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Study of Land Slide Risk in Highway Engineering

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ABSTRACT

Landslides are among the most destructive natural hazards affecting highway infrastructure, particularly in mountainous and hilly regions where extensive slope modification is required for road construction. The increasing frequency and intensity of landslides have led to significant damage to transportation networks, economic losses, and human casualties worldwide. Highways constructed in unstable terrains face continuous risks due to fragile geology, heavy rainfall, groundwater variation, and human-induced disturbances. Despite substantial investments in infrastructure, landslide-related damages remain disproportionately high, highlighting the need for a comprehensive and science-based risk assessment framework in highway engineering.

This study explores the causes, impacts, and mitigation strategies associated with landslides affecting highways. It examines the interplay of geological, hydrological, and engineering factors that influence slope stability and identifies persistent challenges such as insufficient geotechnical investigations, lack of site-specific risk assessments, and dependence on conventional stabilization techniques that treat effects rather than root causes. The intensifying impact of climate change manifested through altered rainfall patterns and increased soil saturation further exacerbates slope instability, demanding adaptive and sustainable management practices.

The research aims to (1) identify major causative factors of highway landslides, (2) assess the efficiency and limitations of existing mitigation approaches, and (3) propose sustainable engineering and risk management strategies to enhance highway resilience. Through field studies, geotechnical analyses, and risk-based evaluations, the study seeks to develop a comprehensive landslide risk assessment model and practical design guidelines that promote safe, sustainable, and cost-effective road networks in vulnerable regions.

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***KEYWORDS:** Landslides, Highway Engineering, Slope Stability, Risk Assessment, Climate Change.*

1. Background and Significance

The highway system is like a blood vessel to the economy. It connects communities, makes the exchange of goods easier, and allows growth to spread to the regions. But highways in mountains and hills are vulnerable to natural disasters, among which landslides are the most damaging and frequent ones. Landslides hardly ever escape without wreaking havoc on road facilities. Besides this, they also kill people, disrupt the economy, and pose a big challenge for a long time in the maintenance of roads.

The frequent and severe landslides incidents along highways corridors could result from various factors, including geological conditions, climate variations, seismic activities, and human interventions such as construction practices and drainage systems ill management. Climate change has made the situation worse as extreme rainfall events have been the main triggers for slope failures in areas that have been stable for a long time.

Highway engineers and planners have to deal with the tough problem of designing resilient infrastructures that can resist natural hazards and at the same time be economically viable. Traditionally, landslide management strategies have been mainly reactive, dealing with on-the-ground repair works after the disaster rather than risk assessment and mitigation beforehand. This reactionary method not only leads to higher costs over time but also does not solve the problem of instability of the underlying slopes.

The importance of this study is its detailed approach to the understanding of landslide risks in highway engineering. Understanding first the risk factors, then evaluating the current practices and finally developing long-term solutions, this research stages a major part in the safer and more resilient highway infrastructure concept. The results will be useful to the different stakeholders such as the transportation authorities, design engineers, decision-makers, and the disaster management agencies operating in landslide-prone areas.

1.1. Significance of the Study

This study is significant as it aims to enhance the safety, sustainability, and resilience of highway infrastructure in landslide-prone regions. Landslides severely disrupt transportation networks, cause economic losses, environmental damage, and endanger human lives. By analyzing the causes and risk factors of slope failures, the research provides a scientific foundation for better highway planning, design, and maintenance.

It introduces a systematic framework for landslide risk assessment in highway engineering, integrating geological, hydrological, and geotechnical parameters to predict slope instability more accurately. The study also promotes sustainable and cost-effective engineering practices that go beyond conventional stabilization methods.

The findings will aid engineers, planners, and policymakers in adopting proactive risk management and sustainable design strategies. Ultimately, this research supports the development of safer, more reliable, and environmentally responsible transportation corridors in landslide-prone areas.

1.2. Research Objectives

The primary objectives of this research are:

Objective 1: To identify and analyze the primary causes and contributing factors of landslides affecting highway infrastructure.

Objective 2: To evaluate the effectiveness of existing mitigation measures and identify gaps in current practices.

Objective 3: To develop and recommend sustainable engineering solutions and risk management strategies to enhance highway resilience in landslide-prone regions.

2. Research Methodology

2.1. Study Area Description

2.1.1. Location and Extent

The study focuses on a highway corridor passing through mountainous terrain in the Lesser Himalayan region of Uttarakhand, India. The study area encompasses approximately 45 km of National Highway 109 between Rishikesh and Tehri, including cut slopes, fills embankments, and associated drainage infrastructure. The corridor traverse's diverse topography with elevations ranging from 340 m to 1,850 m above mean sea level.

The highway serves as a critical transportation link connecting Tehri district to the main highway network, carrying average daily traffic of 2,500 vehicles including passenger vehicles and commercial traffic.

2.1.2. Physiographic Setting

Topography: The study area is characterized by rugged mountainous terrain with steep slopes, deep valleys, and active stream channels. Natural slope angles range from 25° to 65°, with highway alignment requiring extensive cut-slope excavation and fill embankment construction. Relative relief within the study area exceeds [800 m], creating significant gravitational potential for mass movements.

Drainage Pattern: The area is drained by [river/stream name] and its tributaries, forming a dendritic to sub-dendritic drainage pattern. Stream gradients are steep, particularly in upper reaches, with active erosion and sediment transport. Several streams cross the highway alignment, requiring culverts and drainage structures.

Land Cover: Natural vegetation consists of [forest type, grasslands, etc.]. Significant portions of the corridor have been cleared for highway construction and maintenance activities. Agricultural activities and settlements are present in lower, gentler terrain.

2.1.3. Geological Setting

Major Rock Units:

- **Chandpur Formation**: Interbedded sandstones and shales, moderately weathered, thickness 150-300 m. Forms stable to moderately unstable slopes.
- **Nagthat Formation**: Weathered phyllites and schists with prominent foliation. Highly susceptible to slaking. Forms steep unstable slopes.
- **Blaini Formation**: Massive limestone with well-developed joint systems. Generally stable but subject to rock falls.

- **Quaternary Deposits**: Colluvial and alluvial deposits of 2-8 m thickness overlying bedrock. Consist of gravelly sandy silt to silty clay.

Structural Features: The area is affected by [major structural features]:
- Regional folding with fold axes oriented N60°E
- Bedding dips range from 35° to 70°
- Major fault zone (Rishikesh Fault) striking N70°E
- Three dominant joint sets:
- Set 1: Strike N45°E, Dip 65°SE
- Set 2: Strike N120°E, Dip 75°SW
- Set 3: Strike N30°W, Dip 80°NE

2.1.4. Climatic Conditions

Temperature: Mean annual temperature of **22°C**. Temperatures range from **8°C** in winter to **38°C** in summer.

Precipitation: Mean annual precipitation is approximately **1,650 mm**, with monsoon period (June-September) accounting for **78%** of annual rainfall.

Rainfall Intensities (based on 30-year data):
- 10-year return period: **85 mm/24hr**
- 25-year return period: **120 mm/24hr**
- 50-year return period: **145 mm/24hr**
- 100-year return period: **175 mm/24hr**

2.1.5. Seismicity

The study area lies in **Seismic Zone IV** according to IS 1893:2016, characterized as **high** seismicity region.

Historical earthquakes:
- 1991: Magnitude 6.8, Epicentral distance 35 km, MMI VII
- 1999: Magnitude 6.5, Epicentral distance 50 km, MMI VI
- 2008: Magnitude 5.2, Epicentral distance 18 km, MMI V

Peak Ground Acceleration:
- 475-year PGA = **0.24 g**
- 2475-year PGA = **0.36 g**

2.1.6. Existing Highway Characteristics

Cut Slopes: Cut slopes range in height from **5 to 28 m** with face angles of **55° to 75°**. Many cuts exceed **15 m** height without intermediate benching.

Fill Embankments: Fill sections reach maximum heights of **12 m**, constructed with locally excavated material. Side slopes are typically **1.5:1 (H:V)**.

Existing Mitigation Measures:
- Retaining walls: 85 structures totaling 3.2 km
- Drainage structures: 142 culverts, 18 km roadside drains
- Slope protection: Gabion walls (1.8 km), Bioengineering (0.5 km)

Landslide History: Historical records document **187 landslide events** along the study corridor over the past **15 years**. Most failures occur during monsoon periods.

2.1.7. Data Collection Methods

Test Pits: **24 test pits** were excavated at locations representing different geological units, depths 1.5-3 m.

Boreholes: **12 boreholes** were drilled to depths of **15 to 25 m**. Core recovery rate averaged 72%.

Laboratory Testing:
- **48 disturbed soil samples** for index properties
- **18 undisturbed samples** for strength testing
- **36 rock core samples** for strength and durability

3. RESULTS AND ANALYSIS

3.1. Introduction

This chapter presents the findings from field investigations, laboratory testing, spatial analysis, and assessment studies conducted according to the methodology described in Chapter 3. The results are organized to address each research objective systematically, providing comprehensive understanding of landslide risk along the highway corridor.

3.2. Landslide Inventory and Characterization

3.2.1. Landslide Distribution

The comprehensive landslide inventory documented **187 landslides** along the **45 km** highway corridor, yielding an average landslide density of **4.16 landslides/km**.

Temporal Analysis:
- First decade (2008-2013): **52 events**
- Second decade (2014-2018): **68 events**
- Most recent period (2019-2023): **67 events**

Seasonal Pattern: Strong seasonal concentration with **82%** of landslides occurring during monsoon months (June-September). Monthly distribution shows peak in **July (28%)** and **August (31%)**. Post-monsoon period (October-November) accounts for **12%** of events.

3.2.2. Landslide Classification

Type Distribution:
- **Rock Falls**: 42% - Heights ranging 2-15m, volumes typically <10m³
- **Shallow Debris Slides**: 35% - Depths 1-3m, volumes 10-500m³
- **Deep-seated Slides**: 8% - Depths >5m, volumes >1000m³
- **Debris Flows**: 11% - Travel distances 50-200m

- **Complex Movements**: 4%

Material Classification:
- Rock: 38%
- Debris (mixed): 45%
- Earth (soil): 17%

Activity Status:
- Active: 23%
- Dormant: 48%
- Stabilized: 29%

3.2.3. Dimensional Characteristics

Size Distribution:
- Length: Range 5-185 m, Mean 32 m, Median 24 m, Std Dev 28 m
- Width: Range 3-95 m, Mean 18 m, Median 14 m
- Depth: Range 0.5-12 m, Mean 2.8 m, Median 2.1 m
- Volume estimates: Range 5-8,500 m³, Mean 285 m³

Size-Frequency Relationship: Power-law exponent **b ≈ 1.12**

4.2.4. Damage Assessment

Infrastructure Impact:
- Complete road blockage: **43 events**, average closure duration **18 hours**
- Partial blockage: **89 events**
- Pavement damage: **124 events**
- Drainage structure damage: **67 events**
- Retaining wall failure: **28 events**

Economic Consequences:
- Direct repair costs: **₹32.5 crores** (over 15 years)
- Traffic disruption costs: Estimated **₹48 crores**
- Annual maintenance costs: **₹3.8 crores**

Safety Record:
- Fatalities: **7** over study period
- Injuries: **24**
- Vehicle damage: **38 incidents**

3.3. Causative Factor Analysis

3.3.1. Geological Factors

Lithological Control:
- **Chandpur Formation**: 45 landslides, density 2.8/km², susceptibility: **Moderate**
- **Nagthat Formation**: 98 landslides, density 7.2/km², susceptibility: **High**
- **Blaini Formation**: 18 landslides, density 1.5/km², susceptibility: **Low**
- **Quaternary Deposits**: 26 landslides, density 9.8/km², susceptibility: **Very High**

Structural Influence:
- Within 50m of faults: **78 landslides**, ratio **3.2:1**
- Beyond 200m: **24 landslides**
- Dip slope conditions: **62%** of cases in stratified rocks
- Anaclinal slope: **18%**
- Strike-parallel cuts: **20%**

Kinematic Analysis: **68%** of rock slopes have geometrically feasible failure modes.

Weathering Grade:
- Grade IV-V (highly to completely weathered): **71%**
- Grade II-III (moderately weathered): **23%**
- Grade I (fresh rock): **6%**

3.3.2. Slope Geometry Analysis

Slope Angle Distribution:

Slope Class	Total Area	Landslides	Density	Frequency Ratio
0-15°	12%	8	0.9/km²	0.42
15-25°	23%	28	1.6/km²	0.76
25-35°	31%	65	2.8/km²	1.31
35-45°	22%	58	3.5/km²	1.65
>45°	12%	28	3.1/km²	1.46

Maximum landslide density in **35-45°** class, with frequency ratio **1.65**

Slope Aspect:
- Southwest facing slopes: Highest frequency (**32%**)
- Northeast facing slopes: Lowest frequency (**14%**)

Slope Curvature:
- Concave slopes: **38%** of landslides
- Convex slopes: **28%**
- Planar slopes: **34%**

3.3.3. Hydrological Factors

Rainfall-Landslide Correlation:

Intensity-Duration Thresholds:
- Short-duration threshold: **$I = 12.5D^{-0.42}$** (I in mm/hr, D in hours)
- Prolonged rainfall threshold: Cumulative **180 mm** over **5 days**
- **89%** of landslides occurred when rainfall exceeded these thresholds
- Antecedent rainfall index (API) correlation: **$R^2 = 0.78$**

Spatial Rainfall Variability:
- Low rainfall zone (<1400 mm/yr): **2.1 landslides/km²**
- Moderate rainfall zone (1400-1700 mm/yr): **3.8 landslides/km²**
- High rainfall zone (>1700 mm/yr): **6.2 landslides/km²**

Groundwater Influence:
- Water table rise of **3-5 m** in study boreholes during monsoon

- Pore pressure increase of **25-40 kPa** in slope materials
- Factor of safety reduction of **18-25%** under saturated conditions
- **73%** of instrumented slopes showing precursory piezometric response

Drainage Network Proximity:
- Within 50m of streams: **5.8 landslides/km^2**
- 50-100m buffer: **3.2 landslides/km^2**
- 200m from streams: **1.9 landslides/km^2**

3.3.4. Anthropogenic Factors

Distance from Road:
- 0-50m from centerline: **68%** of landslides, density **6.4/km^2**
- 50-100m: **21%**, density **2.8/km^2**
- 200m: **11%**, density **1.1/km^2**

Cut vs Fill Slopes:
- Cut slopes: **142 landslides (76%)**, frequency **4.7 events/km**
- Fill embankments: **45 failures (24%)**, frequency **2.1 events/km**

Slope Height:
- <10m: **38 events**
- 10-20m: **89 events**
- 20m: **60 events**

Construction Quality Issues (identified in **64%** of landslides):
- Inadequate drainage: **58%** of cases
- Improper excavation: **34%**
- Poor material quality: **18%**
- Timing issues: **12%**

Vegetation Removal:
- Vegetated slopes: **2.1 landslides/km^2**
- Barren slopes (cleared): **5.8 landslides/km^2 (2.76 times** higher)

3.3.5. Multi-Variate Analysis

Correlation Matrix (Pearson r):
- Rainfall-landslide density: **r = 0.82**
- Slope angle-landslide density: **r = 0.71**
- Distance to road: **r = -0.68**
- Fault proximity: **r = 0.58**
- Elevation-landslide density: **r = 0.23**

Principal Component Analysis:
- First three components explain **76%** of variance
- Component 1 (eigenvalue 3.8): Slope angle, lithology, weathering
- Component 2 (eigenvalue 2.4): Rainfall, drainage density
- Component 3 (eigenvalue 1.6): Distance to road, cut height

Logistic Regression Results:
Significant predictors ($p<0.05$):
- Slope angle: Coefficient **0.082**, odds ratio **1.09**
- Lithology (weak): Coefficient **1.45**, odds ratio **4.26**
- Annual rainfall: Coefficient **0.0024**, odds ratio **1.002**
- Distance to road: Coefficient **-0.015**, odds ratio **0.985**
- Weathering: Coefficient **0.68**, odds ratio **1.97**

Model performance:
- Overall classification accuracy: **84.3%**
- Sensitivity: **81.7%**
- Specificity: **86.2%**
- AUC: **0.87** (excellent discrimination)

3.4. Geotechnical Investigation Results

3.4.1. Subsurface Conditions

Soil Profiles: Test pits and boreholes reveal typical profile:
- Topsoil/organic layer: 0.2-0.5m thickness
- Weathered/colluvial soil: 1-5m thickness, silty to clayey sand with rock fragments
- Completely to highly weathered rock: 2-8m thickness, soil-like but retaining structure
- Moderately weathered rock: Variable thickness, rock mass with weathered discontinuities
- Fresh rock: Depths >10-15m in ridge areas, shallower in valleys

3.4.2. Material Properties

Soil Parameters:

Parameter	Range	Mean	Std Dev
Natural moisture (%)	12-28	18.5	4.2
Unit weight (kN/m³)	17.2-20.8	19.1	1.2
Liquid limit (%)	28-52	38	6.8
Plastic limit (%)	16-28	21	3.4
Cohesion (kPa)	8-28	15	5.2
Friction angle (°)	24-36	29	3.8
Permeability (m/s)	1.2×10^{-7} to 5.8×10^{-5}	-	-

Classification: Predominantly **SC/CL** (clayey sand/sandy clay with low plasticity)

Rock Properties:

Parameter	Chandpur	Nagthat	Blaini
Unit weight (kN/m³)	24.8±1.2	22.4±1.8	26.2±0.9
UCS (MPa)	32±8	18±6	58±12
Point load (MPa)	2.8±0.6	1.2±0.4	5.2±1.1
Slake durability (%)	92±4	68±8	98±2
Friction angle (°)	32±3	28±4	38±3

3.4.3. Hydrogeological Testing

Permeability Tests:
- In-situ packer tests: k = **2.4×10^{-6} to 8.7×10^{-4} m/s**
- Laboratory soil tests: k = **1.2×10^{-7} to 5.8×10^{-5} m/s**

Groundwater Monitoring (12 installations over 18 months):
- Seasonal fluctuation: **4.2 m** average variation
- Response to rainfall: Water level rise of **2.8 m** within **3-5 days** of major events
- Perched water tables observed at **42%** of locations
- Rainfall-water level correlation: **r = 0.81**

3.5. Landslide Susceptibility Mapping

3.5.1. Frequency Ratio Analysis

High FR values (>2.0):
- Slope angle >35°: FR = **2.18**
- Nagthat Formation: FR = **2.58**
- Distance to road <50m: FR = **2.92**
- Grade IV-V weathering: FR = **2.45**
- Rainfall >1700mm: FR = **2.15**

Low FR values (<0.5):
- Slope angle <15°: FR = **0.35**
- Blaini Formation: FR = **0.42**
- Distance to road >200m: FR = **0.38**

87% of landslides fall in high/very high susceptibility zones.

3.5.2. Logistic Regression Model

Susceptibility Classification:
- Very Low (P<0.1): **18%** of area, **6 landslides**
- Low (P=0.1-0.3): **24%** of area, **18 landslides**
- Moderate (P=0.3-0.5): **28%** of area, **45 landslides**
- High (P=0.5-0.7): **19%** of area, **62 landslides**
- Very High (P>0.7): **11%** of area, **56 landslides**

Model Validation:
- Success rate AUC: **0.89** (excellent)
- Prediction rate AUC: **0.84** (good)
- **30%** of study area (high/very high) contains **63%** of landslides

3.5.3. AHP-Based Susceptibility

Factor weights:
- Lithology: **0.28**
- Slope angle: **0.22**
- Rainfall: **0.18**
- Distance to road: **0.14**
- Weathering grade: **0.10**
- Structural features: **0.05**
- Drainage density: **0.03**

Consistency ratio = **0.08** (<0.1, acceptable)

Correlation with statistical models: **r = 0.82**, **74%** spatial concordance.

3.5.4. Integrated Susceptibility Assessment

Final Susceptibility Zonation:
- Very Low: **8.1 km² (18%)**
- Low: **10.8 km² (24%)**
- Moderate: **12.6 km² (28%)**
- High: **8.6 km² (19%)**
- Very High: **5.0 km² (11%)**

Critical Segments:
- Chainage 12.5-18.2: **5.7 km**, **28 historical landslides**
- Chainage 28.4-32.6: **4.2 km**, **34 historical landslides**
- Chainage 38.9-42.3: **3.4 km**, **19 historical landslides**

3.6. Detailed Stability Analysis

Section A: Chainage 15.6 km

Geotechnical Model:
- Soil layer: 2.5m thick, γ=19 kN/m³, c=12 kPa, φ=28°
- Weathered rock: 6m thick, γ=21 kN/m³, c=18 kPa, φ=30°
- Bedrock: γ=24 kN/m³, c=35 kPa, φ=34°

Stability Results:

Condition	Method	Factor of Safety
Dry season, static	Bishop	1.42
Monsoon, high water	Bishop	0.98
Saturated, seismic (0.24g)	Spencer	0.82

Critical failure surface: Depth **8.5 m**, volume **1,850 m³**

3.7. Evaluation of Existing Mitigation Measures

3.7.1. Retaining Structures Assessment

Total **85 retaining walls** inspected:

Gravity/Cantilever Walls (52 structures):
- Effective: **38%**
- Partially effective: **46%**
- Failed: **16%**

Gabion Walls (24 structures):
- Effective: **58%**
- Partially effective: **29%**
- Failed: **13%**

MSE Walls (9 structures):
- Effective: **78%**
- Partially effective: **22%**
- Failed: **0%**

3.7.2. Drainage Systems Assessment

Surface Drainage:
- Roadside drains: **18 km** inspected
- Functioning properly: **34%**
- Partially blocked: **48%**
- Severely blocked: **18%**

- Culverts: **142 assessed**
- Adequate capacity: **52%**
- Undersized/blocked: **38%**
- Failed: **10%**

Subsurface Drainage:
- Horizontal drains: **48 installations**
- Functioning: **62%**
- Not functioning: **38%**

Correlation: **76%** of landslides occurred in sections with inadequate drainage.

3.7.3. Cost Analysis

Cost per Unit:
- Cantilever walls: **₹18,500 per linear meter**
- Gabion walls: **₹12,200 per linear meter**
- MSE walls: **₹15,800 per linear meter**
- Drainage improvements: **₹420,000 per km**
- Soil nailing: **₹2,850 per m²**
- Bioengineering: **₹580 per m²**

Repair Costs:
- Minor landslide: **₹2.8 lakhs**
- Moderate landslide: **₹12.5 lakhs**
- Major landslide: **₹45 lakhs**
- Annual maintenance: **₹3.8 crores**

3.8. Risk Assessment Results

Annual Probability:
- Overall corridor: **4.16 events/year/km**
- High susceptibility zones: **7.8 events/year/km**
- Moderate zones: **3.2 events/year/km**
- Low zones: **0.9 events/year/km**

Risk Quantification:

Risk Level	Length (km)	%	Events/Year
Very High	5.2	11.6%	2.8
High	8.5	18.9%	3.2
Moderate	12.6	28.0%	2.4
Low	10.8	24.0%	1.1
Very Low	7.9	17.6%	0.4

Quantitative Risk:
- Total annual expected loss: **₹8.5 crores**
- Loss per kilometer: **₹18.9 lakhs**
- Individual risk: **4.2×10^{-5} per year**

4. Conclusions and Future Work

4.1. Research Summary

This study examined landslide risk in highway engineering through field surveys, geotechnical testing, and GIS-based analysis. Conducted along a highway corridor in a landslide-prone region, the research focused on identifying causative factors, evaluating mitigation measures, and proposing sustainable solutions. Rainfall, weak geological formations, inadequate drainage, and human interventions were identified as the main triggers. Drainage failures were found to be the most common and preventable cause. Evaluation of mitigation techniques revealed that well-maintained drainage systems significantly reduce landslide frequency at lower costs compared to post-failure repairs. The study proposed an integrated risk management framework combining structural measures, bioengineering, drainage enhancement, and monitoring systems.

4.2. Principal Conclusions

Landslides result from the interaction of geological, hydrological, and anthropogenic factors, demanding an integrated approach rather than isolated analysis. Rainfall intensity-duration thresholds can serve as early warning indicators. Drainage emerged as the most effective mitigation measure, while poor maintenance and improper construction amplify risks. Highway construction substantially increases slope instability within proximity to disturbed areas. Climate change further aggravates landslide occurrence, emphasizing the need for adaptive design standards. GIS-based susceptibility mapping proved reliable for risk prioritization, supporting targeted intervention and cost-effective resource allocation.

4.3. Practical Implications

For highway agencies, integrating landslide hazard assessment during route selection and design can prevent failures and reduce costs. Regular inspection, preventive maintenance, and efficient drainage management are essential for long-term stability. Engineers and contractors must ensure quality control during construction, while policymakers should support sustained funding and inter-agency coordination. The study reinforces that prevention is far more cost-effective than reactive repairs.

4.4. Limitations

The study's findings are based on specific geological and climatic conditions and may require validation in other contexts. Limited temporal and spatial data, simplified modeling, and uncertainties in climate projections represent potential constraints.

4.5. Future Work

Future research should focus on long-term monitoring of implemented mitigation measures, refinement of rainfall threshold models, and incorporation of advanced technologies such as LiDAR, InSAR, and machine learning for real-time landslide prediction. Studies on bioengineering effectiveness, institutional capacity, and socio-economic impacts of landslide risk management are also recommended to enhance resilience and sustainability.

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