RESEARCH PAPER

Geotechnical and GIS-Based Analysis of Slope Stability for Landslide Hazard Mitigation in the Konkan Region

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Abstract

The Konkan region of Maharashtra is highly susceptible to rainfall-induced slope failures because of steep hill slopes, lateritic soil cover, weathered basalt formations, colluvial deposits, intense monsoon rainfall and continuing anthropogenic disturbance. This paper presents a corrected and integrated research format for slope stability analysis and landslide mitigation in the Konkan region using geotechnical interpretation, GIS-based spatial assessment and ANSYS-based numerical modelling. Land use-land cover, rainfall distribution, slope and terrain roughness indicators were used to identify regional susceptibility, while a representative slope model was analysed under critical pore-pressure loading. The numerical output showed maximum total deformation of 1.0314 mm and maximum equivalent von-Mises stress of 21.382 MPa under 4.0 MPa pore pressure. A stress-based factor of safety was estimated as 1.40, indicating a critical but stable condition that requires engineering intervention. Sensitivity interpretation showed that the factor of safety decreases from 1.80 to 1.40 as pore pressure increases from 0 to 4.0 MPa. The study recommends combined mitigation using surface drainage, subsurface drainage, soil nailing, geogrid reinforcement, retaining structures, toe protection and vegetation restoration. The corrected paper establishes a practical framework for safer infrastructure planning and slope-management decisions in high-rainfall coastal hill terrain.

Keywords: *Slope stability; landslide mitigation; Konkan region; pore-water pressure; ANSYS; GIS; factor of safety; soil nailing; rainfall-induced landslides.*
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1. Introduction

Slope instability and landslides constitute one of the most significant geotechnical hazards in regions characterized by steep terrain, heterogeneous geological formations, and intense rainfall. The Konkan region of Maharashtra, located along India’s western coastline, exemplifies such a landscape, featuring rugged topography, lateritic soil cover, weathered basalt formations, and high monsoonal precipitation. These natural conditions, combined with increasing anthropogenic activities such as hill cutting, excavation, deforestation, and unplanned infrastructure development, have considerably heightened the susceptibility of slopes to failure, posing substantial risks to human settlements, transportation networks, and ecological stability.

The unique geomorphology of the Konkan region plays a pivotal role in shaping slope behavior. Lateritic soils, which form extensive plateaus, are porous, brittle, and highly prone to erosion during heavy rainfall events. Weathered basalts, although mechanically strong in fresh condition, become fractured and weak under prolonged weathering, particularly when saturated with water. Additionally, colluvial deposits—comprising loose soil, rock fragments, and transported debris—accumulate at the bases of slopes and exhibit significant instability under saturated conditions. The interaction of these geological units with hydrological processes such as surface runoff, infiltration, and groundwater fluctuations creates a complex system in which slope stability is highly sensitive to both natural and human-induced changes.

Rainfall is a primary triggering factor for landslides in the Konkan region. Monsoonal precipitation infiltrates soil layers, elevating pore-water pressures and reducing effective stress, which in turn diminishes soil shear strength. Prolonged or intense rainfall often leads to shallow slides, debris flows, rotational slips, and deep-seated slope failures. Observations from historical landslide events in areas such as Ratnagiri, Chiplun, Mahad, Khed, Poladpur, and Sindhudurg underscore the destructive potential of heavy monsoon rains. These incidents not only cause significant damage to transportation corridors, residential areas, and public infrastructure but also result in environmental degradation, including soil erosion, loss of vegetation, and disruption of natural drainage patterns.

Human interventions exacerbate the vulnerability of slopes in the Konkan region. Road widening, hill cutting, excavation for urban development, and construction on or near slopes disturb the natural equilibrium, reducing lateral support and increasing the probability of slope failure. Removal of vegetation through deforestation or land conversion eliminates the mechanical reinforcement provided by root systems, thereby increasing surface erosion and runoff rates. Moreover, poorly planned drainage systems or blocked natural channels amplify the accumulation of water within slopes, raising pore pressures and triggering landslides even under moderate rainfall conditions. The interplay between natural geomorphology, rainfall patterns, and anthropogenic activities necessitates an integrated approach to understanding and mitigating landslide hazards.

Effective slope stability analysis requires a combination of field investigations, laboratory testing, and advanced numerical modeling. Field investigations involve mapping slope geometry, identifying soil and rock types, measuring groundwater levels, and detecting early warning signs such as surface cracks, tilted trees, or displaced soil. Laboratory tests provide critical geotechnical properties including cohesion, friction angle, unit weight, plasticity, permeability, and shear strength, which are essential for understanding the mechanical behavior of slope materials under stress. These data form the basis for numerical models that simulate slope deformation, stress distribution, and failure mechanisms, allowing engineers to predict potential failure zones and evaluate mitigation strategies.

Modern computational tools have significantly enhanced the accuracy and reliability of slope stability assessment. Software such as ANSYS enables the simulation of stress–strain behavior, deformation, and reinforcement response under various conditions, while GIS-based platforms like QGIS support spatial analysis, rainfall mapping, land-use/land-cover assessment, and identification of landslide-prone areas. Integrating geotechnical and hydrological parameters within these frameworks allows for comprehensive evaluations of slope behavior, particularly in complex terrains where heterogeneous soil layers, variable water tables, and anthropogenic modifications exist. These tools facilitate scenario analysis, enabling engineers to optimize mitigation measures prior to field application and reduce the likelihood of catastrophic slope failures.

Slope morphology and terrain characteristics are central to understanding landslide susceptibility. Steep slopes, irregular topography, and concave or convex profiles create stress concentrations that influence the initiation and propagation of mass movements. Critical slopes are typically identified based on factors such as gradient, soil and rock type, thickness of weathered layers, groundwater conditions, prior failure history, and exposure to rainfall. Remote sensing, drone surveys, total station measurements, borehole investigations, and GPS mapping provide precise data for evaluating slope geometry and monitoring changes over time. These methods, when coupled with geotechnical and hydrological assessments, support the identification of zones with high landslide potential and inform the design of stabilization measures.

Geotechnical parameters including cohesion, internal friction angle, soil unit weight, and stratification strongly influence slope stability. Low-cohesion soils, heterogeneous strata, and layered profiles create weak planes along which sliding can occur, particularly under conditions of high-water saturation. Hydrological parameters, such as rising groundwater tables, seepage zones, and rainfall infiltration, further exacerbate slope instability by reducing effective stress and shear strength. Additionally, climatic and seasonal variations affect soil moisture, weathering, and cyclic wetting and drying, which can cumulatively weaken slopes over time. Anthropogenic activities such as hill cutting, excavation, and construction increase slope loads and disturb natural drainage, contributing to erosion and reducing the natural stability afforded by vegetation cover.

Figure 1. Landslides

The Konkan region lies between the Arabian Sea and the Western Ghats and contains narrow valleys, escarpments, coastal plateaus and road-cut slopes. Natural slopes are frequently altered for highway widening, settlement expansion, railway development, excavation and unplanned construction. These interventions reduce lateral support, change surface-drainage pathways and expose weak soil or rock layers. Consequently, localised failures may develop rapidly after heavy rainfall, especially where seepage zones, tension cracks, blocked drains and vegetation loss are present.

2. Problem Statement

The Konkan region experiences recurrent landslide and slope-instability problems because of intense monsoon rainfall, steep slopes, lateritic soil, weathered basalt, loose colluvium and anthropogenic disturbance. Although individual causes such as rainfall, slope geometry and road cutting are frequently discussed, there is a need for a more integrated research framework that connects spatial susceptibility indicators, pore-pressure behaviour, stress-strain response and engineering mitigation. The present paper addresses this need by organising the available study into a corrected research-paper format and by presenting GIS and ANSYS results in a clearer technical sequence.

3. Aim and Objectives

Aim

To evaluate slope stability conditions and improve landslide resistance in kokan through geotechnical data analysis and numerical modelling using ANSYS software, and to determine the most effective mitigation strategies.

Objectives

1. To analyse geotechnical and hydrological parameters influencing slope instability in kokan region.
2. To model existing slope conditions using simulation software such as ANSYS and QGIS and to assess slope behaviour under existing conditions.
3. To simulate engineering and drainage-based mitigation measures and compare stability improvements.
4. To perform sensitivity analysis to identify critical parameters affecting slope stability behaviour.

4. Literature Review

Recent studies indicate that landslide initiation is controlled by the combined influence of slope geometry, soil strength, rainfall infiltration, groundwater rise, weathering and human disturbance. Jhinkwan et al. (2024) reviewed slope instability in the Lesser Himalaya and emphasised that remedial design should combine engineering, hydrological and ecological measures. Kinde et al. (2024) showed that slope sections that remain stable in dry conditions can become unsafe when groundwater rises, confirming the importance of water-table variation in stability assessment. Kamal et al. (2023) demonstrated that technical slope design should be integrated with community risk perception when selecting landslide countermeasures.

Rainfall-induced failure is particularly relevant to Western Ghats and Konkan-type terrain. Paul et al. (2025) found that high rainfall intensity can rapidly reduce suction and factor of safety near the slope surface and toe. Raghuram and Basha (2023) applied a reliability-based framework to a Konkan Railway slope and showed that rainfall intensity, soil-water behaviour and spatial variability strongly influence probability of failure. Similar numerical studies by Bhardwaj and Shrivastava (2022), Sharipov et al. (2023) and Amin et al. (2022) confirm that pore-pressure build-up and saturation reduce shear strength and may lower slope safety below acceptable limits.

Arumugam et al. (2023) developed GIS-based landslide susceptibility mapping using the weighted overlay method in Wayanad, Western Ghats, showing that slope, rainfall, LULC and drainage significantly influence landslide-prone zones. Shukla et al. (2025) highlighted the value of geogrid reinforcement and software-based analysis for identifying vulnerable slope sections. The reviewed literature supports the present study's integrated GIS-numerical approach for high-rainfall terrain. Gopinath et al. (2024) applied fuzzy-AHP based landslide susceptibility modelling in the humid Western Ghats and demonstrated that multi-criteria GIS analysis improves identification of vulnerable slopes under intense rainfall conditions. Lokesh et al. (2025) used machine learning and deep learning with geospatial parameters for landslide susceptibility mapping in Wayanad, proving that advanced models improve prediction accuracy in rainfall-affected hilly regions. Kumar et al. (2021) performed geotechnical investigation and numerical analysis of slope failure in Kolli Hills, highlighting the importance of soil properties, slope geometry and stability assessment for landslide vulnerability evaluation. Meena et al. (2021) mapped rainfall-triggered landslides in the Western Ghats using satellite imagery and deep learning, showing that remote sensing supports rapid landslide inventory preparation and hazard mitigation planning.

5. Research Gap

Existing research often examines rainfall effects, slope geometry, soil nailing, geogrids or retaining structures separately. Many studies are also site-specific to Himalayan, canal, reservoir or roadway slopes. Limited work integrates land use-land cover, rainfall distribution, slope roughness, pore-pressure loading and stress-based factor-of-safety estimation within a single applied framework for the Konkan region. The corrected paper therefore focuses on an integrated approach suitable for lateritic and basaltic coastal hill terrain affected by intense monsoon rainfall and infrastructure development.

6. Methodology

Research Design and Approach

The study adopts a quantitative, analytical, and simulation-based research design to assess slope stability and landslide susceptibility in the Konkan region. Field investigations and laboratory tests provide geotechnical and hydrological parameters, while numerical simulations using ANSYS and QGIS evaluate slope behavior under natural and engineered conditions. This integrated approach ensures realistic representation of rainfall-induced landslides, lateritic–basaltic geology, and topographic variability. The methodology enables testing of mitigation strategies such as soil nailing, drainage improvement, and slope reinforcement, ensuring region-specific applicability and practical insights for monsoon-triggered instability scenarios.

Field Investigation and Data Collection

Critical data for numerical modelling were collected through extensive fieldwork in landslide-prone zones. Slope geometry was mapped using total station surveys, differential GPS, and Google Earth elevation profiles to capture height, inclination, and crest-to-toe irregularities. Disturbed and undisturbed soil samples were collected at multiple depths for Standard Penetration Tests, field density, and moisture content measurements. Groundwater locations, seepage points, and drainage blockages were recorded using manual standpipes and automated piezometers. Historical rainfall data spanning 15–20 years from IMD were analyzed to simulate worst-case monsoon conditions. These comprehensive datasets form the foundation for accurate geotechnical and hydrological modelling.

Laboratory Testing and Soil Characterization

Collected soil samples were tested according to IS 2720 standards to determine critical properties, including bulk and dry unit weight, grain size distribution, plastic and liquid limits, and shear strength via Direct Shear and UU Triaxial Tests. Laboratory results quantified the mechanical behavior of lateritic, colluvial, and basaltic soils under varying moisture conditions. Water-related parameters such as pore-water pressure, capillary suction, hydraulic gradient, and permeability were measured to evaluate groundwater influence and seepage effects on slope stability. These data are essential inputs for ANSYS models, providing the basis for accurate simulation of Factor of Safety and failure mechanisms.

Numerical Modelling and Simulation

Slope stability was modelled using ANSYS, integrating field and laboratory data. True slope geometry, including benches and cut-slope features, was recreated, and soil layers were assigned their respective geotechnical properties. Boundary conditions simulated water table levels, seepage faces, rainfall infiltration, and no-flow conditions at bedrock. The Morgenstern–Price limit equilibrium method was selected to analyze multiple potential slip surfaces. A refined discretization mesh was applied near critical zones to capture stress, pore pressure, and deformation variations. Outputs included Factor of Safety, critical failure surfaces, shear stress distribution, and total head, providing a robust assessment of slope stability.

Mitigation Measures Evaluation

The study assessed the performance of engineering interventions such as surface and subsurface drainage, soil nailing, geogrid reinforcement, gabion walls, and retaining structures. Separate numerical models simulated each strategy to determine improvements in Factor of Safety and stress distribution. Surface drains and lined channels reduced infiltration, while horizontal drains lowered groundwater levels. Soil nailing and geogrids enhanced shear resistance, and retaining walls stabilized steep cuts. Comparative analysis with baseline slopes allowed quantification of stabilization efficiency, demonstrating how integrated mitigation measures can effectively reduce landslide risks in Konkan's monsoon-prone terrain.

Sensitivity Analysis and Validation

To understand slope response under variable conditions, sensitivity analyses were conducted by altering cohesion, friction angle, groundwater depth, rainfall infiltration, and unit weight. Model validation involved comparing simulated results with historical landslide events, observed slope distress indicators (tension cracks, displaced soil, seepage), and published studies. This process ensured that numerical predictions, including critical slip surfaces and Factor of Safety values, realistically reflected field conditions. Validated models support the practical application of mitigation measures, providing confidence in slope stabilization recommendations and enabling safe infrastructure planning in high-risk areas of the Konkan region.

6.1 Study Area

The study area covers the Konkan region of Maharashtra, with particular relevance to landslide-prone districts and locations such as Ratnagiri, Raigad, Chiplun, Mahad, Khed, Poladpur and Sindhudurg. The terrain contains lateritic plateaus, weathered basalt, colluvial deposits, steep slopes, road cuts and high-drainage-density zones. These features increase susceptibility to shallow landslides, debris flows, rock falls and localised slope deformation during monsoon rainfall.

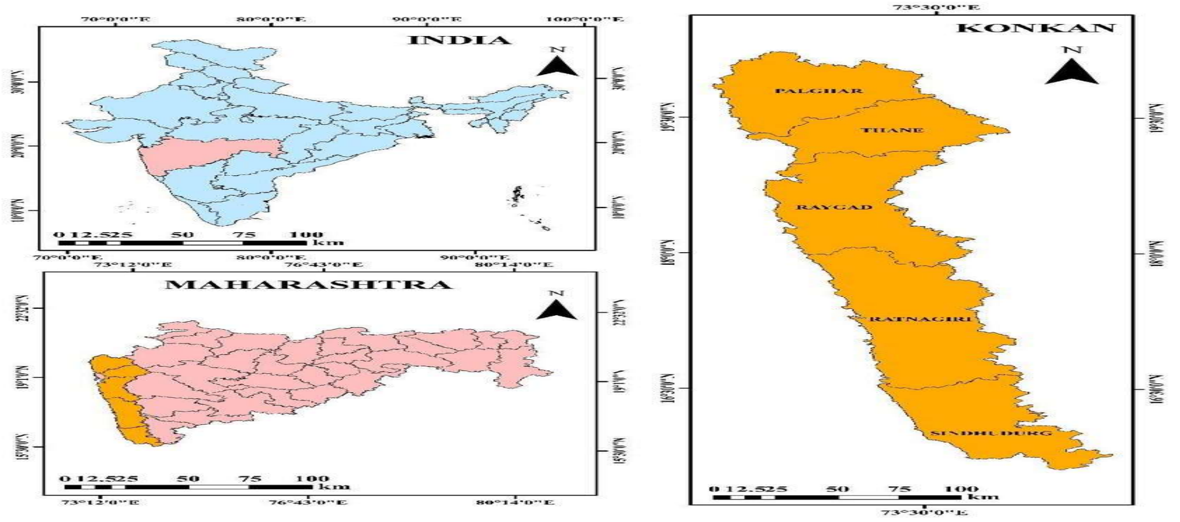


Figure 2: Kokan Region Map

6.2 Data and Parameters

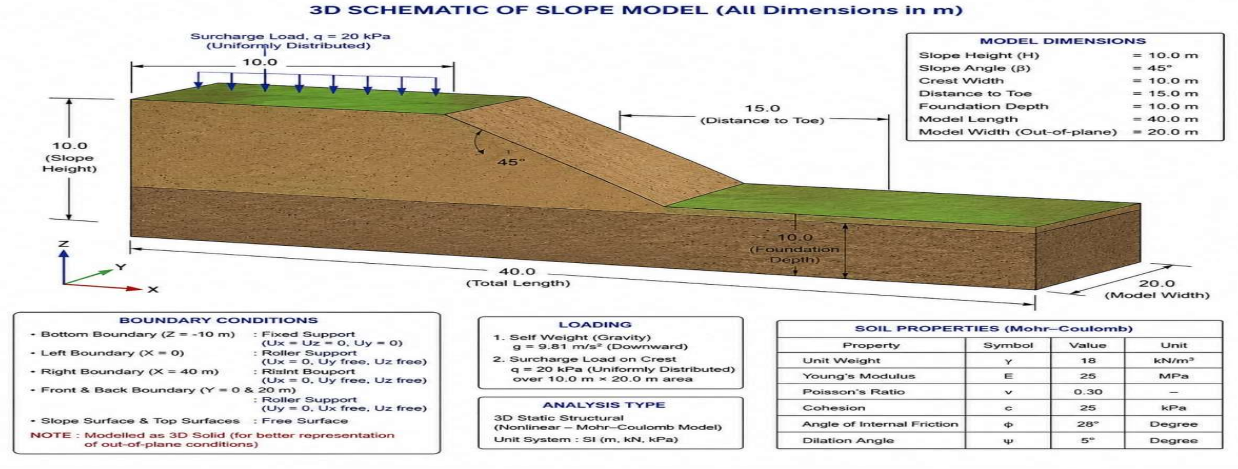
The modelling framework considered slope geometry, terrain condition, land use, rainfall class, pore-water pressure, total deformation, shear stress, normal stress and equivalent von-Mises stress. Hydrological behaviour was interpreted through water-table rise, seepage, hydraulic gradient, permeability and effective stress. The relation $\sigma' = \sigma - u$ was used as the basic theoretical link between pore pressure and reduction in shear strength.

Table 1. Hydrological and geotechnical concepts used for factor-of-safety interpretation.

Parameter / Concept	Role in this study	Relevance to FoS
Water-table depth	Defines saturated and unsaturated zones in the slope model.	A rising water table increases pore pressure and reduces FoS.
Pore-water pressure, u	Used to interpret ANSYS pressure loading and stress results.	Higher u reduces effective stress and shear strength.
Capillary suction	Explains temporary apparent stability in fine-grained unsaturated soil.	Loss of suction during rainfall reduces FoS.
Perched water table	Represents local water accumulation above low-permeability layers.	Creates local weak zones and non-linear pressure distribution.
Hydraulic gradient, i	Defines seepage direction and intensity.	High gradient increases seepage force and failure risk.
Permeability, k	Controls infiltration, drainage and pore-pressure dissipation.	Poor drainage causes prolonged low FoS during monsoon.
Effective stress, sigma prime	Connects total stress and pore pressure with soil strength.	FoS decreases as effective stress decreases.

6.3 Numerical Model

The representative ANSYS slope model used a 10 m slope height, 45° slope angle, 10 m crest width, 15 m distance to toe, 10 m foundation depth, 40 m model length and 20 m out-of-plane width. A surcharge of 20 kPa was applied at the crest. Soil behaviour was represented using Mohr-Coulomb parameters including unit weight of 18 kN/m³, Young's modulus of 25 MPa, Poisson's ratio of 0.30, cohesion of 25 kPa, friction angle of 28° and dilation angle of 5°. Boundary conditions restrained the base and controlled lateral movement to represent a stable foundation and realistic out-of-plane behaviour.



MODEL DIMENSIONS
Slope Height (H) = 10.0 m
Slope Angle (β) = 45°
Crest Width = 10.0 m
Distance to Toe = 15.0 m
Foundation Depth = 10.0 m
Model Length = 40.0 m
Model Width (Out-of-plane) = 20.0 m

BOUNDARY CONDITIONS
- Bottom Boundary (Z = -10 m) : Fixed Support (Ux = Uz = 0, Uy = 0)
- Left Boundary (X = 0) : Roller Support (Ux = 0, Uy free, Uz free)
- Right Boundary (X = 40 m) : Risint Bouport (Ux = 0, Uy free, Uz free)
- Front & Back Boundary (Y = 0 & 20 m) : Roller Support (Uy = 0, Ux free, Uz free)
- Slope Surface & Top Surfaces : Free Surface

NOTE : Modelled as 3D Solid (for better representation of out-of-plane conditions)

LOADING
1. Self Weight (Gravity) $g = 9.81\ m/s^2$ (Downward)
2. Surcharge Load on Crest q = 20 kPa (Uniformly Distributed) over 10.0 m × 20.0 m area

ANALYSIS TYPE
3D Static Structural
(Nonlinear – Mohr–Coulomb Model)
Unit System : SI (m, kN, kPa)

SOIL PROPERTIES (Mohr–Coulomb)

Property	Symbol	Value	Unit
Unit Weight	γ	18	kN/m³
Young's Modulus	E	25	MPa
Poisson's Ratio	ν	0.30	–
Cohesion	c	25	kPa
Angle of Internal Friction	φ	28°	Degree
Dilation Angle	ψ	5°	Degree

Figure 3. Schematic geometry, loading and soil properties of the representative slope model.

7. Results and Discussion

7.1 Land Use and Land Cover

The land use-land cover assessment indicates that forest/tree cover increased from 33.68% in 2017 to 38.60% in 2025. Built-up area increased from 1.82% to 2.48%, suggesting localised anthropogenic pressure along transport and settlement corridors. Crops/vegetation fluctuated over the study period, while rangeland/open land reduced overall from 31.88% to 25.03%. These changes influence runoff generation, infiltration pathways, erosion potential and slope exposure. While forest-cover increase is generally favourable for root reinforcement and erosion control, expansion of built-up pockets can still create local slope distress where drainage and excavation are not properly managed.

Table 2. Land use-land cover change in the Konkan region from 2017 to 2025.

Class	2017 Area (km²)	2017 (%)	2021 Area (km²)	2021 (%)	2025 Area (km²)	2025 (%)
Water bodies	110.81	1.35	105.06	1.28	187.14	2.28
Trees / forest cover	2764.45	33.68	2931.08	35.71	3168.29	38.60
Crops / vegetation	2566.64	31.27	3189.63	38.86	2594.55	31.61
Built-up area	149.39	1.82	201.10	2.45	203.56	2.48
Rangeland / open land	2616.71	31.88	1781.14	21.70	2054.46	25.03
Total	8208.00	100.00	8208.00	100.00	8208.00	100.00

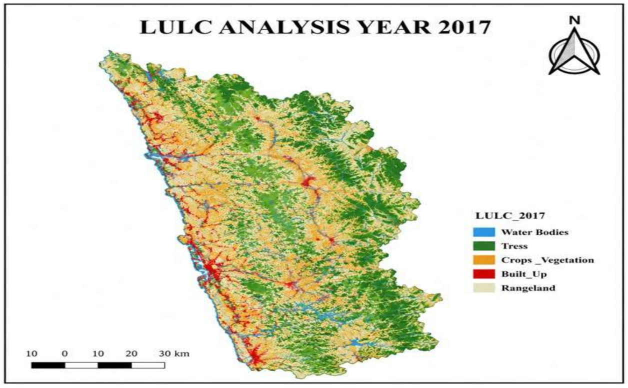


Figure 4. Land Use and Land Cover (LULC) Analysis Map of Konkan Region, 2017

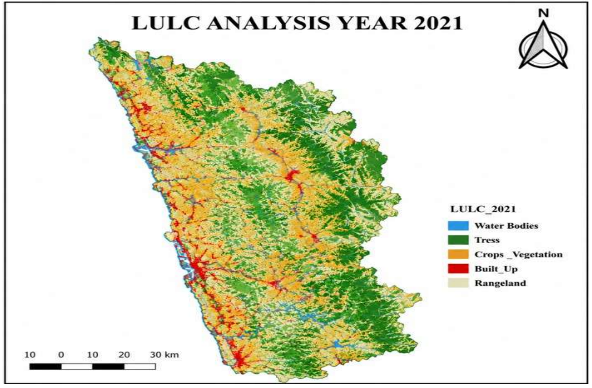


Figure 5: Land Use and Land Cover (LULC) Analysis Map of Konkan Region, 2021

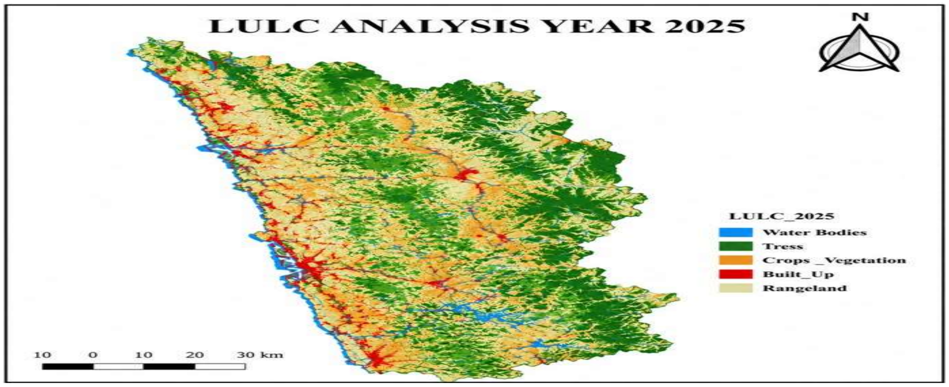


Figure 6. Land Use and Land Cover (LULC) Analysis Map of Konkan Region, 2025

7.2 Rainfall Distribution and Landslide Susceptibility

Rainfall distribution is a major control on landslide susceptibility in the Konkan region. The rainfall class of 3000-3500 mm increased from 975.26 km² in 2017 to 1746.59 km² in 2025, representing an increase of 771.33 km². The 2100-2600 mm rainfall class also increased by 402.07 km². These shifts indicate that larger areas are exposed to high rainfall conditions capable of increasing infiltration, runoff, pore-water pressure and erosion. The reduction in the 2600-3000 mm class suggests redistribution of rainfall intensity rather than uniform decline. High rainfall zones, when combined with steep slope angles and rough terrain, should be treated as priority zones for drainage design and monitoring.

Table 3. Rainfall class-wise area change in Ratnagiri District from 2017 to 2025.

Rainfall class (mm)	2017 Area (km²)	2021 Area (km²)	2025 Area (km²)	Change 2017-2025 (km²)
1200-1700	1723.82	1338.74	1346.64	-377.18
1700-2100	1804.55	2106.04	1797.54	-7.01
2100-2600	1621.20	1335.28	2023.27	+402.07
2600-3000	2083.17	1533.50	1293.97	-789.20
3000-3500	975.26	1894.44	1746.59	+771.33
Total	8208.00	8208.00	8208.00	

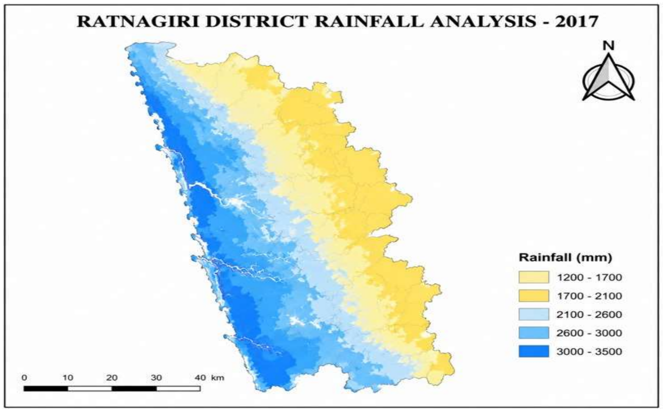


Figure 7. Rainfall Distribution Analysis Map of Ratnagiri District, 2017

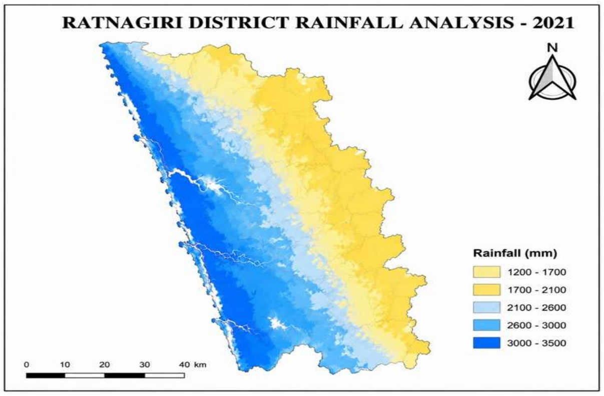


Figure 8. Rainfall Distribution Analysis Map of Ratnagiri District, 2021

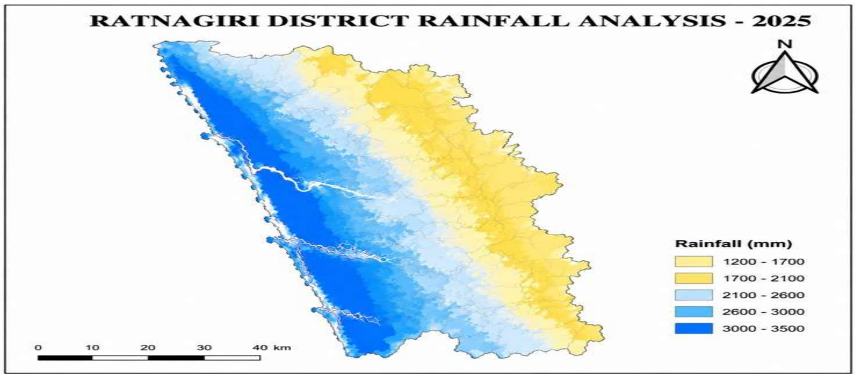
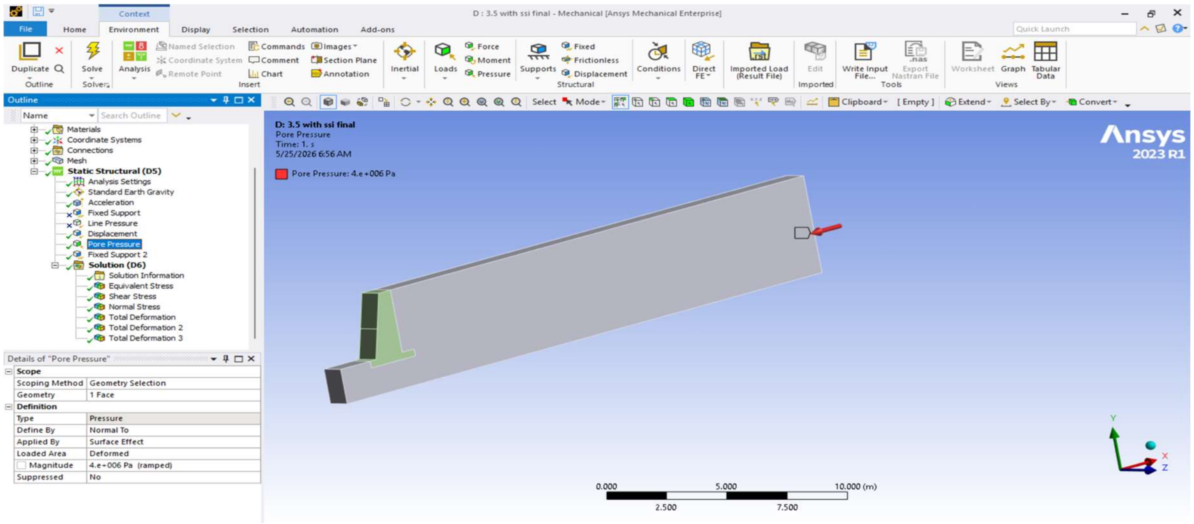


Figure 9. Rainfall Distribution Analysis Map of Ratnagiri District, 2025

7.3 GIS Based Modelling and ANSYS Factor of Safety Evaluation



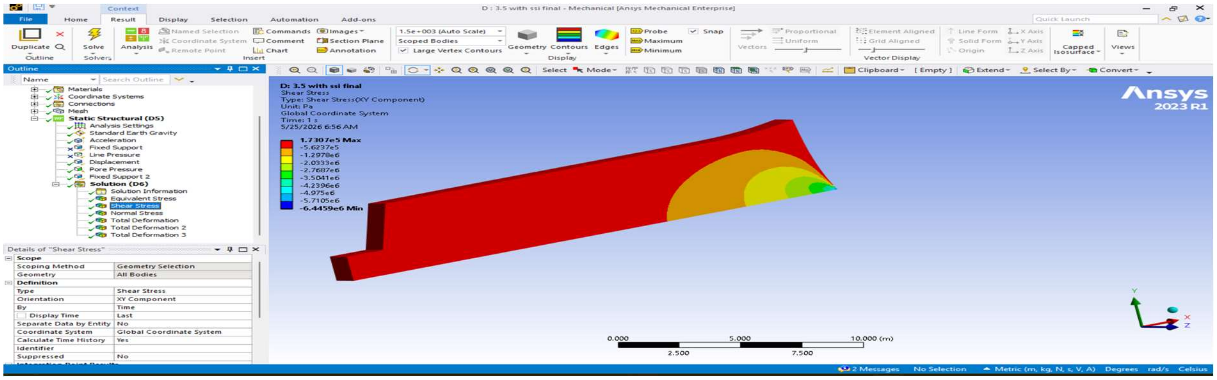
D: 3.5 with ssi final
Pore Pressure
Time: 1. s
5/25/2026 6:56 AM

🟥 Pore Pressure: 4.e+006 Pa

Details of "Pore Pressure"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Pressure
Define By	Normal To
Applied By	Surface Effect
Loaded Area	Deformed
☐ Magnitude	4.e+006 Pa (ramped)
Suppressed	No

Figure 10. Applied pore pressure boundary condition in ANSYS model

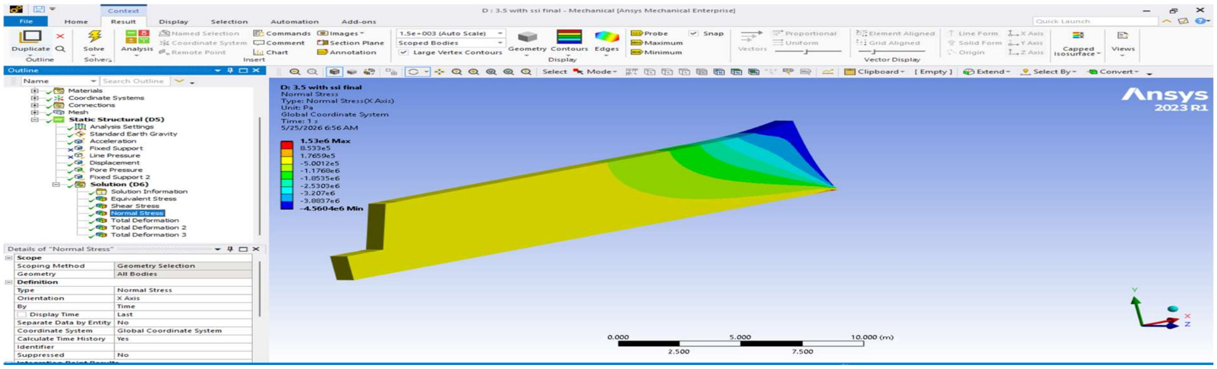


D: 3.5 with ssi final
Shear Stress
Type: Shear Stress(XY Component)
Unit: Pa
Global Coordinate System
Time: 1 s
5/25/2026 6:56 AM

Details of "Shear Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Shear Stress
Orientation	XY Component
By	Time
☐ Display Time	Last
Separate Data by Entity	No
Coordinate System	Global Coordinate System
Calculate Time History	Yes
Identifier	
Suppressed	No

Figure 11. Shear stress distribution in selected slope section



D: 3.5 with ssi final
Normal Stress
Type: Normal Stress(X Axis)
Unit: Pa
Global Coordinate System
Time: 1 s
5/25/2026 6:56 AM

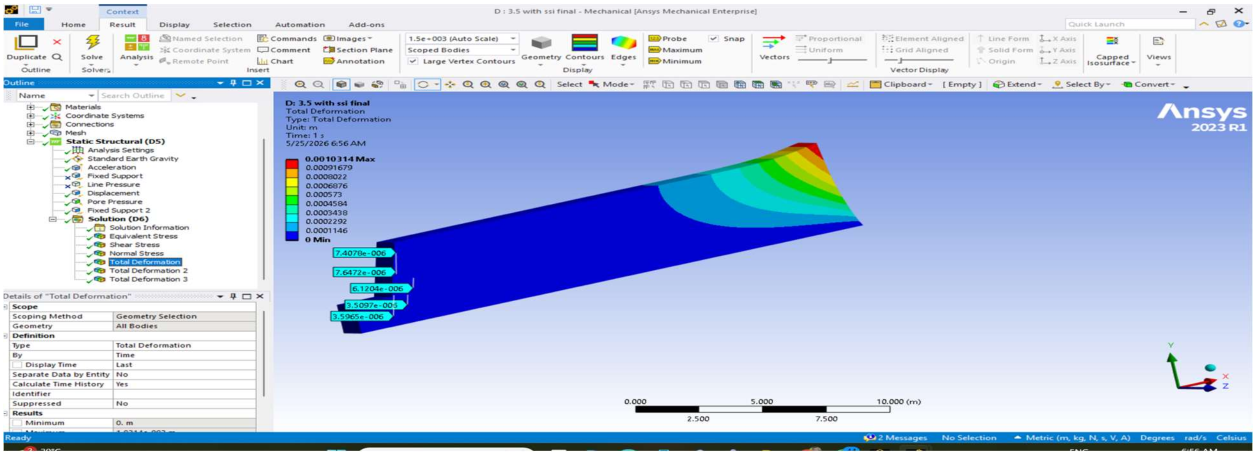
Details of "Normal Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Normal Stress
Orientation	X Axis
By	Time
☐ Display Time	Last
Separate Data by Entity	No
Coordinate System	Global Coordinate System
Calculate Time History	Yes
Identifier	
Suppressed	No

Figure 12. Normal stress distribution in selected slope section

7.3 ANSYS Deformation and Stress Output

The ANSYS model was analysed under an applied pore pressure of 4.0 MPa to represent a severe saturated condition associated with seepage or intense rainfall infiltration. The maximum total deformation was 0.0010314 m, equivalent to 1.0314 mm. Deformation was concentrated near the unsupported or free end of the model, indicating that this region is the most sensitive location for displacement development. The maximum equivalent von-Mises stress was 21.382 MPa, concentrated near the loaded or free end, while the maximum shear stress was 0.173 MPa. The normal stress range showed both compression and local tension, confirming a combined stress state under pore-pressure action.

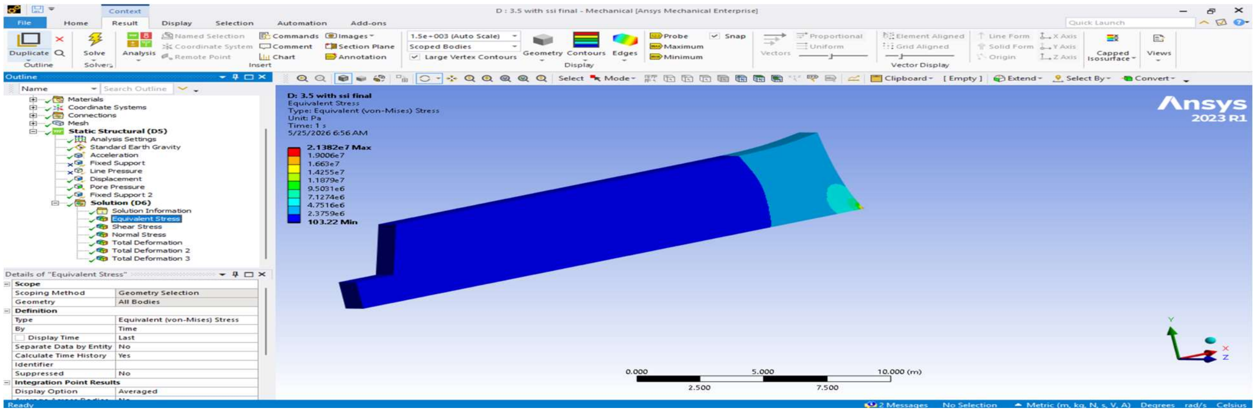


D: 3.5 with ssi final
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
5/25/2026 6:56 AM

Details of "Total Deformation"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
☐ Display Time	Last
Separate Data by Entity	No
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
☐ Minimum	0. m

Figure 13. Total deformation result for the selected ANSYS slope section.



D: 3.5 with ssi final
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1 s
5/25/2026 6:56 AM

Details of "Equivalent Stress"

Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Stress
By	Time
☐ Display Time	Last
Separate Data by Entity	No
Calculate Time History	Yes
Identifier	
Suppressed	No
Integration Point Results	
Display Option	Averaged

Figure 14. Equivalent von-Mises stress result for the selected ANSYS slope section.

Table 4. ANSYS output summary used for factor-of-safety calculation.

Output parameter	Value	Engineering interpretation
Applied pore pressure	4.0 MPa	Represents critical saturated condition due to seepage/rainfall infiltration.
Maximum total deformation	0.0010314 m (1.0314 mm)	Small deformation concentrated near the unsupported/free end.
Maximum equivalent stress	2.1382 × 10^7 Pa (21.382 MPa)	Peak stress concentrated near the loaded/free end of the model.
Maximum shear stress	1.7307 × 10^5 Pa (0.173 MPa)	Relevant for sliding checks even though lower than equivalent stress.
Normal stress range	-4.5504 × 10^6 Pa to 1.53 × 10^6 Pa	Indicates combined compression/tension response.

7.4 Factor of Safety Calculation

A stress-based factor-of-safety estimate was calculated by comparing the adopted limiting strength with the maximum equivalent stress obtained from the ANSYS output. The adopted limiting strength was 30 MPa and the maximum equivalent stress was 21.382 MPa. Therefore, FoS = 30.000 / 21.382 = 1.40. This value is slightly lower than the commonly preferred long-term static safety target of 1.50. The slope component is therefore interpreted as critical or marginally stable under the applied pore-pressure condition. Engineering intervention is required to increase the safety margin, particularly before or during monsoon periods.

Table 5. Stress-based factor-of-safety calculation.

Item	Value	Unit
Maximum equivalent stress from ANSYS output	2.1382 × 10^7	Pa
Maximum equivalent stress	21.382	MPa
Adopted limiting strength	30.000	MPa
Calculated factor of safety	1.40	-
Safety status	Critical / marginally stable	-

7.5 Pore Pressure Sensitivity

Pore-water pressure has a direct influence on stability because it reduces effective stress and shear resistance along potential failure surfaces. The sensitivity interpretation shows a continuous reduction in factor of safety from 1.80 at 0 MPa pore pressure to 1.40 at 4.0 MPa. The slope remains safe at low pore pressure, becomes marginally safe at intermediate pressure and reaches a critical condition at the highest applied pressure. This confirms that drainage improvement is not optional; it is one of the most important mitigation requirements for Konkan slopes.

Table 6. Pore pressure versus estimated factor of safety.

Pore pressure (MPa)	Estimated FoS	Safety interpretation
0.0	1.80	Safe
1.0	1.70	Safe
2.0	1.58	Marginally safe
3.0	1.49	Marginally safe
4.0	1.40	Critical but stable

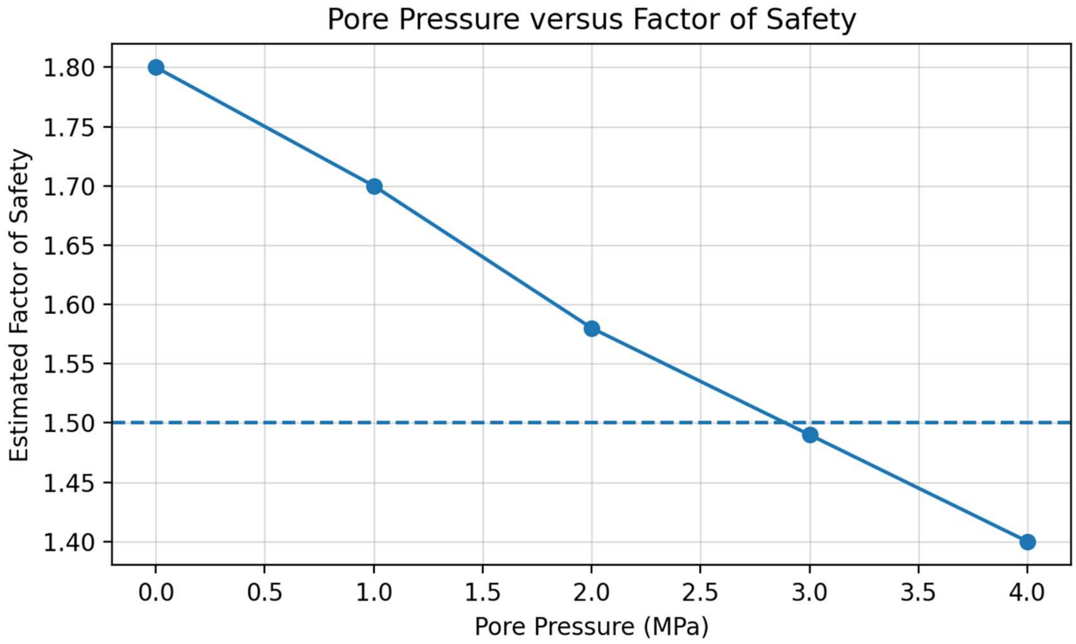


Figure 15. Relationship between pore pressure and estimated factor of safety.

8.

Conclusion

The corrected research paper confirms that landslide susceptibility in the Konkan region is governed by the combined influence of steep terrain, lateritic soil, weathered basalt, colluvial deposits, high rainfall, seepage and anthropogenic slope modification. GIS-based interpretation shows that land use, rainfall class, slope angle and roughness are important indicators for regional susceptibility mapping. The rainfall assessment highlights a substantial increase in the 3000-3500 mm rainfall class from 2017 to 2025, which increases the possibility of pore-pressure build-up and rainfall-triggered failure. The ANSYS analysis under 4.0 MPa pore pressure produced maximum deformation of 1.0314 mm and maximum equivalent stress of 21.382 MPa. The calculated factor of safety was 1.40, indicating a critical or marginally stable condition under severe saturation. Sensitivity analysis further showed that the factor of safety decreases progressively as pore pressure increases. Therefore, drainage improvement, soil nailing, geogrid reinforcement, retaining/toe support, erosion control and vegetation restoration are recommended as an integrated mitigation strategy. The study provides a practical engineering framework for identifying unstable slopes and improving landslide resilience in high-rainfall Konkan terrain.

9. Future Scope

Future work should include detailed field instrumentation using piezometers, inclinometers and rainfall gauges to monitor real-time slope response. Additional laboratory tests such as consolidated drained/undrained triaxial testing, permeability testing and soil-water characteristic curve estimation should be performed for more accurate modelling. The GIS model can be improved by adding historical landslide inventory, drainage density, lineament density, road-cut data and vegetation index. Advanced rainfall infiltration analysis and transient seepage modelling should be carried out for different monsoon return periods. Finally, the performance of soil nailing, geogrids, gabion walls and bioengineering should be compared through cost-benefit and environmental-impact assessment for practical implementation.

References

1. Amin, M. N., Ashfaq, M. U., Mujtaba, H., Ehsan, S., Khan, K., & Faraz, M. I. (2022). Computer-aided slope stability analysis of a landslide: A case study of Jhika Gali landslide in Pakistan. Sustainability, 14(20), 12954.
2. Bhardwaj, A., & Shrivastava, A. K. (2022). Stability analysis of rainfall-induced landslide using numerical modelling. Proceedings of the Indian Geotechnical Conference.
3. Jhinkwan, V. S., Chore, H. S., & Kumar, A. (2024). Assessment of stability of slopes and remedial measures in Lesser Himalayan region: An overview. Indian Geotechnical Journal.
4. Kamal, A. S. M., Hossain, F., Ahmed, B., Rahman, M. Z., & Sammonds, P. (2023). Assessing the effectiveness of landslide slope stability by analysing structural mitigation measures in Cox’s Bazar, Bangladesh.
5. Kinde, M., Getahun, E., & Jothimani, M. (2024). Geotechnical and slope stability analysis in a landslide-prone area: A case study in the Sawla-Laska road sector, Southern Ethiopia.
6. Kumar, A., Rai, S. K., Khan, I., Prashanth, M., Dhar, S., & Verma, O. (2025). Slope stability and surface displacement analysis of the Kuther landslide in the Dehar Watershed, Himachal Himalaya.
7. Malik, M. K., & Karim, I. R. (2020). Seepage and slope stability analysis of Haditha Dam using GeoStudio software. IOP Conference Series: Materials Science and Engineering, 928.
8. Meng, J., Yan, E., Wu, Y., Yang, B., Miao, F., Wang, Y., & Zhan, W. (2025). Long-term stability of landslide considering the strength degradation of slip-zone soil under coupled drying-wetting cycles and loading conditions.
9. Paul, M. M., Varma, M., & Salini, U. (2025). Assessing slope stability and rainfall impact: Case study of Kormala, Muvattupuzha in the Western Ghats of Kerala, India. Indian Geotechnical Journal.
10. Raghuram, A. S. S., & Basha, B. M. (2023). Rainfall-induced probability of failure in spatially variable soil slopes and a case study of the Konkan Railway slope failure. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems.
11. Sharipov, A., Satyanaga, A., Abishev, R., Moon, S.-W., Taib, A. M., & Kim, J. (2023). Influence of slope geometry on stability of

clayey soil slopes. Geotechnical and Geological Engineering.

12. Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. Engineering Geology, 32(4), 269–277. https://doi.org/10.1016/0013-7952(92)90053-2
13. Ayalew, L., Yamagishi, H., & Ugawa, N. (2004). Landslide susceptibility mapping using GIS-based weighted linear combination, Monte Carlo simulation and logistic regression methods in a geologically active area of Japan. Geomorphology, 65(1–2), 15–31. https://doi.org/10.1016/j.geomorph.2004.06.004
14. Bui, D. T., Pradhan, B., Lofman, O., Revhaug, I., & Dick, O. B. (2012). Landslide susceptibility assessment in the Hoa Binh province of Vietnam using support vector machines and GIS. Landslides, 9(1), 79–94. https://doi.org/10.1007/s10346-011-0297-9
15. Dahal, R. K., Hasegawa, S., Nonomura, A., Yamanaka, M., Masuda, T., & Nishino, K. (2008). GIS-based weights-of-evidence modelling of rainfall-induced landslides in small catchments for landslide susceptibility mapping. Environmental Geology, 54(2), 311–324. https://doi.org/10.1007/s00254-007-0906-3
16. Kanungo, D. P., Arora, M. K., Sarkar, S., & Gupta, R. P. (2009). A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. Engineering Geology, 105(1–2), 29–42. https://doi.org/10.1016/j.enggeo.2008.11.003
17. Lee, S., & Pradhan, B. (2007). Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. Landslides, 4(1), 33–41. https://doi.org/10.1007/s10346-006-0047-y
18. Martha, T. R., Kerle, N., Jetten, V., van Westen, C. J., & Kumar, K. V. (2013). Characterising spectral, spatial and morphometric properties of landslides for semi-automatic detection using object-oriented methods. Geomorphology, 116(1–2), 24–36. https://doi.org/10.1016/j.geomorph.2009.10.004
19. Mathew, J., Jha, V. K., & Rawat, G. S. (2007). Weights-of-evidence modelling for landslide hazard zonation mapping in part of the Bhagirathi Valley, Uttarakhand, India. Landslides, 4(4), 343–355. https://doi.org/10.1007/s10346-007-0098-7
20. Nagarajan, R., Mukherjee, A., Roy, A., & Khire, M. V. (1998). Temporal remote sensing data and GIS application in landslide hazard zonation of the Nilgiri Hills, India. International Journal of Remote Sensing, 19(3), 573–585. https://doi.org/10.1080/014311698215108
21. Pourghasemi, H. R., Pradhan, B., & Gokceoglu, C. (2012). Application of fuzzy logic and analytical hierarchy process for landslide susceptibility mapping using GIS. Natural Hazards, 65(3), 1357–1381. https://doi.org/10.1007/s11069-012-0401-8
22. van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102(3–4), 112–131. https://doi.org/10.1016/j.enggeo.2008.03.010
23. Pradhan, B., Lee, S., & Buchroithner, M. F. (2010). A GIS-based back-propagation neural network model and its cross-application and validation for landslide susceptibility analyses. Computers & Geosciences, 36(2), 216–235. https://doi.org/10.1016/j.cageo.2009.10.008
24. Arumugam, T., Kinattinkara, S., Velusamy, S., Shanmugamoorthy, M., & Murugan, S. (2023). GIS based landslide susceptibility mapping and assessment using weighted overlay method in Wayanad: A part of Western Ghats, Kerala. *Urban Climate, 49*, 101508. https://doi.org/10.1016/j.uclim.2023.101508
25. Gopinath, G., Jesiya, N., Achu, A. L., Bhadran, A., & Surendran, U. P. (2024). Ensemble of fuzzy-analytical hierarchy process in landslide susceptibility modeling from a humid tropical region of Western Ghats, Southern India. *Environmental Science and Pollution Research, 31*, 41370–41387. https://doi.org/10.1007/s11356-023-27377-4
26. Lokesh, P., Madhesh, C., Mathew, A., & Shekar, P. R. (2025). Machine learning and deep learning-based landslide susceptibility mapping using geospatial techniques in Wayanad, Kerala state, India. *HydroResearch, 8*, 113–126. https://doi.org/10.1016/j.hydres.2024.10.001
27. Kumar, M., Krishnaveni, V., & Muthukumar, S. (2021). Geotechnical investigation and numerical analysis of slope failure: A case study of landslide vulnerability zone in Kolli Hills,

Tamil Nadu. *Journal of the Geological Society of India, 97*(5), 513–519. https://doi.org/10.1007/s12594-021-1717-z

28. Meena, S. R., Ghorbanzadeh, O., van Westen, C. J., Nachappa, T. G., Blaschke, T., Singh, R. P., & Sarkar, R. (2021). Rapid mapping of landslides in the Western Ghats (India) triggered by 2018 extreme monsoon rainfall using a deep learning approach. *Landslides, 18*(5), 1937–1950. https://doi.org/10.1007/s10346-020-01602-4