



Simulation and Analysis of a Snow Avalanche Accident in Lower Western Himalaya, India

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Abstract

In Western Himalaya, an average 49 person die every year due to snow avalanche activities and this death rate is very high as compared to other Asian countries. A snow avalanche accident was observed on 5 January 2018 on Chowkibal–Tangdhar (CT) road axis at avalanche site number CT-8 located near Chowkibal village in Kupwara district, union territory Jammu and Kashmir, India. In the present paper, we discuss snow avalanche simulation, the climatic condition, avalanche debris height and length, and suggested solutions to handle avalanche situations. Rapid Mass MovementS numerical model in combination with digital elevation model and potential release area has been used to simulate avalanche accident occurred on 5 January 2018 at CT-8. The analysis demonstrates maximum snow avalanche velocity, impact of pressure and height of flow to be $\sim 25 \text{ ms}^{-1}$, $\sim 9.39 \times 10^4 \text{ kgm}^{-1} \text{ s}^{-2}$, and $\sim 3.0 \text{ m}$ respectively on 5 January 2018 at CT-8. Further simulated avalanche debris height and length from road has been validated with ground observed data. Ground reconnaissance of the location was conducted by a team of Snow and Avalanche Study Establishment, Chandigarh and it has been observed that lack of ‘avalanche awareness and Standard Operating Procedures during movement in avalanche prone areas’ among the travellers on the road cause accident. The present paper seems to be first to investigate snow avalanche accident in Western Himalaya and recommend that proper campaigning of avalanche awareness among the people residing in avalanche prone areas of Himalaya could reduce such accidents significantly.

Keywords Chowkibal–Tangdhar road · Snow avalanche · Western Himalaya · RAMMS

Introduction

Himalaya can deliver valuable natural resources to society, i.e. water, construction material minerals, wood for fuel and recreational services (Viviroli et al. 2007; Singh et al. 2020) and also responsible for climate change. However, in mountainous regions, due to harsh weather conditions and complex topography it is responsible for natural hazards such as snow avalanches, debris flows, rockfalls landslides, and flash floods (Singh et al. 2020).

In Himalaya, snow avalanches are common natural phenomenon and widely drift through an open network or

close gullies (McClung and Schaerer 1993). Avalanches become hazardous when people or property comes in their way. Number of avalanche accidents and damage to property reported every year in snow bound regions of the globe. In Indian Himalaya two union territory and three states are more avalanche prone such as union territory Jammu and Kashmir, union territory Ladakh, Himachal Pradesh, Uttarakhand, and Sikkim and contribute $\sim 2.2\%$ of total Indian population. Recently, McClung (2016) reported a statistics of avalanche fatalities during 1895 to 2014 in the high mountains of Asia, e.g. Himalaya, Karakoram, Pamir, Hindu Kush, Tien Shan and Dazu Shan covering snow bound regions of the countries India, China, Pakistan, Nepal, etc. He observed that about three-quarters of the deaths result from improper camp placements and failure to forecast snow avalanches. Ganju et al. (2002) studied the characteristics of avalanche accidents in Western Himalayan region in India and reported total avalanche fatalities of 1452 till 2001 as per records of Snow and

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Avalanche Study Establishment (SASE), Chandigarh. The authors reported that a considerable proportion $\sim 62\%$ of the total fatalities occurred when people were in movement and majority of accident have taken place during snowfall or immediately after the cessation of snow storm. Avalanche accidents and fatalities have also been studied in various other regions, e.g. European Alps (Techel et al. 2016), Switzerland (Pasquier et al. 2017), Norway (Lied 1988), New Zealand (Irwin and Owens 2004), United States (McCammon 2002), Canada (Germain 2016) etc..

In Indian Western Himalaya, Chowkibal–Tangdhar (C–T) road axis is one of the road in Tangdhar region of union territory Jammu and Kashmir which is most vulnerable to snow avalanches. Other regions which are more vulnerable for snow avalanches around Kashmir valley are Drass, Gurej, Keran, Machhal, Gulmarg, Naugam and Banihal (Gusain et al. 2009). Tangdhar region is one of the well-studied region for snow avalanches and many researchers have reported various avalanche prediction techniques for this road axis in the past (Pant and Ganju 2004; Singh and Ganju 2004; Singh et al. 2005, 2019; Joshi and Ganju 2006; Joshi and Srivastava 2014). Pant and Ganju (2004) developed a fuzzy rule-based system for prediction of avalanches for C–T road axis based on six snow-meteorological parameters. Singh and Ganju (2004) developed a statistical-based nearest-neighbour method for avalanche forecasting along the road axis. Joshi and Ganju (2006) combine the conventional and numerical technique to deliver avalanche danger warning for C–T axis in 24 h advance. Joshi and Srivastava (2014) developed a hidden Markov model for avalanche forecasting for the road axis. Joshi et al. (2018) explore the potential of hidden Markov model for avalanche forecasting over road network of Western Himalaya. Using the output from all these models and experience of experts, SASE delivered a ‘Low Danger’ avalanche warning in advance for the road axis for the day of accident (5 January 2018).

The present paper simulates the flow of snow avalanche on the avalanche site and investigates the cause of avalanche and avalanche accident. Further, simulated avalanche debris height and length from road has been validated with ground observed data by SASE at avalanche site.

Study Area and Data Used

Figure 1 shows the geographical location present study area, Chowkibal to Tangdhar and avalanche sites along the road axis. The road axis is a part of lower Western Himalaya (Singh et al. 2018) and join Tithwal with Kupwara district, lies in union territory Jammu and Kashmir of India. This C–T road is about ~ 36 km long and

movement on the road is affected by frequent avalanches from 26 major avalanche sites during winter season (Joshi and Ganju 2006). Formation zone of these avalanche sites are generally in the elevation range of 2800–3500 m m.s.l.. Tree line in the region exists up to 3300 m m.s.l. and beyond that elevation, slopes are generally barren/rocky with scanty trees and few patches of seasonal grass (Gusain et al 2009).

SASE has snow-met observation station named “Stage-II” in the study area at an elevation of 2650 m m.s.l.. Mean maximum and minimum temperature at the observation station for peak winter months December, January and February was observed between $3.2\text{ }^{\circ}\text{C}$ and $-9\text{ }^{\circ}\text{C}$ during last decade. Mean cumulative snowfall recorded for these months was 688 cm. Snow meteorological data reported in this study was collected at SASE observatory at Stage II. Snow-met parameters maximum temperature, minimum temperature, air temperature, relative humidity, sun shine hours, cloud amount, cloud type, snow depth, fresh snow fall amount, rainfall, wind speed, wind direction etc. was recorded at 0830 h and 1700 h local time pas per World Meteorological Organisation (WMO) guidelines.

Avalanche occurrences data in a particular region is essential for analysis of the snow avalanches pattern and development of prediction models. However, collection of data from inaccessible and isolated snow covered regions is difficult. SASE collect and record snow avalanche occurrence data at its meteorological observatories in Western Himalaya using ground reconnaissance, feedback from pedestrians and road traveller as well as feedback from border guarding Army personnel. Figure 2a shows the number of avalanche occurrences during different years from 1992 to 2016, reported to SASE along the C–T road axis. Total 796 avalanches has been recorded by SASE and maximum 84 avalanches has been observed during the year 2004 with average of 33 avalanches per year during past two decades. Total 48 casualties have been reported due to avalanches on C–T road axis during this period. Maximum avalanches are reported in January, February and March month about $\sim 23\%$, $\sim 33\%$, and $\sim 27\%$ of total avalanche during data period and shown in Fig. 2b.

European Avalanche Warning Services (2003) has classified avalanches in 4 classes based on length and volume of avalanche, i.e. sluff avalanche (Length < 50 m, Volume $< 100\text{ m}^3$), small avalanche (Length < 100 m, Volume $< 1000\text{ m}^3$), medium avalanche (Length < 1000 m, Volume $< 1000\text{ m}^3$), and large avalanche (Length > 1000 m, Volume $< 10,000\text{ m}^3$). In study area small and medium type of avalanches occurred very frequently as compared to sluff and large avalanche and shown in Fig. 2c. Figure 2d shows avalanche frequency distribution of avalanche debris height and observed $\sim 70\%$ of total avalanches has debris height < 3 m.

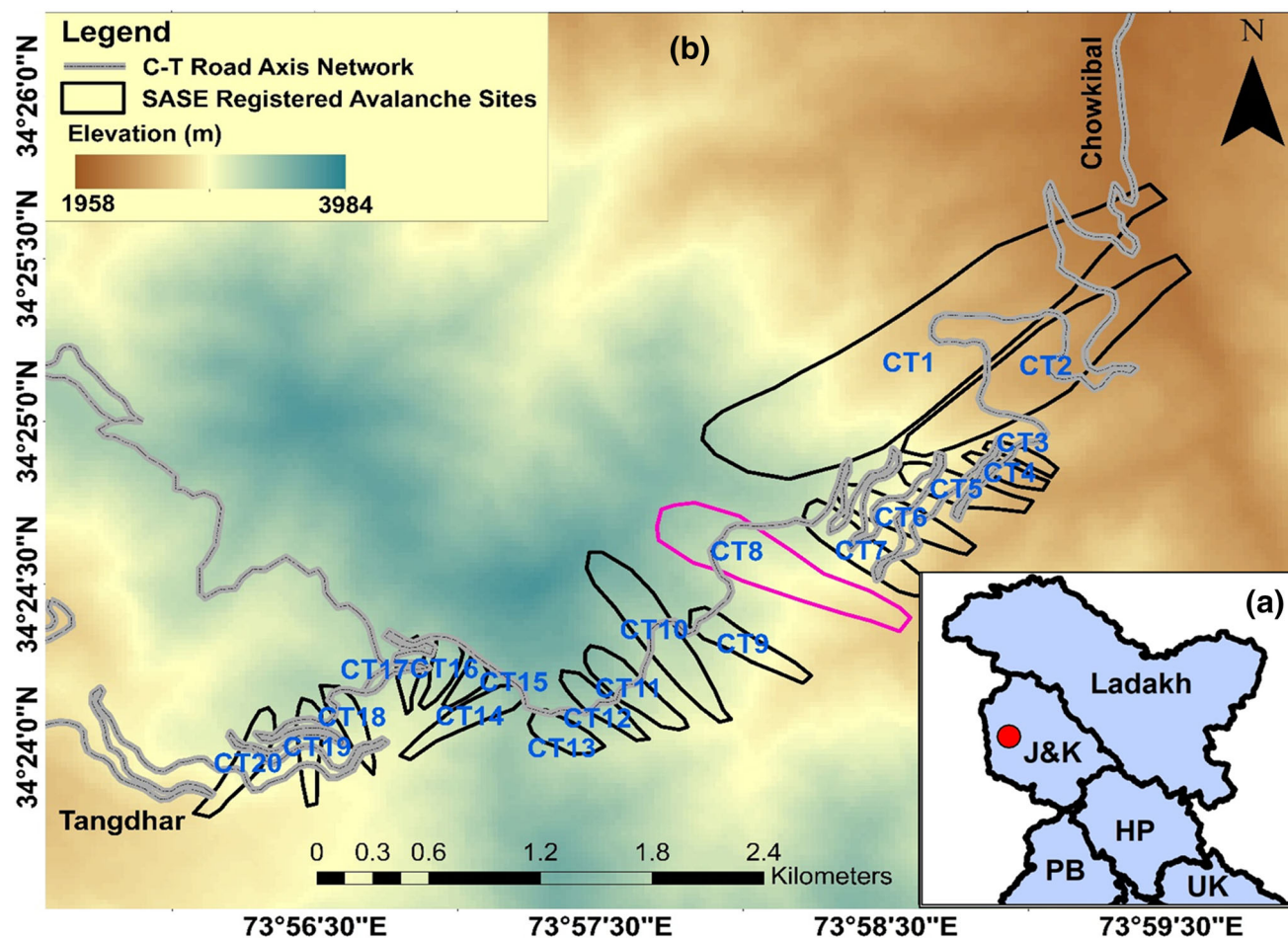


Fig. 1 a Geographical location of study area and red color indicate Tangdhar and Chowkibal regain, and b Elevation variation map of Chowkibal–Tangdhar region consisting of SASE registered avalanche

sites and road network connecting Tangdhar and Chowkibal village. Pink color polygon (CT-8) indicate avalanche occurred site on 5 January 2018

Landsat-8 satellite image at 30-m spatial resolution and Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) Digital Elevation Model (DEM) at high resolution (12.5-m) are download from <https://earthexplorer.usgs.gov/> and <https://www.asf.alaska.edu/sar.dat/palsar/> websites. Further, Landsat-8 image, DEM, vector layers of avalanche sites, field photographs and road form the geospatial data base for the study area are used to simulation and validation of avalanche occurred at C–T 8 on 5 January 2018.

Avalanche Accident Scenario and Field Survey of C–T Road Axis

An avalanche accident shattered in union territory Jammu & Kashmir state lies in Pir Panjal range of Western Himalaya, India on 5 January 2018. Most of the leading national and local newspapers, e.g. The Times of India, Hindustan Times, The Tribune, Deccan Chronicle, Amar

Ujala etc. and other media channels covered the story of the accident. The accident took place on Chowkibal–Tangdhar (C–T) road about 6 km from Chowkibal village towards Tangdhar and shown in Fig. 3. One vehicle (V1) was swept away by the avalanche and taken it to deep gorges and buried it under avalanche debris (Fig. 3c). Total 12 persons were caught in the avalanche. Two persons were rescued alive by the civil authorities and Army, while 10 persons recovered dead. On the same day an another avalanche accident took place on the same road axis, in which one Border Road Organisation (BRO) official was buried in avalanche debris and found dead.

Field photograph of the accident site, i.e. C–T: 8 avalanche site is shown in Fig. 3a. Avalanche site has two gullies, i.e. left and right gully and has scanty trees. Topographic analysis on DEM shows that 4% area of the avalanche site has slope angle in the range of 0 to 12°, 32% area in the range of 12° to 25°, 15% area in the range of 25° to 30°, 47% area in the range of 30° to 45° and only 1%

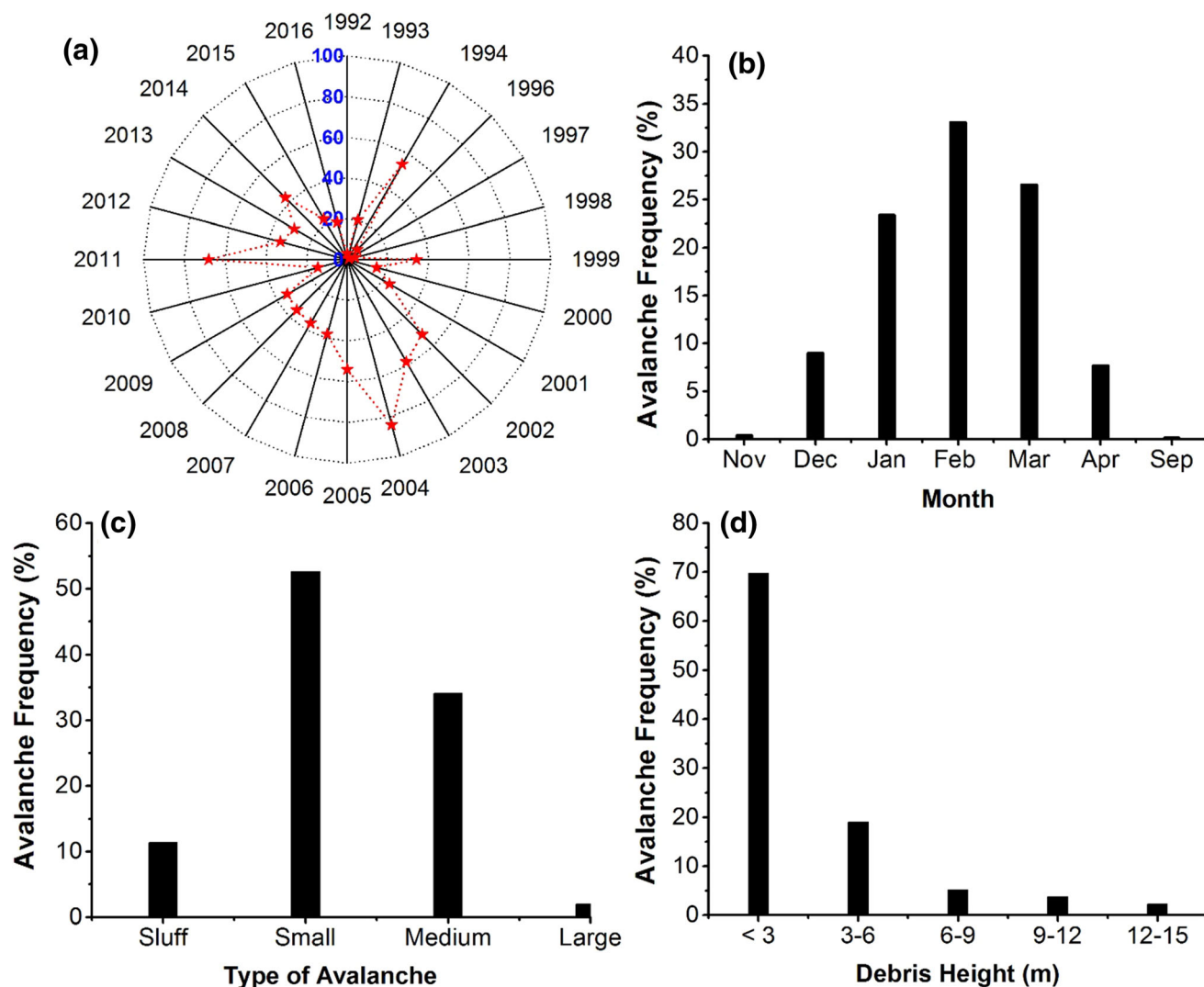


Fig. 2 a Avalanche occurrence data C–T axis during 1992–2016. The radius in the polar coordinate demonstrates the number of avalanches, and the angle indicates the years. Avalanche frequency distribution over b different month, c type of avalanche, and d debris height (m)

area above 45°. Most of the area of the avalanche site is facing towards South (42%) and South-East (37%).

Results and Discussions

Analysis of Snow-meteorological Parameters

Table 1 shows the snow-meteorological parameters analysis on avalanche occurred day and 4 days prior to avalanche accident. On 1 January 2018, weather was clear, average wind was low of the order of ~ 1.1 km/hour and snow depth at the observation location was 8 cm. On January second and third high cloud started appearing over the observation location as western disturbance was approaching. On 4 January 2018 the weather become cloudy with 8 Octa low clouds, average relative humidity

was 83% and air temperature raise to 0 °C during observation at 1700 h. Snowfall started early morning on 5 January 2018 and total fresh snow amount in the evening was 24 cm and snow depth at the observation station build up to 31 cm. On 4 January 2018 Weather Research and Forecast (WRF) model (model run at SASE on daily basis for prediction of snowfall and weather) predicted snowfall for the 5 January 2018 for C–T road axis. Avalanche prediction models were run at SASE for prediction of avalanches by adding the fresh snowfall amount predicted by the WRF model for the C–T road axis. ‘Low Danger’ avalanche warning was predicted by models and ‘Low Danger’ avalanche warning was issued for the C–T road axis.

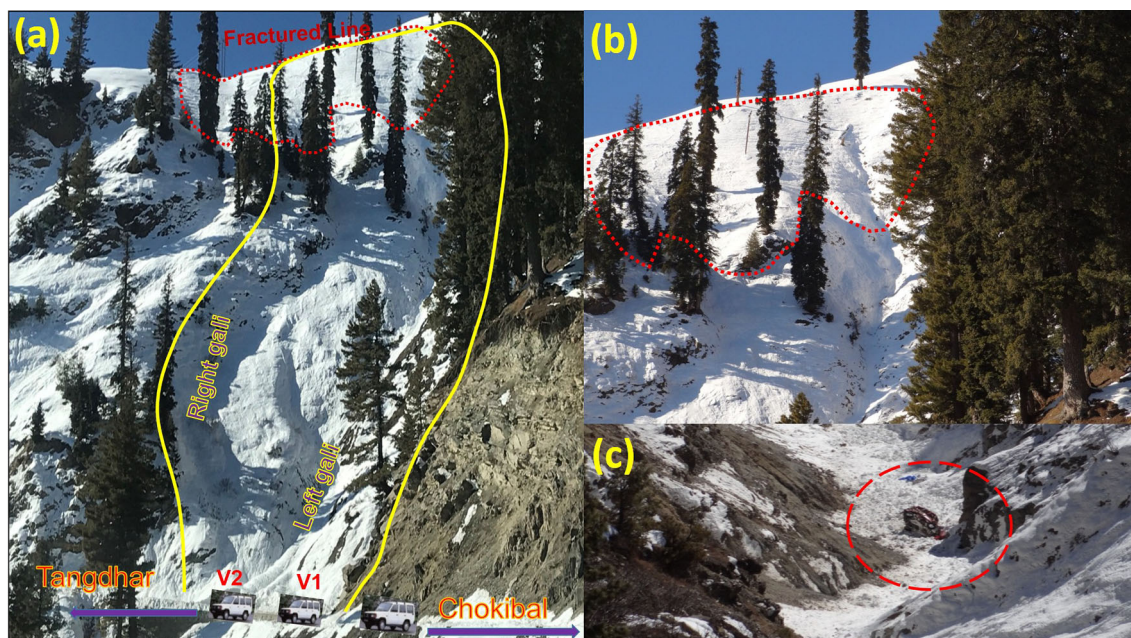


Fig. 3 Field photograph and survey of study area **a** Field photograph of avalanche triggered site (C–T: 8) on 5 January 2018. Fractured line is denoted by red color and V1 and V2 are two vehicle moving from

Chokibal village to Tangdhar, **b** Magnifying view of fractured line, and **d** Vehicle V1 swept away by the avalanche and buried under avalanche debris denoted by red circle

Table 1 Snow-meteorological parameters analysis from 1 January 2018 to 5 January 2018

| Date | Maximum temperature (°C) | Minimum temperature (°C) | Air temperature (°C) at 1700 h | Average wind speed (Kmh ⁻¹) | RH (%) | Weather type | Cloud Type | Snow depth (cm) | Fresh snow amount (cm) |
|-----------------------|--------------------------|--------------------------|--------------------------------|---|-----------|--------------------------|------------|-----------------|------------------------|
| 1 January 2018 | 6.5 °C | – 5.0 °C | – 0.5 °C | 1.1 | 80 | Clear sky | No cloud | 8 | 0 |
| 2 January 2018 | 6.0 °C | – 6.5 °C | – 0.5 °C | 0.1 | 79 | Partly cloudy (1Octa) | High cloud | 8 | 0 |
| 3 January 2018 | 6.0 °C | – 6.5 °C | – 1.0 °C | 0.05 | 69 | Partly cloudy (1Octa) | High cloud | 8 | 0 |
| 4 January 2018 | 4.0 °C | – 5.5 °C | 0.0 °C | 0.1 | 83 | Cloudy (8 Octa) | Low cloud | 8 | 0 |
| 5 January 2018 | – 4.0 °C | – 5.0 °C | – 4.0 °C | 0.05 | 99 | Snowfall (8 Octa) | Low | 31 | 24 |

Bold indicate snow-meteorological parameters on avalanche occurred day

High-resolution Geo-spatial Snow Depth Map and RAMMS

High-resolution geo-spatial snow depth map at 12.5 m spatial resolution was generated for the study area based on in situ observations of snow depth recorded at SASE observatory at Stage II and other observation locations around Kashmir valley. Detailed methodology for the generation snow depth map using in situ measurements in Himalaya is given by Gusain et al. (2016). Singh et al. (2019) explored this technique for C–T axis and

surrounding area over Western Himalaya. Snow depth in Himalaya varies with elevation in a particular mountain range, however from one mountain range to other snow depth pattern is different due to difference in snowfall. There are large spatial variation in snow depth in inter-mountain range also, due to topography and wind re-distribution of fresh snowfall over complex topographic features. Figure 4 shows the high-resolution snow depth map for the study area on 5 January 2018. Snow depth varies in the study area from 0 to 65 cm. Apart of the study area towards Kashmir valley shows less than 20 cm snow depth

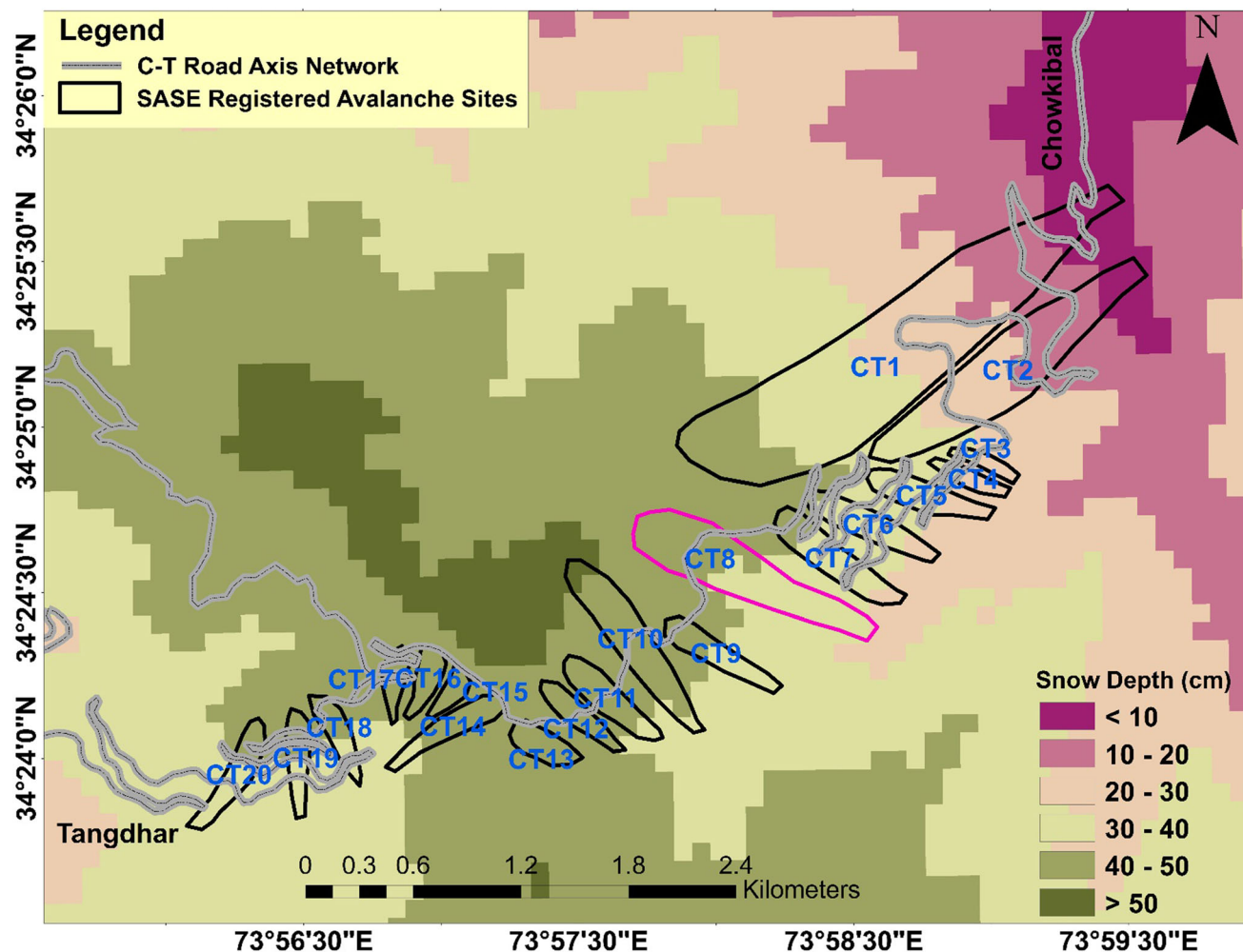


Fig. 4 High-resolution snow depth map of study area on 5 January 2018 generated using geo-spatial interpolation technique. Pink color polygon (CT-8) indicate avalanche occurred site on 5 January 2018

while higher elevation areas have more than 50 cm. Formation zone of the CT-8 avalanche site shows snow depth in the range of 40 cm to 50 cm on the day. Keeping in view of the 24 cm fresh snowfall recorded at SASE observatory, fracture depth of 25 cm was taken to run the flow simulation of avalanche on CT-8 avalanche site.

Potential release area (PRA) of snow avalanche in the formation zone was estimated using methodology given by Buhler et al. (2013). They developed an operational easy to use PRA detection tool in python and the code was shared by the lead author with the authors of this paper for further research in Himalaya. The tool require high spatial resolution DEM and forest cover information as input. ALOS PALSAR DEM having spatial resolution of 12.5 m was used for the estimation of PRA in the present study. Two PRA was estimated for present simulation having area 45,750 m² for PRA-1 and 16,050 for PRA-2 (Fig. 5a). Total release area was calculated ~ 61,800 m² and used

for flow simulation in Rapid Mass MovementS (RAMMS), a snow avalanche simulation toolbox.

RAMMS is a computer model specially designed by Swiss Institute for Snow and Avalanche Research SLF, Davos, Switzerland, for snow avalanche simulation and solves depth average numerical equations governing avalanche flow (Christen et al. 2010). The model require DEM, release zone area, fracture height and model friction parameters as input. ALOS PALSAR DEM, release zone area polygon vectors estimated using tool of Buhler et al. (2013), fracture height of 25 cm as discussed above was given input for RAMMS model. Friction parameters were generated by the software using automated procedures after extensive terrain analysis and were estimated in the range of 0.19–0.27. Figure 5b–d shows the simulation result of avalanche flow velocity (ms⁻¹), avalanche flow height (m) and impact of avalanche pressure (kg m⁻¹ s⁻²).

Figure 6 shows simulated parameters profile for avalanche. Total areal profile distance was observed 832 m

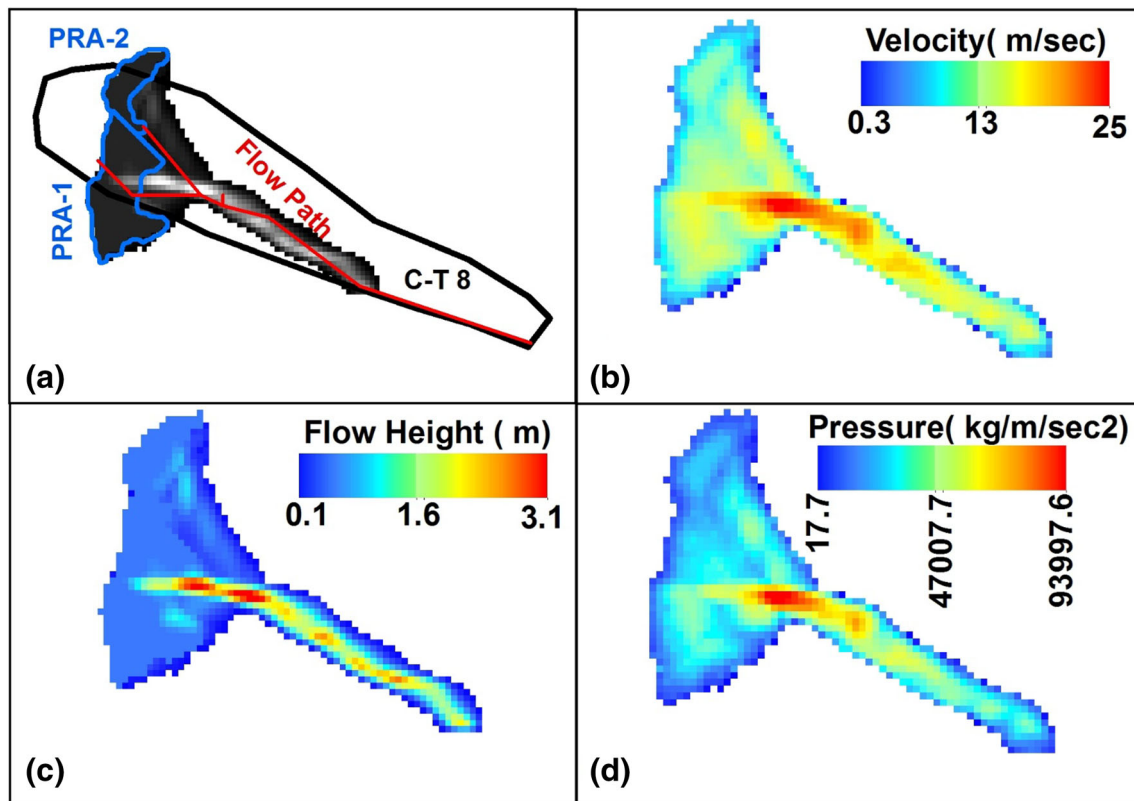


Fig. 5 Avalanche triggered site analysis **a** C-T: 8 avalanche site with potential release area (PRA) and flow path, **b** avalanche flow velocity (m s^{-1}), **c** avalanche flow height (m), and **d** impact of avalanche pressure ($\text{kg m}^{-1} \text{s}^{-2}$), simulated using RAMMS software for 5 January 2018

and maximum avalanche velocity was estimated to be $\sim 25 \text{ ms}^{-1}$ in the middle zone of the avalanche. The avalanche flow height varied from $\sim 0.1 \text{ m}$ in the formation zone to $\sim 3.0 \text{ m}$ in the middle zone and impact pressure varied from $\sim 17.7 \text{ kg m}^{-1} \text{ s}^{-2}$ to $\sim 9.39 \times 10^4 \text{ kg m}^{-1} \text{ s}^{-2}$. The mean impact pressure where the road crosses the avalanche site was estimated $\sim 6.0 \times 10^4 \text{ kg m}^{-1} \text{ s}^{-2}$ in the simulation. This impact pressure was supposed to hit the passenger vehicle V1 parked on the road (Fig. 1).

Validation of Simulated Results

Figure 7 shows manual measurement of avalanche debris height in study area on 5 January 2018 along affected road. A team of SASE visited the accident site location for ground reconnaissance and measured cross-sectional profile of the avalanche debris on road. Figure 7a shows the graph representing avalanche debris height on road and Fig. 7b shows the field photograph during debris height measurement. Maximum height of avalanche debris on road was measured to be 2.2 m and 2.9 m respectively in left gali and right gali of the avalanche site (Fig. 7a). Simulated maximum avalanche flow height of was

estimated $\sim 3.0 \text{ m}$ and shown in Fig. 5c, which was close to the maximum debris observed on the road.

The distance of the avalanche flow from the road was simulated $\sim 700 \text{ m}$ (Fig. 6) and ground measurement of the aerial distance of the maximum debris flow from the road was observed $\sim 650 \text{ m}$. The aerial distance of the maximum flow was estimated using the field instrument VECTORTM Class 1 Laser Product of Vectronix AG, Heerbrugg, Switzerland. Keeping in view of the aerial distance, actual ground distance would have been higher than 650 m which shows a close resemblance with the avalanche simulated distance. Ground measurement of debris thickness on the road and distance of maximum avalanche flow from the road indicate close approximation of the simulated results.

Probable Cause of Avalanche Occurrence and Avalanche Accident

Figure 8 shows the simulation of snowpack at the observation location Stage-II. Snowpack was simulated using ‘SNOWPACK’ model developed by WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland (Bartelt and Lehning 2002; Lehning et al. 2002a, b; Bel-laire et al. 2006). SNOWPACK simulates the development

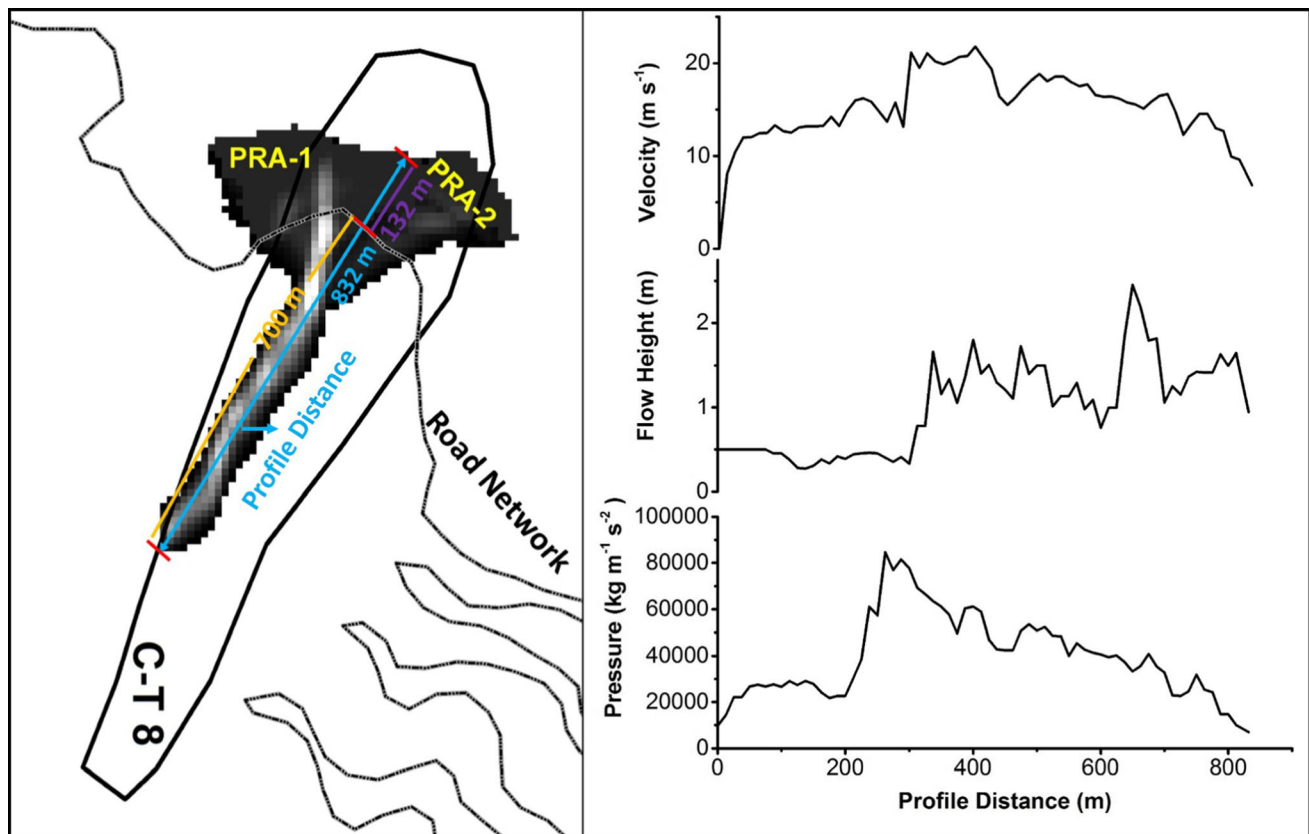


Fig. 6 Simulated parameters, i.e. velocity, flow height and impact of pressure, profile for C–T: 8 avalanche site on 5 January 2018

of snowpack at particular location during winter season based on snow-meteorological data recorded at that location. In the present paper, hourly data recorded by automatic weather station at Stage-II was used for simulation. The snowpack at the observation location started building-up since November 3rd week of 2017, although the snowpack was melted away by first week of December it again started building-up from second week of December. Simulation result shows a hard Melt–Freeze (M–F) layer at the top of the snowpack before fresh snowfall on 5 January 2018. A soft layer of faceted grains was present below the M–F layer having low hand hardness index below 20 N, indicating the presence of probable weak layer. With the overburden pressure of fresh snowfall the layer might have failed. Snowpack stratigraphy profiles of the previous years at Stage II location also show the presence of moist snow layers during January month and the presence of M–F layer at the top of the snowpack.

On 5 January 2018 around 1430 h one passenger vehicle which was parked at the middle of the CT-8 avalanche path on the road, as road was block ahead and snow clearance was going on. Suddenly CT-8 avalanche site triggered with a huge sound and swept away the vehicle in the snow cloud, described by a traveller, eye witness to the incident. The vehicle was later located in the gorges down below and

was buried under avalanche debris (Fig. 3c). Total 10 passengers lost their lives in the accident. The main reason of the accident was observed to be wrong parking of the vehicle in the avalanche path. The passengers and the driver were not aware about the standard operating procedures (SOPs) to be adopted while travelling in avalanche prone areas and parked the vehicle in one of the gully of the CT-8 avalanche site. The avalanche was direct action avalanche as it was triggered during snowfall due to overburden pressure of fresh snow on the snow layers already existing in the formation zone of avalanche. Avalanche site along C–T axis roads are frequently triggered due to specific topographic and snowpack conditions as formation zone are around 30°–35° slopes and surface are generally smooth and barren with very scanty trees. Snow cover depth of ~ 20 cm in the formation zone of avalanche site generally covered the surface undulations and makes surface smooth for triggering of avalanches due to any fresh snow fall over it. Generally, these avalanche sites trigger 2–3 times in a winter season from December to April, mainly due to overburden pressure of the fresh snowfall on existing weak layer in the snowpack. On 5 January 2018 the passenger vehicle was wrongly parked in an avalanche gully of the CT-8 avalanche site. Wrong parking of the vehicle in avalanche path, when avalanche

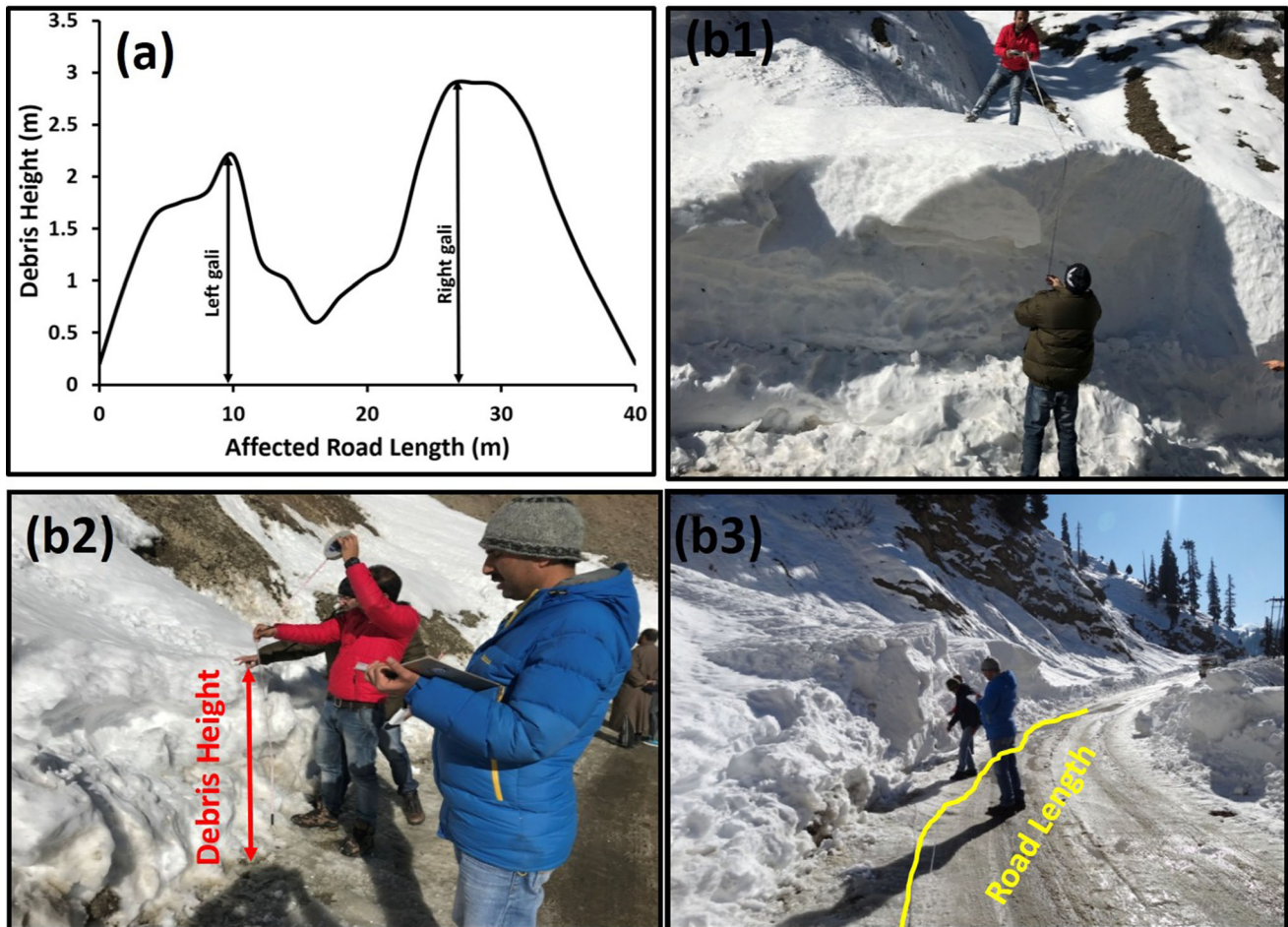


Fig. 7 a Graphical representation of avalanche debris height along avalanche affected road, and b Filed photograph of manual measurement of avalanche debris, on 5 January 2018

danger was building-up in the road axis was main cause of avalanche accident. The incident indicates the lack of awareness of the standard SOPs among travellers while moving in avalanche prone region. McClung (2016) reported that human actions and decisions govern the fatal avalanche patterns in high Asian mountains and attributed about three-quarters of the avalanche deaths to improper camp placements and failure to forecast snow avalanches. Ganju et al (2002) also observed that ignorance of the behaviour of the avalanche slopes has been main factor for the avalanche accidents in western Himalayan region. The present study also observes that improper site selection for parking of vehicle was the root cause of the avalanche accident on 5 January 2018, despite of the avalanche warning on the road axis.

Conclusion

The present paper investigates the avalanche accident at CT-8 avalanche site of Chowkibal–Tangdhar road axis in union territory Jammu & Kashmir, lower Western Himalaya, India. SNOWPACK model simulates the snow cover build-up from the day of first snowfall in the region till the date of avalanche accident. Model had shown a soft, weak layer consisting faceted grain below a hard M-F crust. Fresh snowfall of ~ 24 cm over the already existing snowpack on mountain slope might have failed the weak layer containing faceted grains due to overburden pressure and probably triggered the avalanche.

Geo-spatial snow depth map was generated using methodology proposed by Gusain et al. (2016) for the study area and snow depth in the formation zone of the avalanche site was in the range of 40 cm to 50 cm. Potential avalanche release area was estimated for the avalanche site. Total release area of $61,800 \text{ m}^2$ was estimated by the model and vector layer for the release area was generated. With

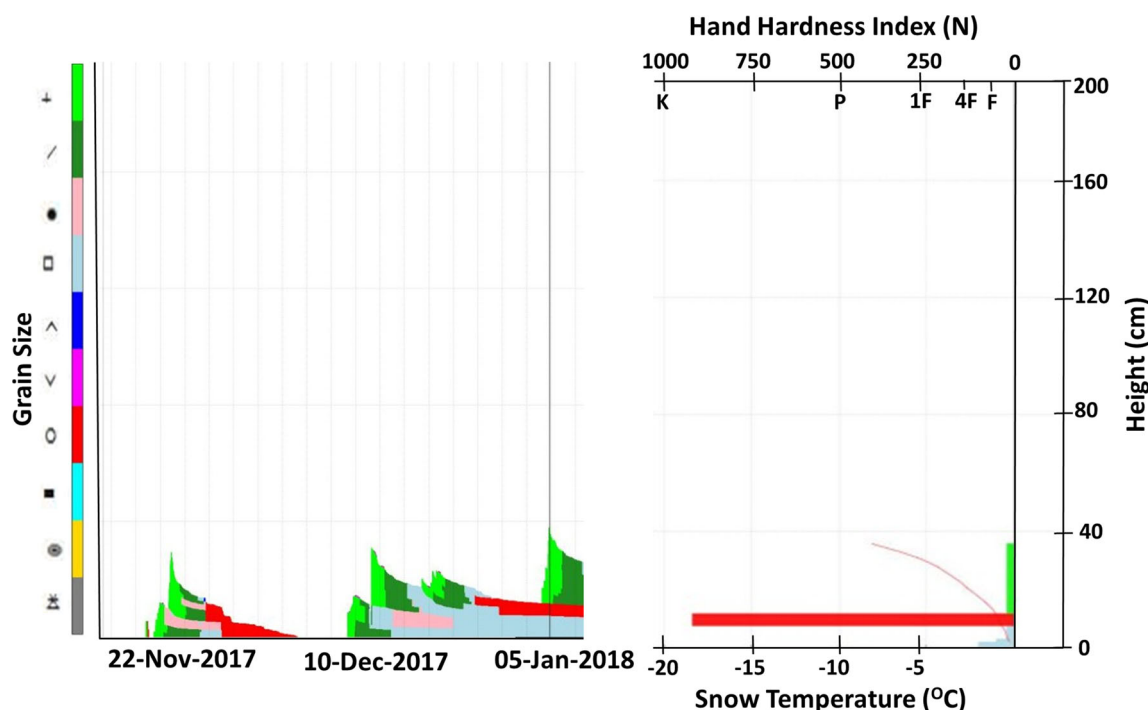


Fig. 8 Simulation of snowpack layers, structure and hardness index at the observation location Stage-II

the help of release area and fracture height of 25 cm, avalanche flow was simulated using RAMMS model. Model estimated maximum avalanche velocity $\sim 25 \text{ ms}^{-1}$, maximum avalanche flow height $\sim 3.0 \text{ m}$ and maximum impact pressure of $\sim 9.39 \times 10^4 \text{ kgm}^{-1} \text{ s}^{-2}$. The mean impact pressure of the avalanche at the cross-section of road was estimated $\sim 6.0 \times 10^4 \text{ kgm}^{-1} \text{ s}^{-2}$. Model simulated the length of debris flow below road $\sim 700 \text{ m}$. A team of SASE personnel visited the accident site and measured cross-sectional profile of the avalanche debris on the road and the debris flow length below road. The maximum debris height was 2.9 m and the straight length of the avalanche debris beyond road axis was measured $\sim 650 \text{ m}$ using VECTORTM Class 1 Laser Product of Vectronix. The ground observations were quite close to the simulated result. The main cause of avalanche accident was improper site selection for parking of the vehicle and lack of awareness of standard SOPs while moving in avalanche prone areas. A proper avalanche awareness program to the people living in snow bound avalanche prone areas may help in reducing such avalanche accidents in future.

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[edu/sar.dat/palsar/](https://www.asf.alaska.edu/sar.dat/palsar/) websites for providing Landsat-8 data and ALOS PALSAR DEM.

References

- Bartelt, P., & Lehning, M. (2002). A physical SNOWPACK model for the Swiss avalanche warning Part I: Numerical model. *Cold Regions Science and Technology*. [https://doi.org/10.1016/S0165-232X\(02\)00074-5](https://doi.org/10.1016/S0165-232X(02)00074-5).
- Bellaire, S., Schweizer, J., Fierz, C., Lehning, M. & Pielmeier, C. (2006). Predicting snow cover stability with the snow cover model SNOWPACK. In Proceeding ISSW 2006, International Snow Science Workshop, Telluride CO, U.S.A., 1–6 October-2006, pp. 38–43
- Bühler, Y., Kumar, S., Veitinger, J., Christen, M., Stoffel, A., & Snehmani., (2013). Automated identification of potential snow avalanche release areas based on digital elevation models. *Natural Hazards and Earth System Science*. <https://doi.org/10.5194/nhess-13-1321-2013>.
- Christen, M., Kowalski, J., & Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Regions Science and Technology*. <https://doi.org/10.1016/j.coldregions.2010.04.005>.
- European Avalanche Warning Services (2003) <https://www.slf.ch/en/avalanche-bulletin-and-snow-situation/about-the-avalanche-bulletin/avalanche-sizes.html>
- Ganju, A., Thakur, N. K. and Rana, V. (2002). Characteristics of avalanche accidents in western Himalayan region, India. In Proceedings of the International Snow Science Workshop, 29 September–4 October 2002, Penticton, B.C., Canada. International Snow Science Workshop, 200–207
- Germain, D. (2016). Snow avalanche hazard assessment and risk management in northern Quebec, eastern Canada. *Natural Hazards*. <https://doi.org/10.1007/s11069-015-2024-z>.

- Gusain, H. S., Chand, D., Thakur, N., Singh, A., & Ganju, A. (2009). *Snow avalanche climatology of Indian Western Himalaya, International Symposium on Snow and Avalanches (ISSA), 6–10 April, 2009*. India: Manali.
- Gusain, H. S., Mishra, V. D., Arora, M. K., Mamgain, S., & Singh, D. K. (2016). Operational algorithm for generation of snow depth maps from discrete data in Indian Western Himalaya. *Cold Regions Science and Technology*. <https://doi.org/10.1016/j.coldregions.2016.02.012>.
- Irwin, D. & Owens, I. (2004) A history of avalanche accidents in Aotearoa New Zealand. In *Proceedings of the international snow science workshop*. Jackson Hole, WY, pp484–491.
- Joshi, J. C., & Ganju, A. (2006). Avalanche warning on Chowkibal–Tangdhar axis (J&K): A hybrid approach. *Current Science*, 91(1), 1558.
- Joshi, J. C., & Srivastava, S. (2014). A hidden markov model for avalanche forecasting on Chowkibal–Tangdhar road axis in Indian Himalayas. *Journal of Earth System Science*. <https://doi.org/10.1007/s12040-014-0510-4>.
- Joshi, J. C., Kumar, T., Srivastava, S., Sachdeva, D., & Ganju, A. (2018). Application of Hidden Markov Model for avalanche danger simulations for road sectors in North-West Himalaya. *Natural Hazards*. <https://doi.org/10.1007/s11069-018-3343-7>.
- Lehning, M., Bartelt, P., Brown, B., & Fierz, C. (2002a). A physical SNOWPACK model for the Swiss avalanche warning Part III: Meteorological forcing, thin layer formation and evaluation. *Cold Regions Science and Technology*. [https://doi.org/10.1016/S0165-232X\(02\)00072-1](https://doi.org/10.1016/S0165-232X(02)00072-1).
- Lehning, M., Bartelt, P., Brown, B., Fierz, C., & Satyawali, P. (2002b). *A physical SNOWPACK model for the Swiss avalanche warning Part II*. Snow microstructure: Cold Regions Science and Technology. [https://doi.org/10.1016/S0165-232X\(02\)00073-3](https://doi.org/10.1016/S0165-232X(02)00073-3).
- Lied, K. (1988). The avalanche accident at Vassdalen, Norway, 5 March 1986. *Cold Regions Science and Technology*. [https://doi.org/10.1016/0165-232X\(88\)90060-2](https://doi.org/10.1016/0165-232X(88)90060-2).
- McCammon, I. (2002). Evidence of heuristic traps in recreational avalanche accidents, International Snow Science Workshop, Penticton, British Columbia, Sept. 30–Oct 4, 2002.
- McClung, D. M. (2016). Avalanche character and fatalities in the high mountains of Asia. *Annals of Glaciology*. <https://doi.org/10.3189/2016aog71a075>.
- McClung, D., Schaerer, P. (1993) *The avalanche handbook*, mountaineers, 1001SW Klickitat Way, Seattle, WA 98134, USA
- Pant, L. M., & Ganju, A. (2004). Fuzzy rule-based system for prediction of direct action avalanches. *Current Science*, 87(1), 99–104.
- Pasquier, M., Hugli, O., Kottmann, A., & Techel, F. (2016). Avalanche accidents causing fatalities: are they any different in the summer? *High Altitude Medicine & Biology*. <https://doi.org/10.1089/ham.2016.0065>.
- Singh, A., & Ganju, A. (2004). A supplement to nearest-neighbour method for avalanche forecasting. *Cold Regions Science and Technology*. <https://doi.org/10.1016/j.coldregions.2004.03.005>.
- Singh, A., Srinivasan, K., & Ganju, A. (2005). Avalanche forecast using numerical weather prediction in Indian Himalaya. *Cold Regions Science and Technology*. <https://doi.org/10.1016/j.coldregions.2005.05.009>.
- Singh, D. K., Mishra, V. D., Gusain, H. S., Gupta, N., & Singh, A. K. (2019). Geo-spatial modeling for automated demarcation of snow avalanche hazard areas using landsat-8 satellite images and in situ data. *Journal of the Indian Society of Remote Sensing*. <https://doi.org/10.1007/s12524-018-00936-w>.
- Singh, K. K., Singh, D. K., Thakur, N. K., Dewali, S. K., Negi, H. S., & Snehmani, & Mishra, V. D., (2020). *Detection and mapping of snow avalanche debris from Western Himalaya*. India using remote sensing satellite images: Geocarto International. <https://doi.org/10.1080/10106049.2020.1762762>.
- Singh, D. K., Gusain, H. S., Mishra, V., & Gupta, N. (2018). Snow cover variability in North-West Himalaya during last decade. *Arabian Journal of Geosciences*. <https://doi.org/10.1007/s12517-018-3926-3>.
- Techel, F., Jarry, F., Kronthaler, G., Mitterer, S., Nairz, P., Pavšek, M., et al. (2016). Avalanche fatalities in the European Alps: Long-term trends and statistics. *Geographica Helvetica*. <https://doi.org/10.5194/gh-71-147-2016>.
- Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*. <https://doi.org/10.1029/2006WR005653>.

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