STATISTICAL ANALYSIS OF SNOW STABILITY, ALPINE MEADOWS SKI RESORT, CALIFORNIA

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## ABSTRACT

Time series relationships between meteorologic conditions and avalanche activity were determined for controlled avalanche paths at Alpine Meadows Ski Resort, California. A forecasting model was developed using least squares multiple regression techniques to forecast avalanche activity based on the U.S. Forest Service avalanche size classification, the crown fracture height and the percentage of the avalanche path the avalanche slide.

## INTRODUCTION

Avalanche forecasting in North America relies extensively on forecaster experience, using meteorologic measurements and direct physical evaluation of snow-pack stability. Due to the interaction of many meteorologic, snow-pack and terrain variables the formation of a deterministic model for avalanche activity is difficult. Most previous statistical studies have used large regional databases of avalanche occurrence. Alpine Meadows records provide a detailed database of avalanche activity on 200 avalanche paths which permits the statistical analysis of individual controlled paths in terms of the magnitude of an avalanche event.

### Objective

The primary objective of this study was to identify the meteorologic and terrain variables that correlate to avalanche activity on several avalanche paths that are characteristic of most of the avalanche paths at Alpine Meadows. Determination of the time series relationships of variables to snow-pack stability was important in understanding the cumulative effects of meteorologic conditions. A secondary objective of this study was to create a statistical forecasting model to assist the forecasters in predicting snow-pack instability. In addition to evaluating snow-pack instability with a binary criteria of "yes" or "no" on whether an avalanche occurred, the Alpine Meadows data set was also evaluated for avalanche activity in terms of run-out distance, the Forest Service avalanche classification, and the crown fracture height.

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Previous Forecasting Models

Avalanche forecasts are based on the ability of an avalanche forecaster to empirically predict snow-pack instability (LaChapelle, 1974). Because of the complex nature of avalanche release mechanisms only a probability and not an exact determination of snow-pack stability can be determined. The avalanche forecast can be based on direct observation of the snow-pack characteristics, indirect observations as in the measurement of meteorologic conditions or the prediction of meteorologic conditions. Most avalanche forecasting models have been unable to use snow-pack characteristics because of the lack of large data bases with snow-pack information such as bed surface shear strength. However, several models have been developed with the use of indirect evidence for forecasting avalanche activity. These can be divided into the following four general types: deterministic, process-oriented, statistical and artificial intelligence models.

A deterministic model which describes the relationships between variables using equations based on physical laws would be preferred in avalanche forecasting. Unfortunately the variety of variables involved has made the development of such a model difficult. The Roche Stability Index is an attempt to measure directly the load of the snow-pack against the shear strength of the failure plane. This ratio is referred to as the Mohr-Coloumb relationship where a value of one or greater represents increasing stability and values less than one, decreasing stability. Attempts to use this index of stability have been predominantly unsuccessful because of erroneously high factors of safety obtained from snow-packs adjacent to snow-packs which have avalanched (Sommerfield and others, 1976; Stetham and Perla, 1980). The lack of successful test results might be attributed to the shear frame which might inadequately measure the poorly understood strengths of snow and thus is ineffective in evaluating the shear strength of the weak layer.

A process oriented model based on a stream-flow model has been proposed by Judson and others (1980) to simulate winter snow accumulation, snow-pack conditions in terms of its energy balance and free-water requirements, and resultant snow melt in time and space. The authors felt that a process oriented approach would more accurately evaluate and incorporate snow available for transportation that can be removed before the wind drops its threshold speed for snow grain transportation.

When deterministic relationships are unavailable to characterize an event such as snow-pack instability, statistical methods are useful for identifying and modeling avalanche activity. Probability theory has been applied Judson and King (1985) for avalanche forecasting. Moreover, multivariate techniques have been used by several researchers. Multiple regression models have been used by several authors (Bovis and others, 1977) including time series models by Salwy and Moyse (unpublished). Due to the clustering of avalanche activity into several types dynamic cluster analysis and discriminant have been used by several authors Good and Obled (1977), Drozdovskaya (1979), Bois and others (1974), Good and Obled (1977), Fohn and others (1977). Many of these have used principle components including factor analysis to handle the meteorologic variables. Because of the non-parametric nature of meteorologic and avalanche variables, authors including Buser and Good (1984) have used nearest neighbors discriminant techniques.

## DATA

Alpine Meadows Ski Resort is located in the Sierra Nevada approximately 350 miles east of the Pacific coast, at a latitude of 39°10'N, four miles west of Lake Tahoe. The resort ranges in elevation from 7000 to 8637 feet and is influenced by a maritime climate accompanied with high winds creating a warm snow-pack averaging 400 inches/year. Most of the resort is located directly northeast of the Sierra Nevada Crest which is perpendicular to the predominant SW storm path. According to the Alpine Meadows Avalanche Atlas (unpublished) this creates a natural snow-fence depositing anomalously deep snow-packs on the steep glacially carved cirques and ridges. The maritime environment and lack of temperature gradient metamorphism produces a predominance of direct action avalanches, occurring within 24 hours after a storm and only involve the snow from that storm. Because of this climate and setting Alpine Meadows is classified by the U.S.F.S. as a "class A" (most hazardous) avalanche area. This requires Alpine Meadows to have among the most rigorous avalanche control programs in the industry.

The winters of 1978-79, 1979-80 and 1982-83 were chosen for this study because of the abundance of avalanche events during these winters. This might restrict the applicability of the final results only to winters with abundant avalanche events, however due to the direct action avalanches in this region the effect is probably minimal. In addition, this data set is too small to optimally constrain the data, however, the regression analysis appears to have adequately constrain most of the data in terms of the database size.

### Meteorologic Variables

Fourteen meteorologic variables were recorded at twelve hour intervals at 6:00 a.m. and 6:00 p.m. (Table 1). All measurements excluding wind speed and direction, which were recorded on the ridge, were taken in the Valley at an elevation of 7000 ft. The air temperature was recorded for the maximum, minimum and current for each 12 hr period. Snow temperature was recorded at the surface and 20 cm below the snow surface. Snowfall was recorded as the depth in inches as well as water equivalence in inches. Moisture content of the snow-pack was recorded in percent moisture. Total snow depth was recorded daily as the total accumulation. Snow settlement was determined using snow boards in the snow study plot. Snowfall and Snow settlement are susceptible to errors in measurement due to drifting and scouring of the snow-pack. Inn addition to these recorded variables many additional variables were drawn from the relationships between variables such as percentage of snow settlement, temperature change, moisture content change etc.

TABLE 1. Recorded variables characterizing meteorologic and snow conditions at the end of the 12 hr measurement period.

| Variable | Description |
|---|---|
| Temperature | |
| TS2 | Snow (20cm below surface) |
| TS0 | Snow ( 0cm below surface) |
| TX | Air Maximum |
| TN | Air Minimum |
| TC | Air 6am recording |
| Wind | |
| WD | Direction |
| WS | Speed |
| Precipitation | |
| PPT | Precipitation (water equivalent) |
| MC | Moisture Content of the 12 hr snowfall |
| S | Snowfall |
| ST | Total (cumulative snow depth) |
| SS | Snow settlement |

t(x) Time of recording for the previous 12 hour recording period, where x represents the number of hours prior to the event.

Avalanche Records

The Alpine Meadows data set is different from previous statistical data sets because all potentially unstable snow-packs have been controlled by artificially releasing unstable snow-packs with either explosives or skier cutting of slabs. Using a controlled data set relies on the assumption that control work only releases an inherently unstable snow-pack, and that the magnitude of avalanche control forms an exponential relationship with the snow-pack instability.

Six avalanche paths were chosen to represent the general characteristics of the 200 avalanche paths at Alpine Meadows. Initial statistical correlations of these paths further reduced the type of avalanche activity to three general types. These will be represented by avalanche paths High Yellow, Arched Pine (subsequently named Big Cirque) and Three Sisters Face. High Yellow Face represents the upper mountain snow-pack stability, which is greatly influenced by wind transported snow creating hard slab conditions. High Yellow Face is below Ward Peak at an elevation between 8000-8400 ft. High Yellow has a northeast aspect and a slope angle of 42 degrees with a vertical drop of 750 feet and releases slides frequently. Path Three Sisters, midway on the mountain, receives abundant wind transported snow. The aspect is northeast with a slope angle of 40-45 degrees. The vertical drop of the sisters face is between 650 and 750 feet. The path is an occasional performer. Path Arched Pine is at the top of Scott Chute at an elevation of 7600-8000 ft. This path has a west aspect and is more susceptible to wind scouring than Arched Pine or High Yellow. The slope angle is 45 degrees at the top with decreasing concavity to 40 degrees. The vertical drop is 850 ft and slides occasionally.

Data Transformation

Most data bases of avalanche activity as well as most data bases encountered in the earth sciences are not Gaussian normal distributions. Since parametric statistics are based on gaussian distribution many statistical studies of avalanche activity relied on non-parametric statistics. However, working closely with a data set and creating a near normal distribution and knowing the limitations of non-gaussian distribution as well as using non-gaussian based statistics permits the modeling of avalanche data. The Forest Service classification for avalanche size, by definition are not parametric values, however comparison of these values to crown fracture height and avalanche run-out distances suggest that these values have been recorded on an approximately interval scale.

## CORRELATION ANALYSIS

The correlation coefficient is a linear estimate of the interrelation between variables that are not influenced by the unit of measure. The correlation coefficient is defined as the ratio of the covariance of two variables to the product of their standard deviation. The correlation coefficient is based on a normal distribution. However, transforming the variables into normal distributions did not significantly change the correlations coefficients to be of greater help in determining the relative importance of various variables through lagged periods. It must be emphasized that although the correlation coefficients can be very useful in a semi-quantitative sense on slightly non-normal distributions to determine the relative importance of variables the analyst must understand the effects of the departure from normal distribution. In addition the analyst must use simple cluster plots to help identify non-linear interrelationships that might occur in the data set.

The relationship between snowfall and avalanche activity produced the greatest correlation coefficient. As would have been suspected path Three Sisters, which receives the greatest snowfall and is not as affected by the wind showed the greatest correlation. However, path High Yellow which is greatly affected by snow transport has the smallest correlation coefficient value. The previous 12 hr snowfall shows a very low correlation coefficient. This might be attributed to skier activity on the path has a stabilizing affect. In fact, path Arched Pine shows a negative correlation to snowfall activity. It would be interesting to postulate that snowfall with skier activity, could actually have a stabilizing affect, however the correlation coefficient is to small to make this presumption. The relationship between snowfall and avalanche activity appears to decrease after 48 hours. This might suggest that the snowfall prior to 48 hours had no effect on avalanche activity or that because of a lack of a gaussian distribution and a predominant storm cycle of 48 hours the correlation coefficient decreases. The 12 hr water equivalent precipitation correlation values are similar to the snowfall values but generally show weaker correlation values.

The correlation coefficients for the total snow depth shows contrasting results for the three paths. Three Sister which runs frequently and does not accumulate a deep snow-pack and shows a lack of correlation to the total snow depth. Arched Pine which has a lot of hummocky terrain and vegetation shows a expected positive correlation with total snow depth. In contrast High Yellow has a negative relationship to total snow depth. There are several possible explanations for this relationship. To begin with the natural terrain is smooth without a lot of vegetation anchors. In addition High Yellow receives snow before avalanche activity is observed eliminating the initial contrast between anchored snow and non-anchored snow-packs. These explanations would suggest a zero correlation, however the combined effects of temperature gradient releases that predominantly occur in the fall, the decrease in slope angle during the year and problems in data collection due to the combing of avalanche paths during the year may create the negative correlation.

The twelve hour snow settlement correlates positively during the previous 24 hr to the observed avalanche activity. An interesting contrast to the snowfall variable is that the previous 12-24 hr settlement correlates more than the previous 12 hr data. This correlation might represent a physical relationship or is just an artifact produced by the data collection. The previous 12 hr settlement is measured directly off snowboards whereas the 12-24 hr data is measured using the total snowfall measuring device and actually measures a component of total settlement.

Moisture content is known not to be a simple linear relationship, in that in a range of between 5 to 30% moisture content, 9% is generally considered to be the least stable at Alpine Meadows. This non-linear relationship explains the low correlations as well as the scatter in the moisture content correlation coefficients.

The correlogram for wind speed also reflects observations in that path High Yellow is affected during the previous 12 hr by wind loading and shows a strong correlation coefficient unlike path Arched Pine and Three Sisters which are susceptible to wind scouring and which show weaker correlations to wind speed during the previous 12 hours. Where in fact the period between 12-36 hr appears more important for snow transport. An alternative hypothesis is that the correlation is strictly a correlation to storm events that are preceded by an increase in wind velocity.

## FORECASTING MODEL

As discussed earlier several sophisticated statistical techniques have been used for forecasting avalanche activity. Some of these models have determined a need for separating classes such as wet snow avalanches, dry snow avalanches and no evident avalanches. This required the model to use a discriminant technique to determine the typology of avalanche activity. In addition several of these models have used principle components or factor analysis to reduce the large number of variables into several principle components or factors. As a result, what these principle components physically represent can become obscure to the forecasters. Moreover, the theory of determining the factors especially in the earth sciences has been questioned by several authors including Temple (1978).

These concerns were considered in determining the model most suited for Alpine Meadows ski resort, as well as making a model that could be qualitatively understood by the forecaster instead of relying on obscure principle components or factor analysis. Thus the forecaster could use these variables flexibly with their own experience in making a semi-quantitative forecast. Since a discrimination between classes was not needed and the author preferred to used variables directly as well as desired the ability to differentiate avalanches on a magnitude scale, multiple regression was the most applicable technique to accomplish these objectives.

## Multivariate Regression Models

Regression analysis determines the relationship between variables when one variable is a function of another variable or group of other variables. In equation 1 the variable which is the function of the other variable is the dependent variable, Y and the independent or regressor variable is called X.

$$Y = B + bX \qquad (1)$$

where B is the intercept of the y axis and b is the slope parameters. The method of least squares was used to fit the data set to this line with the least deviation.

## Results

Forecasting model variables were chosen using values of R-squared, adjusted R-squared and Mallows Constant. Due to a significant number of missing values this process of variable selection requires significant computer time to select variables from the database. Adjusted R-square values of between 0.19 and 0.38 were obtained without any data filtering. Because of the nature of the data set, data filtering is required to eliminate the data bias toward under-predicting avalanche events. After filtering the anomalous events adjusted R-square values of up to 0.75 were obtained. The regression models for crown fracture height, the percentage of avalanche path involved in the run-out and the U.S. Forest Service avalanche size classification produced similar results, however, the regression models based on the U.S. Forest Service avalanche size classification were the most consistent and are presented below for comparison.

Using the Forest Service classification the regression model predicted the class ± 1 class (i.e. an actual value of 3 would be predicted between 2 and 4) with between 60 and 80 percent accuracy. The ± 1 class error margin represents 20 percent of the total range between the classes and is intended to represent the accuracy in estimating the avalanche size.

The regression equation (2) using the previous 12 hr snowfall ($S_{t0}$) and average wind speed ($WS_{t0}$) the total accumulated snow depth ($ST_{t0}$) and the absolute value of the 24 hr change in surface snow temperature produced the most reliable model for avalanche path Arched Pine. The greater reliability of this path can partly attributed to the fact that the path is consistently skied during storms.

$$Y = -0.379 + 0.142S_{t0} + 0.005ST_{t0} - 0.062(ABS(TSO_{t0}-TSO_{t24})) + 0.014WS_{t0} \quad (2)$$

Adjusted R-square = 0.378 Adjusted R-square (filtered) = 0.574
Probability of correct prediction: 79%
Number of days in data set: 148

Avalanche path Three Sisters regression model (Eq. 3) using lagged values as in the use of the previous 12 hr and 24 hr snowfall ($S_{t12}$ and $S_{t24}$) measurements produced similar adjusted R-square values to that of Arched Pine. This model contrasts the other paths in the importance of previous snowfall and the 12 hr maximum temperature and the lack of importance of wind. The importance of lagged snowfall values is probably because path Three Sisters is often not skied during storms.

$$Y = -0.102 + 0.149S_{t0} + 0.0525S_{t24} + 0.057S_{t12} + 0.006TX_{t0} \quad (3)$$

Adjusted R-square = 0.350 Adjusted R-square (filtered) = 0.659
Probability of correct prediction: 73%
Number of days in data set: 157

The adjusted R-square value for path High Yellow is the lowest of the three paths. Equation (4) is the best regression equation for High Yellow. The poor results of this path is attributed to the non-linear interaction of the wind transport of snow near the ridge.

$$Y = -0.072 + 0.156S_{t0} + 0.09S_{t24} + 0.016WS_{t0} \quad (4)$$

Adjusted R-square = 0.187 Adjusted R-square (filtered) = 0.48
Probability of correct prediction: 62%
Number of Days in data set: 150

## CONCLUSIONS

The Alpine Meadows avalanche data set demonstrates significant correlation to the meteorologic data. This supports the use of controlled avalanche paths in statistical analysis, however there is not sufficient data to confirm that controlled avalanche paths provide a more definitive data set for determining snow-pack stability. Previous studies have used regional data bases, that include many avalanche paths, due to the randomness of avalanche activity. Results from this study suggest that individual paths can be effectively used in the statistical analysis of snow-pack stability. In addition to predicting if an avalanche will occur, results from this study show that snow-pack stability based on the size, run-out, and crown fracture height can be statistically modeled.

Because of several unrecorded variables that constrain snow-pack stability (i.e. shear strength data) creating an independent statistical model is not feasible. However, developing a forecasting model to supplement avalanche forecasting is possible using regression techniques.

This model can further supplement the knowledge and ability of the avalanche forecaster.


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