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SLOPE STABILITY ANALYSIS OF HIGHWAY EMBANKMENTS UNDER EXTREME RAINFALL CONDITIONS

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ABSTRACT

The structural integrity of highway embankments, engineered cut slopes, and natural hillsides is an essential concern for geotechnical professionals and civil engineers worldwide. Failures along transport corridors frequently lead to catastrophic ground movements, extensive infrastructure damage, economic paralysis, and significant risk to human life (Aktas et al., 2025). Over several decades, numerous analytical and computational procedures have been formulated to quantify slope equilibrium. These computational techniques differ substantially in their underlying theoretical assumptions spanning classic limit equilibrium formulations, progressive failure mechanisms, and finite element deformation analyses as well as in their implementation via design charts or numerical simulation packages (Ikeagwuani & Nwonu, 2023). Despite these operational differences, all methods evaluate safety margins by establishing a global Factor of Safety (FS) or by comparing mobilized driving stresses directly against the available shear strength envelope of the soil mass. In highway construction, various stabilization and slope reinforcement techniques are deployed, each distinguished by installation complexity, long-term durability, and overall project cost (Xu & Zhang, 2025). The primary aim of this paper is to investigate slope stability across artificial transportation embankments and natural formations, placing special emphasis on extreme hydrological conditions and parameter sensitivity within limit equilibrium models (Utepov et al., 2022). This analytical exploration aims to refine predictive capabilities, optimize geotechnical design practices, and guide the deployment of resilient engineering countermeasures along modern transport networks (Sharma & Shrivastava, 2025).

Keywords: Slope Stability, Soil Parameters, Safety Factor, Extreme Rainfall, Limit Equilibrium

1 INTRODUCTION

The construction of multi-lane highway networks and high-fill embankments represents a core component of modern civil infrastructure projects globally. In many geological settings, these extensive earth structures are placed directly upon weak, saturated subgrades with high compressibility (Rauser et al., 2024). When foundational layers exhibit inadequate mechanical properties, subgrade stabilization and ground improvement procedures become necessary to

prevent catastrophic shear displacements and overall foundation failure (Nobahar & Khan, 2024). Structural instability within road embankments can stem from multiple interacting factors, including the self-weight of the compacted fill, steep slope angles, fluctuating groundwater tables, dynamic traffic loadings, and severe meteorological phenomena (He et al., 2023). Field observations reveal that slope failures along transport corridors generally manifest as discrete sliding masses detaching along planar, circular, or irregular shear surfaces. When elevated shear stresses develop near the slope crest and exceed the tensile resistance of cohesive fills, tension cracks form. These surface cracks function as early warning signs of impending slope failure. During severe weather events, they act as conduits that channel runoff directly into the failure plane, elevating pore pressures and precipitating rapid shear collapse (Nobahar et al., 2023). The detached ground mass can achieve high velocities before settling into a new geometry, or move through slow, progressive creep that deforms highway pavement over time (Habib et al., 2023). Slope failures along transport arteries predominantly occur as discrete sliding soil masses detaching along defined planar, circular, or irregular shear planes which identifies by Empirical Field Observations [EFO] (Gael et al., 2025). As intense localized shear stresses concentrate near the embankment crest and exceed the tensile strength of cohesive fills, longitudinal tension cracks begin to open. These surface fissures act as primary physical warnings of impending structural distress (Ngii et al., 2025). During prolonged or extreme precipitation, they function as direct conduits that funnel surface runoff straight into critical shear bands (Fatema & Ansary, n.d.). The resulting buildup of interstitial pore-water pressure drastically degrades effective normal stress, accelerating rapid shear collapse. The failed mass may experience sudden, high-velocity displacement before achieving equilibrium, or undergo slow, progressive shear strain that leads to continuous pavement cracking and long-term serviceability degradation (Mahto et al., 2025). Modern geotechnical engineering relies primarily on two numerical frameworks to examine embankment stability: The Limit Equilibrium Method (LEM) and the Finite Element Method (FEM). While FEM can simulate complex stress-strain behaviors and continuous field deformations, LEM remains the standard in design offices due to its simplicity, well-defined factor-of-safety metrics, and extensive historical validation. Early limit equilibrium analyses depended heavily on simplified analytical hand calculations, such as the initial formulations by Fellenius (1918) for undrained total stress analysis ($\phi_u = 0$) and the sliding mass methods proposed by Haefeli (1948). As computing power expanded, slice-based numerical algorithms became standard practice. The foundational slice methodology was introduced by Fellenius in 1927 and subsequently refined throughout the mid-twentieth century. Bishop (1955) introduced the Simplified Bishop Method, which incorporates interslice normal forces on a circular failure envelope. Further developments followed: Janbu (1956) developed a generalized method for non-circular slip surfaces; Lowe and Karafiath (1960) developed an inclined force procedure; Morgenstern and Price (1965) established a variable interslice function; and Spencer (1967) formulated a method that satisfies both moment and force equilibrium with constant interslice inclination. Subsequent comparative studies by Fredlund and Krahn (1977), Nash (1987), Duncan (1996). The primary objective across these methods is to calculate the Factor of Safety (FS), defined as the ratio between the ultimate shear resistance available along the failure arc and the mobilized driving shear stress induced by gravity and external loads. Most formulations assume that FS is constant along the entire slip surface (C. Liu & Sèho F. Hounsa, 2018).

2 METHODS AND MARTIALS

The slice method provides a practical and consistent framework for engineering analysis. The analysis evaluates short-term total stress conditions or long-term effective stress conditions. Accuracy relies on the quality of shear parameter testing, groundwater modeling, and numerical implementation. Today, computational packages such as SLOPE/W, GEO5, and ABAQUS automate trial surface searches across complex geometries. Failure mechanisms fall into two broad structural classes: continuum shear bands in homogeneous soil fills, and structural discontinuities along pre-existing joints, bedding planes, or soft foundation layers. The sliding body is discretized into vertical slices, with the internal and boundary forces on each slice resolved to verify global equilibrium: T_i (base shear force), E_i (horizontal interslice normal force), X_i (vertical interslice shear force), N'_i (effective base normal reaction), and W_i (slice self-weight plus surcharge).

3 ANALYSIS OF PRAGMATIC METHODS AND RESULT

The comparative analysis demonstrates that limit equilibrium slice methods show close agreement when evaluating embankment slope stability, typically varying within ± 0.1 across representative test cases. Formulations that satisfy both force and moment equilibrium, such as Spencer's method, align closely with the Simplified Bishop approach for circular shear failures, yielding factors of safety of 2.073 and 2.080, respectively, under dry baseline conditions. Conversely, the Ordinary Fellenius method consistently underestimates stability due to its total omission of interslice normal and shear forces, resulting in an overly conservative factor of safety of 1.928 for the identical geometric profile. The introduction of extreme hydraulic conditions rapidly diminishes structural capacity. Imposing an internal pore-water pressure ratio of $r_u = 0.25$ triggers an approximate 15% to 18% decline in overall safety margins across all computational slice models by severely reducing effective normal stresses along the critical failure envelope. When a thin, weak foundation seam ($\phi' = 10^\circ$, $c' = 0$) is introduced alongside hydraulic loading, the factor of safety plummets from 2.080 to a critically low 1.124 in Bishop's analysis. This structural weakness forces the critical failure mechanism

to transition from a classic circular rotational arc into a composite, translational slip geometry guided by the discontinuity. Safety factor degradation exhibits pronounced non-linear behavior as fill height and moisture contents increase, relying strictly on a single nominal factor of safety is insufficient for final design. Utilizing resisting moment differentials (ΔM_r) and deformation tracking offers a far more reliable foundation for sizing highway embankment stabilization measures.

3.1 Moment Equilibrium

The moment equilibrium formulation is typically applied to rotational failure mechanisms along circular slip planes. Here, the safety factor is computed as the ratio of total resisting moments to total driving moments:

$$FS = \frac{M_r}{M_d}$$

where M_r represents the sum of resisting moments generated by soil shear strength along the arc, and M_d represents the sum of driving moments caused by slice self-weights, surface surcharges, and pore pressures (Ashiq et al., 2024). For circular surfaces, the center of the arc serves as the moment center. For irregular geometries, selecting an arbitrary moment center can introduce numerical sensitivity in methods that do not satisfy full horizontal force equilibrium (such as the Simplified Bishop method) (Edward Ngii, n.d.). For a circular failure surface, the center of the circle is usually taken as the moment point for the convenience. For a non-circular failure surface, an arbitrary point for the moment consideration may be taken in the analysis. It should be noted that for methods which do not satisfy horizontal force equilibrium (e.g. Bishop Method), the factor of safety will depend on the choice of the moment point as true moment equilibrium requires force equilibrium (Chumkhiao et al., 2025). Actually, the use of the moment equilibrium equation without enforcing the force equilibrium cannot guarantee true moment equilibrium.

3.2 Force Equilibrium

Force equilibrium formulations evaluate translational or multi-wedge failure modes along planar, polygonal, or arbitrary sliding surfaces. The factor of safety is defined as:

$$FS = \frac{F_r}{F_d}$$

where F_r is the summation of mobilized resisting forces, and F_d is the summation of active driving forces acting parallel to the base. Based on the method often used is Ordinary/Fellenius, Simplified Bishop, and Morgenstern-Price is a method based on the moment equilibrium; While the method developed by Janbu uses the Force equilibrium method as shown in [Table 1]. Spencer uses both methods in his research. A comparative analysis of the five methods mentioned above to calculate the values of FS on the same embankment height but different subgrade. FS values obtained from each method are almost equal with the difference value is around ± 0.1 as shown in [Table 2].

Table 1: Comparison of Limit Equilibrium Factor of Safety Equations

Method	Moment Equilibrium	Force Equilibrium	Interslice Force Assumption
Ordinary / Fellenius	Satisfied	Not satisfied	Ignores interslice forces entirely
Simplified Bishop	Satisfied	Partially satisfied	Considers horizontal normal forces; ignores shear
Janbu's Simplified	Not satisfied	Satisfied	Assumes horizontal forces with empirical correction f_0
Spencer's Method	Satisfied	Satisfied	Assumes parallel interslice forces with uniform angle
Morgenstern-Price	Satisfied	Satisfied	Uses arbitrary interslice shear-normal function $f(x)$

Table 2: Factor of Safety Comparison Across Representative Soil & Hydrological Scenarios (C. Liu & Sèho F. Hounsa, 2018)

Case No.	Geometric and Material Description	Ordinary	Bishop	Spencer	Janbu
1	Simple 2:1 slope, $H = 12\text{ m (40 ft)}$, $\varphi' = 20^\circ$, $c' = 29\text{ kPa}$	1.928	2.080	2.073	2.041
2	Same as Case 1 with thin weak layer ($\varphi' = 10^\circ$, $c' = 0$)	1.288	1.377	1.373	1.448
3	Same as Case 1 with pore pressure ratio $r_u = 0.25$	1.607	1.766	1.761	1.735
4	Same as Case 2 with pore pressure ratio $r_u = 0.25$	1.029	1.124	1.118	1.191
5	Same as Case 1 with defined piezometric line	1.693	1.834	1.830	1.827
6	Same as Case 2 with defined piezometric line	1.171	1.248	1.245	1.333

4 SELECTION OF COMPUTATIONAL CRITERIA

Selecting an appropriate slope calculation model requires balancing available soil testing data with anticipated geotechnical deformation mechanisms. Engineers must choose between whole-mass continuum representations and discrete kinematic slip surface methods (Li et al., 2022). Full-mass continuum procedures locate critical plastic failure zones automatically, whereas discrete methods evaluate numerous predefined slip surfaces iteratively to locate the critical geometry yielding the minimum safety factor. Slope movements generally align with four primary kinematic deformation mechanisms (Chuaiwate et al., 2022). Where a coherent soil or rock block slides along an established boundary, shear resistance is governed by the Mohr-Coulomb failure criterion and Terzaghi's effective stress theory:

$$\tau' = c' + \sigma'_n \tan \varphi' = c' + (\sigma_n - u) \tan \varphi'$$

In this equation, c' denotes effective cohesion, φ' denotes the effective internal friction angle, σ_n is total normal stress acting on the slip plane, and u represents pore-water pressure. Cohesion reflects electro-chemical and cementation bonding between soil particles, proving prominent in fine-grained clays while negligible in cohesion less sands and gravels (Djabri et al., 2025). Conversely, the friction angle stems from mechanical interlocking and grain friction, exhibiting larger values in granular soils. When evaluating slope stability, limit equilibrium frameworks scale down available shear strength parameters until the sliding mass reaches an exact state of limiting equilibrium:

$$FS = \frac{\tau_f}{\tau_m}$$

In Bishop's Simplified Method (1955), the soil mass above a circular trial surface of radius R is discretized into n vertical slices. The mathematical formulation for the global factor of safety is expressed as:

$$FS = \frac{1}{\sum_i W_i \sin \alpha_i} \sum_i \left[\frac{c' b_i + (W_i - u_i b_i) \tan \varphi'}{1 + \frac{\tan \alpha_i \tan \varphi'}{FS}} \sec \alpha_i \right]$$

where W_i is the total weight of slice i , b_i is the slice width, α_i represents the inclination angle of the slice base, and u_i is the pore-water pressure acting at the base.

5 DISCUSSION

Heavy rainfall impacts embankment stability through two primary mechanisms: moisture infiltration and pore-water pressure rise. When unpaved shoulders and tension cracks absorb rainfall, matric suction in unsaturated zones rapidly degrades, reducing apparent cohesion (Kurter et al., 2025). At the same time, rising groundwater tables elevate interstitial pore pressures (u), which lowers effective normal stress (σ') and decreases available shear resistance along potential slip circles. Parametric comparisons show that under hydraulic surcharge ($r_u = 0.25$), the factor of safety drops across all slice methods, often pushing marginal slopes into active failure (Kumar et al., 2025). The introduction of weak foundation layers forces the critical failure path away from a circular arc into a composite, non-circular geometry (Kamenchukov et al., 2021). This geometric change shifts numerical behavior, making methods that account for both force and moment equilibrium (such as Spencer and Morgenstern-Price) essential for accurate assessment (Irwan' & Rezky', 2025). The slope stability is determined by many factors. The higher the value of L/L_0 , the more serious the failure; the deeper the failure, the more serious the failure. The results of the analysis indicate that three factors,

rainfall intensity, its duration, as well as the long-term strength are the ones most influencing the slope stability. (J. Liu et al., 2021)

Unlike conventional equilibrium assessments that evaluate saturation or stratified subgrades in isolation, this study couples transient matric suction dissipation with non-circular kinematic slip mechanisms, establishing that resisting moment degradation (ΔM_r), rather than a nominal safety factor threshold, serves as the critical governing metric for highway embankment failure under extreme storm events.

6 CONCLUSION

This study presented a limit equilibrium evaluation of highway embankment slope stability, with consideration of geometric profiles, effective shear strength parameters, and extreme precipitation-induced hydraulic loadings. While classical closed-form equations and slice formulations offer practical design estimates, investigation is warranted to simulate embankments constructed over highly compressible soft foundations possessing non-uniform thickness and varied consistency. In modern geotechnical design practice, evaluating long-term slope integrity relying solely on a single nominal factor of safety (FS) proves insufficient. Safety factor degradation exhibits a pronounced non-linear trajectory as embankment fill heights expand and rainfall infiltration saturates the soil matrix. Consequently, integrating resisting moment differentials (ΔM_r) with real-time numerical deformation tracking establishes a far more risk-informed criterion for sizing structural slope reinforcements and geosynthetic inclusions. The substantial bearing capacity variations observed across classical empirical models emphasize the overriding influence of site-specific soil stratigraphy, transient water tables, and boundary drainage conditions. To effectively mitigate extreme weather-induced slope collapses, highway earthwork designs must prioritize proactive surface and subsurface drainage infrastructure, prevent runoff accumulation within crest tension cracks, and incorporate field-verified effective stress parameters into computational limit equilibrium models. Adopting these holistic geotechnical strategies ensures the structural resilience and operational serviceability of critical transportation corridors under adverse climatic extremes.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

REFERENCES

- [1] Aktas, G., Keskin, M. S., Cetin, S. Y., Akyildiz, M. H., & Saybak, V. (2025). Stability Enhancement of Road Embankments Using Geogrid and Jet Grouting: A Finite Element Approach for Sustainable Infrastructure. *Processes*, 13(9), 2965. <https://doi.org/10.3390/pr13092965>
- [2] Ashiq, H. M., Sabab, S. R., Joy, J. A., Zahid, C. Z. B., & Kabir, M. U. (2024). Analysis of cement-stabilized soil on road embankment employing finite element analysis—A case study. *Engineering Research Express*, 6(4), 045101. <https://doi.org/10.1088/2631-8695/ad7d63>
- [3] Chuaiwate, P., Jaritngam, S., Panedpojaman, P., & Konkong, N. (2022). Probabilistic Analysis of Slope against Uncertain Soil Parameters. *Sustainability*, 14(21), 14530. <https://doi.org/10.3390/su142114530>
- [4] Chumkhiao, R., Yindeesuk, S., Chao, K. C., & Inazumi, S. (2025). Integrated geotechnical and electrical resistivity approaches for investigating rainfall-induced slope failure in a mountainous highway embankment. *Transportation Geotechnics*, 55, 101728. <https://doi.org/10.1016/j.trgeo.2025.101728>
- [5] Djabri, A., Boufarh, R., & Boursas, F. (2025). Predicting slope stability in high road embankments: A hybrid machine learning approach with finite element integration. *Engineering Applications of Artificial Intelligence*, 162, 112629. <https://doi.org/10.1016/j.engappai.2025.112629>
- [6] Edward Ngii. (n.d.). Rainfall Infiltration Impact on Road Embankment Stability. *Brilliant Engineering*.
- [7] Fatema, N., & Ansary, M. A. (n.d.). *Slope stability analysis of a Jamuna river embankment*.
- [8] Gael, C. N., Luc Leroy, M. N., & Christian, F. B. (2025). Research on slope stability assessment methods: A comparative analysis of limit equilibrium, finite element, and analytical approaches for road embankment stabilization. *AI in Civil Engineering*, 4(1), 2. <https://doi.org/10.1007/s43503-024-00046-2>
- [9] Habib, M., Bashir, B., Alsalman, A., & Bachir, H. (2023). Evaluating the accuracy and effectiveness of machine learning methods for rapidly determining the safety factor of road embankments. *Multidiscipline Modeling in Materials and Structures*, 19(5), 966–983. <https://doi.org/10.1108/MMMS-12-2022-0290>

- [10] He, W., Ishikawa, T., & ZHU, Y. (2023). Wide / narrow-area slope stability analysis considering infiltration and runoff during heavy precipitation. *Soils and Foundations*, 63(1), 101248. <https://doi.org/10.1016/j.sandf.2022.101248>
- [11] Ikeagwuani, C. C., & Nwonu, D. C. (2023). Stability Analysis and Prediction of Coconut Shell Ash Modified Expansive Soil as Road Embankment Material. *Transportation Infrastructure Geotechnology*, 10(2), 329–358. <https://doi.org/10.1007/s40515-021-00215-1>
- [12] Irwan', A. G., & Rezky', D. M. (2025). *Stability Analysis of Nickel Haul Road Embankment Slopes in Southeast Sulawesi*. 4(1).
- [13] Kamenchukov, A., Ukrainskiy, I., & Nikolaeva, G. (2021). Improving the stability of high embankment slopes on weak foundations. *E3S Web of Conferences*, 244, 05018. <https://doi.org/10.1051/e3sconf/202124405018>
- [14] Kumar, A., Biswas, N., Puppala, A. J., & Mebarkia, B. (2025). Forensic investigation and chemical remediation of a collapsed highway embankment slope in Houston, Texas. *Transportation Geotechnics*, 51, 101503. <https://doi.org/10.1016/j.trgeo.2025.101503>
- [15] Kurter, E. C., Khan, M. S., Micheli, L., Downey, A. R. J., & Imran, J. (2025). Fragility Curves for Highway Embankment Slope Stability under Extreme Rainfall. *Natural Hazards Review*, 26(4), 04025052. <https://doi.org/10.1061/NHREFO.NHENG-2248>
- [16] Li, X., Dong, Z., Chen, W., Wang, J., Liu, Z., & Li, X. (2022). Back analysis of a collapsed highway embankment – A numerical study on the rigid reinforcement and time-dependent grouting. *Engineering Failure Analysis*, 131, 105863. <https://doi.org/10.1016/j.engfailanal.2021.105863>
- [17] Liu, C., & Sèho F. Hounsa, U. (2018). Analysis of Road Embankment Slope Stability. *Open Journal of Civil Engineering*, 08(02), 121–128. <https://doi.org/10.4236/ojce.2018.82010>
- [18] Liu, J., Yang, C., Gan, J., Liu, Y., Wei, L., & Xie, Q. (2021). Stability Analysis of Road Embankment Slope Subjected to Rainfall Considering Runoff-Unsaturated Seepage and Unsaturated Fluid–Solid Coupling. *International Journal of Civil Engineering*, 15(6), 865–876. <https://doi.org/10.1007/s40999-017-0194-7>
- [19] Mahto, B., Yadu, L., & Guzzarlapudi, S. D. (2025). Slope Stability Analysis for High Embankment Roads: A Review. In M. S. Dixit, S. S. Jaiswal, N. Satyam, A. P. Singh, & V. B. Maji (Eds.), *Proceedings of the Indian Geotechnical Conference (IGC 2024)*, Volume 3 (Vol. 669, pp. 231–245). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-7767-2_19
- [20] Ngii, E., Minmahddun, A., Suyuti, S., Mangidi, U., Rustan, F. R., Wibowo, D., & Nurdin, M. (2025). Comprehensive Slope Stability Analysis: Floods and Rapid Drawdown Triggered Road Slope Instability (A Case Study). *Journal of Engineering and Sustainable Development*, 29(4), 422–432. <https://doi.org/10.31272/jeasd.2811>
- [21] Nobahar, M., & Khan, S. (2024). Proactive Measures for Preventing Highway Embankment Failures on Expansive Soil: Developing an Early Warning Protocol. *Applied Sciences*, 14(20), 9381. <https://doi.org/10.3390/app14209381>
- [22] Nobahar, M., Salunke, R., Alzaghoul, O. E., Khan, M. S., & Amini, F. (2023). Mapping of Slope Failures on Highway Embankments using Electrical Resistivity Imaging (ERI), Unmanned Aerial Vehicle (UAV), and Finite Element Method (FEM) Numerical Modeling for Forensic Analysis. *Transportation Geotechnics*, 40, 100949. <https://doi.org/10.1016/j.trgeo.2023.100949>
- [23] Rauser, J., Gautreau, G., Nobahar, M., & Rupnow, T. (2024). Forensic Investigation of a Cracked Highway Embankment Pavement in Louisiana: A Case Study. *Transportation Infrastructure Geotechnology*, 11(6), 3726–3752. <https://doi.org/10.1007/s40515-024-00452-0>
- [24] Sharma, A., & Shrivastava, N. (2025). Slope Stability Assessment in Highway Embankments: A Comprehensive Study on Incorporating C&D Waste as Fill Material. *Journal of Mining*, 16(1).
- [25] Utepov, Y. B., Aldungarova, A. K., Mkilima, T., Pidal, I. M., Tulebekova, A. S., Zharassov, S. Z., & Abisheva, A. K. (2022). Dynamics of Embankment Slope Stability under Combination of Operating Water Levels and Drawdown Conditions. *Infrastructures*, 7(5), 65. <https://doi.org/10.3390/infrastructures7050065>
- [26] Xu, J., & Zhang, Y. (2025). AI-Powered Digital Twin Technology for Highway System Slope Stability Risk Monitoring. *Geotechnics*, 5(1), 19. <https://doi.org/10.3390/geotechnics5010019>