Temperature Gradient Metamorphism and its Relation with the Avalanche Release

PK Satyawali
Snow & Avalanche Study Establishment, Manali,HP.India.

ABSTRACT
In winter there is a considerable amount of solid precipitation in the western part of Himalayas. Avalanche frequently occur here, and often endanger national economic construction and human life. Observations show that the avalanche occurrences are closely related to the physical characteristics of the snow, especially to the development of depth hoar which are determined by thickness of the snow cover, air temperature, ground temperature regime and the duration of negative temperatures. The results of this study has revealed that the maximum depth of snow cover is 40-60 cm in this range for the development of depth hoar. The mean maximum depth of snow cover in this region is 200-225 cm. Therefore the thickness of depth hoar can reach more than 25-30 % of the total snow cover depth. That is one of the main reasons why avalanches occur frequently under the conditions of a limited snow cover depth. Comparison for snowcover buildup has been also made. The results of an artificial triggering conducted on a particular site are also demonstrated.

INTRODUCTION

The field component of this study was located in the southern foothills of Greater Himalayan range at an altitude of 3800m. This part of the Himalaya is generally characterized by low temperatures and moderate snowpacks. The station is representative of the snow-met conditions around this area and in particular the western part of Great Himalaya range. Due to active snow drifting in this region, external traffic is blocked for 7 to 8 months of the year. The seasonal snow cover in this station is characterized by low density, low liquid-water content and low temperature. Large temperature gradients in the basal layer of the snow cover exist throughout the entire period of snow accumulation, and depth hoar therefore develops extremely well.

The snow cover buildup in the avalanche formation zone was followed by extrapolating snow-met data to the observation location. The formation zones are estimated to receive 25 to 30 % more fresh snow than at the observatory. Few sites of avalanches are directly seen from this observatory. However, the avalanche occurrences can be assessed easily, since most of the avalanche sites are within the radius of 10-15 km from the observatory.

Failure of weak planes, collapse of depth hoar layers, and tensile fracturing of soft slabs are the common causes of avalanche activity in the area. However, slopes generally start failing only after the standing snow in the formation zone exceeds 180-200 cm.

A portion of the road axis, which crosses over the Great Himalaya range, experience light to moderate snowfall. Overall lower snowsurface temperatures and a shallow snowpack, produce steep temperature gradients leading to the formation of depth hoar layers. Weak layers thus formed may give way under overburden caused during subsequent spells. It requires 180-200 cm of snow for the slopes to fail. The formation zone requires less than 100 cm of standing snow to cover the terrain irregularities, being mostly rocky surface or scree filled.The second wave, however, generally starts when standing snow in the formation zone exceeds 250 cm.

It is important to reveal the mechanism of avalanche formation for theoretical significance and also for the practical value to predict avalanches and the factors, processes influencing the development of depth hoar.

DEVELOPMENT OF DEPTH HOAR AND/OR FACETED GRAINS IN THE SNOW COVER

1.The main factors influencing the development of depth hoar/sugar grains

The essential condition for the development of depth hoar in the snow cover is the temperature gradient that is dependent on the snow cover depth, air temperature and ground temperature regime. Lower air temperatures produce larger temperature gradients in the snow cover, and correspondingly, better depth hoar develops. Consequently, the longer the negative temperature gradient lasts, especially with low temperatures, the thicker the depth hoar layer will be. According to observations, the temperature in the top 20-25 cm of the snow cover is sensitive to fluctuations in the air temperature. So the development of depth hoar needs maximum of 40-60 cm of snow cover, because if the snow cover is thinner (5-10 cm), the temperature gradient in the snow cover will be influenced by the fluctuations in the air temperature, and even a positive temperature gradient will appear in the snow cover under conditions of high air temperature. But, if the snow cover is too thick, the temperature gradient will be reduced.

2.Development process of depth hoar

The snow cover in this part is seasonal with moderate thickness, very low to low density, and very low temperatures in early winter but higher in late winter. Therefore, once the snow cover is formed, a negative temperature gradient arises and remains for a long period. Owing to this negative temperature gradient, there is a corresponding vapour concentration gradient in the snow cover. In the presence of a strong vapour pressure gradient which exceeds 5mb/m, a relatively rapid transport of water vapour occurs due to this imbalance in water vapour concentration. As the water vapour moves from warmer to colder regions in the snow cover, it comes in contact with colder grains surface. Consequently some of the vapour is deposited as solid ice on the face of the colder grain.

A series of evaporation and deposition processes between the grains yield specific shapes characterized by facets, steps, and eventually hollow cup crystals, called depth hoar. Grain growth may be quite rapid depending on the vapour pressure gradient. This process is generally referred to as TG metamorphism. A sustained strong temperature gradient in new low density snow (0.1-0.2 gm/cc) can form grains of upto 8 mm in few days.

The strong and most sustained temperature gradients are observed on North facing slopes or shaded gullies of high altitude mountains, since the snow surface in such cases remains at low temperature due to continuous radiation loss. The development of depth hoar in these regions is brought about by low ambient temperature and high ground temperature. This provides excellent conditions for the development of depth hoar by a large temperature gradient for a long period. The variation of grain size with time measured in the field stations is shown in fig1, with the prevailing conditions of temperature and temperature gradient in fig2.

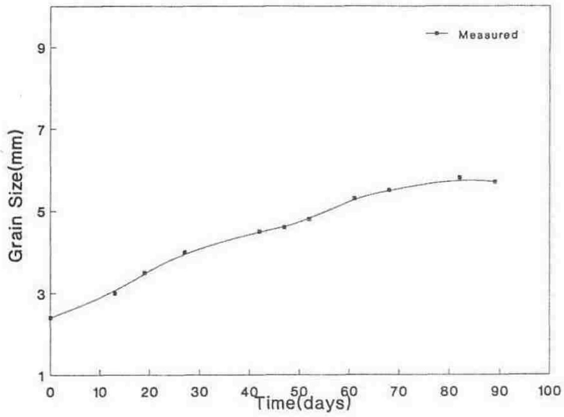

Fig1. Grain growth with time under constant density 0.250 gm/cc, initial grains are depth hoar when measurements were started.(Satyawali,1994)

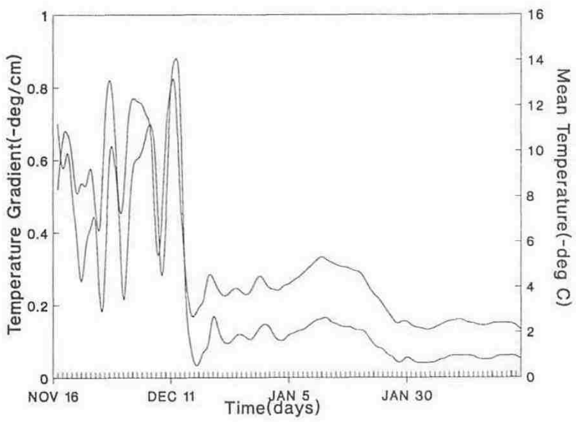

Fig2. Temperature gradient and mean temperature for the basal layer throughout the winter period.(Satyawali,1994)

Our observations show that the temperature of the snow cover decreases and its temperature gradient increases from December with the decrease of the air temperature. At the same time, the amount of vapour transport increases due to high temperature gradient at the ground-snow interface and depth hoar develop from the bottom to the upper layers of the snow cover. There is a decrease in temperature gradient during the snowfall, and this therefore reduces the rate of depth hoar formation. But after the snowfall is over, the temperature gradient again starts rising. Under these conditions the thin snow cover with a low density tends towards a weak layer of depth hoar, the density and hardness of the depth hoar are lower than those of the snow layer above it. If the snow cover depth exceeds 150 cm, with the addition of more snowfall, there is the possibility of avalanches occurring. The grain growth is not significant if the snow cover reaches more than 100 cm in the beginning of snow cover buildup, the temperature gradient remains below 0.1°C/cm of the critical value and only solid type depth hoar may form as it was evident in the year 1994-95. The first layer adjacent to the ground was exposed for 15 days to a temperature gradient in excess of 0.1°C/cm, after which it remained below 0.1 °C/cm till the start of ablation period.

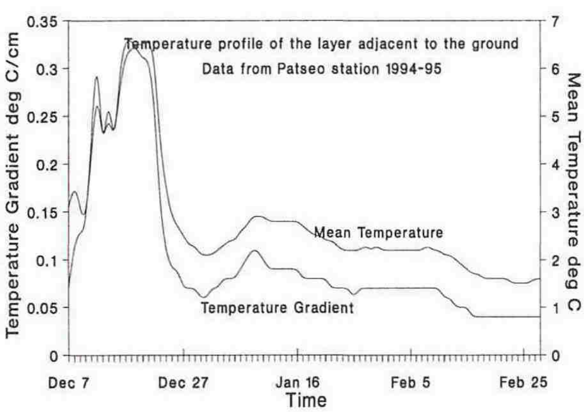

Fig3. Field conditions of temperature and temperature gradient for the basal layer of the snow cover at 3800m.

At the observatory the depth hoar generally occupies 25-30% of the total snow cover depth by the end of February, but we expect it to be more than 50% in the formation zone of nearby avalanche sites. At that time there is a danger of avalanches. The maximum avalanche activities were noticed during snowfall. The months of February and March are very a crucial period due to frequent avalanche activities. From March to early April, the weather alternated between cold and warm with a trend toward warming, and temperatures of the ground under the snowpack and snow cover increased gradually. During this period the transport of water vapour diminished, and the temperature gradient metamorphism in the snow was discontinuously replaced by a regime for melting-refreezing metamorphism. In most cases, the thickness of the depth hoar reached more than 30% of the total thickness of the snow cover, and the snow temperature becomes 0°C from its surface to the bottom by the end of April or the beginning of May. The depth hoar grains at this stage also start rounding their shape and therefore grain size decreases.

Besides its weakness, depth hoar also has a small water capacity, and it is very easy for melt water to percolate from the snow surface to the ground through the snowpack. In addition, the bonds between the grains of the depth hoar are first to melt, and thus the snow cover becomes loose and release of an avalanche becomes easy. That is one of the reason for frequent full-depth avalanches occurring in this part during snow melt season.

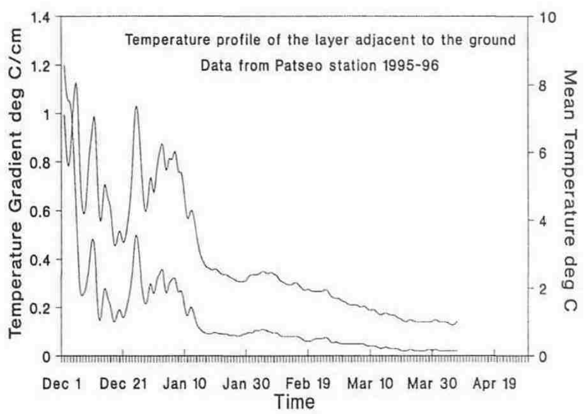

Fig4. Prevailing conditions of temperature gradient and mean temperature at the station for the winter 1993-94.

RELATION BETWEEN AVALANCHE RELEASE AND DEPTH HOAR OR FACETED GRAIN FORMATION

The thickness of the snow cover in this part of Himalaya is less than that of the snowy region in Pir Panjal range. However, depth hoar, which provides very good conditions for avalanche release, develops extraordinarily well in this part of Greater Himalaya. Depth hoar grains, being angular in character, generally do not bond well. They exhibit extremely poor strength in shear. A depth hoar layer, which formed near the ground, causes full depth catastrophic avalanches. If there is snowy weather or the air temperature increases quickly, avalanches occur frequently. Of course, avalanches are also determined by precipitation during the snow season. The comparison of two stratigraphy plots is provided in the Table 1 and Table 2. The avalanche activities during moderate or major spells of snowfall are demonstrated in the fig5 for the year 1992-93.

Snowdrifting is another hazard accompanying avalanches in this region. Snowdrift generally occurs in Himalayan areas higher than 3000m. On the lower Himalayan region, where solid precipitation is large, snowdrifting is not serious. In these regions snow drifting is observed only in the mountain ridges.

The depth hoar layer very close to the ground may not be that dangerous, because it still requires snow to cover the ground irregularities, therefore only smooth and continuous surfaces are required for depth-hoar full-depth avalanches, if the depth hoar development does not extend much beyond the surface irregularities.

COMPARISON BETWEEN TWO SNOWCOVER BUILDUPS

Winter 1992-93

The snow cover buildup in year 1992-93 started on 17 November 1992 with 20 cm of fresh snow. This snow cover was exposed to the atmosphere for 35 days with very steep temperature gradient (fig.2). However, the ground-snow interface temperature was very low compared to other winters. Of course, this was due to very thin snow cover, and atmospheric temperature directly affected the ground-snow interface temperature. But the ground-snow interface temperature was always subzero till the beginning of ablation. This winter was less severe than other winters. Snow storms were light to moderate throughout the winter, and only one storm on 20 March was heavy with 90 cm of fresh snowfall.

Snow drift in this area is predominant, it is generally observed just after snowfall. Two avalanches were triggered on 1st and 5th January 1993. These were due to excessive loading by snow drift which occurred during night time. These two avalanches were full depth. They brought all the snow mass along with them, including the snow mass consisted of depth hoar grains. On 24th February, we triggered an avalanche artificially, the conditions were very good, and we did all tests and found that conditions were favourable for triggering. Half of the snow cover consisted of depth hoar/faceted grains layers, and the remaining pack was rounded and melt-freeze grains of relatively high strength compared to depth hoar/faceted grains layers. The shear strength of depth hoar/faceted grains layers were between 5-20 gm/cm^2.

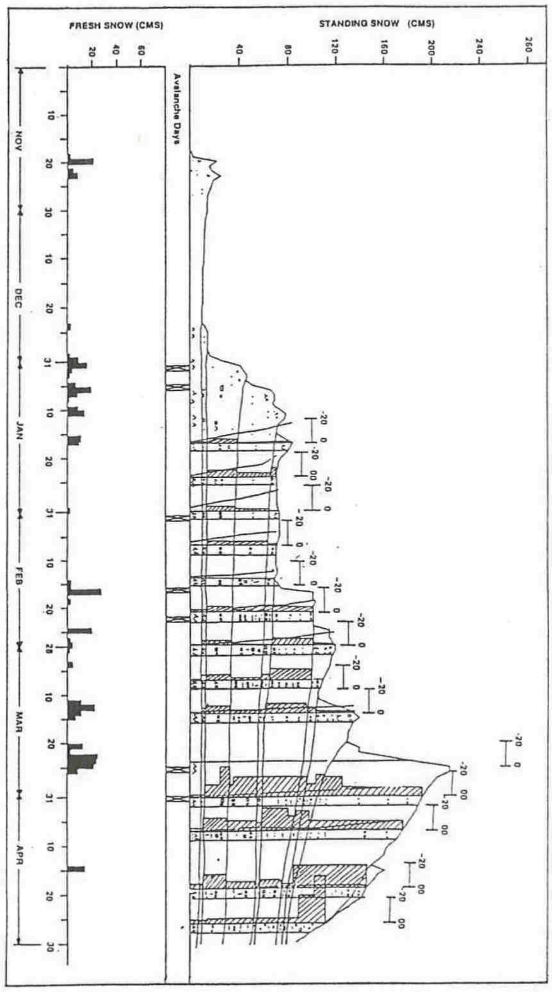

Fig.5 Snowcover buildup for the year 1992-93 and avalanche occurrence with the snow pit observation data.

From 5th to 8th March 1993, we have found radiation recrystallisation crystals (Armstrong,1983) except on the northerly slopes. But it did not affect the snow stability much. Between 11 March and 15 March 1993, it snowed 46 cm, but no avalanches were seen or reported in the area. One reason could be the thickness of this layer, which was probably not sufficient to cause a failure. Second, the precipitation rate was less than 2.0 cm per hour throughout the snowfall.

On 21st March only 14 cm of snowfall was observed, but due to high wind drift in this area the formation zones were assumed to have received excessive loading of snow. One avalanche was reported by the observer.

On 26th March 1993 just after a heavy snowfall of about 90 cm, we made a pit observations and other stability tests. The conditions were again favourable for artificial triggering, and a full depth avalanche was released with explosives.

From 27 March to 31 March 1993, the radiation recrystallisation crystals were again observed, but due to no further major snowfall, the snowpack started settling down from 27 March 1993 onward.

Comparison of stratigraphy data as on:

Table 1. *02 Feb 1994*

110		
	λλλ	
	....	
	....	
	....	
42		0.283
	○ ○ ○	
32		0.257
25		0.311
15	∧∧∧	0.396
12	∧//∧//	0.462
7	ΔΔΔ	0.285
0	ΔΔΔ	0.283

Table 2. *07 Feb 1995*

116	∨∨∨	0.094
	....	
111	....	0.205
	....	0.283
73		0.254
35		0.309
24	∧∧∧	0.296
	∧//∧//	0.336
	∧∧∧	0.314
17	∧//∧//	0.453
8	∧//∧//	0.457
0	ΔΔΔ	0.235

Winter 1995-96

The snow cover buildup in the year 1995-96 started on 28 Nov. 1995. Till 14 Jan 1996 a total of 5 light spells of snowfall accumulated 50 cm of standing snow. On 14 Jan 1996 the entire snowpack was converted into either depth hoar grains or faceted grains. Fresh snowfall started with 80 cm of snowfall, this brought two avalanches during the snowfall. After this storm a fresh snow storm started on 21 Jan 1996 and one more avalanche was observed. This storm brought only 15 cm of snow, but due to high wind activity the snow was deposited in the formation zone, and avalanche was triggered.

On 14 Feb. 1996, due to heavy snowfall of 55 cm in one day, a few avalanches were triggered. More than 60% of the snow cover was consisted of depth hoar or faceted layers. After a pit observation at the site, the fracture plane was reported as depth hoar layer just above the ground. The snow lying on top had a strength of 10 gm/cm^2 with the depth hoar layer.

This analysis reveals that in comparison to lower Himalayan region, the snow precipitation is less in Greater Himalayan range, but avalanche activities are more in this region because of the weak structure of snow due to depth hoar and faceting. Also there is a maximum avalanche activity during snowfall. But at lower altitudes the avalanche activity is less even though the snow precipitation is greater.

CONCLUSION

To improve the knowledge on avalanche initiation due to depth hoar or temperature gradient metamorphism, more specific measurements are needed to model and predict the avalanches. Especially formation of faceted or depth hoar grains in old and new snow interfaces need more work. These are the locations of maximum potential for future avalanches.

Snow drift at the higher elevations is predominant and this factor is very important for extra loading on the slopes. Therefore, temperature gradient metamorphism with snow drift and new precipitation needs more attention for predicting an avalanche danger.

ACKNOWLEDGEMENTS

I thank Maj. Gen. SS Sharma, KC, Director SASE for permitting me to present this work in the conference and Sh DN Sethi, for his kind support during my field stay. I also thank Prof. RL Brown for his useful comments and reviewing of the paper. Thanks are also due to Sh Trilok Das, Uttam Chand, Uday Kaushal for their help during field work and collection of data.

REFERENCES

Hu Ruji,et al.1992. An outline of avalanches in the Tian Shan mountains. Ann. Glaciol,16,1992.

Ma Weilin and HU Ruji,1990. Relationship between the development of depth hoar and avalanche release in the Tian Shan mountains, China.J. Glaciol. Vol. 36, No.122.

Wie Wenshou.1992. Avalanche in the Tian Shan mountains, China.Ann. Glaciol,16,1992.

Satyawali,P.K.1994.Grain growth under temperature gradient:A simple approach.Proceedings International Symposium, 'SNOWSYMP 94', held at SASE Manali, India,26-28Sep,1994.