapping and zoning, and the dynamic behavior of moving avalanches.

Artificial release of avalanches

Artificially initiating the fall of avalanches is a standard and widely deployed method of reducing avalanche hazard. It is often used today for the protection of highways, railways and ski slopes, all in circumstances where the traffic can be restricted or diverted while the avalanche falls. For obvious reasons this technique has little attraction for protecting fixed structures which cannot be removed from the fall path. In such cases avalanche prevention or diversion is the preferred protective measure. Almost all artificial release measures are addressed to the slab avalanche, where an initiating trigger can propagate snow fracturing over wide areas. Loose-snow avalanches beginning at a point require many initiating events applied at separate points across a slope and hence respond much less efficiently to artificial release. This is especially true for wet loose-snow avalanches, where the time of release is critical. Slab avalanches, on the other hand, tend to develop in snow which remains unstable for appreciable lengths of time, hence the timing of the trigger mechanism is much less critical. In the vernacular of space science, most slab avalanches have a large "launch window".

For the release of unstable snow slabs a triggering mechanism is required which can impart enough mechanical disruption or shock to initiate fracturing. Because the degree of instability in snow slabs varies widely, so does the required amplitude of disruption. Diverse means have been used to provide this mechanical disruption, the conventional method of choice being high explosives placed by hand, delivered by aircraft or aerial cableways, or fired as projectiles. Another common technique is to release the more unstable slabs by weight and dynamic loading of a moving skier, unintentionally in the case of many avalanche accidents and intentionally in the case of organized control programs at ski resorts, although the latter demands considerable skill and experience for safe execution. There appears to be little limitation on the form of mechanical loading: avalanches have been released by sonic boom, the concussion from energetic explosions, direct displacement by a bulldozer, and even by

"riding them out" with a snow packing tractor, a venture possibly even more hazardous than release by ski-ing.

All of these techniques depend on an uncertain understanding of the way in which a slab avalanche forms. There is much conjecture and theoretical debate about whether a snow slab fractures and becomes an avalanche through first failing in shear at the base or first failing in tension at the top. Clarification of this question undoubtedly would lead to improved application of release techniques. In the meantime, most past and current research related to artificial avalanche release has addressed the questions of how much explosive should be used, what kind, and where it should be placed on the slide path. Conventional practice today calls for explosive charges at least equivalent in energy to 1 kg of TNT. Smaller charges are sometimes used on small, shallow slabs, larger ones on deep, heavy slabs. Highly brisant explosives are strongly preferred, usually for subjective reasons (big noise = big avalanche) but on a reasonable basis since most avalanche blasting is done with charges at or near the snow surface. Some early research on this subject by Fuchs and LaChapelle has been described by Fuchs (1957). These investigators tested different explosive types for effects on fracturing and crater formation in a winter, alpine snow cover. They demonstrated that the most efficient fracturing is obtained by the slower dynamites buried in stemmed shot holes well beneath the snow surface. A similar but far more comprehensive study was later carried out on the surface snow layers of the Greenland ice sheet by Livingston (1968), who studied in detail the effects of 141 test blasts. He established empirical criteria for predicting dimensions of complete rupture in snow for a given explosive charge and introduced an energy utilization number which depends on both the explosive and the material blasted. Livingston found that the dimensions of the apparent crater in snow are not accurately predictable with conventional cube-root scaling.

A basic reference on explosions in snow, though without particular reference to avalanche control, is the work of Mellor (1965), who discusses available theory and field data to that date. His treatment includes cratering, ground shock, elastic waves, blast waves, overpressure and dynamic pressure, with considerable reference to practical applications. Important data on this subject are also found in the little-noticed work of Wisotski and Snyer (1966), who used sophisticated instrumentation to study the character of shock-wave propagation in a winter snow cover. They obtained extensive peak-pressure data above and within the snow from pentolite charges fired both above and within the snow.

More recently, Mellor (1973) has reviewed the basic effects of explosives on snow and discussed recent developments in explosives and their application to avalanche release. He suggests a basis for calculating size and distribution of explosive charges for positive snow disruption and introduces the idea of using non-conventional explosives such as air cartridge blasting and propane–air gas exploders for avalanche release. The gas exploder system has subsequently been developed and successfully field-tested; the results are reported for the present Symposium in a separate paper, which also reports tests of vibrators and air-bag inflation for avalanche release.

Much operational use of explosives for avalanche release today makes use of military projectiles. The most commonly used weapons are the 81 mm mortar, bazooka, 75 mm and 105 mm recoilless rifles and 75 mm and 105 mm howitzers. Though efficient and highly effective for avalanche control, these weapons suffer such disadvantages such as high cost, uncertain availability of ammunition and unwanted side effects (e.g. shrapnel dispersion in the target area). The disadvantages have encouraged the development of several alternative avalanche-control systems. One approach mentioned above seeks to eliminate conventional explosives entirely through use of devices like gas exploders or air bags. Another line of experiments initiated 20 years ago by M. M. Atwater of the U.S. Forest Service has led through several stages of evolution to a highly effective air cannon for firing explosive projectiles. The current model of this weapon, called the "Avalauncher", fires 1 kg charge of pentolite with a

point-detonating fuse over 2 400 m and hence is comparable in performance to the smaller military weapons. Most recently, an innovation developed in Canada (Everts, 1976) has been tested for large avalanche paths in inaccessible locations. This consists of an array of short-range spigot mortars which fire heavy explosive canisters onto an adjacent avalanche-release zone on receipt of a coded radio signal.

Although the body of experimental and theoretical knowledge about effects of explosives on snow cited above is now fairly extensive, the actual application to avalanche-release procedures remains highly empirical and in many cases uncertain. This situation is clearly illustrated by recent concern over the developing number of "post-control releases", incidents where an avalanche slope has been blasted by explosives and found stable as part of a control program, then later has avalanched under skier use without any obvious intervening circumstances which might renew the snow instability. There are numerous reasons why this may occur. Inadequate or misapplied explosive charges are an obvious possibility. The snow slab may have been weakened by the explosion and become more sensitive to later disturbance, less likely but still possible. Metamorphic changes or a shift in the mechanical state of the slab may have gone on unobserved. The only readily apparent common denominator for these incidents is that most involve the presence of depth hoar. The point here is that, given our uncertain knowledge of the mechanisms of slab release, the explanation of post-control releases becomes elusive. But the problem is an important safety concern for ski resorts, and the practical man who must deal with it has little guidance except the rule of thumb: when in doubt, use a larger explosive charge. This approach has economic and practical limitations. Such situations have led to a renewed interest in the basic behavior of explosives in snow. The most recent initiative in this respect has been a serious investigation organized in Switzerland (personal communication from H. Gubler). The obvious conclusion can be drawn that empirical improvements will continue to be made in artificial release methods, but no real advance can take place until a better fundamental understanding is gained of avalanche release mechanisms.

Numerical methods of avalanche forecasting

As long as men have dwelled in mountains, avalanches have been forecast in one manner or another, even by appeals to witchcraft when no other resources were available. Experienced mountain men have long been able to develop an intuitive grasp of unstable snow conditions through experience and tradition. It is only in the past half-century that scientific attention has focussed on methods of forecasting, but with only a modest degree of success—most operational forecasting today still depends largely on empirical experience. A complete review of trends in forecasting theory and practice is beyond the scope of this present paper and will be developed elsewhere. Some of the principles have been outlined by LaChapelle (1966, 1970). Summarized in brief, there are two basic sources of information about avalanche formation: meteorological elements and internal structure of the snow cover. Typical forecasting procedures utilize both, but the emphasis shifts with climate and type of avalanche. The procedures are further divided into two categories: causal–intuitive and statistical. The former applies knowledge of physical cause-and-effect in the snow cover to deduce qualitatively conditions of instability. The latter depends on quantitative analysis of accumulated past weather, snow and avalanche patterns to predict future ones. There is still a notable lack of codification of forecasting methods. Bois and Obled ([1972]) found this to be the case when they investigated the use of snow climate data as a tool for avalanche forecasting:

> "Pour cela nous avons interrogé les spécialistes de l'Institut Suisse de Davos et quelques spécialistes français. Le moins que l'on puisse dire est que certaines divergences apparaissent."

In recent years a strong effort has developed toward putting avalanche forecasting on a quantitative and verifiable basis. Such effort can be subsumed under the general category of numerical forecasting, which includes predominantly statistical analysis of accumulated data but is not limited to this. Various statistical approaches have been proposed and tested; none is yet fully developed nor applied on a fully operational basis. The data dealt with are largely meteorological, for these are available on a reasonably consistent, objective and long-term basis. Researchers in this field have not yet surmounted the problem of quantifying snow-structure data in a form which can be manipulated statistically. A further weak link is the problem of accurately recording avalanche occurrence and presenting this information in a form amenable to analysis.

The current trend toward statistical analysis began with the work of Obled (1970) and Perla (1970). Obled introduced an elementary index method of utilizing meteorological parameters to identify avalanche days for a limited region. (An avalanche day is marked by the fall of at least one avalanche.) As parameters he used the five-day moving sum of precipitation and the cumulative precipitation since the beginning of a storm period, and then adjusted for daily snow settlement as deduced from temperature. Perla examined 20 years of data for a limited number of adjacent large avalanche paths with common orientation and quantified avalanche occurrence by summing the size numbers of all avalanches for a given event. He then constructed scatter diagrams of occurrence versus several contributory factors and found that precipitation and prevailing storm-wind direction were the best indicators of avalanching.

The next step to improve statistical methods came in a research paper published by Bois and Obled ([1972]) which was based on an analysis of 15 years of snow, weather and avalanche data from the Parsenn area of Switzerland. These authors applied the method of principal components to sort preferentially 17 retained snow and weather variables and to treat these by discriminant function analysis to sort avalanche from non-avalanche days. This work dealt only with natural avalanches (artificial release complicates the problem) and was to some extent handicapped by uncertainties in the historical record of avalanche occurrence (personal communication from W. Good). Working with different climate and terrain, Judson and Erickson (1973) also introduced a discriminant-function model to analyze accumulated data for Berthoud Pass, Colorado and vicinity. They coupled their model with a linear regression analysis to show that unstable conditions could be sorted from stable ones by a linear combination of data for precipitation intensity, wind-speed resolved to optimum direction for each avalanche path, and the sum of negative temperature departures from −6.7°C. They also developed a storm index utilizing precipitation intensity modified by wind-speed to predict the number of avalanches on 23 selected paths which in part were subjected to artificial release.

A further basic improvement came with the subsequent work of Bois and others ([1975]). They continued the use of discriminant function analysis but introduced elaborated variables which they felt to be physically better related to the avalanche phenomena than simple snow or meteorological parameters. The first step was thus taken to introduce physical understanding of cause-and-effect in avalanche formation to the hitherto purely statistical treatments. As examples, their elaborated variables included absorbed radiation flux per day and cumulative number of avalanche days since the start of the winter. In the meanwhile, Bovis (1974) had also addressed the problem using a more limited sequence of data from the San Juan Mountains of Colorado. He also adopted the discriminant-function approach and was able to draw on high-quality observations to improve his treatment of the avalanche data by stratifying avalanche occurrence according to size, type and natural versus artificial release. More recently, Bovis (1977) has extended his treatment with an enlarged data base.

These developments have placed a strong emphasis on discriminant-function analysis. A notable departure from this trend is the attack by Salway (unpublished) on accumulated

data for the Rogers Pass area of the Trans-Canada Highway in British Columbia. Salway turned to a sophisticated time-series model for correlating avalanche occurrence and weather factors. This allowed a fully-developed consideration of the fact that avalanches do not fall in response to isolated meteorological events, but rather result from the cumulative effects of weather and snow development. Salway introduced autoregressive integrated moving averages in a manner which exploits intercorrelation of the variables to considerable advantage. He also improved quantification of avalanche occurrence data by using run-out distance to describe size, thus substituting for the usual nominal scale a ratio measurement which is theoretically better suited to statistical treatment. Of considerable interest is his finding of a significant correlation between atmospheric humidity and avalanche occurrence, a much debated topic in avalanche forecasting which extends clear back to the work of Seligman (1936).

Researchers in the field of statistical avalanche forecasting uniformly agree that this approach will not provide a 100% basis for forecasting. Rather it is thought that a sound statistical treatment of accumulated past data will provide the forecaster with a framework which he can further modify for individual situations according to physical analysis and accumulated experience. The full application of this combination for operational use has yet to be developed. It is noteworthy that some current operational forecasting centers which are under pressure to produce practically useful avalanche warnings have not turned to the statistical approach at all, but rather have concentrated on improvement of specifically targeted mountain meteorological forecasts. This reflects the common understanding that an avalanche *forecast*, as distinguished from an *evaluation* of current conditions, is no better than the relevant mountain weather forecast. There presently is a strong trend in this direction in the United States, exemplified by the work of O. Rhea in Colorado and F. W. Reanier in Washington State. Reanier (unpublished) has described techniques for quantitative precipitation forecasts which are currently being tested for the Cascade Mountains of western Washington. These depend on the local modification of computer-generated numerical weather forecasts prepared by the National Weather Service from theoretical models of global circulation. Both the numerical forecasts and their local modifications for avalanche forecasting are improving in sophistication and accuracy, leading in a round-about fashion to numerical avalanche forecasting with a sound theoretical basis.

Avalanche mapping and zoning

The delineation of avalanche hazard areas and determination of their effects on developing land use at first glance may appear to be a relatively simple undertaking, but in fact this is one of the most difficult and controversial areas of avalanche science. It is here that applied glaciology comes to its full expression as scientific and engineering principles interact with economics, law, social problems and public policy. Owing to an accelerating trend in development and use of alpine lands, avalanche hazards are now coming into increasing conflict with land use. This has brought to the fore problems associated with evaluating avalanche behavior and even identifying the existence of an avalanche threat. A good introduction to the subject, including social and political ramifications, is given by Frutiger (1970). General guidelines to the identification and evaluation of avalanche sites have been compiled by Martinelli (1974). A method of map delineation has been discussed by Cazabat (1972).

A practically useful avalanche-path analysis must bear information about maximum current extent of avalanche areas, maximum probable extent (overruns of existing paths inevitably will occur), historical record of avalanche activity, expected recurrence interval of avalanches of various sizes, and estimations of impact pressures on objects which may be exposed to overrun by avalanches. Determining these factors is complex and difficult; hence

any given analysis seldom furnishes optimum information on all of them. The first consideration is terrain. If slopes are steep enough, a potential for avalanche fall always exists. If the slopes are long enough, large avalanches must always be considered. Many steep slopes never avalanche for complex reasons of topography, climate and vegetation. It is the vegetation which usually provides the most direct evidence of avalanche extent and frequency, thus the effects of avalanches on vegetation (and vice versa) has been the topic of considerable study in diverse mountain climates around the world. In chronological order, studies of particular interest on this subject have been carried out by Potter (1969) in the northern Rocky Mountains of the United States, Gorchakovskiy and Shiyatov (1971) in the high Urals of Russia, Wakabayashi (1971) in the northern Japanese island of Hokkaido, Schaerer (1972) in the Selkirk Mountains of Canada, and Smith (unpublished) in the North Cascade Mountains of the United States. These workers have sought to identify the relation between species distribution in an avalanche path and avalanche occurrence frequency. In some instances they have introduced dendrochrology as a tool for dating past avalanches and establishing average return intervals. The strength of the dendrochronological method has recently been demonstrated by C. J. and V. L. Burrows (personal communication), who were able at one avalanche path in the San Juan Mountains of Colorado to date 24 major avalanches which had occurred since 1795 and to demonstrate periodic clustering of avalanche activity during the intervening 181 years.

The problem of determining avalanche return intervals is an acute one for land-use planning. There are many marginally hazardous zones which are exposed to avalanche damage only at long intervals of 20, 50 or perhaps 100 years. In order to establish risk criteria for development, the probability that an avalanche will reach the area in question must be determined. If several hundred years of accurate record exist, then this probability can easily be calculated. Even in traditionally populated regions like the European Alps, high-quality information of this nature tends to be scarce. In most mountainous regions of the world it is non-existent. Most often the return interval is not known from direct records but must be inferred from vegetative evidence, terrain characteristics and knowledge of local avalanche behavior. Such inferences can also be supported by adequate precipitation statistics but suffer further from the likelihood of secular climate changes which may alter the return interval over significantly short periods of time, hence the kind of work demonstrated by the Burrows becomes especially valuable. The land-use planner who must distinguish a high-hazard zone (high impact forces, short return intervals) from a moderate-hazard zone (low forces and/or long intervals) or from safe areas thus must depend on probability estimates which often are little better than educated guesses. The only fundamental analysis of this problem is that of de Quervain (1974), who examines the concepts of high-, medium- and low-hazard zones in respect to recurrence intervals for avalanche releases of various fracture-line heights (determination of avalanche size) and consequent runout distances. He suggests criteria for determining the return intervals for different runout distances and introduces the useful category of the acceptable residual risk. This paper deserves more attention from avalanche-zoning analysts than it has received to date.

Another avalanche-zoning problem closely related to return intervals is the determination of avalanche runout distances and impact forces on exposed objects. In principle these ought to be determined by terrain configuration and local snow characteristics, but in practice they are often uncertain owing to the limited information on avalanche dynamics. This whole subject is sufficiently important to the modern development of avalanche science that it is reviewed separately below.

Current practice in avalanche mapping and zoning draws on a multi-disciplinary approach which compiles evidence from a variety of sources, each often fragmentary, to reach reasonably workable overall conclusions. A recent example of this approach is found in the work of Ives and others (1976), who made use of historical data, vegetation analysis, dendrochronology,

infra-red aerial photography, debris mapping, tree damage and calculation of avalanche dynamics to determine avalanche type, frequency and runout distance for a major avalanche path affecting development of the town of Ophir, Colorado.

Dynamics of moving avalanches

A very active area of avalanche research concerns the behavior of moving avalanches. This has both intense scientific interest and critical practical value. The flow of a compressible, non-homogeneous, two- or three-phase medium is a challenging theoretical problem. The problem is further complicated by the existence of two different modes of avalanche flow: surface avalanches where the snow particles are in continuous contact, and powder avalanches where the particles are dispersed in the air. It also presents an extremely difficult observational problem, for avalanches are erratic, short-lived and often destructive phenomena. The calculation of flow velocity, runout distance and impact force are constantly recurring practical problems in avalanche zoning and the design of structures which must resist moving avalanches. Today there are active parallel developments of basic theory and refinements of engineering formulae for calculating avalanche behavior. The collection of hard observational data lags behind, but only because such data are so difficult to obtain; more information is gathered from avalanche effects measured after the event than from direct measurements during an avalanche fall.

Means of computing avalanche behavior have developed along several lines over the past 40 years. Moskalev (1966) gives a good summary to that date, with emphasis on Russian efforts. He describes the work in the late 1930's by A. G. Goff and G. F. Otten, which is still used as the basis for engineering calculations of avalanche behavior in the Soviet Union. This appears to represent the earliest development of a scientific approach to dealing with moving avalanches. In Western countries, most treatments of the subject have stemmed from the fundamental work of Voellmy (1955), who began by systematically examining the destructive effects of avalanches and calculating the forces that were required to cause the observed destruction. He then went on to develop a theoretical basis for calculating avalanche behavior under the basic assumption that to a first approximation flowing snow could be considered to behave like flowing water, and hence the principles of hydraulics could be applied.

The assumption of a basic analogy between flowing snow and flowing water underlies much of avalanche dynamics as it is applied today. But there have been other approaches to this problem, none of which has yet received the accolade of widespread practical application. Moskalev (1965) and other Russian workers have derived calculations based on the assumption that the snow moves as a rigid body. Losev (1965) criticized this approach, pointing out that its validity is limited to special cases like falling cornices or the initial motion of a snow slab. He notes that avalanches in general must be treated as fluid flow and cites katabatic winds, turbidity currents and mudflows as more useful analogies. A theoretically much more rigorous method was adopted by Tebuyev and Khalkechev (1967), who applied the hydromechanics of compressible fluids from the viewpoint of energy conservation to calculate avalanche velocity and impact force. These authors deduce that the dynamic coefficient of viscosity can be calculated if variations in temperature and amount of free water plus velocity distribution in the moving avalanche are known. The practical limitations of this approach are obvious, for these are highly inaccessible quantities. They also derive a very complex expression for impact pressure which includes such terms as the temperature and density of the snow immediately before and after impact. In the case of avalanche dynamics, rigorous theory alone has had limited practical use.

The most significant extension of Voellmy's work has come from the theoretical studies of Salm (1966, 1968). He has introduced several considerations, including the effects of velocity on the frictional forces among snow clods in a moving avalanche, the application of hydraulic

principles to calculate non-uniform flow, and the calculation of forces assuming that snow behaves like an ideal dry sand. His work has shown that surface waves cannot propagate in flowing snow and that under certain conditions it is impossible to stop a flowing avalanche with an artificial obstacle. In 1970, Shen and Roper (1970) published a paper which introduced a two-dimensional dynamic model based on fluid mechanics and confirmed Voellmy's estimates of friction coefficients. They also showed that a comparison with known behavior of density currents essentially confirmed the methods of Voellmy. The first independent investigation of avalanche dynamics through model studies in the laboratory has come from Tochon-Danguy and Hopfinger ([1975]). They used the turbidity currents of saline solution in water as a model of powder avalanches and were able to demonstrate velocity distributions and characteristics of the avalanche front.

For practical engineering applications, a useful summary of the Voellmy approach has been prepared by Sommerhalder (1966). This provides a concise, step-by-step description for the calculation of avalanche behavior with consideration for different types of terrain. In 1971, E. Sommerhalder (unpublished annotation) amended the terminology and introduced minor modifications based on the work of Salm. Similar practical guidelines with more thorough discussion have recently been prepared by Mears (1976). This also reviews general considerations for analyzing and mapping avalanche paths. The Voellmy approach common to all these applied methods suffers from a conceptual difficulty in the formulation of the coefficient of turbulent friction in such a fashion that increased friction is accompanied by increased avalanche velocity. Strictly speaking, the Voellmy coefficient is an inverse one.

Recent developments in avalanche dynamics with practical effects have come from observations of actual avalanche behavior. Schaerer (1973) installed load cells in an avalanche path near Rogers Pass, Canada, and determined that for relatively low velocities (15–25 m s^{-1}) and small loading surfaces, dry-snow avalanche impact pressure could be calculated from avalanche velocity and density of the deposited snow. Expanding his observations to include records of avalanche velocities on several paths, Schaerer ([1975]) was able to show that the coefficient of kinetic friction for sliding snow was a function of the velocity. Moreover, he was able to collect enough data to deduce independently the average values for Voellmy's coefficient of turbulent friction and found that these were over twice the ones recommended by Voellmy (1955) and other workers. He also found that this coefficient was virtually independent of whether the avalanche moved over new snow or old. The publication of Schaerer's 1974 paper had an immediate impact on practical estimation of avalanche behavior, especially since his results came from the independent observation of actual avalanche velocities rather than theoretical deductions. Raising the values of the coefficient of turbulent friction raised the corresponding calculated velocities, runout distances and impact pressures, other parameters being equal. Engineering design necessarily tends to be conservative, hence when higher values of this coefficient were demonstrated to exist, there has been an overwhelming compulsion to use them.

Designers and engineers concerned about these escalating magnitudes of calculated velocities and forces can find little comfort in the observational data collected by Shimizu and others (1972, 1973, 1974) in the Kurobe gorge of the Japanese Alps, an area noted for its formidable avalanches. These investigators installed a series of increasingly sophisticated instruments to measure impact forces in the lower reaches of the Shiai-dani and Azowara-dani avalanche paths. The first winter their equipment at Shiai-dani was swept away, yielding only partial estimates of forces exceeding 47 Mg m^{-2}. During the second winter, one of light snowfall and avalanche activity, forces ranging from 101 Mg m^{-2} to 139 Mg m^{-2} were observed. The third winter brought unusually heavy snowfall and avalanches. The maximum impact force recorded was 201 Mg m^{-2}, the maximum impulse 389 Mg s m^{-2}, and the maximum excursion of atmospheric pressure during passage of an avalanche −21 mbar. These are forces large enough to give pause to even the most resolute engineer. While it may be argued that normal

design considerations would be unrealistic to consider such large forces, for surely no one would choose to erect any kind of structure in the middle of such major avalanche paths, nevertheless quite the contrary was true at one of these sites. Shimizu and his colleagues located their instrumentation at Shiai-dani on the partially destroyed, reinforced concrete understory of a three-story construction barracks. In 1938 this barracks was struck by an avalanche which carried away the superstructure on a 600 m aerial trajectory across an intervening ridge, across the Kurobe gorge, and smashed it against a rock cliff on Mt Okukane, carrying to their deaths all 73 occupants.

It is instructive to compare these large impact forces with a theoretical suggestion advanced by Bryukhanov and others (1967). A number of researchers have pointed out that the development of a shock wave in the air in advance of an avalanche is impossible because avalanche velocities are always less than that of sound in air. (This topic is discussed, for instance, in the paper by Shen and Roper cited above.) Bryukhanov and his colleagues noted that the sound velocity in a snow–air mixture of certain density range may be less than observed avalanche velocities and hence it is possible for a shock wave to propagate *within* the flowing avalanche. They calculated the effects of this supersonic flow on impact forces and showed that for a sufficiently high combination of velocities and densities, pressures in excess of 200 Mg m^{-2} could be expected.

The most recent efforts in field observations have returned to the original approach of Voellmy. Mears (1975) has analyzed the factors affecting Voellmy's velocity equation and shown that variations in estimated values of these factors can cause calculated impact forces to vary over a range of 4 : 1 and total force on an object over a range of 8 : 1. In an effort to reduce these uncertainties, he has examined tree damage from wet-snow avalanches to determine flow height and impact forces and gone on to show that coefficients of turbulent friction deduced from these data are consistent with the findings of Schaerer ([1975]). In order to seek an independent check on runout distances, Bovis and Mears (1976) have examined 67 avalanche paths in the Rocky Mountains of Colorado where maximum runout distance could be established from terrain and vegetation evidence. They analyzed their data by statistical comparison with several characteristics of each avalanche path and found that runout distance had a higher correlation with starting zone area than with other path variables. This brings the study of avalanche dynamics full circle. Forty years ago the work of Goff and Otten mentioned above led to an equation for the calculation of runout distance which included a "coefficient dependent on area of the snow basin".

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DISCUSSION

M. R. DE QUERVAIN: A full symposium could be based on the excellent presentation of Dr LaChapelle. We need an objective criterion for *testing* the success of a forecast whether conventional or statistical. Observing avalanche events afterwards does not reveal medium degrees of danger. Proposals would be welcome.

The *frequency* (or return period), used in avalanche zoning, is sometimes taken as the frequency of any avalanche formation in a given avalanche path. Actually we have to deal with the frequency of an avalanche reaching a given point in the path with a given pressure.

E. R. LACHAPELLE: These are good points which have been raised. We need more investigation to answer these questions. One useful test of a forecast is to fire a cannon and see if an avalanche results.