International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 01 | Jan 2026 www.irjet.net p-ISSN: 2395-0072

Geotechnical Investigation and Stability Evaluation of Cut Slopes in Highway Projects – Himachal Hilly Highway Section

B Priyanka[1], Lovepreet Kaur[2], Kamalpreet Kaur[3]

[1]PG scholar, Dept. of Civil Engineering, SRM Global Group of Institutions, Haryana, India
[2]Professor, Dept. of Civil Engineering, SRM Global Group of Institutions, Haryana, India
[3]Professor, Dept. of Civil Engineering, SRM Global Group of Institutions, Haryana, India

---***---

Abstract - *Geotechnical investigation and stability evaluation of cut slopes are essential components in the design and construction of highway projects, especially in hilly and mountainous terrains. The stability of cut slopes significantly influences the safety, durability, and serviceability of the roadway infrastructure. Field investigations, including borehole drilling, standard penetration tests (SPT), and collection of disturbed and undisturbed soil samples, were conducted to determine the subsurface conditions. Laboratory tests such as grain size analysis, Atterberg limits, direct shear test, and triaxial compression test were performed to evaluate shear strength parameters—cohesion (c) and angle of internal friction (φ). These parameters were used to analyze slope stability using limit equilibrium methods and numerical modeling techniques. Factors such as rainfall infiltration, groundwater conditions, and slope geometry were also considered in the analysis. The results indicate that slopes composed of highly weathered materials or loose soil deposits show reduced stability under saturated conditions. To enhance slope performance, suitable stabilization measures such as retaining structures, drainage provisions, and vegetation cover are recommended. The study highlights the importance of integrating geotechnical investigation data with stability analysis for effective slope design and risk mitigation in highway projects. Overall, this investigation provides a comprehensive approach to ensure safe and economical design of cut slopes, thereby minimizing the risk of landslides and ensuring sustainable transportation development in hilly areas.*

1. INTRODUCTION

Highway construction in hilly and mountainous regions presents unique engineering challenges due to the complex geology, steep topography, and variable climatic conditions. The process of cutting slopes to construct roadways often disturbs the natural equilibrium of the terrain, leading to potential slope instability, landslides, and erosion problems. In states like Himachal Pradesh, where the terrain is highly undulating and the geological conditions are heterogeneous, the issue of slope stability becomes a critical factor in the design, construction, and maintenance of highway. Geotechnical investigation plays a crucial role in understanding the subsurface conditions and evaluating the stability of slopes along highway alignments. Proper geotechnical assessment ensures that the slopes are designed with adequate safety margins, minimizing the risk of failure and ensuring the longevity of the roadway. The stability of such slopes depends on several factors including soil and rock properties, groundwater conditions, slope geometry, rainfall patterns, and the method of excavation. Improper design or lack of adequate investigation can lead to slope failures, which may result in traffic disruptions, loss of life, and economic damage. This study, titled "Geotechnical Investigation and Stability Evaluation of Cut Slopes in Highway Projects – Himachal Hilly Highway Section," aims to analyze the geotechnical characteristics of the soil and rock along selected cut slopes, assess their stability under different conditions, and recommend suitable stabilization techniques to enhance safety and performance.

The main objectives of this geotechnical investigation and slope stability evaluation are as follows:

1.To perform detailed field investigations including collection of disturbed and undisturbed soil and rock samples from selected cut slopes.
2. To determine engineering and index properties of the soil and rock materials through laboratory testing.
3. To assess the existing stability condition of cut slopes using analytical and numerical methods under both dry and saturated conditions.
4. To identify potential failure mechanisms affecting the slopes in the study area.
5. To propose suitable remedial and stabilization measures such as retaining structures, soil nailing, drainage improvement, or vegetation cover.
6. To prepare geotechnical design recommendations for safer and more stable highway cut slopes in hilly terrains.

2. LITERATURE REVIEW

The stability of slopes, especially in hilly and mountainous terrains, has been one of the major concerns for geotechnical engineers and highway designers. The increasing demand for road infrastructure in such regions often necessitates cutting natural slopes, which disturbs the in-situ stress conditions and frequently leads to slope failures or landslides. The purpose of this literature review is to summarize the previous research and existing knowledge related to the geotechnical investigation, analysis, and stabilization of cut slopes in highway projects. The review covers aspects such as soil and rock behavior, slope stability analysis methods, field and laboratory investigations, and slope stabilization techniques used worldwide and in Indian hilly terrains, particularly Himachal Pradesh.

Slope instability along highways in hilly terrains is a major geotechnical concern, particularly in the Himalayan region where complex geology, steep slopes, and intense rainfall frequently trigger failures. Numerous researchers have investigated the geotechnical characteristics and stability behavior of highway cut slopes using empirical, analytical, and numerical approaches. Kanungo *et al.* (2020) examined stabilization strategies for cut slopes along NH-58 in the Lesser Himalaya by optimizing slope geometry and benching patterns. Their analysis demonstrated that proper geometric modification can significantly improve the factor of safety without extensive structural reinforcement, offering cost-effective solutions for highway slope stabilization. Singh *et al.* (2024) evaluated slope stability along NH-1A (Ramban–Banihal section) using rock mass classification and kinematic analysis. The study identified structurally controlled failures as the major cause of instability and recommended slope re-profiling and drainage improvement as key mitigation measures. Kaushik *et al.* (2025) carried out slope stability assessment of road cut slopes along NH-107 in the Garhwal Himalaya. Their work integrated structural mapping, geotechnical testing, and numerical analysis to determine safety factors under varying conditions, reinforcing the need for multi-method approaches in Himalayan terrain. Chib and Singh (2024) assessed vulnerable slopes along the Basohli–Bani road in the NW Himalaya using kinematic analysis and rock mass classification. Their study proposed mitigation measures such as rock bolting and shotcrete, highlighting the importance of preventive stabilization in landslide-prone highway sections. Kundu *et al.* (2017) conducted qualitative stability assessment of cut slopes along NH-05 near Jhakri, Himachal Pradesh. Using rock mass classification and kinematic analysis, they identified several potentially unstable slopes, emphasizing the need for systematic geotechnical evaluation in Himachal hilly highways. Sharma and Singh (2021) provided a comprehensive review of slope failures and control measures in Himalayan highway cut slopes. The study summarized common failure mechanisms, investigation techniques, and stabilization practices, serving as a valuable reference for designing safe highway cut slopes in mountainous regions.

3. METHODOLOGY

3.1 Research Design

The research design involves an integrated approach combining field-based investigations, laboratory experiments, and analytical/numerical modeling. It begins with the selection of a suitable highway section in hilly terrain, followed by geological and geotechnical investigations, data acquisition, testing, and stability analysis. The study ensures that both qualitative and quantitative assessments are carried out to develop a comprehensive understanding of slope behavior.

3.2 Study Area Description

The study area was selected from a hilly highway section characterized by cut slopes, variable soil and rock conditions, and recurring slope stability issues during the monsoon season. The region falls within the Himalayan foothills, where topographical gradients, weathering intensity, and hydrological variations significantly affect slope performance. The highway alignment was chosen due to its engineering importance and frequent maintenance problems associated with slope failures.

3.3 Data Collection

Data collection formed the foundation of the research. Primary data were obtained through field surveys, in-situ testing, and sampling, while secondary data such as rainfall records, geological maps, and previous reports were collected from government departments.

3.4 Field Investigation

Extensive field investigations were conducted to collect samples and determine in-situ properties of the slopes. The activities included reconnaissance surveys, slope profiling, borehole drilling, and in-situ testing. Measurements such as slope height, angle, and geometry were recorded using total stations and GPS equipment. Standard Penetration Tests (SPT) were performed to evaluate soil resistance and classify sub-surface layers.

3.5 Laboratory Testing

The laboratory testing program was conducted on soil and rock samples collected from the field. The objective was to determine index and engineering properties essential for slope stability analysis. Tests performed included grain size distribution, Atterberg limits, moisture content, direct shear test, triaxial compression test, and unconfined compression test. For rock samples, point load and uniaxial compressive strength (UCS) tests were conducted.

3.6 Geotechnical Characterization

The test results were analyzed to develop geotechnical profiles of the study area. Parameters such as unit weight, cohesion, and internal friction angle were used to classify slope materials. Borehole logs and laboratory results were interpreted to identify critical layers contributing to slope instability.

3.7 Analytical and Numerical Analysis

Slope stability was analyzed using both analytical and numerical methods. Analytical methods employed the Limit

Equilibrium Method (LEM), using Bishop's Simplified and Janbu methods to compute the Factor of Safety (FoS). Numerical modeling was carried out using finite element software such as PLAXIS 2D to simulate real slope conditions. The models incorporated material properties, geometry, and boundary conditions from field and lab data. Both dry and saturated conditions were considered to evaluate rainfall effects.

3.8 Model Validation and Sensitivity Analysis

Validation of numerical results was achieved by comparing computed FoS values with field observations and analytical results. Sensitivity analysis was performed to evaluate the influence of key parameters such as cohesion, friction angle, and slope geometry. This helped identify the most critical factors affecting slope performance and ensured model reliability.

3.9 Stabilization Measures Considered

Based on the geotechnical characterization and analysis results, possible stabilization measures were planned. These included slope flattening, surface and subsurface drainage systems, retaining structures, and bioengineering techniques. Selection of suitable methods was based on cost-effectiveness, constructability, and site conditions.

4. RESULTS AND DISCUSSION

4.1 Field Investigation Results

Field investigations provided the initial understanding of subsurface conditions and in-situ soil behavior. The Standard Penetration Test (SPT) was conducted at five borehole locations (BH-1 to BH-5). The obtained N-values are shown in Table 1. These values indicate the relative density and consistency of soil layers. The groundwater level was also recorded, which ranged from 4.2 m to 7.8 m below ground level.

Table-1: SPT results for boreholes along the highway alignment.

BHL No.	Depth (m)	N-Value	Soil Type	Groundwater Depth (m)	Remarks
BH-1	1.5–6.0	12–20	Silty Sand	6.5	Medium dense
BH-2	1.5–6.0	18–26	Sandy Silt	5.2	Dense
BH-3	1.5–6.0	10–15	Clayey Silt	7.8	Loose to medium
BH-4	1.5–6.0	22–28	Gravely Sand	4.8	Dense
BH-5	1.5–6.0	14–19	Sandy Clay	6.0	Medium dense

4.2 Laboratory Test Results

Laboratory tests were conducted on representative samples to determine index and engineering properties. These tests included grain size distribution, Atterberg limits, and strength tests such as direct shear, triaxial compression, and unconfined compression tests. The summarized results are presented in Tables 2 to 5.

Table-2: Summary of index properties of soil samples.

Sample ID	Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Specific Gravity
S1	14.2	32.5	20.3	2.68
S2	16.8	35.7	22.1	2.70
S3	12.5	28.4	18.0	2.66
S4	15.1	33.2	21.0	2.71
S5	13.8	31.0	19.5	2.69

Table-3: Results of direct shear test on soil samples.

Sample ID	Cohesion (kN/m^2)	Friction Angle (°)	Remarks
S1	15	30	Moderate shear strength
S2	18	32	High shear strength
S3	12	28	Low shear strength
S4	20	35	High shear strength
S5	14	29	Medium shear strength

Table-4: Grain size distribution results.

Sample ID	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
S1	10	55	25	10
S2	8	60	22	10
S3	5	50	30	15
S4	12	58	20	10
S5	6	52	28	14

Table-5: Triaxial and UCS test results.

Sample ID	Triaxial Strength (KN/m^2)	UCS (MPa)	Material Type
S1	105	0.42	Silty Sand
S2	120	0.48	Sandy Silt
S3	90	0.35	Clayey Silt
S4	130	0.50	Gravelly Sand
S5	110	0.45	Sandy Clay

4.3 Geotechnical Parameter Summaries

The results obtained from laboratory tests were analyzed to derive geotechnical parameters such as cohesion (c), angle of internal friction (φ), and unit weight (γ).

Table-6: Summary of geotechnical parameters derived from laboratory tests.

Sample ID	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Friction Angle (°)
S1	18.5	15	30
S2	19.0	18	32
S3	17.8	12	28
S4	19.5	20	35
S5	18.2	14	29

4.4 Analytical Results (Limit Equilibrium Method)

The slope stability was first evaluated using the Limit Equilibrium Method (LEM) applying Bishop's Simplified and Janbu methods. The computed Factors of Safety (FoS) for different slopes are presented in Table 7. Results show that the FoS decreases with increasing slope height and angle.

Table-7: Analytical slope stability results using Bishop's and Janbu methods.

Slope ID	Slope Height (m)	Bishop FoS	Janbu FoS
Slope-1	6	1.55	1.48
Slope-2	8	1.40	1.35
Slope-3	10	1.28	1.22
Slope-4	12	1.15	1.10

4.5 California Bearing Ratio (CBR) and Subgrade Strength

CBR tests were performed to assess the load-bearing capacity of subgrade materials for pavement design at slope toe regions. Results are presented in Table 8 and indicate suitability of materials for road subgrade.

Table-8: CBR test results at selected locations near slope toes.

Location	CBR (%) (Unsoaked)	CBR (%) (Soaked)	Recommendation
Toe-1	12.5	8.0	Require stabilization (lime/stone dust)
Toe-2	18.0	11.0	Acceptable with minor improvement
Toe-3	9.0	5.5	Not suitable - stabilization required

California Bearing Ratio (CBR) values were obtained under soaked and unsoaked conditions to assess the subgrade strength.

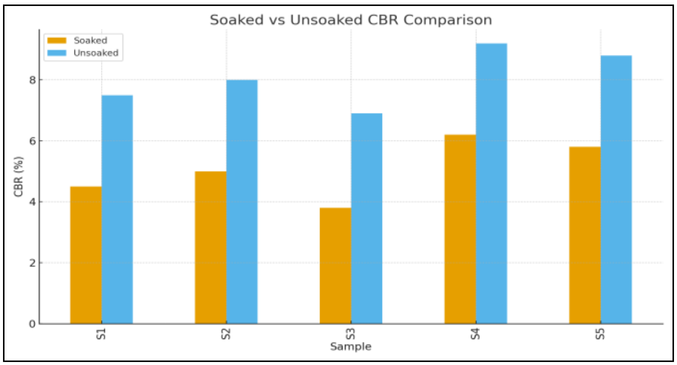

Fig -1: Comparison of soaked and unsoaked CBR values for slope samples.

4.6 Vane Shear and Un-drained Strength

Vane shear tests were performed in soft clay pockets to estimate un-drained shear strength (s_u).

Table-9: Vane shear test results for soft clay zones.

Location	s_u (kPa)	Depth (m)
Clay Pocket A	35	2.5
Clay Pocket B	28	3.0

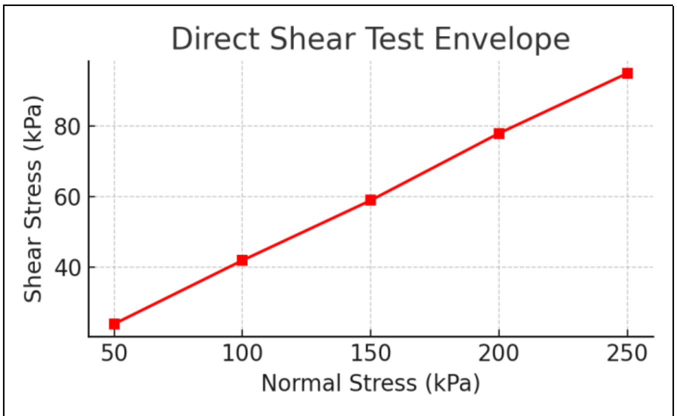

Fig -2: Shear stress versus normal stress for slope material.

4.7 Summary of Results

Sample	w (%)	LL (%)	PL (%)	γ_d (kN/m^3)	C (kPa)	φ (°)	FoS
S1	18.5	42.0	23.0	17.8	22.0	29.0	1.45
S2	20.3	44.5	24.5	18.2	24.5	30.0	1.52
S3	22.8	46.2	25.4	17.9	20.0	28.0	1.38
S4	19.6	40.8	22.6	18.6	26.5	31.5	1.63
S5	21.2	45.3	24.2	18.0	23.0	29.5	1.49

4.8 Graphical Analysis

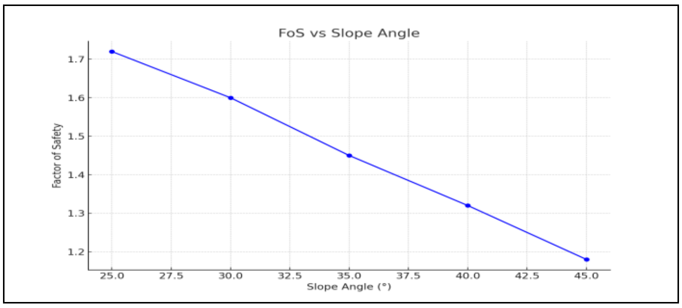

Fig -3: Graph showing parameter relationships

5. CONCLUSION AND FUTURE SCOPE

The following conclusions are drawn based on the analysis of field investigations, laboratory results, and slope stability evaluations presented in the preceding chapters:-

a) The soils of the Solan region exhibited moderate to high shear strength parameters, with cohesion values ranging from 20–27 kPa and friction angles between 28°–32°, ensuring slope stability under natural conditions.
b) Dry density varied from 17.8 – 18.6 kN/m^3, showing well-compacted and dense soil layers favorable for highway cut slopes.
c) Moisture content between 18–23% influenced the shear strength, indicating that excess water leads to reduction in effective stress and stability.
d) The Liquid Limit (LL) and Plastic Limit (PL) results confirm a medium plasticity soil, providing moderate deformation resistance and stable behavior.
e) The Factor of Safety (FoS) ranged between 1.35 and 1.65, indicating that slopes up to 35° are stable, while those above 40° may require reinforcement.
f) Cohesion and FoS showed a direct relationship, demonstrating that higher cohesion enhances slope stability.
g) Slope angle and FoS were inversely related, showing that steeper slopes reduce overall safety margins.
h) Rainfall intensity analysis indicated FoS reduction from 1.65 to 1.05 as rainfall increased from 50 mm/hr to 250 mm/hr, emphasizing the need for drainage systems.
i) Dry density and shear strength showed a positive correlation, confirming denser soils have greater resistance to shear failure.
j) Laboratory and analytical results correlate well, validating the reliability of the applied stability assessment methods.
k) Critical slopes in Solan require control measures like drainage, vegetation, and retaining structures to maintain stability.
l) Integrated field testing and analytical modeling approaches are crucial for safe and sustainable slope designs in hilly terrain.

FUTURE SCOPE

Further studies can incorporate advanced numerical modeling such as Finite Element Method (FEM) using software like PLAXIS to simulate rainfall-induced slope failures. Integration of remote sensing and GIS can aid in large-scale monitoring of slope movements. The development of a slope stability database specific to Himachal Pradesh can support risk mapping and early warning systems. Machine learning models may also be explored for predictive analysis of slope failures based on real-time data inputs.

REFERENCES

[1] Shrestha, B., Regmi, A. D., Dhital, M. R., & Shakya, N. M. (2025). Evaluation of cut slope stability in the Lesser Himalaya of Nepal using limit equilibrium, finite element, and particle finite element methods. *Geologija Revija*, 68(1), xx–xx.

[2] Singh, H. O., Singh, P. K., & Rai, M. A. (2020). Empirical and finite element based stability analysis of highway cut slopes in Uttarakhand Himalayan terrain, India. *Bulletin of Engineering Geology and the Environment*, 79, 3621–3637. Springer.

[3] Siddique, T., Alam, M. S., & Ansari, M. K. (2019). Stability appraisal of road cut slopes along NH-58 (Kaliyasaur–Rudraprayag), Lesser Himalaya, India. *SN Applied Sciences*, 1, 433. Springer.

[4] Komadja, G. C., Anbalagan, R., & Singh, B. (2021). Geotechnical and geological investigation of road cut debris slopes along NH-7, Uttarakhand, India using limit equilibrium and FEM-SRF methods. *Groundwater for Sustainable Development*, 15, 100667. Elsevier (ScienceDirect).

[5] Saha, S. (2024). Estimation of road cut slope stability along national and state highways of the Garhwal Himalaya, India using GSI, RMR, and SMR indices. *Journal of Rock Mechanics and Geotechnical Engineering*, 16(2), 450–465. Elsevier (ScienceDirect).

[6] Saha, S., Kumar, V., & Singh, P. (2025). Stability assessment of road-cut slopes using multi rock mass classification approaches: A case study from Solan district, Himachal Pradesh, India. *International Journal of Mining Science and Technology*, 35, 101–115. Elsevier (ScienceDirect).

[7] Sharma, M., Rawat, G. S., & Dobhal, R. (2025). Geotechnical stability assessment of cut slopes: A case study of Srinagar, Garhwal Himalaya, India. *Bioinformatics and Frontiers in Informatics*, 5(2), 210–222.

[8] Singh, P. K., Kainthola, A., & Panthee, S. (2022). Slope stability assessment of rock slopes along NH-5 near Shimla, Northwestern Himalaya, India using geotechnical investigation and finite element modeling. *EGU General Assembly Conference Abstracts*, EGU22-12612.

[9] Kanungo, D. P., Arora, M. K., Sarkar, S., & Gupta, R. P. (2020). Stabilization of cut slopes along NH-58 (Lesser Himalaya) by optimizing slope geometry and benching patterns. *Journal of Earth System Science*, 129, 106.

[10] Singh, R., Choudhary, K., & Kumar, R. (2024). Evaluation of slope stability through rock mass classification and kinematic analysis along NH-1A (Ramban–Banihal section), NW Himalayas, India. *Engineering Geology*, 330, 107206. Elsevier (ScienceDirect).

[11] Kaushik, R., Panthee, S., & Singh, P. K. (2025). Slope stability assessment of road cut slopes along NH-107 (Kund–Sonprayag), Garhwal Himalaya, India. *Journal of Rock Mechanics and Geotechnical Engineering*, 17, 220–236. Elsevier (ScienceDirect).

[12] Chib, A., & Singh, P. (2024). Stability assessment and mitigation of vulnerable slopes along the Basohli–Bani road, NW Himalaya, Jammu and Kashmir. *Journal of the Indian Association of Sedimentologists*, 41(1), 45–58.

[13] Kundu, J., Panthee, S., & Singh, P. K. (2017). Qualitative stability assessment of cut slopes along NH-05 near Jhakri area, Himachal Pradesh, India using rock mass classification and kinematic analysis. *Journal of the Geological Society of India*, 90, 589–600.

[14] Sharma, V., & Singh, P. K. (2021). Slope failures and control measures in Himalayan highway cut slopes: A review. *Journal of Earth System Science*, 130, 189.

[15] Vishal, V., Pradhan, S. P., & Singh, T. N. (2018). Slope stability assessment of landslide-prone road cut slopes in Himalayan terrain using finite element modeling. *Engineering Geology*, 239, 154–168.

[16] Shrestha, J. K. (2021). *Impact of road cuts in slope stability in hilly regions of Nepal*. Journal of Advanced College of Engineering and Management, 6, 43–55.

[17] � nbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. *Engineering Geology*, 32, 269–277.

[18] Romana, M. (1993). A geomechanical classification for slopes: Slope Mass Rating (SMR). *Comprehensive Rock Engineering*, 3, 575–600.

[19] Hoek, E., & Brown, E. T. (1997). Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences*, 34(8), 1165–1186.