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A Preliminary Assessment of Landslide Occurrence in Relation to Slope Angle in the Bharmour Development Block, Himachal Pradesh

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ABSTRACT

This study investigates the relationship between slope angle and landslide occurrence in the Bharmour Development Block, Himachal Pradesh, India. Using a landslide inventory of 1,511 events and a DEM-derived slope map, the Frequency Ratio (FR) method was employed to quantify the association between slope classes and landslide occurrence. The results show that although 58.64% of all mapped landslides occurred on very steep slopes, the highest Frequency Ratio (2.39) was recorded for gentle slopes, indicating a disproportionately high landslide occurrence relative to their areal extent. These findings suggest that slope angle alone does not fully control landslide occurrence in the study area, and that additional landslide conditioning factors, such as lithology, proximity to roads, land use, and rainfall, are likely to play important roles. The study provides a useful preliminary assessment of landslide susceptibility and demonstrates the importance of normalised measures, such as the Frequency Ratio, for understanding landslide distribution in complex Himalayan terrain

INTRODUCTION

Landslides are among the most destructive geomorphic hazards affecting mountainous regions worldwide, causing substantial loss of life, damage to infrastructure, disruption of transportation networks, and environmental degradation. They are generally defined as the downslope movement of rock, debris, or earth under the influence of gravity (Cruden & Varnes, 1996). Landslide occurrence is governed by the complex interaction of topographic, geological, hydrological, climatic, and anthropogenic factors rather than by a single conditioning factor. Consequently, landslide susceptibility varies considerably across different regions depending on local geological conditions, terrain characteristics, rainfall, land use, seismic activity, and human interventions such as road construction and slope modification. Among various conditioning factors, slope angle is one of the widely recognised influential topographic parameters controlling landslide occurrence as it directly affects the balance between gravitational driving forces and resisting forces acting on a hillslope. In addition to influencing shear stress and slope stability, slope angle regulates surface runoff, infiltration, groundwater movement, soil moisture, and erosion, thereby controlling several hydrological and geomorphological processes associated with slope failure. Owing to its fundamental role in slope instability, slope angle has been incorporated as a key conditioning factor in almost all landslide susceptibility and hazard assessment studies.

There are many studies that identify slope angle as one of the most influential conditioning factors governing landslide occurrence. A global literature review confirms that slope angle is the most frequently utilised terrain variable in susceptibility modelling (Cellek, 2022). For example, in Kuala Lumpur, Malaysia, an Artificial Neural Network (ANN) model ranked slope angle with the highest relative importance weight of 100.0% among eight physical factors (Zulkafli et al., 2023). Similarly, a study of 4,262 landslides in the alpine Tianshan Mountains of China found that slope angle was a top-tier predictor (Zhang et al., 2025). In the Western Ghats of India, a hybrid Normalised Frequency Ratio-Random Forest (NFR-RF) approach proved that slope angle is the dominant factor across all three failure mechanisms, debris flows, shallow slides, and rockfalls, outperforming elevation, geology, and lineament distance (Sasidharan et al., 2026). The interaction between slope angle, antecedent groundwater conditions, and soil saturation ultimately governs both triggering and post-failure mobility (Beddoe & Take, 2015). Empirical case studies prove that even steep cut slopes () can remain stable under dry conditions due to high soil cohesion and friction, but their safety factors drop significantly under saturated conditions (Misriani et al., 2025). Similar observations were reported by Qiu et al. (2019), who found that most loess landslides occurred on slopes between 30° and 40°, whereas larger landslides were generally associated with gentler slopes. These findings collectively reinforce the importance of slope angle as a key parameter in understanding and predicting landslide occurrence across diverse mountainous environments, while also emphasising that its influence must be evaluated in conjunction with soil properties, hydrological conditions, and anthropogenic modifications.

Evidence from the Himalayan region further confirms the importance of slope angle in controlling landslide occurrence. Adhikari and Dhakal (2026) identified slope angle as the conditioning factor with the highest Information Value among ten causative factors.

Although previous studies consistently recognise slope angle as one of the most important conditioning factors governing landslide occurrence, considerable variation exists in the reported slope ranges associated with maximum landslide activity. These inconsistencies primarily arise from differences in lithology, climatic conditions, weathering characteristics, terrain morphology, and the slope classification schemes adopted by different researchers. Consequently, the relationship between slope angle and landslide occurrence remains region-specific and requires detailed local investigations. Furthermore, relatively few studies have focused exclusively on quantifying the relationship between slope angle and landslide occurrence in the northwestern Himalaya using a simple and interpretable statistical approach such as the Frequency Ratio (FR) method. The Bharmour Development Block of Himachal Pradesh is highly susceptible to landslides because of its rugged topography, fragile geological formations, intense monsoonal rainfall, and expanding road network. Frequent landslide occurrences along major transportation corridors result in recurrent disruption of connectivity, damage to infrastructure, and socio-economic losses. Understanding the relationship between slope angle and landslide occurrence is therefore essential for identifying the slope ranges most susceptible to failure and for supporting effective land-use planning and disaster risk reduction in the region. Thus, the present study investigates the relationship between slope angle and landslide occurrence in the Bharmour Development Block using the Frequency Ratio (FR) method. A comprehensive inventory comprising 1,511 mapped landslides was analysed to quantify the relative susceptibility of different slope classes and to identify the slope ranges most strongly associated with landslide occurrence. Unlike previous studies that incorporated slope angle as one of several conditioning variables within multi-factor susceptibility models, the present study evaluates the independent influence of slope angle on landslide occurrence. The findings provide region-specific evidence for the northwestern Himalaya and contribute to a better understanding of slope-dependent landslide behaviour, thereby supporting landslide susceptibility assessment, infrastructure planning, and disaster risk reduction in mountainous regions.

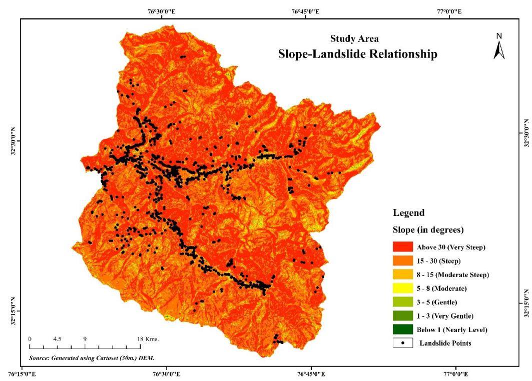

Figure 2. Figure-2: Slope-Landslide Relationship Map of Bharmour Development Block

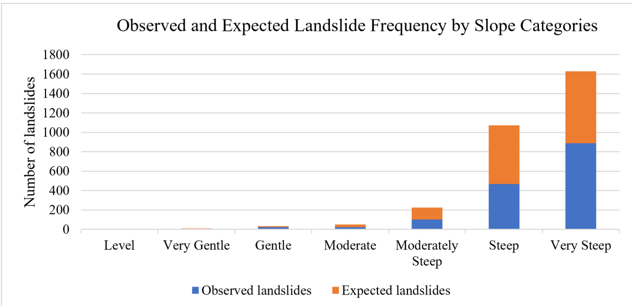

Figure 3. Figure 3: Observed and expected landslide frequencies across slope categories

STUDY AREA

The study area, Bharmour development block, is one of the seven development blocks of Chamba district in Himachal Pradesh. It comprises the Bharmour tehsil and Holi sub-tehsil. It is a tribal block inhabited by the Gaddi tribe. It covers a total area of 1818.37 sq. kms. The total population of the area is about 39,108 persons as per the 2011 census (DCH, 2011). It covers about 27.88 % of the total geographical area, and about 7.53 % of the total population of the Chamba district. The longitudinal extent of the study area ranges between 76°21'15" and 76°53′09" E, and its latitudinal extent is 32°10′41" - 33°40′17" N (Fig. 1). There are 31 gram-panchayats in Bharmour block as per the 2011 census. Out of 252 villages in the Bharmour block, only 96 villages are inhabited rest are uninhabited.

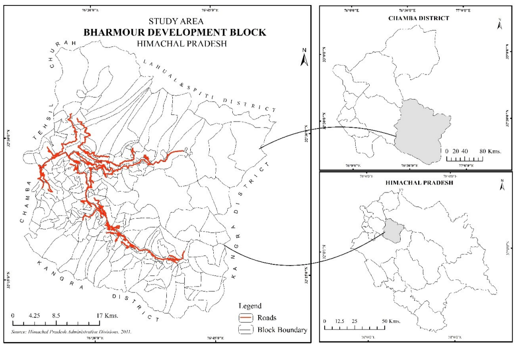

Figure 1. Figure-1: Study area

OBJECTIVE

The objective of this study is to determine which slope angle classes exhibit the highest susceptibility to landslides.

DATA PREPARATION AND METHODOLOGY

The present study utilised both primary and secondary sources of data. The base map of the study area was prepared by digitising the administrative map of Himachal Pradesh. A landslide inventory comprising 1,511 landslide locations was developed through detailed field surveys and supplemented with landslide inventory data obtained from the Bhukosh portal of the Geological Survey of India (GSI). A slope map of the study area was generated from the 30 m Cartosat Digital Elevation Model (Cartosat DEM) using ArcGIS. To examine the relationship between slope angle and landslide occurrence, the study area was classified into seven slope categories. The Frequency Ratio (FR) for each slope class was calculated by comparing the percentage of landslides occurring within a slope class with the percentage area occupied by that class. The Frequency Ratio was computed using the following equation (Bluman, 2018):

where:

= Frequency Ratio for slope class

= Number of landslides in slope class

= Total number of landslides in the study area

= Area of slope class

= Total study area

To evaluate whether the observed distribution of landslides across the slope classes differed significantly from a random distribution, a Chi-square goodness-of-fit test was performed. Subsequently, standardised residuals were calculated for each slope class to identify the categories contributing most to the overall Chi-square statistic and to determine whether individual slope classes contained significantly more or fewer landslides than expected under the null hypothesis.

Chi-square goodness-of-fit formula:

where is the observed number of landslides in the i^{th} slope class, is the expected number of landslides based on the proportional area occupied by that slope class, and is the total number of slope classes.

Standardised residual formula:

where:

= Standardised residual for the ith slope class

= Observed landslides

= Expected landslides

DATA PREPARATION AND DESCRIPTIVE STATISTICS

The analysis utilised slope data categorised into seven classes based on standard geomorphological classification (Table-1).

Table-1: Slope Classes, landslide count and area (km^2)

Slope Classes	Category	Slope Range (°)	Landslide Count	Area (km^2)
1	Level	<1	1	1
2	Very Gentle	1-3	5	5
3	Gentle	3-5	24	11
4	Moderate	5-8	23	30
5	Moderately Steep	8-15	103	134
6	Steep	15-30	469	663

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7	Very Steep	>30	886	817
	Total		1511	1661

Source: *Filed Survey and Bhukosh, GSI*

FREQUENCY RATIO CALCULATION AND RESULTS

The complete Frequency Ratio analysis is presented in Table-2. Calculations followed a systematic procedure mentioned below:

Area Percentage Calculation:

Landslide Percentage Calculation:

Landslide Density Calculation:

Frequency Ratio Calculation:

All these calculations were performed in the Microsoft Excel software, and the results are mentioned in the table below.

Table-2: Frequency Ratio Analysis Results

Slope Category	Area (km^2)	% Area	Landslide Count	% Landslides	Landslide Density (km^2)	Frequency Ratio
Level	1.00	0.06	1	0.07	1.000	1.09
Very Gentle	5.00	0.30	5	0.33	1.000	1.09
Gentle	11.00	0.66	24	1.59	2.18	2.39
Moderate	30.00	1.81	23	1.52	0.77	0.85
Moderately Steep	134.00	8.07	103	6.82	0.76	0.85
Steep	663.00	39.92	469	31.04	0.70	0.78
Very Steep	817.00	49.19	886	58.64	1.08	1.19
Total	1,661.00	100.00	1,511.00	100.00		

Source: Field Survey and Bhukosh, GSI (2025).

The interpretation of FR values follows these criteria:

: Landslides occur in exact proportion to area availability (no association)

: Positive association (landslides are more frequent than expected)

: Negative association (landslides are less frequent than expected)

The magnitude of deviation from 1 indicates the strength of association

RESULTS AND DISCUSSION

Strong Positive Associations

The results depict that the gentle slope class (3-5°) exhibits the strongest positive association with landslide occurrence, with an FR value of 2.39. This indicates that landslides are 2.39 times more frequent in this slope class than would be expected if landslides were randomly distributed according to slope area. Though this slope class comprises only 0.66% of the total study area, this category contains 1.53% of all landslides. This results in the highest landslide density of 2.18 landslides/km^2.

The very steep slope class (>30°) shows a moderate positive association (FR = 1.19), with landslides occurring 1.19 times more frequently than expected. This class dominates the study area (49.19%) and contains the majority of landslides (58.64%), though with moderate density (1.19 landslides/km^2).

Ø

Weak Associations

Level (<1°) and Very Gentle (1-3°) slopes show minimal positive associations (FR = 1.13 and 1.10, respectively). This indicates a near-random distribution of landslides in these nearly flat areas.

Negative Associations

Three slope categories demonstrate negative associations (FR < 1):

· Moderate (5-8°): FR = 0.85 (15% fewer landslides than expected)

· Moderately Steep (8-15°): FR = 0.85 (15% fewer landslides than expected)

· Steep (15-30°): FR = 0.78 (22% fewer landslides than expected).

Notably, the Steep slope category (15-30°), despite containing the second largest area (39.92%) and considerable landslide count (30.98%), shows the strongest negative association, with landslides occurring only 78% as frequently as expected based on area availability. Most landslides occur in steep slopes, with the very steep slope category containing 58.7%, while the steep slope category containing 31% of the total landslides. But the strongest correlation was found to be on the gentle slopes with FR = 2.39, meaning landslides are 2.39× more frequent than expected based on area. The highest density was found to be on gentle slopes (2.18 landslides/km^2) despite having a small total area.

STATISTICAL VALIDATION

To validate the statistical significance of the observed associations, a Chi-square goodness-of-fit test was performed (to analyse whether landslides are proportionally distributed according to area or not). This test is suitable when one categorical variable (slope class) is being compared to the observed distribution and a theoretical/expected distribution.

Hypothesis

· H_0 (Null hypothesis): Landslides are uniformly distributed according to slope area (i.e., more area is equal to more landslides, purely by chance).

· H_1 (Alternative hypothesis): Landslides are not proportional to slope area (i.e., slope steepness influences landslide occurrence).

Table-3: Observed and Expected Frequencies (Landslides vs Slope classes)

Slope Category	Area (km^2)	landslide occurrences (O)	Expected landslides (E)	χ2	SR
Level	1	1	0.90	0.009	0.09
Very Gentle	5	5	4.54	0.045	0.21
Gentle	11	24	10.00	19.569	**4.42**
Moderate	30	23	27.29	0.675	-0.82
Moderately Steep	134	103	121.89	2.930	-1.71
steep	663	469	603.12	29.828	-5.46
very steel	817	886	743.21	27.430	**5.23**
Total	1661	1511			

To statistically analyse whether landslide occurrence was dependent on slope categories, a Chi-square goodness-of-fit test was performed. The null hypothesis assumed that landslides are distributed proportionally to the areal extent of each slope class, meaning no influence of slope steepness on landslide occurrence. The expected landslide frequencies for each slope category were calculated by normalising the total number of llandslides with respect to the corresponding slope area. The calculated Chi-square value was $\chi^2 = 80.48$ with 6 degrees of freedom. The associated p-value was <0.001, which is far below the 0.05 significance level**.** Therefore, the null hypothesis is rejected, and the alternative hypothesis is accepted. This indicates a statistically significant deviation between observed and expected landslide frequencies across slope categories. The results clearly show that landslides are not randomly distributed with respect to slope area. Steep and very steep slope categories show disproportionately higher landslide occurrences, whereas gentle and moderate slopes show relatively fewer landslides than expected based on their areal coverage. This confirms slope steepness as a dominant conditioning factor influencing landslide occurrence in the study area.Figure-3 depicts the comparison between observed and expected landslide frequencies across different slope categories. Expected frequencies were computed based on the proportional area of each slope class. A marked deviation between observed and expected values is evident, particularly in steep and very steep slope categories, where observed landslide counts substantially exceed expected values. In contrast, gentle and moderate slopes show lower or comparable observed frequencies relative to expectations. These deviations visually support the statistically significant Chi-square test results, confirming that landslide occurrence is strongly controlled by slope steepness rather than being randomly distributed according to area.

STANDARDISED RESIDUALS

After the Chi-Square test standardized residuals were calculated for each slope class to determine which slope classes contribute most to χ^2. Standardised Residuals simply tell how much each slope class deviates from expectation, after accounting for sample size.

Table 4: Standardised residuals showing deviation of observed landslide frequency from expected values across slope categories.

Slope Category	landslide occurrences (O)	Expected landslides (E)	SR

Level	1	0.90	0.09
Very Gentle	5	4.548	0.22
Gentle	24	10.00	4.42
Moderate	23	27.29	-0.82
Moderately Steep	103	121.89	-1.71
Steep	469	603.12	-5.46
Very steel	886	743.21	5.23

Rule of thumb

· SR > +1.96 = Significantly more landslides than expected

· SR < −1.96 = Significantly fewer landslides than expected

· −1.96 to +1.96 = No significant deviation

Standardised residuals for each slope class were calculated to identify which slope categories contributed most to the Chi-square statistic. Very steep slopes exhibit a strong positive residual (SR = +5.23), indicating significantly higher landslide occurrence than expected based on area alone. Gentle slopes also show a significant positive deviation (SR = +4.42). In contrast, steep slopes display a strong negative residual (SR = −5.46), suggesting fewer landslides than expected relative to their extensive areal coverage. These results highlight the non-uniform influence of slope classes on landslide occurrence.

The hypothesis that landslide occurrence increases with slope angle is generally supported by the study, as higher slope classes exhibit significantly greater landslide frequencies. However, standardised residual analysis indicates that this relationship is non-linear, with certain slope classes showing deviations due to local terrain conditions and human interventions. Slope angle strongly influences landslide occurrence, but the relationship is non-linear and modified by geological and anthropogenic factors.

CONCLUSION

· The Paradox of Gentle Slopes: The Frequency Ratio analysis reveals a complex, non-monotonic relationship between slope gradient and landslide occurrence in the study area. The most significant finding is the strong association between landslides and gentle slopes (3-5°), which contradicts the conventional understanding that landslides primarily affect steeper terrain. This is because of the fact that Landslides on gentle slopes are more frequently reported due to their impact on human activities, while remote steep slope landslides may be under-reported.

· Under-representation of Steep Slopes: The negative association in steep slopes (15-30°) suggests these areas may be because steep slope gradients promote rapid drainage, reducing pore water pressure buildup, and the human interventions are comparatively lower on steeper slopes.

· Very steep slopes (>30°) show a moderate positive association (FR = 1.19), confirming their role as landslide-prone terrain but with less intensity than gentle slopes.

The statistical significance of the overall pattern is confirmed by the chi-square test ($p < 0.0001$)

LIMITATIONS

Though the Frequency Ratio method effectively identifies slope classes with the highest spatial association to landslide occurrences, its application in this study is subject to several inherent limitations. First, the FR values are sensitive to the chosen slope classification intervals; different slope widths could yield different susceptibility rankings. Second, FR is a univariate statistical tool that does not account for interactions between slope angle and other critical factors such as lithology, rainfall, or human disturbances, which may confound the observed relationship. Third, the method establishes correlation rather than causation; a high FR on moderate slopes may simply reflect the spatial coincidence of these slopes with weak geological formations or road networks. Finally, FR relies on a static landslide inventory and does not incorporate dynamic environmental changes, such as land-use conversion or climate-induced rainfall intensification, which could alter future slope stability. Therefore, while the FR results provide a valuable preliminary ranking of susceptible slope classes, they should be interpreted with caution and complemented by multivariate analyses or physically-based models to validate the controlling role of slope angle.

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