MAXIMUM AVALANCHE RUNOUT MAPPING; A CASE STUDY FROM THE CENTRAL SIERRA NEVADA

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ABSTRACT

In 1983 an avalanche hazard map (AHM) had been prepared for Galena Basin in the Central Sierra Nevada. That area was to be developed as a ski resort and the map was later incorporated in the Concept Plan for the resort. Forty-nine avalanche paths were identified in that eight square mile area and for each path the limits of a 20-years and a 100-years avalanche were drawn on a large scale topographic map.

Two years after the map had been prepared a very severe snowstorm hit the Sierras. Numerous avalanches released and felled trees up to 300 years old. The storm is considered to be the "storm of the century". In Galena Basin 16 avalanches ran and their outer edges were mapped and compared to the predictions of the AHM.

The observed runout distances of those February 1986 avalanches were an excellent opportunity for a calibration of the two friction coefficients $\mu$ and $\xi$ used in the Voellmy equations for the computation of avalanche velocity and runout distance. With a slab depth of 2.0 meters, a sliding friction coefficient $\mu = 0.17$ and a turbulent friction coefficient $\xi = 1200 \text{ m/s}^2$ the results of the Voellmy model fitted fairly well the observed runout distances.

INTRODUCTION

After the disastrous avalanche cycle which hit the Central Sierra Nevada at the end of March 1982 causing the tragic avalanche of the Poma Rocks at Alpine Meadows near Tahoe, California known as "the worst ski area avalanche in U.S. history" I had the opportunity of preparing an Avalanche Hazard Map (AHM) for Galena Basin, a proposed future ski resort on Mt. Rose Pass, 37 km (23 mi.) northeast of Tahoe and 35 km (22 mi.) southwest of Reno, Nevada. The area to be inspected for avalanche hazard measured 21 square kilometers (8 square miles). The AHM was delivered to Alpine Meadows in November 1983.

The map shows 49 avalanche paths. Each path contains a red zone within which a major avalanche with an average return interval of 20 years is expected. The red zone is bordered by a yellow zone the outer border of which represents the limit of an extreme avalanche with an average return interval of 100 years.

It was a lucky chance that not long after the AHM had been prepared an extremely severe snowstorm hit the Sierras in February 1986. The project manager of the Galena Ski Area Corp., Doug Clyde, reported: "The storm produced a large number of extreme avalanches throughout the length of the
Sierras resulting in extensive timber damage. An investigation by Norman Wilson yielded an age range of damaged timber from the low 100s to a maximum of 300 years old." And the AVALANCHE NOTES mentioned: "In California, they're calling it <the storm of the century>". The avalanches which had run in Galena Basin were reported to me on the topographic Composite Avalanche Hazard Map in a scale of 1'' to 400' (1:4800). Of the 49 paths shown on that map 16 had run.

Opportunities of observing - and especially mapping on a large scale topographic map - avalanches which released under extreme weather and snow conditions are rare. In the case of Galena Basin it might be of interest to compare predictions with what nature produced. It will be of special interest to the practitioner to know how the maximum runout distances determined basically by the Swiss Calculation Method compare to those experienced in February 1986 (Frutiger 1987).

SITE DESCRIPTION

Galena Basin lies immediately east of the California/Nevada borderline in Washoe County, Nevada within the headwaters of Galena Creek which drains the Carson Range into the east. The Carson Range with a top elevation of roughly 10'100 ft. (3080 m) runs north-south. The range is 35 km east of the main divide of the Central Sierra Nevada. Galena Basin has an average elevation of 8'600 ft. (2620 m) and is surrounded by the four highest peaks in that range, namely Mt. Rose, 10'778 ft., North Peak, 10'490 ft., South Peak, 10'338 ft. and Slide Mtn., 9'658 ft.

The AHM covers an area of eight square miles (21 km²) in which 49 avalanche paths were identified. Scattered timber is present in most of the paths, especially on the north-facing ones. The east-facing slopes are bare of trees near the crest. This very probably is due to excessive accumulation of wind blown snow. The long and steep south-facing slopes of Mt. Rose are also mostly bare of trees and covered by bolder. The terrain characteristics of only those paths which became active in February 1986 are given in table 3.

EFFECTS OF THE 1986 AVALANCHES ON THE AHM

The different slope aspects of the 49 paths and of those which became active in 1986 are given in table 1:

Table 1

<table>
<thead>
<tr>
<th>Aspect of the slope</th>
<th>N</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of paths</td>
<td>11</td>
<td>3</td>
<td>11</td>
<td>14</td>
<td>7</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Avalanches 1986</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Four days during the snowstorm winds averaged 60 to 80 mph (100 to 130 km/h) with an Alpine Meadows one-hour average of 115 mph (185 km/h) on 12th February and a Squaw Valley peak gust of 171 mph (275 km/h) on the 17th. Those winds blew from the southwest and we expect that especially north to east facing paths became active. We do not know if the reported and mapped
avalanches include all those which ran during that cycle. It cannot be excluded that some of the avalanches escaped notice.

The AHM of November 1983 indicated the outer limits of a 20-years avalanche and a 100-years avalanche. Of the 16 avalanches which became active in 1986 three stopped within the limit of a 20-years avalanche, 7 stopped in between the 20-years and the 100-years limits, and 6 avalanches overran the 100-years limit, 5 of them by 30 to 40 meters, and one (No.27) by 108 meters. Note that path No.27 is the only one with a NE-aspect.

SNOW CONDITIONS OF EXTREME AVALANCHES

Studies from the Swiss Alps have shown that almost all avalanches with extreme runout distances were of the soft slab direct action type. In most cases the avalanche involved only the snow which fell during the storm on the old snowpack. The increment of the total snow depth on the ground during the storm, \( 4H_S \), can be used as a substitute for the average depth of the slab. The settling of the old snowpack due to the overburden can be taken into account when computing \( 4H_S \). For the Swiss Alps the \( 4H_S \) for the different return periods of the storms and the different climatic regions have been evaluated statistically from long term observations.

It must be pointed to the fact, that \( 4H_S \) gives a better figure for the average depth of the slab, \( h_0 \), than does the fracture depth, measured at the crown of the slab. This can be proven by figures reported by the AVALANCHE NOTES for the February 1986 storm in the Sierras. Maximum total snow depth on the ground was reached at Alpine Meadows on February 21st with 115 in. (2.92 m) and at Mammoth Mtn. on February 20th with 182 in. (4.62 m). The difference of minimum and maximum total snow depth for the two stations was 65 in. (1.65 m) and 111 in. (2.82 m) respectively. For Galena Basin the \( 4H_S \) must have been around two meters, the average of the two stations being 2.24 m. The elevation of Mammoth Mtn. is 9,600 ft. (2930 m) and is about the same as the elevation of the starting zones in Galena Basin. If we would take the reported fracture depth of Mammoth Mtn. (21 ft./6.40 m) as the average slab depth, \( h_0 \), we would overestimate \( h_0 \) by at least 1.8 m and very probably by more, up to 3.60 m.

The assumption that only the newly fallen snow is involved in most of the far reaching avalanches applies especially to maritime climate regions. This assumption is supported by a publication by Armstrong and Armstrong (1987), where they state: "...the majority of failures in the maritime zone occur at the old snow - new snow interface". The snowpit profile taken in Galena Basin on 27 February 1986 supports the above findings. It shows at several levels "rain or wet snow".

When preparing the AHM in 1983 the maritime climate was taken into consideration by assuming that during almost all snowstorms relatively high air temperatures will cause a damp snow which will have a rather high friction. On February 14th. 1986, at the beginning of the storm, the maximum air temperature rose to +0.6°C. But at the beginning of intense precipitation it dropped down to -5.6°C. What is called "climate" for a given region is the sum of average weather factors. It is plausible that weather may change and that continental spells may occur temporarily in a region called "maritime".
This is also true for the Central Sierra Nevada where for extreme avalanches dry and cold new snow with low friction must be taken into account.

The question arises if the qualification "storm of the century" is justified. When the age of the trees felled by the avalanches is considered which were 100 to 300 years old, with a single report of one 500 years old, then we may deduce an average return period exceeding 100 years. An analysis of big and intense snowstorms of that region recorded for 14 winters, 1969/70 - 1982/83, confirms this statement. If one defines the magnitude of a snowstorm by its total precipitation (inches of water) and its intensity (inches of water per day) then the storm of February 13 - 20 of the winter 1985/86 was really outstanding. With a total precipitation in eight days of 32.60 in. and an average intensity of 4.08 in./day it really exceeds all the figures known from big storms in the last 20 winters in that region. However, it must be kept in mind that the 1986 data are from Mt.Rose Pass, el. 8740 ft. whilst the other data 1969/70-1982/83 are from Donner Memorial Park (5937 ft.), Tahoe City (6230 ft.), and Mt.Rose Bowl (7400 ft.) (Frutiger, 1985).

THE VOELLMY CALCULATION METHOD

The estimation of maximum runout for every particular avalanche path was essentially supported by the results obtained from the Voellmy equations for avalanche velocity, flow depth and runout distance.

The work of Voellmy is accessible to the English reader through the translation of R.E.Tate in 1964 (Voellmy, 1955). A thorough discussion of the Voellmy equations is found in Leaf and Martinelli (1977). The initial Voellmy model is used with minor alterations by the Swiss Federal Institute for Snow and Avalanche Research (SFISAR, B.Salm). The modified equations can be found in Buser and Frutiger (1980). The Voellmy model is presently used in Switzerland as a standard in AHM engineering (Salm and Burkard, 1988). The model can easily be handled but nevertheless it is enough diversified in taking into account most of those factors which will considerably influence the dynamics of a flowing snowmass. The parameters used in the model can be classified in terrain parameters and snow parameters.

Terrain parameters

Table 2 Terrain parameters of the Voellmy model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle of the starting area</td>
<td>$\psi_0$</td>
</tr>
<tr>
<td>Width of the starting area</td>
<td>$b_0$</td>
</tr>
<tr>
<td>Slope angle of the approach section</td>
<td>$\psi$</td>
</tr>
<tr>
<td>Width of the approach section</td>
<td>$b$</td>
</tr>
<tr>
<td>Hydraulic radius of the approach section</td>
<td>$R$</td>
</tr>
<tr>
<td>Slope angle of the runout zone</td>
<td>$\psi_u$</td>
</tr>
</tbody>
</table>
An evaluation of the terrain was made on the basis of a large scale topographic map in a scale of 1" : 600' (1:7200) with contour intervals of 10 ft. (3.0 m). First the starting areas (slope angle >30°) were defined on the map and then the center line of the path of a flowing snowmass releasing in that area was estimated. For every single path a longitudinal profile in a scale of 1:2500 or 1:4000 was drawn. On the basis of the map and the profiles the terrain parameters were determined. The typical terrain parameters of those paths which became active in February 1986, and of which the pertinent runout distances were observed are given in table 3.

Table 3

<table>
<thead>
<tr>
<th>Path No.</th>
<th>Slope angle in degrees and percent</th>
<th>observed runout distance in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \psi_0 ) ( \psi ) ( \psi_{ul} )</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>29 56 13 23 8.0 14</td>
<td>65</td>
</tr>
<tr>
<td>15</td>
<td>31 61 12 22 1.7 3</td>
<td>70</td>
</tr>
<tr>
<td>25</td>
<td>37 74 18 32 2.9 5</td>
<td>85</td>
</tr>
<tr>
<td>27</td>
<td>31 59 21 38 2.3 4</td>
<td>450</td>
</tr>
<tr>
<td>46</td>
<td>34 68 19 35 4.6 8</td>
<td>200</td>
</tr>
<tr>
<td>47</td>
<td>35 70 19 35 13 23</td>
<td>550</td>
</tr>
<tr>
<td>61</td>
<td>36 73 19 34 4.0 7</td>
<td>140</td>
</tr>
<tr>
<td>62</td>
<td>39 80 13 24 4.0 7</td>
<td>200</td>
</tr>
</tbody>
</table>

When there is no definite transition from track to runout zone, i.e. no definite break in slope angle, and the tangent of the angle of the runout zone is close to the value chosen for \( \mu \), as is the case for path no.12, then the result of the Voellmy equation for the runout distance becomes critical.

Another special case is path no.47 where the tangent of the average gradient of the runout zone has a higher value than the \( \mu \) applied for the calculation. Theoretically, the avalanche will not stop on a slope with a tangent \( \psi_{ul} > 0.16 = \mu \). In February 1986 avalanche no.47 ran over a distance of 550 m on a slope of 13° the tangent of which is 0.23. This avalanche confirms other observations that gradients around 9 to 13° (15 to 23%) are critical and extreme avalanches will have runout distances of considerable length. In another paper we reported similar cases (Buser and Frutiger, 1980).

For the remainder of the paths the observed runout distances are close to those modeled with the Voellmy equation when applying a \( h_0 = 2.0 \) m, a \( \xi = 1200 \) m/s² and a \( \mu = 0.17 \).

Snow parameters

There are only three snow parameters used in the Voellmy model, namely

- the average depth of the slab \( h_0 \), m
- the coefficient of sliding friction \( \mu \), -
- the coefficient of turbulent friction \( \xi \), m/s²
As discussed in a previous section $h_0$ can be substituted by $\Delta HS$ derived from snow data of the region. The AHM of 1983 had been prepared without any information on runout distances of past avalanches. A first approach in estimating $h_0$ for Galena Basin was made by using what was known from the Swiss Alps and setting $h_0$ invariably to 2.8 meters. Considering the maritime climate rather high friction coefficients were chosen, namely $\mu = 0.17$ and $\xi = 1200 \text{ m/s}^2$ and the results of the computations were compared to the field evidence of the end of March 1982 avalanches.

As already mentioned it was a piece of good luck when nature produced that "storm of the century" which released avalanches in Galena Basin in those paths already under study. Although 10 of the 16 avalanches stopped within the limits of the 100-years avalanche, as indicated on the 1983 AHM, it was not acceptable that six of them had overrun those limits. On the basis of the measured runout distances and the storm data of February 1986 a revision of the AHM was undertaken (Frutiger, 1987).

When the data of the February 1986 storm are considered a $h_0$ of 2.8 m is adequate for an extreme situation. However, to cover all the observed runout distances by the Voellmy equation it was necessary to slightly change the friction coefficients. Thus for modelling extreme avalanches a $\mu = 0.16$ and a $\xi = 1360 \text{ m/s}^2$ was used. The same $h_0$ and the same friction coefficients gave good results when the Poma Rocks avalanche of March 31st, 1982 was computed (Frutiger, 1983).

**CONCLUSIONS**

The February 1986 avalanches offered an opportunity for a further calibration of those factors in the Voellmy equations which, up to date, can be determined only indirectly.

For Galena Basin situated in the Central Sierra Nevada the best fit of the results of the Voellmy equations to the observed runout distances was obtained by using $\xi = 1200 \text{ m/s}^2$ and $\mu = 0.17$.

The avalanches of the February 13 - 20, 1986 storm confirmed the usefulness of the model when runout distances have to be determined for paths of which records of past avalanches are not available.

The friction coefficients which best fit the observed runout distances are comparable to those reported from other places and gained by calibrating them against measured avalanche velocities (Schaerer, 1974; LaChapelle and Lang, 1980).
REFERENCES


Buser, O., and H. Frutiger, 1980, "Observed maximum runout distance of snow avalanches and the determination of the friction coefficients \( \mu \) and \( \xi \)," Journal of Glaciology, Vol. 26, No. 94, 121-130, 1980


