Postprint: Spatial Distribution and Factor Detection of Avalanches in the Alxian Gully Section of the Duku Expressway

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Abstract

The proposed Duku Expressway Arxan Gully section is characterized by alpine canyon landforms, with frequent snow avalanches due to snowfall and climate change. Using a collaborative survey method combining UAV remote sensing interpretation and field investigation, 92 avalanche sites were identified. Elevation, slope, surface cutting degree, ground roughness, maximum snow depth during the snow period, maximum wind speed, average temperature, and average snowfall were selected as driving factors, and geographical detector was employed to analyze the relationship between terrain factors of different resolutions and avalanche stability. The results indicate that snow avalanche development is relatively active and stability is poor in the study area; however, most avalanche release zones and movement zones are located on mountain slopes, while deposition zones are situated in valley bottoms far from the proposed route, resulting in minimal impact on the proposed line. Through geographical detector analysis, the explanatory power of slope and ground roughness on avalanche stability shows a positive correlation with resolution, while elevation and surface cutting degree exhibit a negative correlation. Interaction detection results all demonstrate either dual-factor enhancement or nonlinear enhancement, with nonlinear enhancement being more significant than dual-factor enhancement. The combination of slope with other factors is crucial for influencing avalanche stability. This study can provide reliable data support for avalanche susceptibility and hazard assessment, and offer scientific basis for the construction and operation of the Duku Expressway.

Spatial Distribution and Factor Analysis of Avalanches in the Aerxiangou Section of the Duku Expressway

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Abstract

The proposed Aerxiangou section of the Duku Expressway is characterized by high mountainous terrain and deep canyons, where avalanches occur frequently due to heavy snowfall and climate change. This study identified 92 avalanche points through a collaborative investigation combining UAV remote sensing interpretation and field surveys. Eight driving factors were selected for analysis: elevation, slope, surface cutting degree, ground roughness, maximum snow depth during the snow accumulation period, maximum wind speed, average temperature, and average snowfall. The Geographical Detector method was employed to analyze the relationship between terrain factors at different resolutions and avalanche stability. Results indicate that avalanche development in the study area is relatively active with generally poor stability. However, most avalanche release and motion zones are located on mountain slopes, while accumulation zones lie on valley floors far from the planned route, resulting in minimal impact on the expressway. Geographical Detector analysis reveals that the explanatory power of slope and ground roughness for avalanche stability shows a positive correlation with resolution, while elevation and surface cutting degree exhibit a negative correlation. Interaction detection results demonstrate either double-factor enhancement or nonlinear enhancement, with nonlinear enhancement being more significant than double-factor enhancement. The combination of slope with other factors proves crucial for avalanche stability. This study provides reliable data support for avalanche susceptibility and hazard assessment, offering a scientific basis for the construction and operation of the Duku Expressway.

Keywords: Aerxiangou; avalanche; Geographical Detector; driving factors; spatial distribution

1 Introduction

Avalanches represent one of the most destructive natural disasters in mountainous regions, frequently destroying forests, blocking transportation routes, and posing severe threats to human life, production, and livelihoods [ ]. Avalanche disasters remain in sharp contradiction with the goals of harmonious human-nature coexistence and sustainable social development. For instance, an avalanche in the Khumbu Glacier region on the southern slope of Mount Everest in April 2014, and another on the Pai Town-Medog highway in Nyingchi, Tibet, caused significant casualties and property damage. In January 2010, a sudden avalanche in Guozigou, Tianshan, blocked traffic and stranded over 200 vehicles. Therefore, understanding the driving forces of avalanche influence factors and the spatial distribution characteristics of avalanches is critical for improving regional avalanche disaster prevention and mitigation capabilities, safeguarding mountain economic development, and ensuring the safety of people’ s lives and property [ ].

Avalanche development is influenced by multiple factors including terrain, climate, and snow cover [ ]. Hao et al. [ ] analyzed triggering factors for avalanche disasters in the Asian high mountain region, concluding that avalanches are primarily caused by natural environmental conditions, with heavy snowfall accounting for the largest proportion of avalanche events, and rapid temperature increases during spring melt representing another major triggering factor. Valley winds can alter snow distribution and significantly influence new snow avalanche development [ ]. Snow depth constitutes a primary factor affecting avalanche development, with higher snow depth on slopes corresponding to lower stability and increased avalanche probability. Additionally, scholars have noted that wind-blown snow is more likely to trigger avalanches than natural snowfall, as valley winds redistribute snow and increase snow depth on certain slopes, enhancing snowpack instability [ ].

Terrain conditions represent constant, unchanging factors in avalanche development, including slope, ground roughness, and surface cutting degree [ ]. For large-scale avalanche prediction, single parameters often fail to reflect regional terrain morphology [ ], and classification accuracy for complex and diverse landforms remains insufficient [ ]. While avalanche disasters are influenced by numerous factors, current understanding of avalanche influence factor patterns lacks consensus. Avalanche factor detection forms the foundation of avalanche risk management, representing a crucial prerequisite for avalanche susceptibility and hazard zoning, and providing essential data for avalanche prevention, land use planning, and route selection in engineering design.

The Geographical Detector is a statistical method for exploring spatial stratified heterogeneity and revealing its underlying driving forces [ ]. Zhou et al. [ ] employed Geographical Detector to analyze the spatial distribution of debris flows in Guangxi and the relationships among eight driving factors including slope, terrain relief, and rainfall. Ji et al. [ ] used Geographical Detector to study geological hazard driving factors in the Beijing-Tianjin-Hebei urban agglomeration, revealing that slope and elevation showed high driving force in the region, with factor interactions demonstrating double-factor enhancement and nonlinear enhancement. Multi-factor interaction detection has been extensively studied in other geological hazards but remains relatively scarce in avalanche research. Geographical Detector can analyze not only single-factor effects but also the degree of interaction between multiple factors [ ], enabling quantitative analysis of avalanche triggering factors.

The Aerxiangou section of the proposed Duku Expressway experiences frequent and destructive avalanches. This study employs Geographical Detector as the primary analytical tool, focusing on 92 avalanche points identified through UAV field surveys in the Aerxiangou section. Based on terrain characteristics, climate conditions, and snow cover features that promote avalanche development, eight driving factors were comprehensively analyzed to quantitatively detect influencing factors of avalanche susceptibility in the Tianshan Mountains, examine the driving force of each factor on avalanche spatial distribution, and analyze the impact degree of avalanche disasters under dual-factor interactions.

2 Model Methods and Data Sources

2.1 Geographical Detector Geographical Detector can detect both numerical and qualitative data, as well as the interaction effects between two influencing factors on a dependent variable [ ]. Based on this principle, factor detection and interaction detection in Geographical Detector were utilized to analyze the spatial distribution of 92 avalanche points in the Aerxiangou section and the influence degree of different driving factors on avalanche stability.

2.1.1 Factor Detection Factor detection examines the spatial stratified heterogeneity of the dependent variable Y (avalanche stability) and the explanatory power of an independent variable X for Y' s spatial differentiation [ ], expressed by the q-value. The q-value indicates the explanatory power of an independent variable on avalanche stability, calculated as:

$$q = 1 - \frac{SSW}{SST} = 1 - \frac{\sum_{i=1}^{n} N_i \sigma_i^2}{N\sigma^2}$$

where q represents the explanatory power of an influencing factor on avalanche stability; i = 1,2, , n; Ni represents the number of units in category i; σ^2i represents the variance of dependent variable Y values in category i; N represents the total number of units in the study area; σ^2 represents the variance of dependent variable Y values in the entire study area; SSW represents the sum of variances across n categories; and SST represents the total variance in the study area. The q-value ranges from [0,1]. A q-value closer to 1 indicates more pronounced spatial stratified heterogeneity of avalanche stability and stronger explanatory power of independent variable X on Y. Conversely, weaker explanatory power is indicated. Specifically, q = 1 means X completely controls Y' s spatial distribution, while q = 0 indicates no relationship between X and Y.

2.1.2 Interaction Detection Interaction detection investigates the effects of different influencing factors' interactions, determining whether factors X_1 and X_2 acting together enhance, weaken, or remain independent in their influence on avalanche stability. First, the explanatory power q(X_1) and q(X_2) of X_1 and X_2 on avalanche stability are calculated separately. Then, the q-value after interaction, q(X_1 X_2), is computed. The specific interaction criteria are shown in .

2.2 Data Sources

2.2.1 Avalanche Point Data Based on the breeding environment of avalanche hazards along the proposed expressway and considering structures such as roadbeds, bridges, and tunnel portals, investigations were conducted on avalanche locations, trajectories, impacts on the highway, motion paths, snow density, and temperature. A total of 92 potential avalanche hazard points were extracted through field surveys and UAV remote sensing interpretation. The distribution of avalanche points is shown in [Figure 2: see original paper].

2.2.2 Baseline Data Digital Elevation Model (DEM) represents the digital expression of surface topography through elevation data. Using a DJI Matrice 300 RTK UAV equipped with a Zenmuse camera, sub-meter resolution images were captured to collect point cloud data and generate 3D models at 0.43 m resolution. To further analyze the sensitivity of Geographical Detector at different spatial scales, DEM data at 12.5 m resolution were obtained from the Geoscience Data website. All driving factors were processed under the WGS_{{{1984}}*{{UTM}}*}{{{Zone}}_{{44N}}} coordinate system using ArcMap 10.8 software to extract terrain factors at different resolutions for the study area. Climate and snow cover factors were obtained through spatial interpolation of meteorological data from surrounding weather stations.

2.3 Selection of Avalanche Driving Factors Different influencing factors trigger avalanches with varying probabilities. This study extracted terrain factors and meteorological snow cover factors based on the terrain, meteorology, and snow conditions of the Aerxiangou section, selecting eight influencing factors suitable for avalanche stability analysis in this region.

2.3.1 Terrain Driving Factors at Different Resolutions Terrain data represent constant parameters in avalanche prediction [ ]. Field investigations revealed that avalanches are prevalent in the study area, with small to medium-sized avalanche disasters occurring frequently. Considering that slope gradient affects snow thickness, elevation and slope determine avalanche scale and frequency [ ]. For large-scale avalanche prediction, single parameters often cannot reflect regional terrain morphology [ ], making statistical analysis difficult. Therefore, composite parameters such as surface cutting degree and ground roughness were introduced to measure regional avalanche stability and reveal the relationship between terrain morphology and snow cover.

2.3.2 Driving Factors Under Climate and Snow Conditions Avalanche triggering is primarily caused by natural factors including wind, temperature, and heavy snowfall [ ]. Avalanches in the Tianshan Mountains are mostly triggered by heavy snowfall [ ]. In early spring, sudden temperature increases cause snowpack instability. Temperature affects not only surface evaporation but also snowmelt rate, determining snow cover area and depth to some extent. The Tianshan Mountains have relatively low temperatures with predominantly solid precipitation, creating favorable material conditions for avalanche development. On slopes, higher snow depth corresponds to lower stability and increased avalanche probability. Additionally, scholars have noted that wind-blown snow is more likely to trigger avalanches than natural snowfall, as valley winds redistribute snow and increase snow depth on certain slopes, enhancing snowpack instability [ ]. Analyzing temperature, wind speed, snowfall, and snow depth can better reveal the temporal and spatial relationships between climate-snow factors and avalanche development.

In summary, eight influencing factors—elevation, slope, surface cutting degree, ground roughness, maximum snow depth, average temperature, maximum wind speed, and average snowfall—were selected as important driving factors for avalanche stability in the study area.

3 Results and Analysis

3.1 Avalanche Stability Classification

3.1.1 Avalanche Stability Classification Using ArcGIS software, the eight driving factors (elevation, slope, surface cutting degree, ground roughness, maximum snow depth, average temperature, maximum wind speed, and average snowfall) were superimposed for analysis. The superposition results were classified into five stability categories using the natural breaks method: stable, relatively stable, relatively unstable, unstable, and extremely unstable. Based on comprehensive evaluation of terrain, snow cover, and climate conditions, avalanches with poor stability were most numerous, reaching 34 points. Stable and relatively stable avalanches accounted for a smaller proportion of the total. The overall classification shows that avalanches classified as relatively unstable, unstable, and extremely unstable represent 73.9% of the total, indicating that avalanche development in this section is relatively active with poor stability.

3.1.2 Classification of Avalanche Impact on the Proposed Expressway Sub-meter resolution images captured by UAV were interpreted to determine avalanche morphology and assess impacts on the proposed route. Avalanche flow trajectories were simulated using RAMMS::Avalanche software. Based on avalanche characteristics including direction, trajectory, and motion path, impacts on expressway structures (roadbeds, bridges, tunnel portals) were classified into four categories: no impact, general impact, significant impact, and severe impact. Avalanches with no impact have release, motion, and accumulation zones that do not affect the proposed route. Generally impactful avalanches have accumulation zones at the route edge where large avalanches may deposit but do not affect structures, or motion zones crossing bridges or tunnels. Significantly impactful avalanches occur where the route passes through roadbed sections where medium to large avalanches may deposit and affect traffic safety. Severely impactful avalanches have long trajectories and large impact forces, with motion and accumulation zones severely affecting expressway structures or even occupying the entire route width, posing serious traffic safety hazards.

Field surveys and remote sensing interpretation identified 92 avalanches in the Aerxiangou section of the proposed Duku Expressway. Among these, avalanches with no impact on the proposed route were most numerous. Eight avalanches had significant impact, with motion and accumulation zones affecting special structures. Although avalanches occur frequently in the study area, most release and motion zones have no impact on the proposed route, with accumulation zones located on valley floors far from the route.

3.2 Spatial Distribution of Avalanches Using ArcGIS reclassification tools, driving factors were divided into five categories. The classification results are shown in , and the proportional characteristics of avalanche classification numbers for each factor are illustrated in [Figure 4: see original paper] and [Figure 5: see original paper].

Avalanches were most numerous at elevations of 2400-2700 m (34 points), followed by 2700-3000 m (28 points). Avalanche development is frequent around 3000 m in the Tianshan Mountains. On slopes of 30°-45°, avalanche activity peaks (42 points), showing strong correlation between slope gradient and avalanche development. Ground roughness analysis revealed that avalanches were most numerous (46 points, half of the total) in the 0.2-0.4 range. Higher ground roughness values indicate rougher surfaces that hinder avalanche development. Avalanche numbers gradually increased with maximum snow depth and maximum wind speed, as greater snow depth increases pressure and promotes avalanche development.

4 Discussion

4.1 Analysis of Avalanche Factor Detection Results Compared with Pearson correlation coefficient (which only analyzes linear relationships) and grey correlation degree (which only reflects curve associations) [ ], Geographical Detector can detect not only single-factor spatial stratified heterogeneity but also interactions between two factors. This study primarily used Geographical Detector to analyze relationships between terrain factors at 0.43 m and 12.5 m resolutions and avalanche stability, as well as meteorological snow cover factors.

Results show that slope has the greatest explanatory power among terrain factors, followed by maximum snow depth among meteorological snow cover factors. Elevation, maximum wind speed, and ground roughness have secondary explanatory power. The explanatory power q-value of slope and ground roughness for avalanche stability increases with resolution, while that of elevation and surface cutting degree decreases with resolution. Geographical Detector shows low sensitivity to terrain factors at different resolutions, as evidenced by small q-value variations.

4.2 Interaction Analysis of Avalanche Influence Factors Interaction detection of terrain factors at different resolutions and meteorological snow cover factors revealed that all dual-factor interactions show either double-factor enhancement or nonlinear enhancement, with nonlinear enhancement being more significant than double-factor enhancement. Ground roughness interacting with any driving factor shows nonlinear enhancement, with explanatory power exceeding the sum of individual factor contributions. The interaction between slope and maximum snow depth shows the greatest explanatory power for avalanche stability, reaching 0.73 at 0.43 m resolution. The interaction explanatory power between slope and other factors is not less than 0.54, demonstrating that slope combined with other factors is crucial for avalanche stability. Avalanche stability results from the combined effects of multiple influencing factors.

5 Conclusions

This study focused on the Aerxiangou section of the proposed Duku Expressway, identifying 92 avalanche points through collaborative UAV remote sensing interpretation and ground field surveys. Eight driving factors were selected: elevation, slope, surface cutting degree, ground roughness, average temperature, average snowfall, maximum wind speed, and maximum snow depth. Geographical Detector was applied to investigate avalanche spatial stratified heterogeneity, yielding the following conclusions:

1) Analysis of avalanche points based on slope, aspect, and snow depth revealed that relatively unstable, unstable, and extremely unstable avalanche points account for 73.9% of the total. Avalanche development in this section is relatively active with poor stability. However, most avalanche release and motion zones have no impact on the proposed route, with accumulation zones located on valley floors far from the route. Only 8.7% of avalanches severely affect expressway structures.
2) Spatial distribution analysis of the eight driving factors shows that avalanche development is frequent in the 3000 m elevation zone of the Tianshan Mountains. Avalanches are most active on slopes of 30°–45°. Rougher ground surfaces increasingly hinder avalanche development. Avalanche numbers increase with maximum snow depth and maximum wind speed.
3) Geographical Detector analysis of terrain factors at different resolutions and meteorological snow cover factors indicates that the explanatory power of slope and ground roughness for avalanche stability correlates

positively with resolution, while elevation and surface cutting degree correlate negatively. Small q-value variations across different resolutions demonstrate Geographical Detector' s low sensitivity to terrain factor resolution in avalanche stability analysis.

4) Interaction detection between terrain factors at different resolutions and other factors shows all interactions exhibit double-factor enhancement or nonlinear enhancement, with nonlinear enhancement being more significant. Ground roughness interacting with any factor shows nonlinear enhancement. The combination of slope and maximum snow depth provides the greatest explanatory power for avalanche stability, with slope interactions not less than 0.54. This confirms that slope combined with other factors is crucial for avalanche stability, which results from multiple influencing factors working together.

References

[1] Hu Ruji, Ma Weilin, Wang Cunniu. Avalanches in Tianshan Mountains, China, and their control[J]. Journal of Glaciology and Geocryology, 1987, 9(S1): 13-24, 150.

[2] Yang Jinming, Zhang Xu, Mao Weiyi, et al. Investigation and analysis of snow avalanche disaster in Tianshan Mountains of China[J]. Journal of Natural Disasters, 2022, 31(1): 188-197.

[3] Hao Jiansheng, Li Lanhai. Research progress and prospect of snow avalanche disaster prevention and control[J]. Journal of Glaciology and Geocryology, 2022, 44(3): 762-770.

[4] Ma Dongtao, Cui Peng, Wang Zhonghua. An approach on snow hazards and their countermeasures along Sino-Nepalese highway[J]. Mountain Research, 2002, 20(1): 59-63.

[5] Hu Ruji, Ma Hong, Jiang Fengqing. Geographical environment in the area of Tianshan station for snow & avalanche research, Yili, Xinjiang, China[J]. Arid Land Geography, 1997, 20(2): 25-33.

[6] Wang Jian, Che Tao, Li Zhen, et al. Investigation on snow characteristics and their distribution in China[J]. Advances in Earth Science, 2018, 33(1): 12-26.

[7] Liu Yang, Li Lanhai, Yang Jinming, et al. Snow depth inversion based on D-InSAR method[J]. National Remote Sensing Bulletin, 2018, 22(5): 802-809.

[8] Hao Jiansheng, Huang Farong, Feng Ting, et al. Analysis of spatio-temporal distribution characteristics of snow avalanche disaster and its triggering factors in the high mountain Asia[J]. Mountain Research, 2021, 39(2): 304-312.

[9] Hao Jiansheng, Cui Peng, Zhang Xueqin, et al. The triggering mechanisms for different types of snow avalanches in the continental snow climate of the central Tianshan Mountains[J]. Scientia Sinica(Terrae), 2022, 52(12): 2428-2440.

[10] Wen Hong, Wang Dong, Wang Shengren, et al. Key predisposing factors and susceptibility mapping of snow avalanche in Parlung Tsangpo catchment, Southeast Tibetan Plateau[J]. Journal of Engineering Geology, 2021, 29(2): 404-415.

[11] Liu Y, Li L, Chen X, et al. Spatial distribution of snow depth based on geographically weighted regression Kriging in the Bayanbulak Basin of the Tianshan Mountains, China[J]. Journal of Mountain Science, 2018, 15(1): 33-45.

[12] Armelle D, Najat B, Janie F R, et al. The Development of Kangiqsualujjuaq and the Threat of Snow Avalanches in a Permafrost Degradation Context, Nunavik, Canada[M]. Université des Sciences et Technologies de Lille, 2020.

[13] Yang Weitao, Sun Jianguo, Ma Hengli, et al. A multi-scale integrated classification method for landforms[J]. Arid Zone Research, 2022, 39(2): 638-645.

[14] Bühler Y, Kumar S, Veitinger J, et al. Automated identification of potential snow avalanche release areas based on digital elevation models[J]. Natural Hazards and Earth System Science, 2013, 13(5): 1321-1325.

[15] Soteres R L, Javier P, Carrasco R M. Snow avalanche susceptibility of the Circo de Gredos (Iberian Central System, Spain)[J]. Journal of Maps, 2020, 16(2): 1717655.

[16] Caiserman A, Sidle R C, Raj G D. Snow Avalanche Frequency Estimation (SAFE): 32 years of monitoring remote avalanche depositional zones in high mountains of Afghanistan[J]. The Cryosphere, 2022, 16(8): 3295-3312.

[17] Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective[J]. Acta Geographica Sinica, 2017, 72(1): 116-134.

[18] Li Xinlei, Li Ruiping, Wang Xiuqing, et al. Spatio-temporal change and analysis of factors driving forest-grass vegetation coverage in Hetao Irrigation District based on geographical detector[J]. Arid Zone Research, 2023, 40(4): 623-635.

[19] Zhou Jin, Fan Qiuyan, Zhu Zhen. Analysis of the driving factors of the geological disaster of debris flow in Guangxi based on the geographic detector[J]. Geomatics & Spatial Information Technology, 2022, 45(11): 245-248.

[20] Zhu Z, Wang J, Hu M, et al. Geographical detection of groundwater pollution vulnerability and hazard in Karst areas of Guangxi Province, China[J]. Environmental Pollution, 2019, 245: 627-633.

[21] Liu Xiao, Guo Peng, Qi Jiafeng, et al. Spatio-temporal changes and driving forces in the ecological environment of Altay City determined using an MRSEI model[J]. Arid Zone Research, 2023, 40(6): 1014-1026.

[22] Hao J, Mind'je R, Liu Y, et al. Characteristics and hazards of different snow avalanche types in a continental snow climate region in the Central Tianshan Mountains[J]. Journal of Arid Land, 2021, 13: 317-331.

[23] Shi Zhiwen, Xu Junrong, Chen Zhongsheng, et al. Analysis on climatic changes under global climatic change: A case study of Tianshan snow and avalanche research station[J]. Mountain Research, 2009, 27(1): 41-48.

[24] Zhi Zemin, Chen Qiong, Zhang Qiang, et al. Application of geographic detector in identifying influencing factors of landslide stability: A case study of the Jiangda County, Tibet[J]. The Chinese Journal of Geological Hazard and Control, 2021, 32(2): 19-26.

[25] Chen Lianjun. Avalanche Hazard Assessment Based on Multi-Source Data: A Case Study in Northern Xinjiang[D]. Beijing: China University of Geosciences, 2021.

[26] Singh D K, Mishra V D, Gusain H S, et al. Geo-spatial Modeling for Automated Demarcation of Snow Avalanche Hazard Areas Using Landsat-8 Satellite Images and In Situ Data[J]. Journal of the Indian Society of Remote Sensing, 2019, 47(3): 513-528.

[27] Nicolas E, Florie G. Towards a holistic paradigm for long-term snow avalanche risk assessment and mitigation[J]. Ambio, 2022, 52(4): 711-732.

[28] John S, Pascal H, Yves B. Automated snow avalanche release area delineation in data sparse, remote, and forested regions[J]. Natural Hazards and Earth System Sciences, 2022, 22(10): 3247-3270.

[29] Miao Yunling, Yu Haisong, Fan Min, Ni Wankui, et al. Analysis of winter snowfall variability and its influencing factors on the north slopes of the middle Tianshan Mountains[J]. Arid Zone Research, 2023, 40(1): 9-18.

[30] Liu Yongbo, Huo Da, et al. Analysis of winter snowfall variability and its influencing factors on the north slopes of the middle Tianshan Mountains[J]. Arid Zone Research, 2023, 40(1): 9-18.

[31] Liu Yongbo, Huo Da, et al. Application of the method of gray correlation in risk evaluation of highway geological hazard[J]. Hydrogeology & Engineering Geology, 2005(3): 32-34.

[32] Wen Linke, Xiang Lingzhi, Cai Yi, et al. Research on the formation mechanism of avalanche[J]. Mountain Research, 2016, 34(1): 1-11.

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Note: Figure translations are in progress. See original paper for figures.