Pokhara Engineering College Journal (PECJ)
Applied Sciences and Engineering Insights
ISSN: 3021-9795 (Print) / 3059-9628 (Online)
(Volume-3, Issue- I)

Comparative Influence of Cohesion and Friction Angle on the Stability of Dry Slopes: A Parametric Sensitivity Study of Ramche Landslide

Sanjay Baral[1*]
[1]*School of Engineering, Faculty of Science and Technology, Pokhara University, Nepal*
**Corresponding email: sanjaybaral@pu.edu.np https://orcid.org/0009-0009-8742-5821*

Received:02- February-2026; Revised: 24- February-2026; Accepted: 08- March-2026
DOI: https://doi.org/10.3126/pecj.v3i1.93540

Abstract

The reliability and safety of slope designs largely depend on accurately understanding and measuring the soil properties of slope, because small errors in estimating this parameter can significantly affect stability predictions. This study investigates the sensitivity of slope stability to variations in cohesion (c) and internal friction angle (ϕ) with respect to the Factor of Safety (FoS). The research focuses on the Ramche landslide in Rasuwa District, Nepal, representing a typical Himalayan slope condition. Six disturbed and undisturbed soil samples were collected from different locations along the slope profile during a detailed field investigation. Laboratory testing was conducted to determine key engineering properties, including cohesion, friction angle, and unit weight. Based on field measurements, slope geometry was prepared using AutoCAD and SW DTM software, and a numerical model was developed in Slide2. The soil behavior was simulated using the Mohr–Coulomb failure criterion. Slope stability was evaluated using four limit equilibrium methods: Bishop Simplified method, Janbu Simplified method, Spencer method, and Morgenstern–Price method. Sensitivity analyses, including tornado and spider plots, indicate that ϕ is the most influential parameter, producing significantly greater variation in FoS compared to cohesion. The results consistently show that slope stability is more sensitive to uncertainties in the friction angle, highlighting the importance of accurate shear strength characterization for reliable slope design and risk assessment.

Keywords: Sensitivity analysis of slope, Slide2 numerical modeling, Cohesion and friction angle, Factor of Safety

1. Introduction

Landslides represent one of the most persistent and destructive natural hazards affecting mountainous regions worldwide (Osman, 2018). In countries characterized by steep terrain, intense rainfall, and fragile geological formations, slope failures frequently disrupt communities, damage infrastructure, and hinder sustainable development. Nepal, situated in the central Himalaya, exemplifies this vulnerability. The country's dramatic topographic relief from the low-lying Terai plains to the towering peaks of the Mountain region creates sharp elevation gradients within a relatively short north south distance (Chhetri and Easterling, 2010). Such geomorphological conditions, combined with active tectonics and seasonal monsoon precipitation (Shrestha et al., 2000, Sharma et al., 2020), make slope instability a recurring and critical national concern. In this context, understanding the mechanical behavior of slopes and the parameters that govern their stability is not only an academic pursuit but also a practical necessity for engineering design and disaster risk reduction.

To appreciate the complexity of slope failures in Nepal, it is important to define several key concepts. A landslide is the downslope movement of soil, rock, and debris under the influence of gravity, often triggered by external factors such as rainfall, earthquakes, or human activity (Skilodimou et al., 2018, Ahmed, 2021, Highland and Bobrowsky, 2008). The stability of a slope is commonly evaluated using the FoS, defined as the ratio of resisting forces to driving forces. When the FoS is greater than one, the slope is considered stable; when it approaches or falls below one, failure becomes likely. The shear strength of soil, a fundamental property governing slope stability, is primarily described by two parameters derived from the Mohr Coulomb failure criterion: cohesion (c), representing the bonding between particles, and friction angle (ϕ), representing the internal resistance due to particle interlocking and friction. Variations in these parameters whether due to changes in moisture content, weathering, or stress conditions can significantly influence the FoS and, consequently, slope performance (Iverson, 2000, Medina et al., 2021, Malla and Dahal, 2021).

In Nepal, more than seventy-five percent of the annual rainfall occurs during the monsoon season, typically from June to September (Shrestha et al., 2000, Sharma et al., 2020). This intense and prolonged precipitation increases soil moisture, raises groundwater levels, and reduces effective stress within slopes (Findell and Eltahir, 1997). As pore water pressure rises, the apparent cohesion and effective friction angle may decrease, thereby reducing shear strength (Iverson, 2000, Medina et al., 2021, Malla and Dahal, 2021, Baral et al., 2025, Baral and Tiwari, 2025). Numerous studies have identified monsoon rainfall as the primary triggering mechanism for slope failures in the Himalayan region (Dahal, 2012, Gnyawali et al., 2023, Kincey et al., 2024). Furthermore, rapid infrastructure expansion such as road construction, hydropower development, and urban growth has altered natural slope geometries and drainage conditions, exacerbating instability in many areas (McAdoo et al., 2018, Paudyal et al., 2023). Although extensive research has been conducted on landslide occurrence, mapping, and rainfall thresholds in Nepal (Dahal and Hasegawa, 2008, Basnet and Acharya, 2019), a critical gap remains in site-specific geotechnical investigations that quantitatively evaluate how variations in shear strength parameters influence slope stability. Many existing studies provide regional-scale hazard assessments or focus on identifying triggering factors, yet fewer studies systematically examine the sensitivity of the FoS to changes in cohesion and friction angle at the local scale. In practice, soil parameters are inherently uncertain due to spatial variability, limited sampling, and laboratory testing constraints (Stark et al., 2008). Designers often rely on representative or conservative values without fully understanding how small deviations in these parameters may affect stability outcomes. Neglecting to analyze parameter sensitivity may produce either excessively conservative designs that drive up costs or overly optimistic assumptions that could endanger safety.

Previous analytical approaches to slope stability have predominantly employed the Limit Equilibrium Method (LEM), including Bishop’s simplified method, Fellenius’ method, and Janbu’s method (Li et al., 2019, Zhu et al., 2003). These techniques divide the slope into slices and satisfy force and moment equilibrium to compute the FoS (Zolkepli et al., 2019). LEM remains widely used due to its conceptual simplicity and computational efficiency (Aryal, 2006, Liu et al., 2015). More recently, numerical methods such as the Finite Element Method (FEM) have gained prominence relationships (Matthews et al., 2014, Hammouri et al., 2008, Salih, 2021, Griffiths and Lane, 1999). FEM-based approaches, particularly those employing the Shear Strength Reduction (SSR) technique, enable simulation of stress–strain behavior and progressive failure mechanisms (Ramadhani and Ihzan, 2023, VandenBerge and McGuire, 2019). Despite these advancements, many applications in Nepal have focused on obtaining a single FoS value under assumed parameter sets, rather than conducting comprehensive sensitivity analyses that explore the relative influence of cohesion and friction angle on slope stability.

The rationale for this study arises from the recognition that cohesion and friction angle are not fixed constants but variable properties influenced by geological conditions, weathering, saturation, and sampling uncertainty (Abramson et al., 2001). A rigorous sensitivity analysis provides insight into which parameter exerts the greatest control on the FoS and how variations within realistic ranges affect slope safety. Such understanding is essential for prioritizing field investigations, optimizing laboratory testing programs, and improving the reliability of geotechnical designs. Moreover, in data-scarce mountainous environments, identifying the most influential parameters can guide resource allocation and risk mitigation strategies.

Accordingly, the primary objective of this paper is to investigate the sensitivity of slope stability to variations in cohesion and friction angle with respect to the FoS. The study focuses on a representative Himalayan slope in Nepal, where six soil samples were collected from different locations along the Ramche slope profile. The soil mass is modeled as a single homogeneous layer to isolate the effects of shear strength parameters. The FoS is computed using Bishop Simplified method, Janbu Simplified method, Spencer method, and Morgenstern–Price method implemented in Slide 2D software. External influences such as building loads and seismic forces are not considered in order to concentrate specifically on the intrinsic material parameters. By systematically varying cohesion and friction angle within plausible ranges, the research quantifies their relative impact on FoS and identifies the parameter to which the slope is most sensitive.

2. Materials and Methods

2.1. Study area

The study area is located at the Ramche landslide in Rasuwa District, Nepal (Figure 1), along the 36-km section of the Trishuli–Dhunche road at 28.026072 N, 85.223361 E above the Trisuli River. Geologically, the site lies within the Kuncha Formation of the Lower Nawakot Group in central Nepal (Jharendra et al., 2018). These rocks are highly weathered and fractured, making the slope weak and vulnerable to failure. The Ramche landslide is classified as a debris flow type movement (Jharendra et al., 2018). It extends for more than 3 km downslope and regularly damages the road section. According to local residents, the landslide was first activated in 1983 and reactivated on 14 August 2003, causing significant loss of life and property (Ghimire et al., 2007). Since then, it has remained active, especially during the monsoon season.

High rainfall increases pore water pressure in the slope materials, reducing soil strength and triggering debris movement over the bedrock. In addition, heavy traffic vibrations along the highway further destabilize the slope (Ghimire et al., 2007, Jharendra et al., 2018). Human activities such as haphazard road cutting, unplanned settlements, and unscientific agricultural practices have increased the size and intensity of the landslide. The absence of proper geotechnical mitigation measures has further increased the vulnerability of the area. The surrounding area is densely populated and widely used for cultivation, placing local communities at high risk. The settlement near the landslide remains in serious danger due to the continued activity of the slope and the potential for further expansion during intense rainfall events.

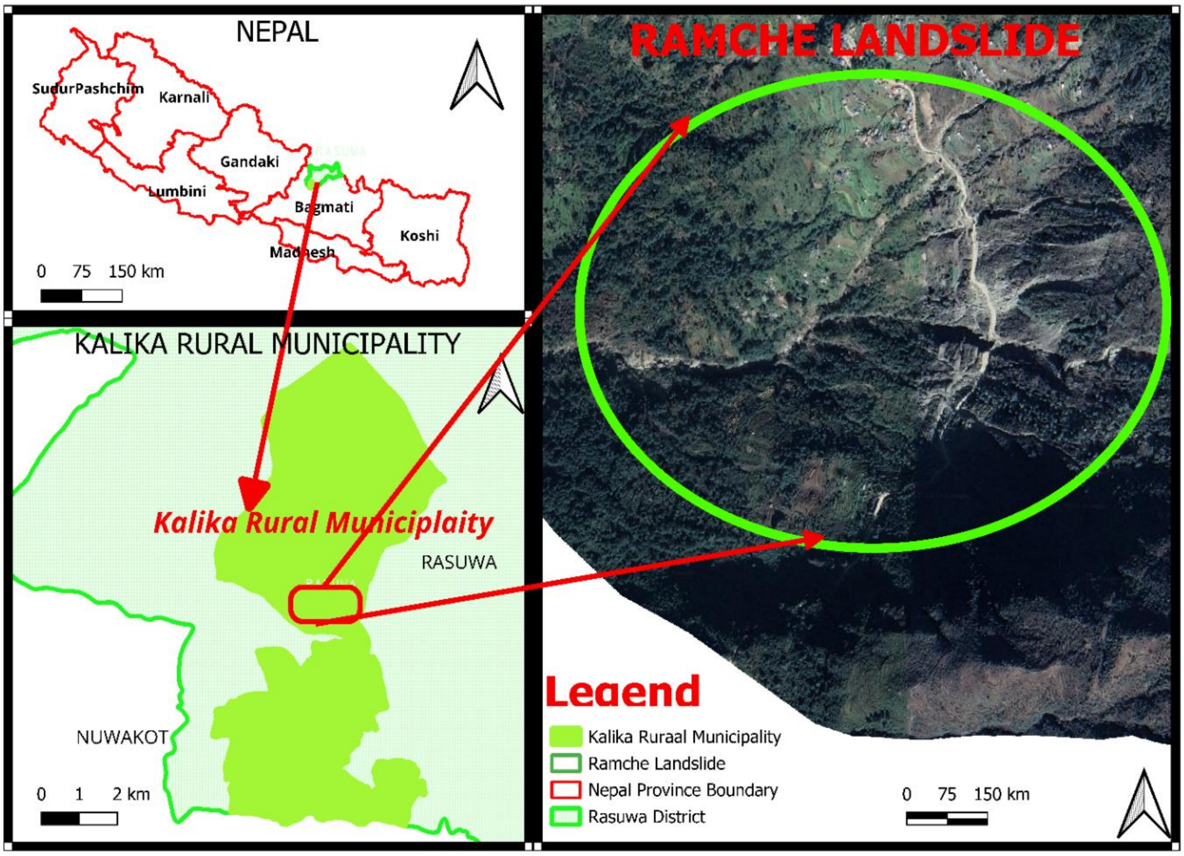


Figure 1: Study area map of Ramche Landslide, Rasuwa, Bagmati Province, Nepal

The detailed site visit was conducted to collect necessary field information. During the visit, topographic data, available reports, and soil samples were gathered. Both disturbed and undisturbed soil samples were collected from six different locations along the slope. These samples were tested in the laboratory to determine the required engineering properties, particularly cohesion (c), internal friction angle (ϕ), and unit weight.

After obtaining the laboratory results, a numerical model of the slope was developed using AutoCAD, SW DTM - Software and Slide2. The slope geometry was first defined based on field measurements in AutoCAD with the help of SW DTM - Software. Then only the model is prepared in Slide2 (Figure 2). After that, material properties obtained from laboratory testing were assigned to the model. The soil behavior was simulated using the Mohr–Coulomb failure criterion, which relates shear strength to cohesion and friction angle.

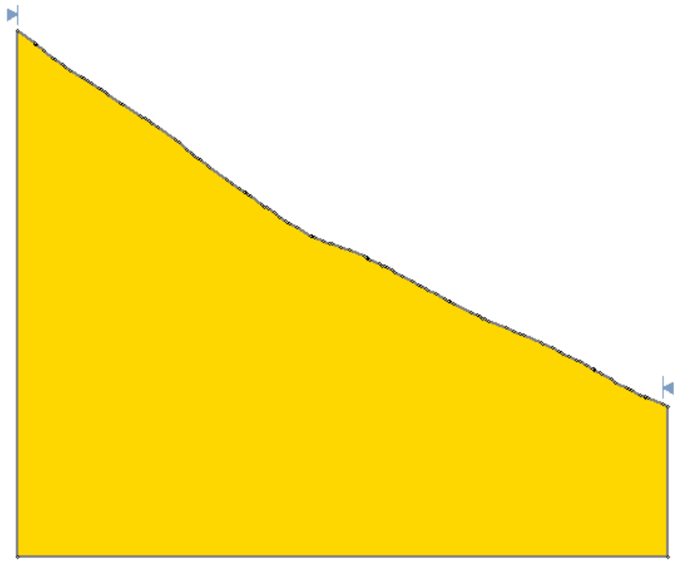


Figure 2: Model for Ramche Slope with material assignment (Slide2 model)

To ensure uniformity and reliability in the analysis, identical slope geometry was maintained for all simulation cases. Consequently, any observed variation in the FoS can be attributed solely to changes in the shear strength parameters, eliminating the influence of other modeling factors.

Slope stability was evaluated using four different limit equilibrium methods: The Bishop Simplified method, Janbu Simplified method, Spencer method, and Morgenstern–Price method. These methods were adopted to evaluate how variations in the assumptions regarding inter-slice force interactions affect the computed FoS. All analyses were performed under dry conditions. Groundwater effects, pore water pressure, surcharge loads, and seismic forces were not included. The earthquake coefficient was set to zero so that the results reflected only the effect of soil shear strength.

Finally, a parametric sensitivity analysis was conducted. Cohesion (c) and friction angle (ϕ) were varied systematically within selected ranges, while all other parameters remained constant. For each variation, the model was reanalyzed using all four methods, and the minimum global FoS was recorded. The relationship between FoS and the shear strength parameters was then established to identify which parameter had greater influence on slope stability and to compare the consistency of results among the different methods. Detail work flow is shown in Figure 3.

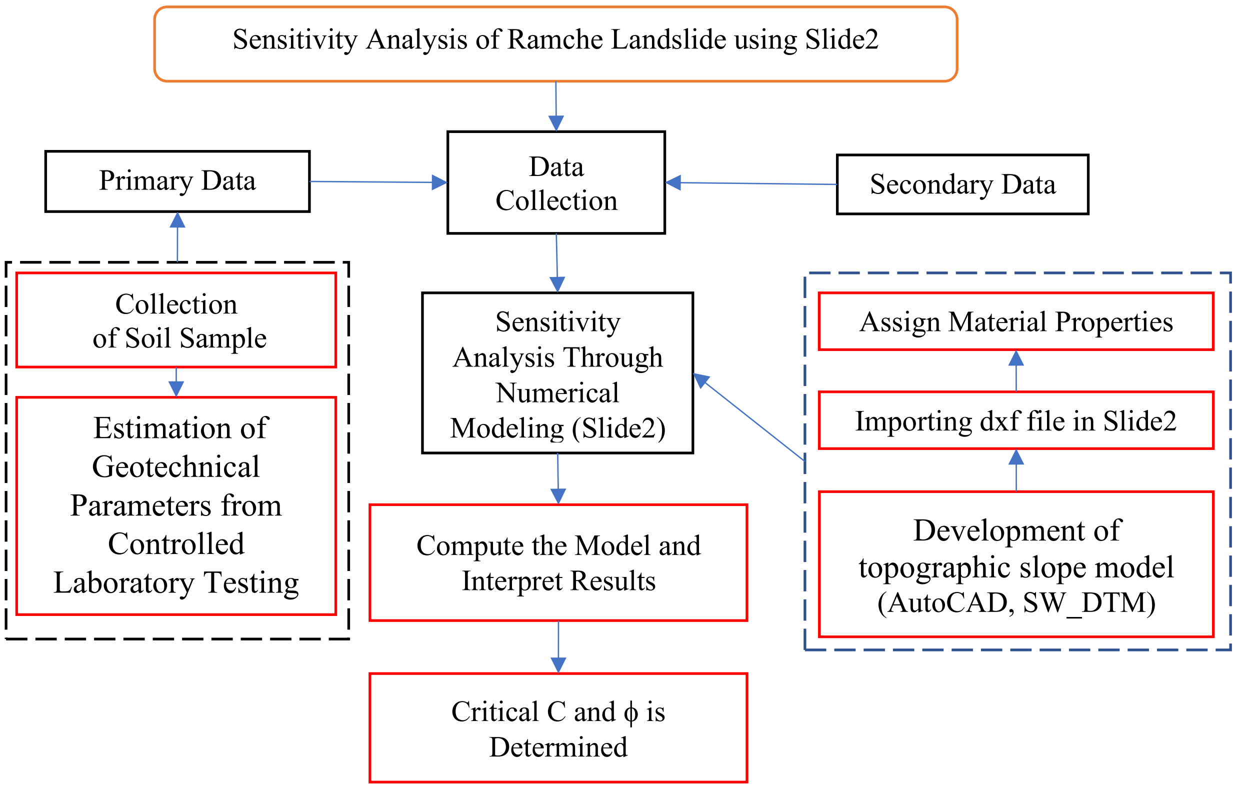


Figure 3: Presents the workflow for the numerical and computational analysis.

3. Results and Discussion

The case study focuses on a landslide located along the Trishuli Highway at Ramche in Rasuwa District (28.026072° N, 85.223361° E), situated above the Trishuli River. The fundamental soil parameters required for the development of the numerical model were determined through laboratory testing of collected soil samples. These soil parameters were subsequently used to evaluate the sensitivity analysis of the Ramche slope.

The results of the direct shear tests demonstrate that the shear strength characteristics of the soil conform to the Mohr–Coulomb failure criterion. This is evidenced by the linear relationship observed between shear stress (y-axis) and normal stress (x-axis), as presented in Figure 4. The shear stress and normal stress relationships derived from the six representative soil samples were used as key input parameters for the sensitivity analysis of the slope. These relationships help to understand how variations in soil strength properties influence the overall stability of the slope and identify which parameters have the most significant impact on potential failure. The dispersion of the plotted data reflects inherent variability in the soil properties, indicating that the slope materials are not perfectly uniform across the site. This natural heterogeneity plays an important role in sensitivity analysis, as even small variations in strength parameters can produce significant changes in the predicted stability condition of the slope.

The tested samples show relatively low cohesion values (2.95–7.93 kN/m²) and internal friction angles (16.12°–21.19°), which correspond to limited shear strength. Since cohesion (c) and friction angle (ϕ) directly govern the shear resistance of soil, minor reductions in these parameters can considerably lower the FoS. This highlights the sensitivity of the slope to variations in shear strength properties and explains its vulnerability to instability under unfavorable conditions. For the sensitivity analysis, the average values of cohesion (4.326 kN/m^2) and friction angle (19.14°) were adopted as representative baseline parameters. Using the mean values provides a rational and balanced estimate of the overall shear strength of the slope material, minimizing the influence of extreme test results while still reflecting site specific conditions (Duncan et al., 2014, Chowdhury et al., 2023). These average parameters were then systematically varied to evaluate how changes in c and ϕ affect slope stability, thereby offering a clearer understanding of the slope's response to uncertainty in soil strength characteristics.

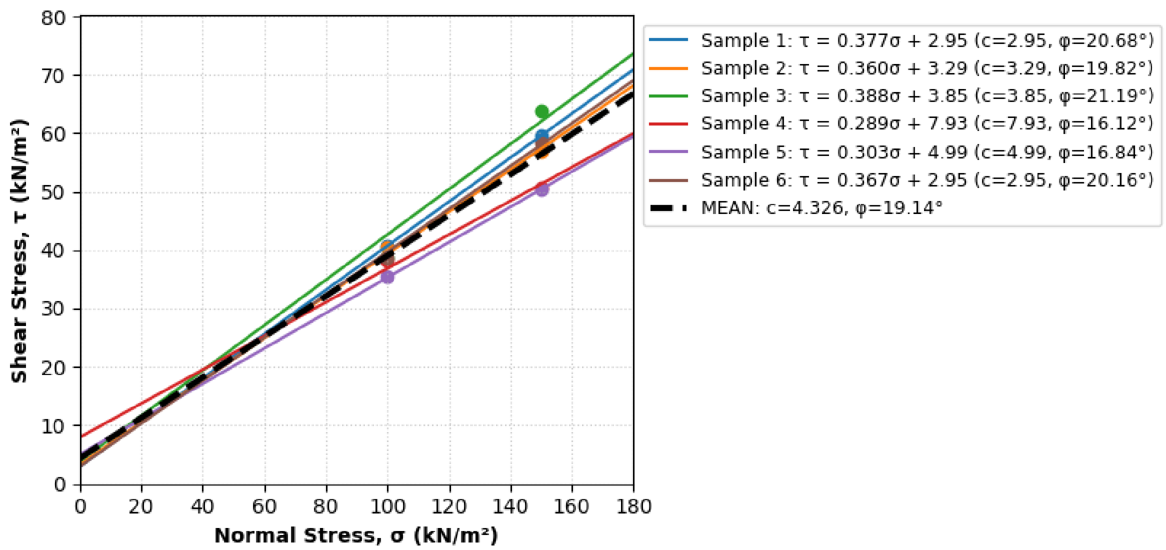
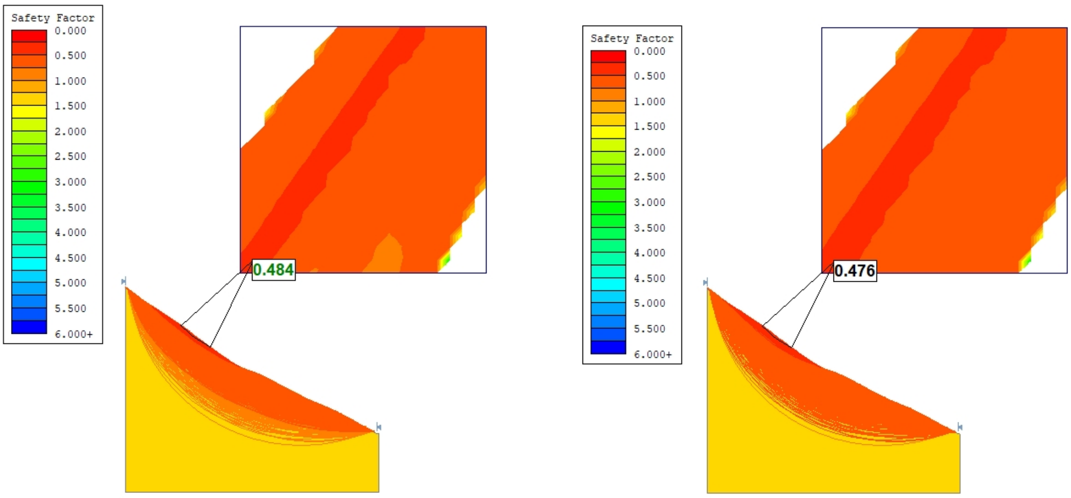


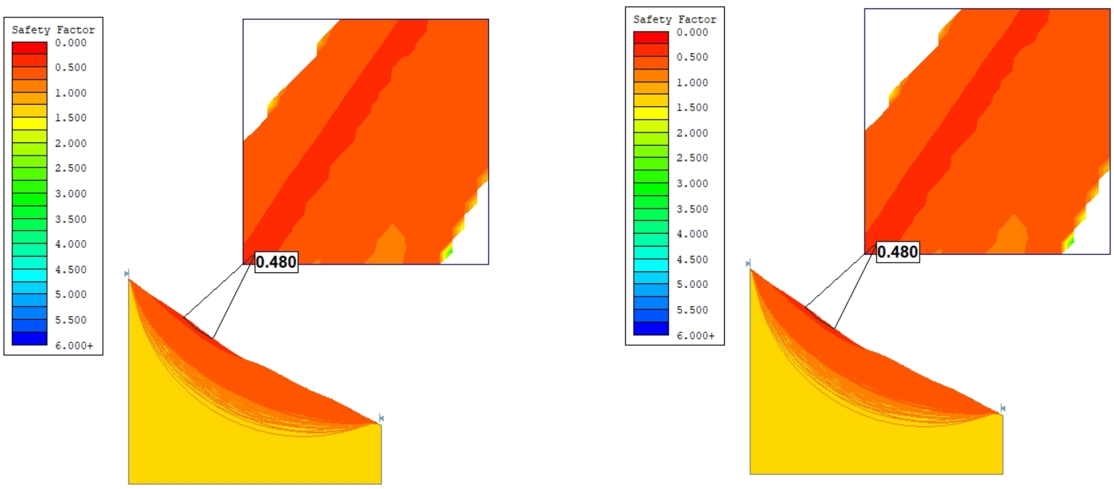
Figure 4: Experimental Determination of Shear Strength Parameters Using Direct Shear Test

The Figure 5 presents the contour distribution of the FoS for the analyzed slope under fully dry and unloaded conditions for the four different methods. The color scale illustrates the variation in stability within the slope mass, where warmer colors such as yellow to red indicate lower FoS values and relatively less stable zones. Most of the slope appears in yellow to light orange shades, suggesting that the FoS is close to 1.0 across a significant portion of the slope. However, the highlighted area identifies a critical zone with a minimum FoS less than one.

Because a FoS value less than 1.0 indicates that the available shear strength is insufficient to resist the driving forces, this result confirms an unstable condition along the identified slip surface. The contour pattern further reveals a curved failure surface extending from the crest toward the toe of the slope, which is characteristic of rotational failure in homogeneous soil. Since groundwater pressure, external surcharge loads, and seismic effects were not considered in the analysis, the observed instability is attributed solely to inadequate shear strength parameters, namely cohesion and internal friction angle. These findings demonstrate the high sensitivity of slope stability to variations in shear strength (Di Matteo et al., 2013, Khan and Wang, 2021) and indicate that the selected parameter combination is insufficient to maintain equilibrium under dry conditions.



(a) Bishop Simplified Method (b) Janbu Method Simplified



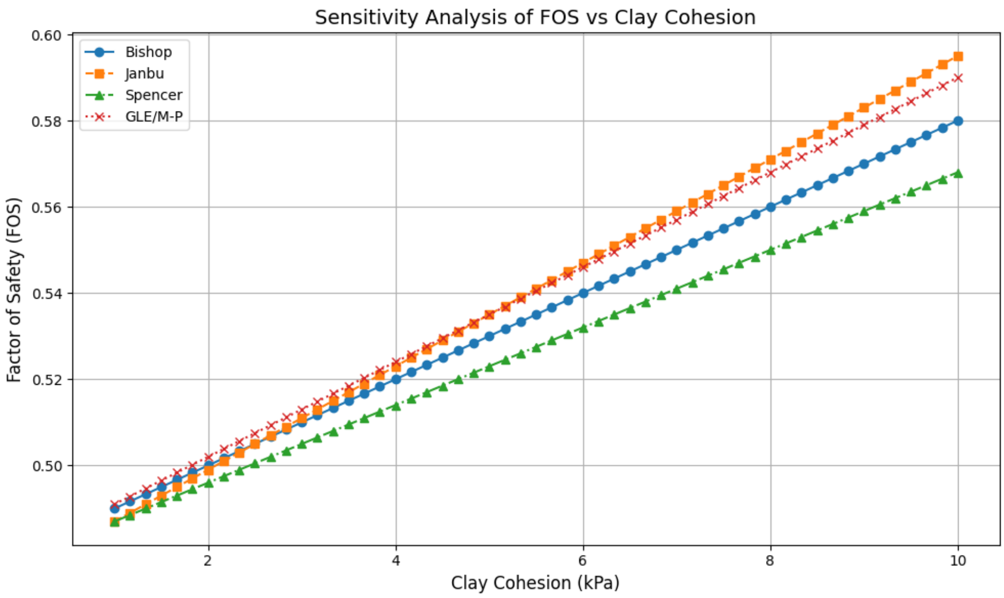
(c) Spencer Method (d) GLE / Morgenstern-Price Method

Figure 5: Sensitivity analysis of Ramche slope for average base value of Cohesion and friction angle for obtaining FoS for soil sample

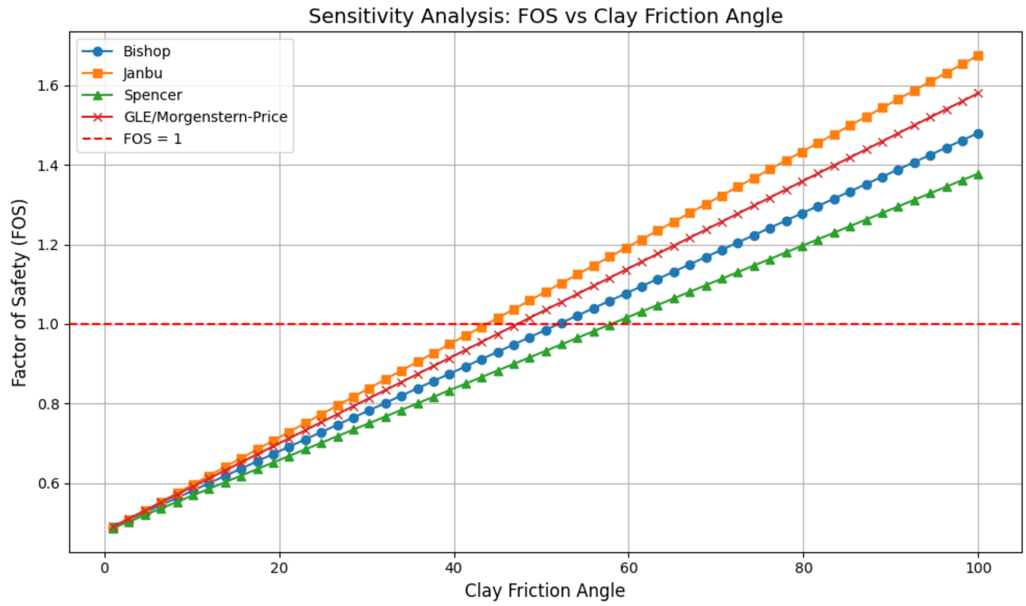
The Figure 6 (a and b) illustrates how the FoS varies with changes in clay friction angle and cohesion using four limit equilibrium methods: Bishop, Janbu, Spencer, and Morgenstern–Price (GLE). The horizontal axis represents the clay friction angle (Figure 6 a) and cohesion (Figure 6 b), while the vertical axis shows the corresponding FoS values. A red dashed line marks the critical stability threshold at FoS = 1.0. Across all methods, FoS increases almost linearly as the friction angle and cohesion increases, clearly demonstrating that slope stability is strongly controlled by the shear strength contribution from friction angle and cohesion (Khan and Wang, 2021).

At low friction angles, all methods predict FoS values well below 1.0, indicating unstable conditions. As ϕ increases, FoS gradually improves and crosses the stability threshold at different points depending on the method. Janbu consistently predicts the highest FoS values, followed by Morgenstern–Price and Bishop, while Spencer provides slightly lower estimates. Although there are small differences in magnitude among the methods, the overall trend remains consistent, confirming that increasing the friction angle significantly enhances slope stability.

From a practical standpoint, the results highlight the dominant influence of the internal friction angle on slope performance. Even modest increases in ϕ produce noticeable improvements in FoS, while low ϕ values quickly lead to unsafe conditions. This emphasizes the need for accurate laboratory and field determination of friction angle in clayey soils, as uncertainty in this parameter can substantially affect design reliability and safety assessments (Khan and Wang, 2021, Phoon and Tang, 2019).



(a)



(b)

Figure 6: Sensitivity analysis of slope for (a) Clay cohesion Vs FoS (b) Friction Angle Vs FoS for Ramche slope

The Figure 7 presents a sensitivity spider plot illustrating the impact of percentage changes in cohesion and internal friction angle on the FoS, evaluated using four limit equilibrium methods: Bishop, Janbu, Spencer, and Morgenstern–Price (GLE/MP). The horizontal axis represents percentage variation from baseline soil parameters (−80% to +80%), while the vertical axis shows the corresponding FoS values. A red horizontal line marks the failure threshold at FoS = 1.0.

The results indicate that FoS is highly sensitive to variations in the internal friction angle across all methods. As ϕ increases, FoS rises nonlinearly and significantly, crossing the failure threshold at approximately +35% to +40% variation. Conversely, reductions in ϕ cause a sharp decline in FoS, indicating critical instability. In contrast, cohesion (c) shows minimal influence on FoS within the same variation range. The cohesion curves remain nearly horizontal, with only slight increases in FoS as c increases, demonstrating a comparatively weak sensitivity response. This consistent pattern across Bishop, Janbu, Spencer, and Morgenstern–Price methods confirms that frictional resistance governs slope stability behavior in the analyzed model.

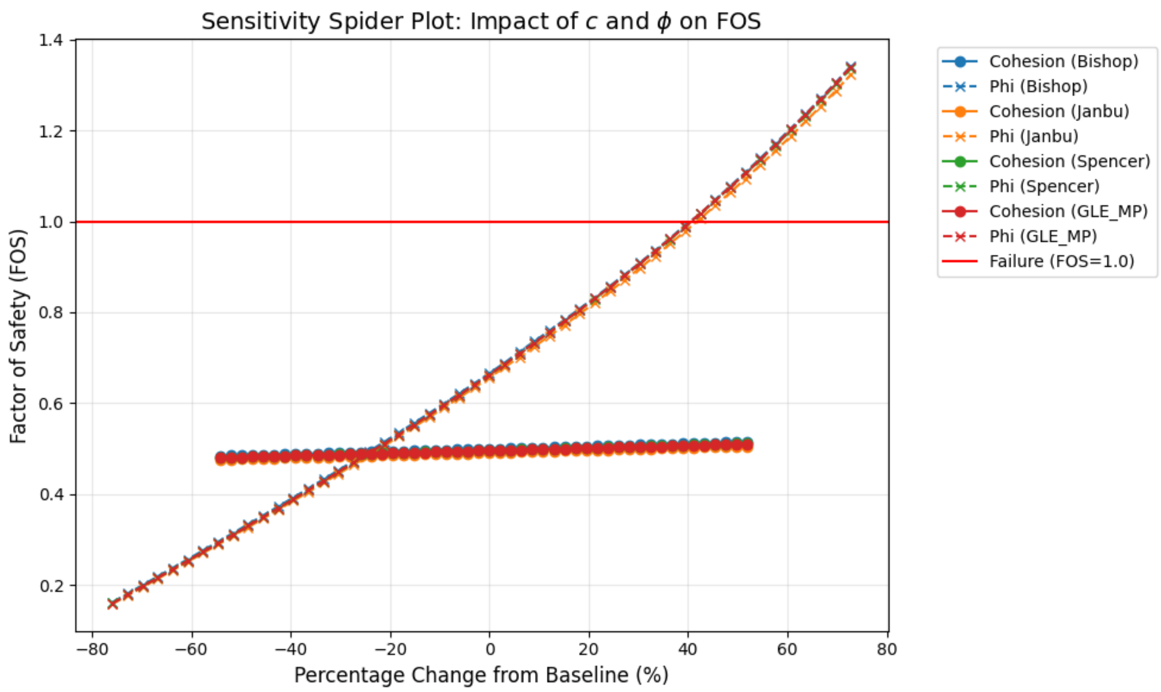


Figure 7: Sensitivity analysis of slope and Comparison of the influence of friction angle and cohesion, on slope stability across Ramche slope (Spider plot)

The relative influence of shear strength parameters cohesion (c) and internal friction angle (ϕ), on the FoS was also evaluated using a Tornado diagram based on the Spencer Method as shown in Figure 8. The results indicate that ϕ is the most sensitive parameter, producing a total FoS variation of approximately 1.177, compared to 0.032 for cohesion. This confirms that slope stability is more susceptible to uncertainties in the friction angle, suggesting that the frictional component contributes more significantly to shear resistance for the studied configuration (Deng et al., 2017).

Also cohesion shows very low influence, its relative impact is very lower than that of ϕ (Deng et al., 2017). The sensitivity ranking (ϕ >> c) highlights the importance of accurate determination of ϕ through laboratory testing such as triaxial or direct shear tests. Given that both parameters generate FoS variations, the slope may be classified as highly sensitive to shear strength fluctuations. Consequently, environmental factors that reduce shear strength such as elevated pore water pressure or weathering may significantly decrease stability.

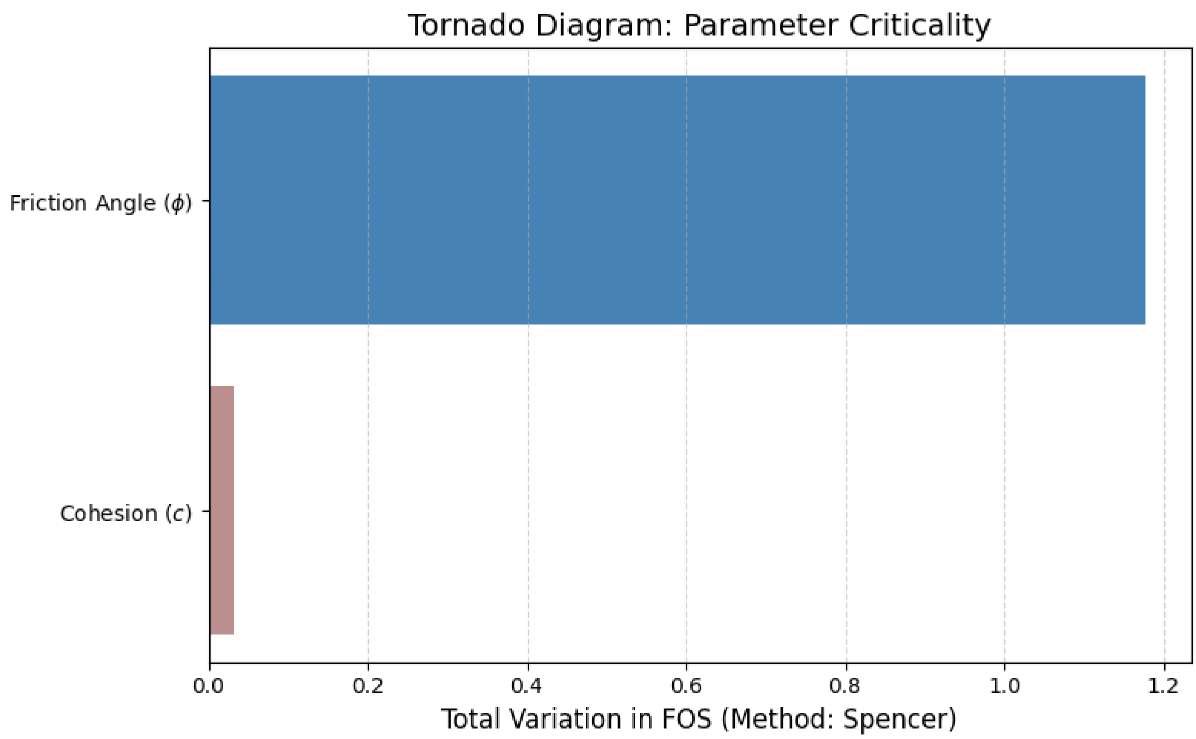


Figure 8: Sensitivity analysis of the Ramche slope to evaluate and compare the effects of cohesion and internal friction angle on overall slope stability

The Figure 9 presents FoS stability contours obtained using limit equilibrium method, illustrating the combined influence of cohesion (c) and internal friction angle (ϕ) on slope stability. Cohesion varies along the horizontal axis (approximately 5–14 kN/m^2), while the internal friction angle ranges from about 7° to 43° on the vertical axis. The color gradient transitions from red (low FoS, unstable) to green (high FoS, stable), with a distinct contour marking FoS = 1.0, which represents the critical boundary between stable and unstable conditions.

The contour pattern shows that FoS is significantly more sensitive to changes in the internal friction angle than to cohesion. The predominantly horizontal contour bands indicate that small increases in ϕ produce substantial improvements in stability, whereas similar proportional changes in cohesion result in comparatively minor changes in FoS. The FoS = 1.0 line occurs at higher friction angles (around 41.75°) for low cohesion values, and slightly lower friction angles as cohesion increases, demonstrating the compensatory relationship between the two shear strength parameters.

The results suggest that slope stability in this analysis is primarily governed by the frictional component of shear strength rather than cohesion. Instability is concentrated in regions with low ϕ values, even when moderate cohesion is present. These findings emphasize the importance of accurate determination of the internal friction angle in design and reliability assessments, as uncertainties in ϕ are likely to have a greater impact on stability predictions than comparable uncertainties in cohesion.

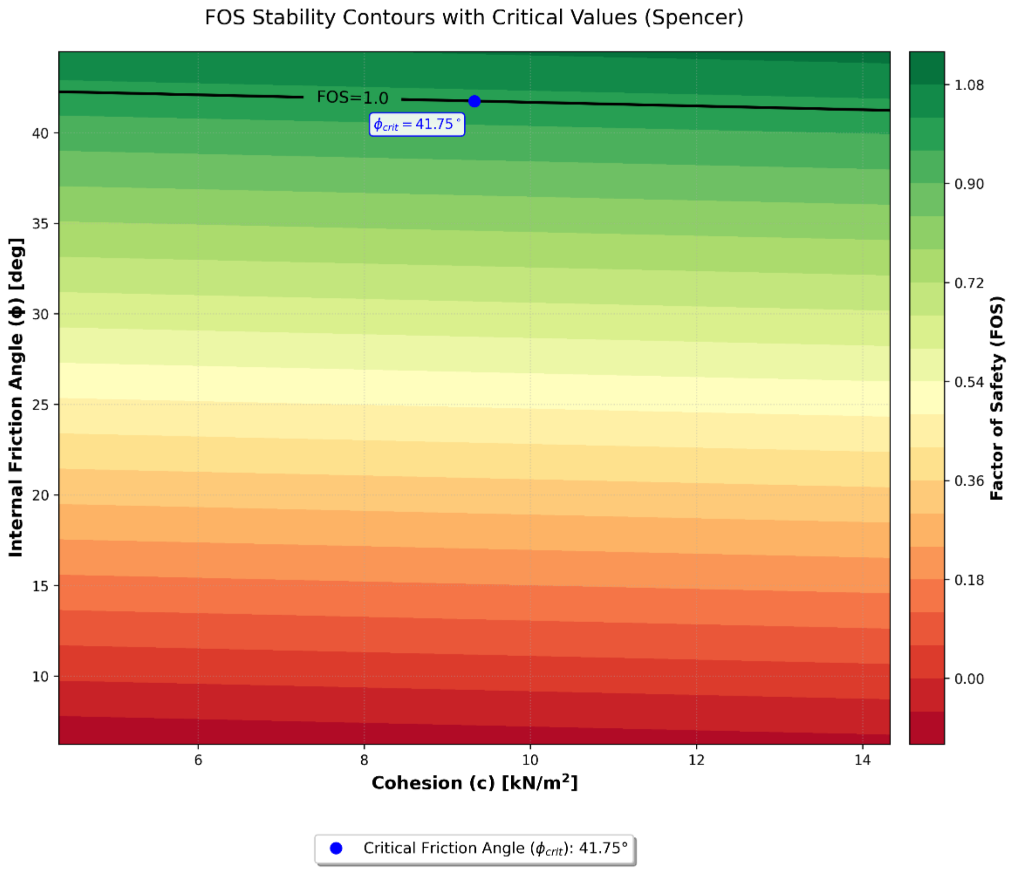


Figure 9: Sensitivity analysis of slope and Comparison of the influence of friction angle and cohesion, on slope stability across Ramche slope (FoS stability contours).

4. Conclusions

This study evaluated the sensitivity of slope stability to variations in cohesion (c) and internal friction angle (ϕ) of clay using four limit equilibrium approaches, Bishop Simplified Method, Janbu Method, Spencer Method, and Morgenstern–Price Method. The results consistently demonstrate that the internal friction angle is the dominant parameter governing the FoS for the analyzed clay slope.

Across all methods, FoS increased almost linearly with increasing ϕ, and reductions in ϕ led to rapid decreases in stability, frequently driving FoS below the critical threshold of 1.0. In contrast, cohesion exhibited a comparatively moderate influence. Although increases in c improved FoS, the magnitude of change was smaller than that associated with equivalent variations in ϕ. Sensitivity spider plots and stability contours further confirmed that slope response is strongly controlled by the frictional component of shear strength, while cohesion plays a secondary but still meaningful role.

The tornado diagram analysis quantified this hierarchy, showing a greater total FoS variation attributable to ϕ than to c. This indicates that uncertainties in friction angle have a more pronounced impact on predicted stability than comparable uncertainties in cohesion. Importantly, the similarity of trends obtained from all four limit equilibrium methods suggests that the sensitivity ranking (ϕ > c) is methodologically robust, even though slight differences exist in absolute FoS values.

From an engineering perspective, these findings underscore the critical importance of accurately determining the internal friction angle in clayey soils. Given the high sensitivity of FoS to ϕ, even modest errors in its estimation may significantly alter design outcomes and safety margins. While cohesion should not be neglected particularly under short-term or undrained conditions the frictional component ultimately governs long-term stability behavior for the slope configuration analyzed.

Overall, the study confirms that reliable slope design and risk assessment in clay soils require careful characterization of shear strength parameters, with particular emphasis on minimizing uncertainty in the internal friction angle to ensure dependable and safe stability predictions.

References

- ABRAMSON, L. W., LEE, T. S., SHARMA, S. & BOYCE, G. M. 2001. Slope stability and stabilization methods, John Wiley & Sons.
- AHMED, B. 2021. The root causes of landslide vulnerability in Bangladesh. Landslides, 18, 1707-1720.
- ARYAL, K. P. 2006. Slope stability evaluations by limit equilibrium and finite element methods.
- BARAL, S., JOSHI, N. & TIWARI, R. C. 2025. Stability Assessment of Landslide in Himalayan Terrain: A Spectral Element Method and Back Analysis-Based Approach. Engineering Reports, 7, e70541.
- BARAL, S. & TIWARI, R. C. 2025. Slope Stability Analysis of Landslide in the Nepalese Himalaya: A Case Study of Kuiyadaha Landslide, Gokuleshor, Baitadi. Himalayan Journal of Applied Science and Engineering, 5, 23-44.
- BASNET, K. & ACHARYA, D. 2019. Flood Analysis at Ramghat, Pokhara, Nepal Using HEC-RAS. Technical Journal, 1, 41-53.

- CHHETRI, N. B. & EASTERLING, W. E. 2010. Adapting to climate change: Retrospective analysis of climate technology interaction in the rice-based farming system of Nepal. Annals of the Association of American Geographers, 100**,** 1156-1176.
- CHOWDHURY, R., BHATTACHARYA, G. & METYA, S. 2023. Geotechnical slope analysis, Crc Press.
- DAHAL, R. K. 2012. Rainfall-induced landslides in Nepal. International Journal of Erosion Control Engineering, 5**,** 1-8.
- DAHAL, R. K. & HASEGAWA, S. 2008. Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology, 100**,** 429-443.
- DENG, Z.-P., LI, D.-Q., QI, X.-H., CAO, Z.-J. & PHOON, K.-K. 2017. Reliability evaluation of slope considering geological uncertainty and inherent variability of soil parameters. Computers and Geotechnics, 92**,** 121-131.
- DI MATTEO, L., VALIGI, D. & RICCO, R. 2013. Laboratory shear strength parameters of cohesive soils: variability and potential effects on slope stability. Bulletin of Engineering Geology and the Environment, 72**,** 101-106.
- DUNCAN, J. M., WRIGHT, S. G. & BRANDON, T. L. 2014. Soil strength and slope stability, John Wiley & Sons.
- FINDELL, K. L. & ELTAHIR, E. A. 1997. An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois. Water Resources Research, 33**,** 725-735.
- GHIMIRE, T., PAUDEL, L. & PANT, B. 2007. The devastating Ramche Landslide (Rasuwa) and the future of Polchet residents. Journal of Nepal Geological Society, 36**,** 27-27.
- GNYAWALI, K., DAHAL, K., TALCHABHADEL, R. & NIRANDJAN, S. 2023. Framework for rainfall-triggered landslide-prone critical infrastructure zonation. Science of the Total Environment, 872**,** 162242.
- GRIFFITHS, D. & LANE, P. 1999. Slope stability analysis by finite elements. Geotechnique, 49**,** 387-403.
- HAMMOURI, N. A., MALKAWI, A. I. H. & YAMIN, M. M. 2008. Stability analysis of slopes using the finite element method and limiting equilibrium approach. Bulletin of Engineering Geology and the Environment, 67**,** 471-478.
- HIGHLAND, L. M. & BOBROWSKY, P. 2008. The landslide handbook-A guide to understanding landslides, US Geological Survey.

- IVERSON, R. M. 2000. Landslide triggering by rain infiltration. Water resources research, 36, 1897-1910.
- JHARENDRA, K., GAUTAM, D., NEUPANE, P. & PAUDYAL, K. R. 2018. Landslide inventory mapping and assessment along the Ramche-Jharlang area in Dhading, Rasuwa and Nuwakot districts, Lesser Himalaya Central Nepal. Journal of Nepal Geological Society, 55, 103-108.
- KHAN, M. I. & WANG, S. 2021. Slope stability analysis to correlate shear strength with slope angle and shear stress by considering saturated and unsaturated seismic conditions. Applied Sciences, 11, 4568.
- KINCEY, M., ROSSER, N., SWIRAD, Z., ROBINSON, T., SHRESTHA, R., PUJARA, D., BASYAL, G., DENSMORE, A., ARRELL, K. & OVEN, K. 2024. National-scale rainfall-triggered landslide susceptibility and exposure in Nepal. Earth's Future, 12, e2023EF004102.
- LI, L., WANG, Y., ZHANG, L., CHOI, C. & NG, C. W. 2019. Evaluation of critical slip surface in limit equilibrium analysis of slope stability by smoothed particle hydrodynamics. International Journal of Geomechanics, 19, 04019032.
- LIU, S., SHAO, L. & LI, H. 2015. Slope stability analysis using the limit equilibrium method and two finite element methods. Computers and Geotechnics, 63, 291-298.
- MALLA, B. & DAHAL, B. K. Effect of Rainfall on Stability of Soil Slope. Proceedings of 10th IOE Graduate Conference Peer Reviewed ISSN, 2021. 2350-8914.
- MATTHEWS, C., FAROOK, Z. & HELM, P. 2014. Slope stability analysis–limit equilibrium or the finite element method. Ground Engineering, 48, 22-28.
- MCADOO, B. G., QUAK, M., GNYAWALI, K. R., ADHIKARI, B. R., DEVKOTA, S., RAJBHANDARI, P. L. & SUDMEIER-RIEUX, K. 2018. Roads and landslides in Nepal: how development affects environmental risk. Natural Hazards and Earth System Sciences, 18, 3203-3210.
- MEDINA, V., HÜRLIMANN, M., GUO, Z., LLORET, A. & VAUNAT, J. 2021. Fast physically-based model for rainfall-induced landslide susceptibility assessment at regional scale. Catena, 201, 105213.
- OSMAN, K. T. 2018. Soils on steep slopes. Management of soil problems. Springer.
- PAUDYAL, P., DAHAL, P., BHANDARI, P. & DAHAL, B. K. 2023. Sustainable rural infrastructure: guidelines for roadside slope excavation. Geoenvironmental Disasters, 10, 11.

- PHOON, K.-K. & TANG, C. 2019. Characterisation of geotechnical model uncertainty. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 13, 101-130.
- RAMADHANI, S. & IHZAN, M. The Slope Instability Potential in the Balaroa area based on the Finite Element Method using Shear Strength Reduction. IOP Conference Series: Earth and Environmental Science, 2023. IOP Publishing, 012020.
- SALIH, A. G. Stability Analysis of Residual Soil Slope Model by Numerical Modeling Using FEM Against LEM. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012046.
- SHARMA, S., HAMAL, K., KHADKA, N. & JOSHI, B. B. 2020. Dominant pattern of year-to-year variability of summer precipitation in Nepal during 1987–2015. Theoretical and applied climatology, 142, 1071-1084.
- SHRESTHA, A. B., WAKE, C. P., DIBB, J. E. & MAYEWSKI, P. A. 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. International Journal of Climatology: A Journal of the Royal Meteorological Society, 20, 317-327.
- SKILODIMOU, H. D., BATHRELLOS, G. D., KOSKERIDOU, E., SOUKIS, K. & ROZOS, D. 2018. Physical and anthropogenic factors related to landslide activity in the Northern Peloponnese, Greece. Land, 7, 85.
- STARK, T., NEWMAN, E. J. & AUST, R. 2008. Back-analysis of a PVC geomembrane-lined pond failure. Geosynthetics International, 15, 258-268.
- VANDENBERGE, D. R. & MCGUIRE, M. P. 2019. Practical use of modified Hoek–Brown criterion for soil slope stability analysis. Geotechnical and Geological Engineering, 37, 5441-5455.
- ZHU, D., LEE, C. & JIANG, H. 2003. Generalised framework of limit equilibrium methods for slope stability analysis. Geotechnique, 53, 377-395.
- ZOLKEPLI, M., ISHAK, M. & ZAINI, M. Slope stability analysis using modified Fellenius’s and Bishop’s method. IOP Conference Series: Materials Science and Engineering, 2019. IOP Publishing, 012004.