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Elucidating the causal relationship between earthquake activity and avalanche occurrences

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सार – वर्तमान अध्ययन उत्तर-पश्चिमी हिमालय में भूकंपीय गतिविधि और हिमस्खलन (एवलांच) घटनाओं के बीच संबंध की जाँच करता है, जिसमें केंद्र शासित प्रदेश जम्मू एवं कश्मीर, लद्दाख, तथा हिमाचल प्रदेश और उत्तराखंड के कुछ भाग शामिल हैं। यह क्षेत्र भूकंपीय दृष्टि से अत्यधिक सक्रिय है और हिमालय के सर्वोच्च भूकंपीय क्षेत्रों में स्थित है। साथ ही, उच्च ऊँचाई, तीव्र ढाल वाले भू-भाग एवं हिमनदीय पर्यावरण के कारण यह क्षेत्र हिमस्खलनों के प्रति अत्यंत संवेदनशील है।इस अध्ययन में 1980 से 2018 तक के चार दशकों के हिमस्खलन घटनाओं एवं भूकंपीय गतिविधियों के आँकड़ों का उपयोग किया गया है। अध्ययन का उद्देश्य ताज़ी हिमपात एवं पवन द्वारा हिम निक्षेपण जैसे मौसमीय कारकों को अलग रखते हुए, हिमस्खलन के उत्प्रेरण में भूकंपीय गतिविधि के प्रभाव को स्पष्ट करना है। यद्यपि कंपन (ट्रेमर) की तीव्रता और हिमस्खलन के विलंब समय (लैग टाइम) के बीच एक कमजोर सकारात्मक सहसंबंध पाया गया है, फिर भी हिस्टोग्राम आँकड़ों से यह स्पष्ट होता है कि कंपन के बाद 38.32-76.32 घंटे (केस 1) तथा 1.97-14.57 घंटे (केस 2) के भीतर हिमस्खलनों की अधिकतम घटनाएँ दर्ज की गईं। यह दर्शाता है कि भूकंपीय गतिविधि के प्रति हिमस्खलनों की प्रतिक्रिया विलंबित किंतु समय-सीमित होती है।ये निष्कर्ष संकेत देते हैं कि इस क्षेत्र में हिमस्खलन को प्रेरित करने में भूकंपीय कंपन महत्वपूर्ण भूमिका निभाते हैं। इस अध्ययन से प्राप्त जानकारी उत्तर-पश्चिमी हिमालय में हिमस्खलन पूर्वानुमान एवं आपदा आकलन को बेहतर बनाने में सहायक होगी, जहाँ भूकंप-प्रेरित हिमस्खलन मानव जीवन एवं आधारभूत संरचना के लिए गंभीर जोखिम उत्पन्न करते हैं। भविष्य में, भूकंप के केंद्र (एपिसेंटर) की दूरी का हिमस्खलन उत्प्रेरण पर प्रभाव समझने हेतु और अधिक अनुसंधान की आवश्यकता है, जिससे पूर्वानुमान क्षमताओं एवं जोखिम न्यूनीकरण रणनीतियों को और अधिक सुदृढ़ किया जा सके।

ABSTRACT. The present study investigates the relationship between seismic activity and avalanche occurrences in the North-west Himalayas, focusing on the Union Territory of Jammu and Kashmir, Ladakh, parts of Himachal Pradesh, and Uttarakhand. The region is seismically active, lying within the highest seismic zones of the Himalayas, and is prone to avalanches due to its high-altitude, steep terrain, and glacial environment. Using four decades of data (1980–2018) on avalanche occurrences and seismic events, the aim of this study is to isolate the influence of seismic activity on avalanche triggers, excluding meteorological factors such as fresh snowfall and wind deposition. Although there exists a weak positive correlation between tremor magnitude and avalanche lag time but there are peak occurrences observed within 38.32–76.32 hours (Case 1) and 1.97–14.57 hours (Case 2) post-tremor, as indicated by histogram data, highlighting a delayed yet time bounded response of avalanches to seismic activity. These findings suggest that seismic tremors play a critical role in triggering avalanches in this region. The insights of this study will contribute to improve the avalanche forecasting and hazard assessment in the North-west Himalayas, where seismic-induced avalanches pose significant risks to life and infrastructure. Further research is recommended to refine the understanding of the influence of earthquake epicenter distance on avalanche triggers, potentially enhancing predictive capabilities and mitigation strategies.

Key words – Avalanche, Seismic tremors, Earthquake, Himalayas.

1. Introduction

The continent-continent collision between the Indian and the Eurasian plates resulted in the formation of the mighty Himalayas during the Late Cretaceous to Early Eocene times (Le Fort, 1975; Valdiya, 1984; Searle *et al.*, 1987). Since 50 million years, there has been continued convergence of these continental plates causing persistent lithosphere deformation that has modified the seismo-tectonic setup of the entire region (Le Fort, 1975). The North-west Himalayas are recognized as seismically active regions within the broader context of the Himalayan seismic belt, with significant historical earthquake records, including the 1905 Kangra earthquake (M_w 7.8) and the 2015 Gorkha earthquake (M_w 7.8) (Narayan *et al.,* 2024, Kumar *et al.,*2022). The tectonic complexity of this area is underscored by the presence of various active faults, such as the Khetpurali Taksal Fault, which plays a crucial role in slip partitioning and seismic hazard assessment (Kumar *et al.,*2022). Additionally, the impact of Western Disturbances, which is a significant meteorological phenomenon, exacerbate the effects of seismic activities, leading to increased risks of avalanches and landslides in these mountainous terrains (Chauhan *et al.,*2023).

The North-west Himalayas receive snowfall during winters due to Western Disturbances. The snowpack on a slope forms layer by layer, with each snowfall or snowstorm adding a new layer on top of the previous ones. Due to varying meteorological conditions during each event, each layer develop unique properties in terms of grain shape, size, inter-granular bonding, density, hardness, and wetness. Wind further influences this process by redistributing fresh snow, resulting in complex layering. With the advancement of time, each layer undergoes physical and mechanical changes, including settlement under overburden pressure, heat and mass transfer between layers, and energy exchange with the atmosphere. Additionally, meltwater production and refreezing processes modify the structure and stability of each layer. The snowpack's stability or strength is dynamic, as it continuously metamorphoses due to these atmospheric interactions. Avalanches occur when either the snowpack becomes too weak to bear its own weight or when external stresses exceed the strength threshold of the snowpack. Stress factors include gravitational forces, the cumulative weight of new snowfall, and dynamic forces such as wind loading. Under certain conditions, even a minor additional stress, such as a skier or seismic tremor, can destabilize a transitional snowpack, causing it to fail. Conversely, a snowpack may also stabilize over time and gain enough strength to resist higher stresses. High-altitude avalanches pose significant threat to life and property, often triggered by direct meteorological factors (such as snow loading, wind, and radiation), which affect the snowpack's weak layers. Indirect factors, such as seismic activity or volcanic eruptions, can serve as triggers for avalanche events (Singh *et al.,* 2002). All land and submarine slope failures are threat to human population and property (Tappin *et al.,* 1999). It is known that temporary instability upon slopes also occur by short lived inertial stresses which are produced by acceleration due to earthquake. A number of catastrophic geological processes, including slope-collapse phenomena such as landslides, debris slides, rockslides, rock falls (Keefer, 1984, 2002; Hewitt *et al.,* 2008), sediment sliding on the ocean floor (Heezen *et al.,*1952), and seismogenic mudflows and slush flows are caused by strong ground motions produced by earthquakes. Snow avalanches are the rare type of catastrophic slope failure triggered by earthquakes (Chernous *et al.,* 2004). Loss of life and infrastructure is the consequence of unstable snowpack triggered by an earthquake (LaChapelle, 1968). The 1970 Huascaran avalanche in Peru, triggered by an earthquake, stands as the most catastrophic event of its kind, buried the towns of Yungay and Ranrahirca and caused tens of thousands of deaths (Chernous *et al.,* 2002). Similarly, the Nepal earthquake on April 25, 2015 (M_w 7.8) triggered an avalanche that completely engulfed Langtang village, which resulted in the deaths of approximately 350 people (Podolskiy *et al*., 2010). In the present study, we focus on the North-west Himalayas which is frequented by seismic activity of various intensities. The objective of this study is to understand the relationship between seismic activity and avalanche occurrences in the North-west Himalayas, excluding meteorological influences by considering events with no fresh snowfall prior six days and post three days. This also includes the exclusion of avalanches triggered as a result of the excessive build up on slopes when angle of repose exceeds the slope angle and result in triggering of avalanche without any seismic activity.

1.1. *Study area*

The study area of the present investigation falls within latitude 28° N to 37° N and longitude 72.5° E to 81.5° E encompassing the North-west Himalayas, including the Union Territory of Ladakh, Jammu and Kashmir, parts of Himachal Pradesh, and Uttarakhand (Fig. 1). These regions constitute the Kashmir Gap, recognized as the highest earthquake-prone seismic zone in the Himalayas (Sharma *et al.,* 2013). The observatory names have not been mentioned due to the DRDO restrictions whereas further in result section to clarify the location of avalanche and seismic tremor, broader sector and district of the station has been mentioned.

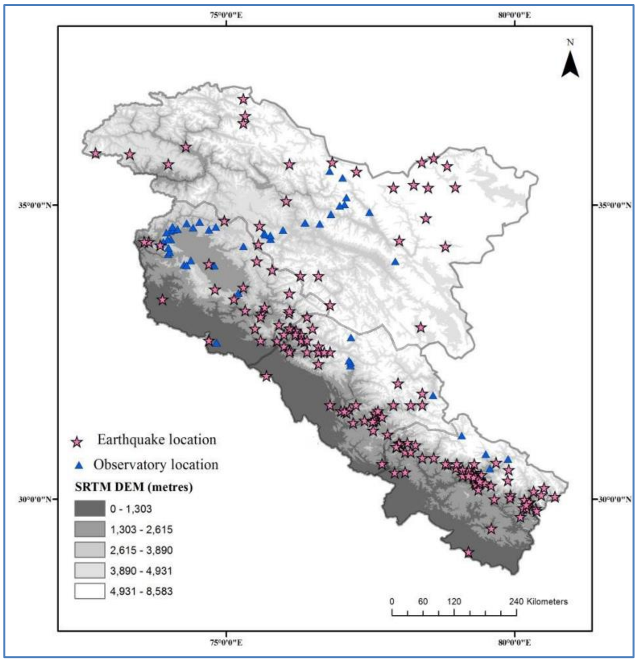

Fig. 1. Study Area showing North-west Himalayas with DRDO observatory and earthquake locations

According to the seismic zonation map, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Ladakh lie in earthquake zone IV whereas a part of Kashmir lies in zone V which indicate the highest level of seismicity. The region's susceptibility to earthquakes is further compounded by the presence of numerous active faults and thrust zones, which are capable of generating large magnitude earthquakes. (Singh *et al.*, 2018). The seismic activity in the region has the potential to trigger various secondary hazards, such as avalanches, landslides, and rockfalls. The high-altitude, steep terrain, and glacial environment of the Himalayas make the region particularly prone to avalanche events, which can be triggered by seismic shaking or other factors such as heavy snowfall, rapid snowmelt, or human activities (Singh *et al.*, 2018, Sur *et al.*, 2020, Kanwal *et al.*, 2017, Agrawal *et al.*, 2022).

2. **Data and methodology**

The dataset comprises recorded avalanche occurrences and seismic tremors from 1980 to 2018. Avalanche occurrence data was obtained from the Defence Geoinformatics Research Establishment (DGRE), Chandigarh, while seismic data was sourced from various agencies, including the Indian Meteorological Department (IMD), open-access seismic platforms, and published reports and research articles. Additionally, data from Singh *et al*. (2002) and Parshad *et al*. (2019) was incorporated for comparative analysis. To systematically analyze the relationship between seismic activity and avalanche occurrences, the dataset was categorized based on avalanche occurrence type and seismic magnitude.

Avalanche data was segregated into direct occurrences, which refer to avalanches triggered immediately due to seismic tremors; delayed occurrences, which include avalanches occurring with a time lag after seismic activity; and indirect occurrences, where avalanches are influenced by tremor activity but potentially modulated by other factors. Seismic events were classified into three magnitude categories: low magnitude (1.0-3.0 M_w), moderate magnitude (3.1-5.0 M_w), and high magnitude (>5.0 M_w), and included key parameters such as day, month, year, date, time, latitude, longitude, magnitude, and depth.

To establish a relationship between seismic activity and avalanche occurrences, a comparative analysis was conducted for the months of November to April, when avalanches are most frequent in the Indian Himalaya. This period coincides with precipitation from Western Disturbances, which typically lasts five to six days (Dimri *et al.*, 2015). Subsequently, it was observed that after three days, 25% of the snow settles or melt while remaining snow is referred as the standing snow. Thus, this combination of standing snow and fresh snow plays an important role in triggering the avalanches. Therefore, to make sure that avalanche is not due to any meteorological factor, no fresh snow prior six days and post three days of seismic activity was considered in the present study. A similar study was conducted by Singh *et al*. (2002); however, the present study employs a novel methodology by specifically excluding fresh snow data for defined periods around seismic events. In this study, two distinct cases were considered to evaluate the relationship between tremor activity and avalanche occurrences. Case 1 examines the tremor activity of varying magnitudes and corresponding avalanche occurrences, accounting for periods with no fresh snowfall during the six days preceding and three days post the seismic event (Table 1). Case 2 focuses on the same-day avalanche occurrences due to tremor activity which illustrate the immediate impact of seismic event on avalanche triggering (Table 2). Furthermore, a lag evaluation was conducted to analyse the time difference between the tremor occurrence and avalanche occurrence, providing insight into whether avalanches occur as an immediate response to tremors or with a delay.

3. **Result and discussion**

The present study encompasses the regions of Jammu and Kashmir, Ladakh, Uttarakhand, and Himachal Pradesh, and includes a comparative analysis of seismic

TABLE 1

Avalanche occurrences and corresponding seismic events for Case 1. with lag evaluation

Sector/Location	Avalanche occurrence	Avalanche occurrence time	Tremor Date	Tremor Time	Magnitude	Lag evaluation
Gulmarg (J&K)	3/31/2000	1600	3/30/2000	8:41 PM	3.5	19.32
Kashmir (J&K)	11/22/2005	1000	11/20/2005	11:05 AM	4.8	46.92
Kashmir (J&K)	12/4/2005	1500	12/1/2005	9:08 PM	4.7	65.87
Kashmir (J&K)	12/4/2005	1800	12/1/2005	9:08 PM	4.7	68.87
Kashmir (J&K)	12/4/2005	2030	12/1/2005	9:08 PM	4.7	71.37
Base Camp (Siachin)	4/27/2006	1910	4/26/2006	6:11 AM	4.7	36.98
Talwar (Siachin)	4/27/2006	1910	4/26/2006	6:11 AM	4.7	36.98
Talwar (Siachin)	4/27/2006	1915	4/26/2006	6:11 AM	4.7	37.08
Base Camp (Siachin)	4/28/2006	1910	4/26/2006	6:11 AM	4.7	60.98
Talwar (Siachin)	4/28/2006	1910	4/26/2006	6:11 AM	4.7	60.98
Talwar (Siachin)	4/28/2006	1915	4/26/2006	6:11 AM	4.7	61.08
Machaal (J&K)	3/16/2010	1700	3/15/2010	12:39 AM	4.9	40.35
Machaal (J&K)	3/16/2010	1710	3/15/2010	12:39 AM	4.9	40.52
Machaal (J&K)	3/16/2010	1720	3/15/2010	12:39 AM	4.9	40.68
Machaal (J&K)	3/16/2010	1730	3/15/2010	12:39 AM	4.9	40.85
Tangdhar (J&K)	4/30/2011	1345	4/28/2011	3:23 PM	3.8	46.37
Keran (J&K)	4/13/2015	1100	4/10/2015	2:49 PM	3.8	68.18
Tangdhar (J&K)	11/19/2015	1343	11/18/2015	1:55 PM	3.5	23.8
Keran (J&K)	2/1/2016	1430	1/30/2016	3:09 PM	3.1	47.35
Base Camp (Siachin)	3/19/2016	1205	3/17/2016	10:16 PM	4.1	37.82
Base Camp (Siachin)	4/2/2016	930	3/30/2016	7:34 AM	3.4	49.93
Jammu (J&K)	1/25/2017	1303	1/23/2017	3:03 PM	3.2	22.0
Drass (J&K)	3/4/2017	1030	3/2/2017	1:39 AM	3.8	56.85
Drass (J&K)	3/17/2017	1400	3/14/2017	5:48 AM	3.6	76.2
Keran (J&K)	3/17/2017	1830	3/14/2017	5:48 AM	3.6	80.7
Keran (J&K)	3/17/2017	2000	3/14/2017	5:48 AM	3.6	82.2
Tangdhar (J&K)	3/17/2017	2000	3/14/2017	5:48 AM	3.6	82.2

TABLE 2

Avalanche occurrences and corresponding seismic events for Case 2. with lag evaluation.

Sector/ Location	Avalanche occurrence	Avalanche occurrence time	Tremor Date	Tremor Time	Magnitude	Lag evaluation
Drass (J&K)	1/28/2002	1125	1/28/2002	4:03 AM	5.2	7.37
Drass (J&K)	1/28/2002	1355	1/28/2002	4:03 AM	5.2	9.87
Haddan Taj (J&K)	3/1/2008	1408	3/1/2008	2:06 PM	4.1	12.03
Haddan Taj (J&K)	3/1/2008	2010	3/1/2008	2:06 PM	4.1	18.07
Talwar (Siachin)	3/11/2008	1030	3/11/2008	10:14 PM	3.5	11.73
Durga (Siachin)	3/16/2008	1605	3/16/2008	11:14 AM	3.5	4.85
Jwala (Siachin)	3/16/2008	2300	3/16/2008	11:14 AM	3.5	11.77

Table 2 Continued

Drass (J&K)	3/15/2010	1550	3/15/2010	12:39 AM	4.9	15.18
Siala (Siachin)	11/7/2010	1108	11/7/2010	9:10 AM	4.2	1.97
Zullu (Siachin)	2/12/2015	1215	2/12/2015	1:44 AM	3.6	10.52
Pharkian (J&K)	2/14/2015	1250	2/14/2015	3:51 AM	3.9	8.98
Kanzalwan (J&K)	2/14/2015	1309	2/14/2015	6:14 AM	3.9	7.08
Bahadur (Siachin)	11/13/2015	400	11/13/2015	1:14 PM	3.2	9.23
Base Camp (Siachin)	1/23/2017	1730	1/23/2017	3:03 PM	3.2	2.45
Talwar (Siachin)	1/23/2017	1730	1/23/2017	3:03 PM	3.2	2.45
Durga (Siachin)	3/2/2017	1245	3/2/2017	1:39 AM	3.8	11.1

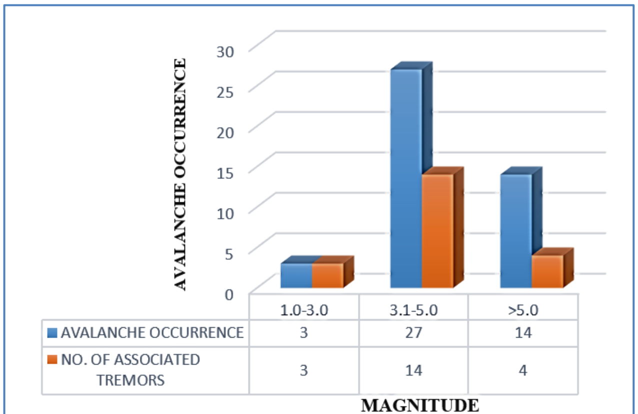

Fig. 2. Relationship between tremor activity of varying magnitudes and corresponding avalanche occurrences, considering periods without fresh snowfall for six days prior and three days post the seismic events.

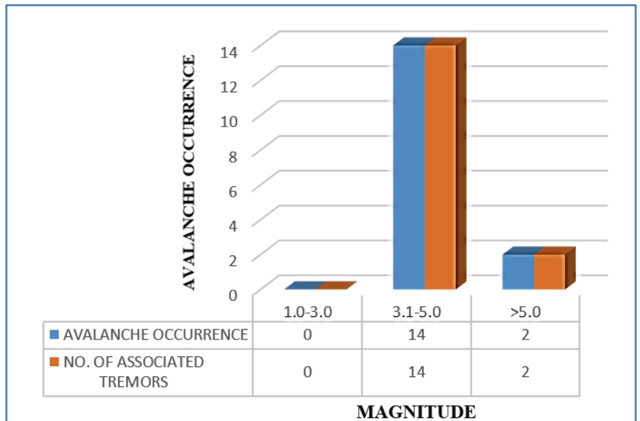

Fig. 3. Relationship between tremor magnitudes and same-day avalanche occurrences, illustrating the immediate impact of seismic events on avalanche triggering

data and avalanche occurrences across these areas. To systematically assess the impact of tremor activity on avalanche occurrences, two distinct cases were examined.

3.1. *Case 1: Avalanche Occurrences in the Absence of Fresh Snowfall*

Fig. 2. represents the relationship between tremor activity of varying magnitudes and corresponding avalanche occurrences, considering periods without fresh snowfall for six days prior and three days following the seismic events. The results indicates that avalanches are most frequently triggered by seismic events of magnitude 3.1–5.0 M_w, with 27 avalanche occurrences linked to 14 seismic tremors. For lower-magnitude tremors (1.0–3.0 M_w), both the number of avalanches and associated tremors remain minimal, with only 3 events in each category. Higher-magnitude tremors (greater than 5.0 M_w) result in 14 avalanche events, triggered by just 4 seismic occurrences. These observations, while accounting for the exclusion of meteorological influences, suggest that seismic activity is a key trigger for avalanches during this period.

The calculated Pearson correlation coefficient between the lag evaluation (in hours) and the magnitudes of the tremors is 0.12. This indicates a weak positive correlation, suggesting that there is no strong relationship between the lag evaluation and the magnitudes of the tremors. This weak correlation is attributed to variations in topography, slope gradients, altitude, and localized geological conditions across different stations (sectors in which stations are situated are mentioned in Table 1) of the North-west Himalayas. These factors influence the susceptibility of specific regions to avalanches. The comparison of lag correlation doesn't hold much significance rather the histogram representing the percentage of avalanche occurrence due to tremor with respect to time difference/lag evaluation is relevant (Fig. 4.). The histogram indicates that avalanche occurrences peak within the time delay range of 38.32 to 76.32 hours after a tremor, with the highest number observed between 38.32 to 57.32 hours. This suggests a delayed response of avalanches to seismic activity, potentially due to gradual destabilization of the snowpack following the initial ground motion. Occurrences significantly decrease beyond 76.32 hours, highlighting a temporal limit to the

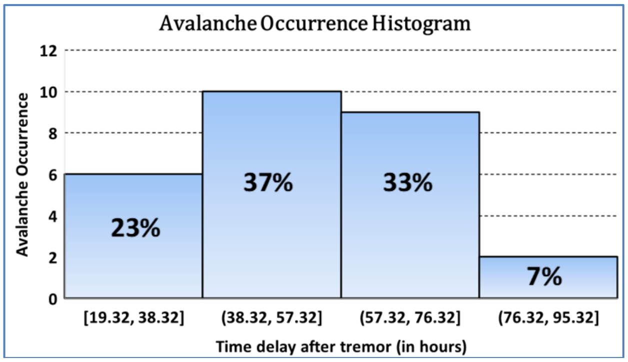

Fig. 4. Histogram depicting avalanche occurrences based on time delay post seismic tremors (in hours) for Case 1

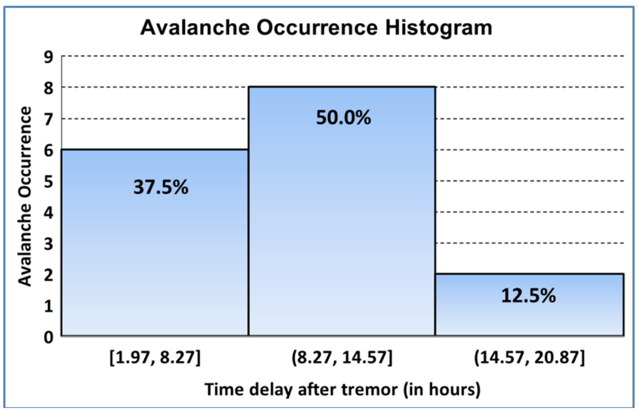

Fig. 5. Histogram depicting avalanche occurrences based on time delay post seismic tremors (in hours) for Case 2

TABLE 3

Statistical summary of time lag between seismic events and avalanche occurrences (in hours) for Case 1

Statistic	Value (in hours)
Mean	47.2
Standard Deviation	20.3
Minimum	19.32
Maximum	82.20

influence of tremors on avalanches. The statistical summary in Table 3. further supports this trend, with an average lag time of approximately 47.2 hours between a tremor and avalanche occurrence (Table 3).

3.2. *Case 2: Immediate Avalanche Occurrences Following Seismic Tremors*

Fig. 3. shows the relationship between tremor activity of varying magnitudes and same-day avalanche occurrences, illustrating the immediate impact of seismic events on avalanche triggering. Similar to Case 1, moderate magnitude tremors (3.1–5.0 M_w) are associated

TABLE 4

Statistical summary of time lag between seismic events and avalanche occurrences (in hours) for Case 2

Statistic	Value (in hours)
Mean	8.92
Standard Deviation	4.13
Minimum	1.97
Maximum	18.07

with the highest number of avalanches, peaking at 27 occurrences. Interestingly, higher-magnitude tremors (>5.0 M_w) result in fewer avalanches (14 occurrences), suggesting that while such tremors induce strong ground shaking, they may not always directly lead to avalanche initiation.

For Case 2 where tremor occurrence and avalanche occurrence fall on the same date, the Pearson correlation was calculated and it turns out to be 0.293, indicating a weak positive correlation between the two variables. The histogram in Fig. 5 provides further insights, revealing that avalanche occurrences predominantly fall within the 1.97–8.27 hour and 8.27–14.57 hour intervals, with the latter being the most frequent. Beyond 14.57 hours, the number of avalanche occurrences drops significantly, highlighting a limited temporal window in which tremor-induced avalanches are most likely. The statistics in Table 4 indicates an average lag of 8.92 hours, suggesting that avalanches triggered by seismic events on the same day tend to occur within this timeframe.

3.3. *Comparative Analysis of Both Cases*

The data also reveals that tremors in the 3.1–5.0 M_w range tend to trigger most of the avalanches ((Pérez-Guillén *et al.*, 2013) in both cases. This suggests that moderate-magnitude tremors are sufficient to destabilize the snowpack without causing excessive compaction or structural shifts that might delay avalanche initiation. However, this does not generalize the tremor magnitude window for other regions, as local topographic and geological conditions play a crucial role. Interestingly, for tremors >5.0 M_w, the recorded avalanche occurrences are lower, with 14 events in Case 1 and only 2 in Case 2. This suggests that stronger tremors may significantly alter the stability of the snowpack, making avalanches less likely to occur immediately.

Although our study area encompassed the entire Northwest Himalayas, the results predominantly indicate significant findings confined to Jammu & Kashmir and Ladakh. This can be attributed to higher Peak Ground Acceleration (PGA), steep terrain, and geological vulnerabilities in these regions, which result in Critical Safety Factor (FSc) values exceeding stability thresholds (Bhagyaraj *et al.*, 2023). The findings suggest that while seismic tremors contribute to avalanche initiation, their impact varies based on magnitude, time delay, and local topographic conditions.

4. Conclusions

(i) Analysis of four decades of data (1980–2018) indicates that avalanches predominantly occur in areas influenced by seismic activity, even after excluding meteorological factors.

(ii) Jammu & Kashmir and Ladakh are identified as highly susceptible due to strong seismic acceleration, steep slopes, and geological instability.

(iii) This study lays the foundation for future research that should ideally explore the impact of earthquake epicenter distance on avalanche triggering to define the seismic influence radius.

(iv) Integrating meteorological parameters such as temperature, snowfall intensity, wind dynamics, and humidity could enhance understanding of avalanche behaviour.

(v) A combined approach using seismic, meteorological, and topographical data could improve predictive models and mitigation strategies for avalanche-prone regions.

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Authors' contributions

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