Dry-Slab Density and Thickness During Major Storms

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ABSTRACT

Observations of forest destruction throughout various snow climates suggest that design avalanches (≈100-year return periods) usually result from fracture and release of thick, widespread slabs of new dry snow. Such avalanches usually travel the longest distances into runout zones and probably achieve the largest velocities and impact energies.

Dry, new snow slab densities and thickness were estimated from analysis of sustained storms of several days duration at eleven sites in the United States. The sites chosen represent *continental* (Gothic, CO; Yule Creek, CO; Elkton, CO; Wolf Creek, CO) *intermountain* (Alta, UT; Jackson, WY) and *maritime* (Mammoth, CA; Alpine Meadows, CA; Paradise, WA; Stevens Pass, OR; Mt. Hood, OR) snow climates. The 18 storms selected for study were all characterized by a steady increase in snowpack depth through the storm period (e.g., accumulation exceeded settlement), were below freezing, and did not have rain associated with the storm. Data were collected at standard high-elevation snow study plots that represent starting zone conditions where wind effects were not important. Mean densities in the new snow layer were estimated by the relationship $\rho = HW/DH$, where ρ = average density of the new snow layer, HW = the water equivalent during the storm, and DH = the snowpack depth increase during the storm.

The following conclusions result from the storm analysis: (1) mean slab densities and thickness did not vary significantly from one snow climate to another; (2) average daily precipitation rates were greater within the maritime climates, (3) storms were colder and of longer duration in continental climates.

INTRODUCTION

As pointed out by de Quervain (1972) major avalanches affecting valley-bottom locations in Switzerland are usually associated with storms of several days' duration in which new snowfall exceeds about 1.2m. Salm, et. al. (1990), defined a parameter d_0 that is used to estimate the thickness of new snow slabs resulting from major storms of several days duration. Slab thickness was found to vary with climate region in Switzerland. The assumption in both the older and more recent Swiss work is that the major "design" avalanches with return periods, T, on the order of 100 years (30 years < T < 300 years) are associated with thick slabs of new, dry snow. The resulting avalanches reach high velocities, produce large impact pressures, and travel the longest distances into the runout zones where land development and engineering works may be planned.

Direct observations of damage to forests and man-made structures from avalanches with long return periods throughout various climate regions of the United States (Mears, 1992) confirms some of the Swiss assumptions. Long-return period avalanches that affect the largest areas in the runout zones and produce the largest destructive forces are usually associated with dry snow regardless of the snow climate of a given site (McClung, 1990). Such avalanches achieve the largest velocities and energies, and cover the largest areas. Given a long return period, dry-snow avalanches will produce the design, long return-period avalanche in maritime as well as in continental climates. Large avalanches of wet snow, or course, also occur and may produce the largest deposit depths and static avalanche loads, particularly in maritime climates. Such avalanches, however, because of lesser velocities, runout distances and areas covered, usually do not produce the design case for most land use planning and engineering applications.

When structures must be exposed to the design avalanche, information about avalanche-release volumes and flow densities are necessary so the engineer can compute impact pressures, forces, and moments on exposed structures. In some avalanche-dynamics models calculation of avalanche flow thickness also depends on released snow thickness and/or volume. Such information can be estimated, as is done in Switzerland, from data on new slab thickness and density. Avalanche velocities can be computed independently through application of statistical and physical modeling, as discussed by McClung (1984) and Mears, (1992).

THE DATABASE AND "STORM" CHARACTERISTICS

The entire database of the Westwide Reporting Network, consisting of 125 stations that reported weather records in the United States during the period 1967-1995, was searched for this study. Some of the record begin in 1944. In addition, detailed snow and precipitation records from Yule Creek, Colorado were made available by Mr. Chris Landry of Yule Creek Avalanche Services. Of the reporting stations available, 11 had records of sufficient length, detail, and quality to be useful in this study. Four stations (Gothic, CO; Yule Creek, CO; Elkton, CO; and Wolf Creek, CO) represented the continental sites, two stations (Alta, UT; Jackson, WY) represented the intermountain climate, and five stations (Alpine Meadows, CA; Mammoth, CA; Paradise Ranier, WA; Stevens Pass, OR; and Mt. Hood, OR) represented the maritime sites. As noted, many other stations have reported data to the Westwide Network, however, these data were not sufficient in detail and/or length to be used in this study.

"Storms" were defined as any continuous period in which (1) the snowpack increased in depth (i.e. new snow accumulation > settlement), (2) temperatures remained below freezing throughout the period, and (3) rain did not fall. Condition "1" defined the storm period and the thickness of the new snow slab. Conditions "2" and "3" are important because either warm temperatures or rain will tend to induce density increases. When above-freezing temperatures are followed by cold temperatures meltfreeze layering and strengthening of the snowpack may occur. Such layering reduces the ability of the snowpack to quickly fluidize as a dry-flowing avalanche and reach high velocity.

The precipitation periods called "storms" in this paper were not necessarily storms in the meteorological sense. If a continuous precipitation period satisfying the conditions listed above occurred, it was considered to be a storm even if that period consisted of more than one distinct source for atmospheric moisture. The emphasis here was to view storms in terms of developing new, dry slabs on the snowpack.

In some cases the storms analyzed here are known to have produce major avalanches In other cases it is not known if major avalanches occurred or were reported. Avalanches may not have occurred during some of the storm periods analyzed because the new snow layer was strongly bonded to the old snow. I have not attempted to correlate the storms with actual avalanche occurrences. The objective was to determine what slab thickness and density each climate area has produced during a dry, cold, precipitation period and to compare each area.

ANALYSIS OF THE DATA

Two parameters were analyzed in each area: (1) HW = the total water equivalent of the new snow, and (2) DH = the height increase of the snowpack during the storm (depth after the storm minus depth before the storm). From these data the mean slab density, ρ was computed from the relationship ρ = HW/DH. This relationship tends to systematically overestimate mean density and underestimate the thickness of the new snow layer. The weight of new snow tends to push the old snow/new snow surface closer to the ground. This systematic error, because it applies to data collected from all 11 sites and 18 storms, does not affect the validity of the comparison between areas.

Table 1 lists the 18 storms analyzed in each of the 11 areas. Column 1 - 3 list the location, month of the storm and the duration of the storm in days. Column 4 provides the average temperature from the beginning to the end of the storm period. Column 5 is the total snowfall, measured as the $\sum$ 24-hour totals. Column 6 is the total snow water equivalent (HW) and column 7 is the average precipitation rate per day of the storm. Column 8 is snowpack depth increase (DH) which is taken as the slab depth, and column 9 is the average slab density ρ =HW/DH.

Surprisingly little variation in average slab thickness and density occurred between the snow climate areas, as indicated in Table 2 where the seven maritime storms, eight continental storms, and three intermountain storms are compared. The major differences between the snow climates was found to be in storm duration and average daily precipitation intensity. The major dry storms were of much shorter duration and of higher precipitation rates during the big maritime vs. continental storms.

STUDY LIMITATIONS AND DISCUSSION

This study is limited by the short data base used. The period of record ranged from only 3 snow seasons at Elkton, Colorado to 46 snow seasons at Alta, Utah with an overall average of 25 years. The four continental sites had the shortest periods of record, with an average of only 13 years. Application of encounter-probability calculations (LaChapelle, 1966) indicates that a "100-year" return-period event has only a 39% chance of occurring in a 50-year period and has only a 22% chance of occurring in a 25 year period. There exists a high probability that the major dry-slab formation would not have occurred at *any*

TABLE 1. Major Storms, Slab Thickness, and Densities

Location	Dates	Days	Avg. Temp.	New Snow	H_2O Equiv.	Precip. Rate	Slab H (ΔH)	Mean ρ
Alta	Dec 1964	6	-6.7°C	1.96m	281mm	47mm/day	1.60m	176 kg/m^3
Alta	Jan 1965	6	-7.2°C	2.67m	280mm	47mm/day	1.30m	215 kg/m^3
A. Meadows	Jan 1982	5	-6.2°C	2.49m	239mm	48mm/day	1.63m	147 kg/m^3
A.Meadows	Mar 1982	4.5	-4.2°C	2.46m	206mm	46mm/day	1.55m	133 kg/m^3
Mammoth	Feb 1986	8	-3.8°C	3.56m	695mm	87mm/day	2.82m	247 kg/m^3
Paradise	Jan 1971	6	-4.2°C	3.46m	343mm	57mm/day	1.88m	182 kg/m^3
Paradise	Jan 1972	4	-6.5°C	2.41m	217mm	54mm/day	1.40m	155 kg/m^3
Stevens P.	Dec 1953	4	-1.8°C	2.29m	180mm	45mm/day	1.30m	138 kg/m^3
Mt. Hood	Jan 1980	3	-7.8°C	2.08m	230mm	77mm/day	1.27m	181 kg/m^3
Gothic	Mar 1978	9	-6.8°C	2.52m	178mm	20mm/day	1.12m	159 kg/m^3
Gothic	Feb 1986	8	-5.0°C	2.13m	245mm	31mm/day	1.24m	198 kg/m^3
Gothic	Feb 1995	6.5	-5.1°C	2.40m	184mm	28mm/day	1.12m	164 kg/m^3
Gothic	Jan 1996	16	-10.7°C	2.96m	197mm	12mm/day	1.27m	155 kg/m^3
Yule Creek	Mar 1995	6.5	-3.7°C	-------	190mm	29mm/day	1.17m	162kg/m^3
Elkton	Mar 1978	9	-2.9°C	2.90m	230mm	26mm/day	1.50m	153 kg/m^3
Wolf Creek	Mar 1985	4	-6.4°C	1.68m	208mm	52mm/day	1.40m	149 kg/m^3
Wolf Creek	Mar 1995	7	-5.8°C	1.91m	225mm	32mm/day	1.40m	161 kg/m^3
Jackson	Feb 1986	7	-1.8	1.75m	226mm	32mm/day	1.09m	207 kg/m^3

TABLE 2. Snow climate averages

Climate	Avg. Storm Duration	Avg. Snowfall	Avg. H_2O	Avg. P.I	Avg. ΔH	Avg. p
Maritime	4.9 days	**2.68 m**	**301mm**	61mm/day	1.69m	169 kg/m^3
Intermountain	6.3 days	2.13 m	262mm	42mm/day	1.33m	199 kg/m^3
Continental	8.3days	2.26m	212mm	26mm/day	1.30m	164 kg/m^3

of these sites during the short period of record available. Although the database is not long at any site, there exists a large difference in length of record between the sites. This makes comparisons between the areas and snow climates difficult.

Measurements at the snow study plots cannot always be transferred to starting zones because of elevation differences and wind effects. Elevation differences may be accounted for if local data on precipitation variation with elevation exist. Wind often transports large amounts of snow into starting zones, therefore the slab thickness at study plots probably are not representative of thickness at the crown in some avalanche starting zones. This mis-representation is probably smaller in large avalanche starting zones where wind erosion and deposition effects tend to cancel one another than in small starting zones.

The following conclusions probably can be drawn from the data analyzed in this paper:

- Dry "storms," as defined in this paper, do tend to be longer and of lesser precipitation intensity in the continental areas;
- Although the maritime storms have much larger average precipitation intensities (for fewer days), they do not appear to result in significantly thicker or denser dry slabs;
- The "design, 100-year" dry-slab avalanches may therefore be similar in thickness in the various climate areas;
- Slab densities, appear to be less than 200kg/m^3, on average, in the major storms; this is significantly less than the 300kg/m^3 assumed as a "default" value in standard Swiss avalanche-dynamics calculations.

THE FEBRUARY, 1986 STORM AT MAMMOTH, CALIFORNIA

This storm probably had a much longer return period than the other storms analyzed. This storm produced a larger number of extremely large, long-return-period avalanches in the eastern Sierra Nevada (from Mammoth Ski Area north to Alpine Meadows Ski Area) than any other storm to have been documented this century. Many of the avalanches, judging from forest destruction and the ages of trees, had return periods of more than 100 years. The return period of the storm is not known, but may also be on the order of one century. The eight-day storm produced 695mm of water equivalent (87mm/day average), resulted in a snowpack depth increase of 2.82m with an average density of 247kg/m^3. No other storm listed in the Westwide data approached the magnitude of the Mammoth storm of 1986.

The relatively high elevation (2,700m) of the snow study plot at Mammoth ensured that temperatures remained below freezing throughout the storm and all of the precipitation was snow. Other sites in the Sierra, such as Alpine Meadows at 2,100m, recorded large amounts of rain with the storm therefore did not produce highly mobile, dry-slab avalanches in spite of high precipitation amounts.

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