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Impact of Water Table Variability and Seismic Activity on Landslide Stability: Insights from the Kuiyadaha Slope

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Abstract

Landslides are one of the most common and destructive natural hazards in mountainous regions, causing significant damage to infrastructure, property, and human lives worldwide. This study examines the sensitivity of water table fluctuation and seismic effect on stability of slope located on the left bank of the Chameliya River above the Mahakali Highway at Kuiyadaha village, Baitadi District, Nepal. The landslide was triggered by prolonged heavy rainfall and has continued to move gradually, especially during the monsoon season, causing damage to residential structures and indicating persistent slope instability. Laboratory direct shear tests on soil samples reveal moderate shear strength characteristics, with internal friction angles ranging from 15.58° to 18.43° and cohesion values between 9.29 and 11.45 kN/m², which were used as input parameters for slope stability modelling in Slide2. The stability of the slope was evaluated using limit equilibrium methods under varying groundwater and seismic conditions to analyse the sensitivity of the Factor of Safety (FoS). The results show that slope stability decreases significantly under saturated conditions due to increased pore water pressure and reduced effective stress. Sensitivity analysis further indicates that increasing seismic coefficients substantially reduce the FoS, highlighting the destabilizing influence of seismic forces. Conversely, groundwater drawdown improves slope stability by lowering pore pressure and increasing effective stress. Overall, the findings demonstrate that slope stability is highly sensitive to both seismic loading and groundwater conditions, emphasizing the importance of integrating seismic hazard assessment and groundwater management in landslide mitigation strategies.

Keywords: *Factor of Safety, Groundwater drawdown, Landslide stability, Seismic loading, Sensitivity analysis*

1. Introduction

Landslides are among the most common and destructive natural hazards affecting mountainous and hilly regions worldwide. They cause significant loss of life, damage to infrastructure, and long-term socio-economic impacts, particularly in developing countries where settlements often expand into unstable terrain (Ahmed, 2021; Alcántara-Ayala, 2025; Kumar, 2024; Nseka et al., 2021). Slope instability is generally controlled by a combination of geological, hydrological, and external loading factors that influence the balance between resisting and driving forces acting on a slope (Kolapo et al., 2022; McColl, 2022; Scaringi & Loche, 2022). Among these factors, groundwater conditions and seismic loading play a critical role in determining the stability of natural slopes and engineered earth structures. Changes in these conditions can significantly alter the mechanical behavior of soils and lead to slope failure if the resisting forces are insufficient to counteract the destabilizing forces.

Water infiltration and groundwater fluctuation are widely recognized as primary triggers of landslides in many parts of the world (Jaafari, 2024; McColl, 2022). When rainfall infiltrates into a slope, it increases pore water pressure within the soil mass and reduces effective stress, which directly decreases the shear strength of the soil (Y. Chen et al., 2020; Liu et al., 2021; Tian et al., 2022; Zhang et al., 2023). This reduction in shear strength can lead to slope instability, especially in areas with weak soil layers or steep terrain. Studies have shown that even small changes in groundwater levels can significantly affect the FoS of slopes by altering the balance between shear strength and driving forces (Chowdhury et al., 2023; Ni et al., 2018; Yang et al., 2024; Zeng et al., 2024). For example, increases in groundwater levels due to prolonged rainfall or seasonal fluctuations may cause slopes that are otherwise stable to become unstable. Numerical and field investigations have consistently demonstrated that groundwater conditions are a dominant controlling factor in landslide initiation and progression (Wang et al., 2024; Wei et al., 2020).

In addition to hydrological factors, earthquakes represent another major triggering mechanism for slope failure (Wang et al., 2019; Yang et al., 2023; Zhao et al., 2020). Seismic shaking generates dynamic inertial forces within the soil mass, increasing the driving forces acting along potential failure surfaces. These additional forces can reduce the FoS of slopes and may trigger landslides even in slopes that appear stable under static conditions. Earthquake induced landslides are particularly hazardous because they occur suddenly and can affect large areas simultaneously. Recent studies have shown that increasing seismic coefficients significantly decreases slope stability, highlighting the importance of considering seismic loading in landslide hazard assessments (Y.-L. Chen et al., 2020; Yiheng et al., 2025).

Although rainfall-induced and earthquake-induced landslides have often been studied independently, real-world conditions frequently involve the combined influence of multiple triggering factors. For instance, slopes that are already saturated due to heavy rainfall may become highly vulnerable during seismic events. In such cases, the combined effects of elevated pore water pressure and earthquake-induced inertial forces can drastically reduce the stability of slopes. Recent research has emphasized the need to evaluate slope stability under combined hydro-mechanical and seismic conditions in order to better understand the mechanisms of slope failure and improve hazard prediction.

Slope stability analysis methods have evolved significantly over the past several decades. Traditional approaches such as the limit equilibrium method remain widely used due to their simplicity and reliability in estimating the FoS (Azarafza et al., 2021; Firincioglu & Ercanoglu, 2021; Liu et al., 2020). These methods evaluate slope stability by comparing resisting forces derived from soil shear strength parameters with driving forces generated by gravity, water pressure, and external loads. Common limit equilibrium techniques include methods developed by Bishop, Janbu, and Morgenstern–Price, which are frequently applied in geotechnical software packages for slope stability modeling (Wubalem, 2022). Advances in computational tools have made it possible to perform sensitivity analyses, allowing researchers to evaluate how changes in input parameters such as water table depth or seismic coefficients affect the FoS of slopes.

Sensitivity analysis is particularly useful in landslide studies because soil properties and environmental conditions often vary spatially and temporally. By systematically varying key parameters, sensitivity analysis helps identify the most critical factors controlling slope stability. For example, variations in groundwater level may significantly influence pore pressure distribution and effective stress within the slope, while seismic loading may increase driving forces along potential failure surfaces (Chai et al., 2022; Huang et al., 2021). Understanding how these parameters influence the FoS is essential for identifying critical thresholds and designing appropriate mitigation measures.

Despite the considerable progress made in slope stability research, several gaps remain in understanding the combined influence of groundwater fluctuation and seismic loading on landslide sensitivity. Many previous studies focus primarily on either rainfall-induced or earthquake-induced landslides, while fewer investigations examine the sensitivity of slopes under varying groundwater levels together with seismic effects. In addition, site-specific analyses are often required because geological conditions, soil properties, and slope geometry vary widely between locations. Consequently, detailed geotechnical investigations and numerical modeling are necessary to better understand the stability behavior of individual landslides and assess their response to changing environmental conditions.

The present study aims to address this gap by conducting a sensitivity analysis of slope stability considering both water table fluctuation and seismic loading. The research focuses on evaluating how variations in groundwater levels and seismic coefficients influence the FoS of a landslide-prone slope. The specific objectives of the study are: (1) to determine the shear strength parameters of the slope materials through laboratory testing; (2) to develop a slope stability model using numerical analysis techniques; and (3) to evaluate the sensitivity of the FoS under different groundwater and seismic scenarios. It is hypothesized that an increase in groundwater level and seismic loading will reduce the FoS of the slope, thereby increasing the likelihood of slope failure.

The findings of this study are expected to contribute to a better understanding of the interaction between hydrological and seismic factors in slope stability. By identifying the most sensitive parameters affecting slope stability, the results can assist engineers and planners in designing effective landslide mitigation strategies such as drainage systems, slope reinforcement, and early warning systems. Furthermore, the study provides insights that can support risk assessment and sustainable infrastructure development in landslide-prone regions.

2. Materials And Methods

2.1 Study area

A field visit was carried out as part of the case study on the landslide occurring in Kuiyadaha Village, located in Baitadi District of the Far-Western region of Nepal. The purpose of the visit was to observe the site conditions and collect representative samples from the affected area. The map of the study area is shown in Figure 1. The site visits were conducted to collect necessary survey data, available reports, and soil samples for laboratory investigation. A field survey of the study area was also carried out during the visit. For detailed analysis, different soil samples were collected from five different sections. Disturbed and undisturbed soil samples were collected from each section accordingly. Undisturbed samples were obtained using a thin-wall tube sampler through the open-pit sampling method. Laboratory tests were performed to determine the physical and mechanical properties of the collected soil samples. Shear strength parameter was determined by performing direct shear test and average value of soil parameters were used for the analysis in slide2 software.

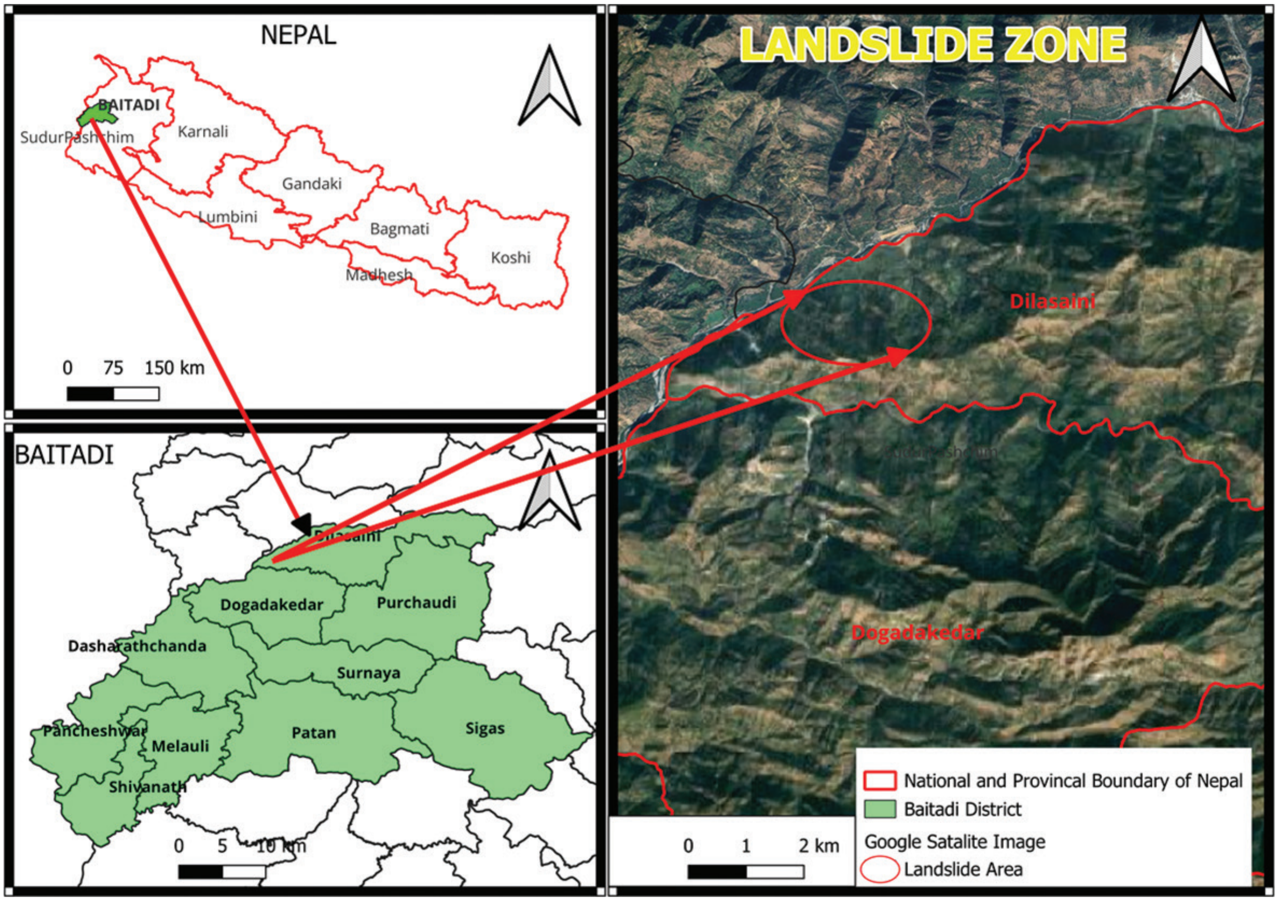


Figure 1: Study area map of the Kuiyadaha landslide, located in Baitadi District

The shear strength characteristics of the collected soil samples were determined using the direct shear test. In this study, soil samples were collected from five distinct sections within the selected locations of the study area. Sampling from multiple sections ensured that the spatial variability of soil properties was represented, which is important for reliable slope stability assessment. During the direct shear test, different normal stresses (σ) were applied to the soil specimens while the corresponding shear stresses (τ) at failure were recorded. The relationship between normal stress and shear stress was then plotted to develop the shear strength envelope. From this envelope, the key shear strength parameters cohesion (c) and the internal friction angle (φ) were determined. These parameters provide essential information about the soil's resistance to shear and its potential failure behavior under varying loading conditions. The obtained average shear strength parameters were subsequently used for slope stability analysis within the study area. The methodological approach followed established geotechnical principles as described in Soil Mechanics by R.F. Craig (Craig, 2013).

2.2 Numerical tools and Model

Slope stability and sensitivity analysis were performed using Slide2, a two–dimensional limit equilibrium slope stability software developed by Rocscience. The software is widely used in geotechnical engineering for analyzing the stability of natural and engineered slopes under various loading and environmental conditions. Slide2 allows users to model soil stratigraphy, groundwater conditions, and external forces, and evaluate their effects on the FoS of slopes. The slope geometry used in the analysis was developed based on field observations and the measured cross-sections of the study area using SW DTM and AutoCAD. Geotechnical parameters obtained from laboratory testing, including cohesion (c), internal friction angle (φ), and unit weight (γ), were assigned as input parameters in the model.

Slope stability was evaluated using the limit equilibrium method implemented in Slide2. This method calculates the FoS by comparing the resisting forces along a potential failure surface to the driving forces acting on the slope. Several built-in methods are available in the software, such as the Bishop Simplified Method, Janbu Method, and Morgenstern–Price Method. In this study, the analysis was primarily performed using the Bishop Simplified Method and Janbu Method as it is considered one of the most reliable approaches for slope stability assessment.

To evaluate the influence of groundwater conditions on slope stability, different groundwater table scenarios were simulated within Slide2. Groundwater levels were varied to represent possible seasonal or rainfall-induced fluctuations. The water table was defined within the model using the water table fluctuation conditions provided by the groundwater feature in the software. Sensitivity analysis was then performed by progressively raising and lowering the water table level. As groundwater levels increase, pore water pressure within the soil mass also increases, which reduces the effective stress and consequently decreases the shear strength of the soil. For each groundwater condition, the FoS was calculated to determine how sensitive the slope stability is to variations in the water table. The results of this analysis provided insight into the critical groundwater levels at which the slope becomes unstable.

In addition to groundwater fluctuations, the impact of seismic loading on slope stability was also evaluated using the pseudo-static analysis capability in Slide2. Seismic forces were incorporated into the model by applying horizontal and vertical seismic coefficients representing earthquake-induced inertial forces acting on the soil mass. The pseudo-static approach simulates earthquake effects by introducing an equivalent horizontal force proportional to the weight of the soil mass. This force increases the driving forces along potential failure surfaces, thereby reducing the FoS. Several seismic coefficient values were tested to assess the sensitivity of the slope to different levels of seismic activity.

Slide2 includes a sensitivity analysis tool that allows systematic variation of input parameters to observe their influence on the FoS. In this study, the sensitivity of the slope stability was examined by varying two key factors: groundwater table elevation and seismic coefficients. For each scenario, the software automatically recalculated the FoS and identified the critical failure surface. The resulting analyses provided a range of FoS values corresponding to different environmental conditions. By comparing these values, the study identified the conditions under which the slope becomes most vulnerable to failure. Figure 2 describe about the numerical and computational procedure of sensitivity analysis of landslide.

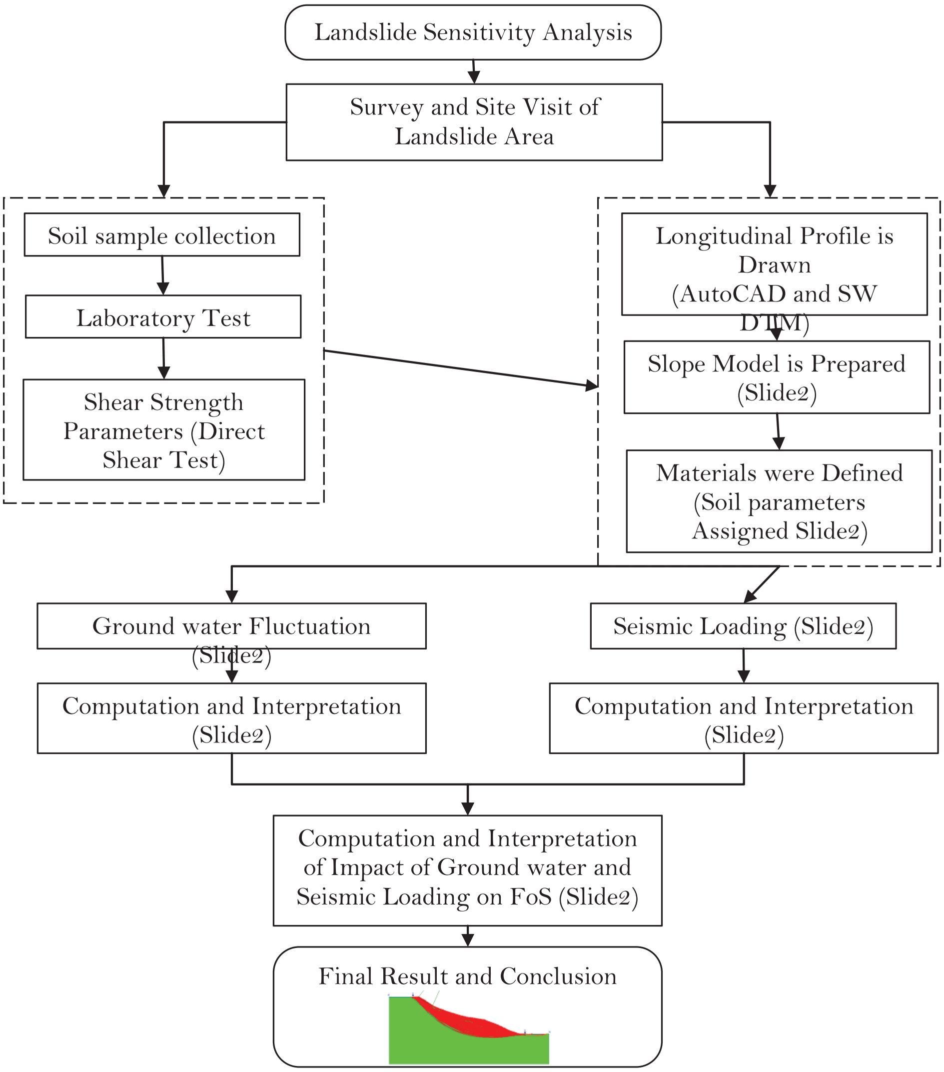


Figure 2: Numerical and computational procedure of Sensitivity analysis of Landslide

3. Results and Discussion

The case study focuses on a landslide located on the left bank of the Chameliya River, above the Mahakali Highway at Kuiyadaha village in Gokuleshor, Baitadi District, Nepal. The landslide is identified as a creeping type failure, characterized by slow and gradual movement of the slope material over time (Baral & Tiwari, 2025). The landslide was primarily triggered by continuous heavy rainfall that lasted for about seven days, which significantly destabilized the slope and caused serious damage to 11 residential houses. Since then, the slope has continued to move gradually, particularly during the monsoon season (July to September). Local residents first noticed the landslide activity through the appearance of visible cracks in their houses and the slow movement of the ground, which indicated ongoing slope instability.

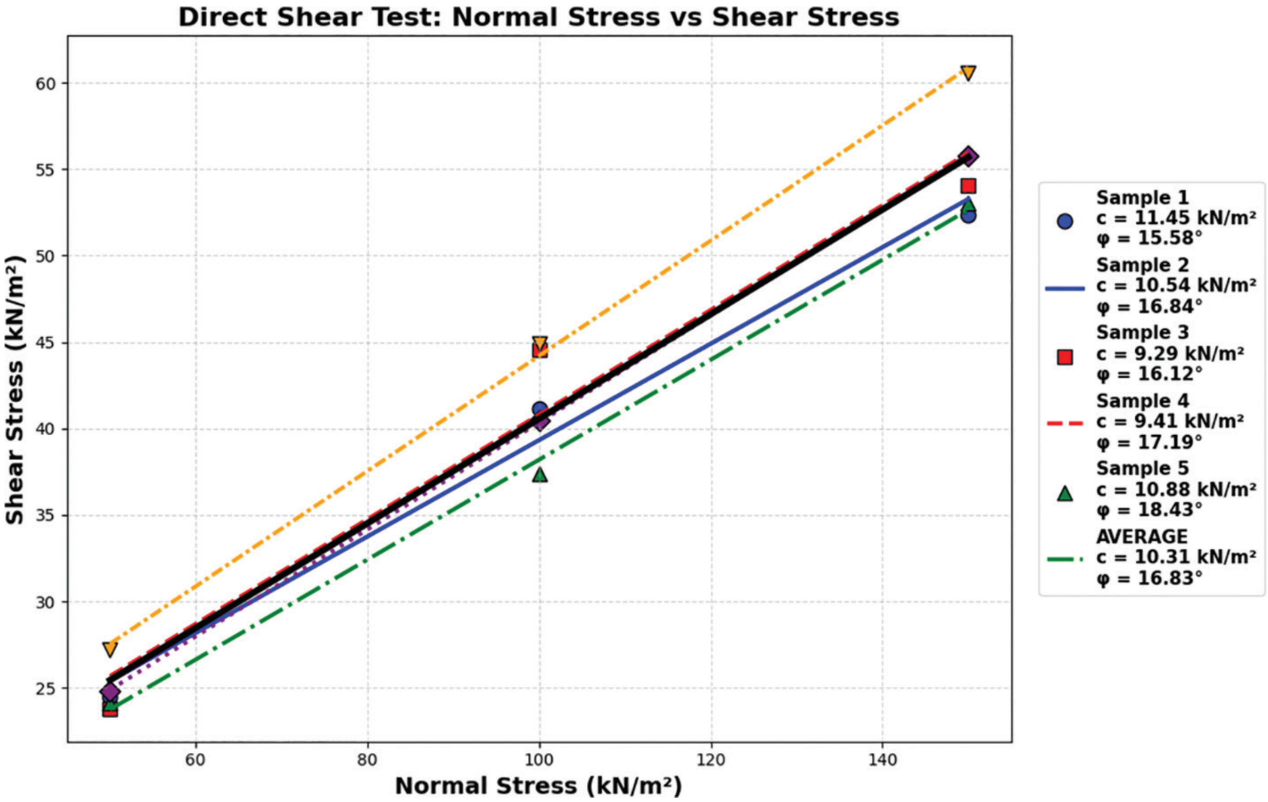
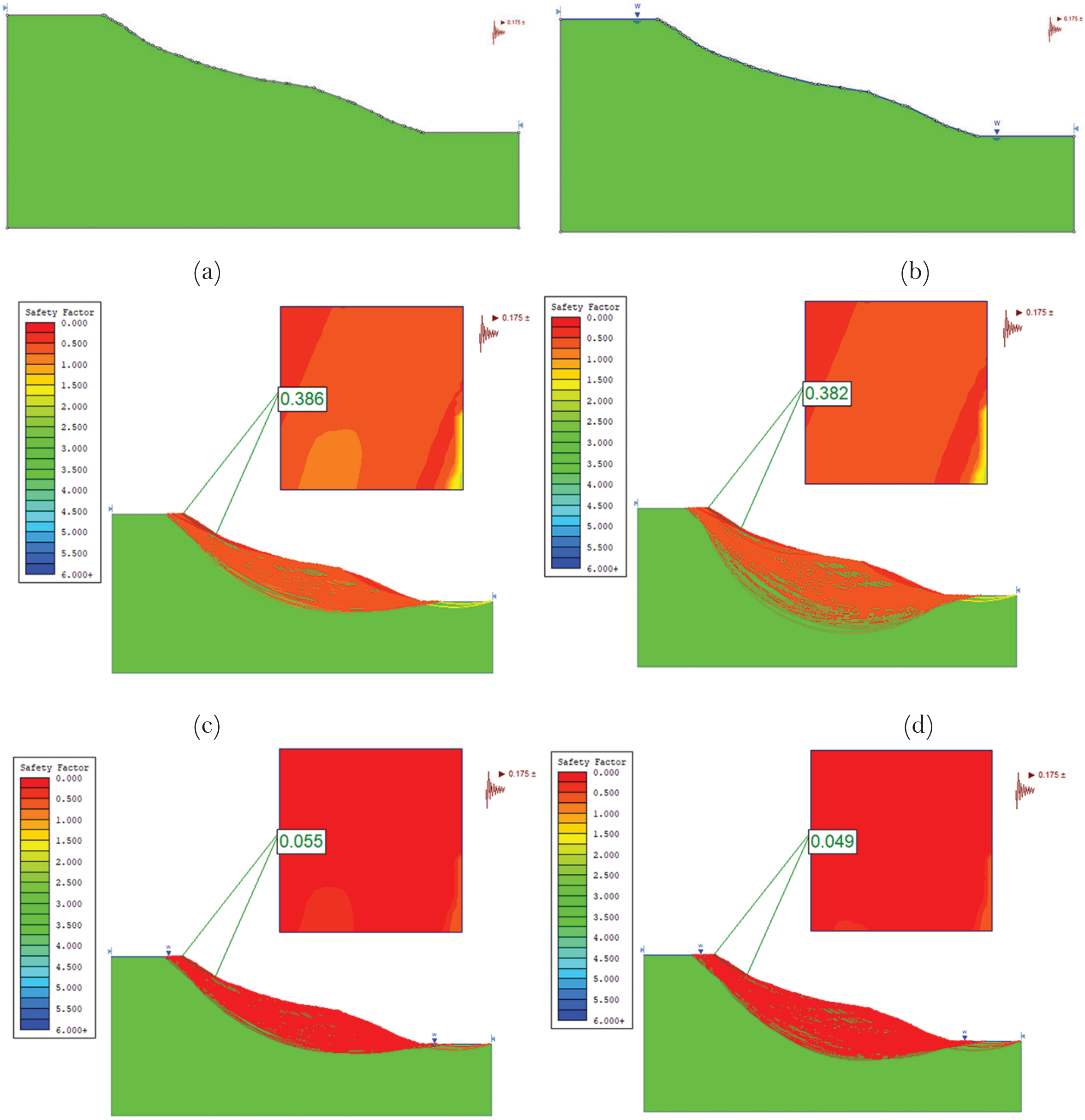


Figure 3: Determination of shear strength parameters using the direct shear test.

The direct shear test results shown in Figure 3 illustrate the relationship between normal stress and shear stress for the five soil samples collected from the Kuiyadaha landslide area. The plotted data display indicating that the soil behavior follows the Mohr–Coulomb Failure Criterion. As the normal stress increases, the shear stress at failure also increases proportionally for all samples. The shear strength envelope derived from the graph shows that the soil possesses small but positive cohesion, as the lines intercept the shear stress axis slightly above zero. Based on the test results, the internal friction angle of the soil ranges from about 15° to 19°, while the cohesion values vary between 9 kN/m^2 and 12 kN/m^2. These shear strength parameters indicate moderate shear resistance of the slope material and average value was determined to use as input parameters for the slope stability modelling. The obtained values were applied in the numerical analysis to evaluate the sensitivity of the slope stability to water table fluctuations and seismic loading, particularly in assessing their influence on the FoS.



(a) (b)

(c) (d)

(e) (f)

Figure 4: Slope stability models and corresponding factors of safety obtained from Slide2 analysis under different groundwater and seismic conditions. (a) and (b) show the slope models under fully dry and fully saturated conditions. (c) and (d) present the FoS results under fully dry conditions with seismic loading using the Bishop Simplified Method and the Janbu Method, respectively. (e) and (f) illustrate the FoS under full water table conditions with seismic loading using the Bishop and Janbu methods.

Figure 4 presents the slope stability analysis carried out under two groundwater conditions: fully dry condition and fully saturated condition using the Bishop simplified limit equilibrium method. This method is widely applied in slope stability analysis because it satisfies moment equilibrium and provides reliable estimates of the FoS for circular failure surfaces (Duncan et al., 2014; Huang, 2014). Under the fully dry condition (Figure 4 (a), 4 (c), and 4 (d)) the slope demonstrates a comparatively higher FoS than that of full saturation condition with seismic loading. The critical slip surface develops near the lower portion of the slope, but the overall stability remains relatively high because pore water pressure is absent. In dry conditions, the shear strength of soil is primarily governed by cohesion (c) and internal friction angle (φ), while the effective stress within the soil mass remains high. This results in greater shear resistance along the potential failure surface and consequently improves slope stability (Duncan et al., 2014; Fredlund, 2006; Tao et al., 2020).

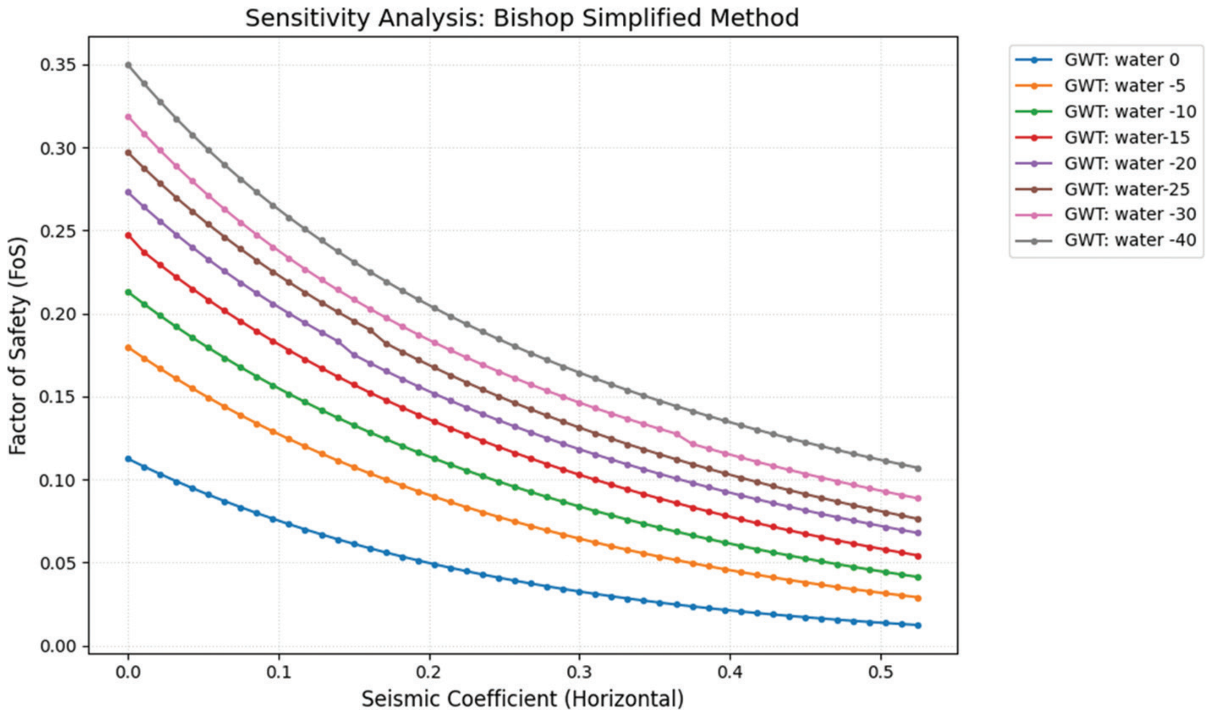
In contrast, the fully saturated condition (Figure 4(b), 4(e), and 4(f)) shows a noticeable reduction in the FoS. The contour plot indicates a larger and deeper critical failure surface compared to the dry condition. This reduction in stability occurs because saturation increases pore water pressure, which decreases the effective stress in the soil and consequently reduces the available shear strength along the failure surface. As a result, the slope becomes more vulnerable to instability. Similar behaviour has been widely reported in slope stability studies where increased groundwater pressure significantly reduces the safety factor and contributes to slope failure (Kafle et al., 2022; Kolapo et al., 2022; Zeng et al., 2024).

The sensitivity analysis clearly indicates that the slope stability is highly sensitive to groundwater conditions. When the slope becomes saturated, the decrease in effective stress and shear strength leads to a substantial reduction in the FoS. In mountainous regions such as the Himalayas, intense rainfall infiltration often increases pore water pressure, which can trigger landslides by reducing slope stability (Pelascini et al., 2022; Tian et al., 2022; Zhang et al., 2023). Therefore, groundwater conditions and rainfall infiltration should be carefully considered in slope stability assessments and in the design of appropriate drainage and mitigation measures.

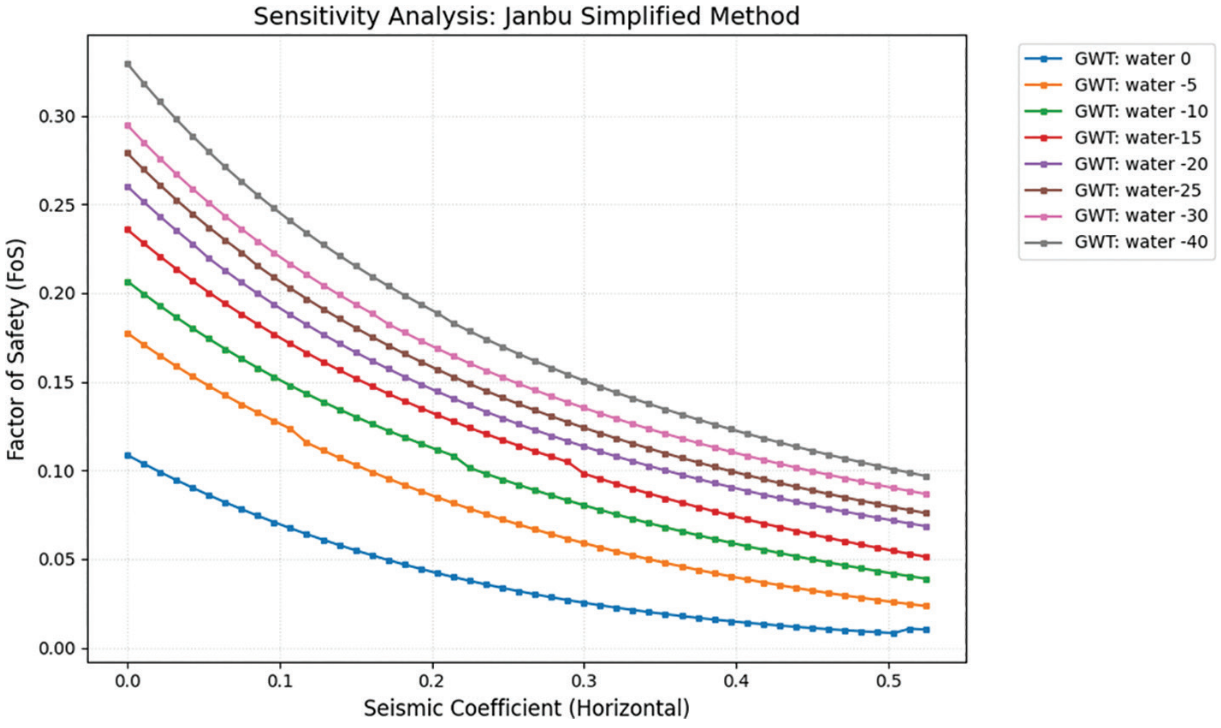
The sensitivity analysis results presented in Figure 5(a) and 5(b) illustrate the variation of the FoS with respect to the seismic coefficient (k_h) under different water table drawdown conditions using the Bishop and Janbu simplified method. The plot demonstrates the combined influence of seismic loading and groundwater conditions on slope stability. The results (Figure 5 (a) and (b)) show a consistent decreasing trend in the FoS with increasing seismic coefficient for all drawdown scenarios. When the seismic coefficient (Horizontal) increases from 0.0 to 0.5, the FoS significantly decreases. This behaviour occurs because increasing seismic forces introduce additional horizontal inertial forces acting on the soil mass, which increases the driving forces along the potential failure surface and consequently reduces slope stability (Y.-L. Chen et al., 2020; Duncan et al., 2014; Jin et al., 2024; Wang et al., 2021). The reduction in FoS with increasing seismic coefficient is a well-documented phenomenon in pseudo-static slope stability analysis.

The analysis also indicates that groundwater conditions strongly influence slope stability. As the water table drawdown increases from 0 m to 40 m, the FoS gradually increases for a given seismic coefficient. This improvement in stability occurs because lowering the groundwater level reduces pore water pressure within the slope, thereby increasing the effective stress and shear strength of the soil mass (Y.-L. Chen et al., 2020; Duncan et al., 2014; Jin et al., 2024; Wang et al., 2021). Consequently, slopes with greater water table drawdown exhibit relatively higher safety factors compared to slopes with shallow groundwater levels. This suggests that under the combined influence of seismic loading and groundwater conditions, the slope remains unstable or marginally stable (Y.-L. Chen et al., 2020). Such conditions are commonly observed in steep mountainous regions where seismic activity and groundwater infiltration significantly influence slope behaviour.

Overall, the sensitivity analysis clearly demonstrates that the FoS is highly sensitive to both seismic loading and groundwater conditions. While seismic forces act as a destabilizing factor by increasing driving forces, groundwater drawdown improves stability by reducing pore pressure. Therefore, proper consideration of seismic loading and groundwater management is essential in slope stability assessment and landslide mitigation strategies.



(a)



(b)

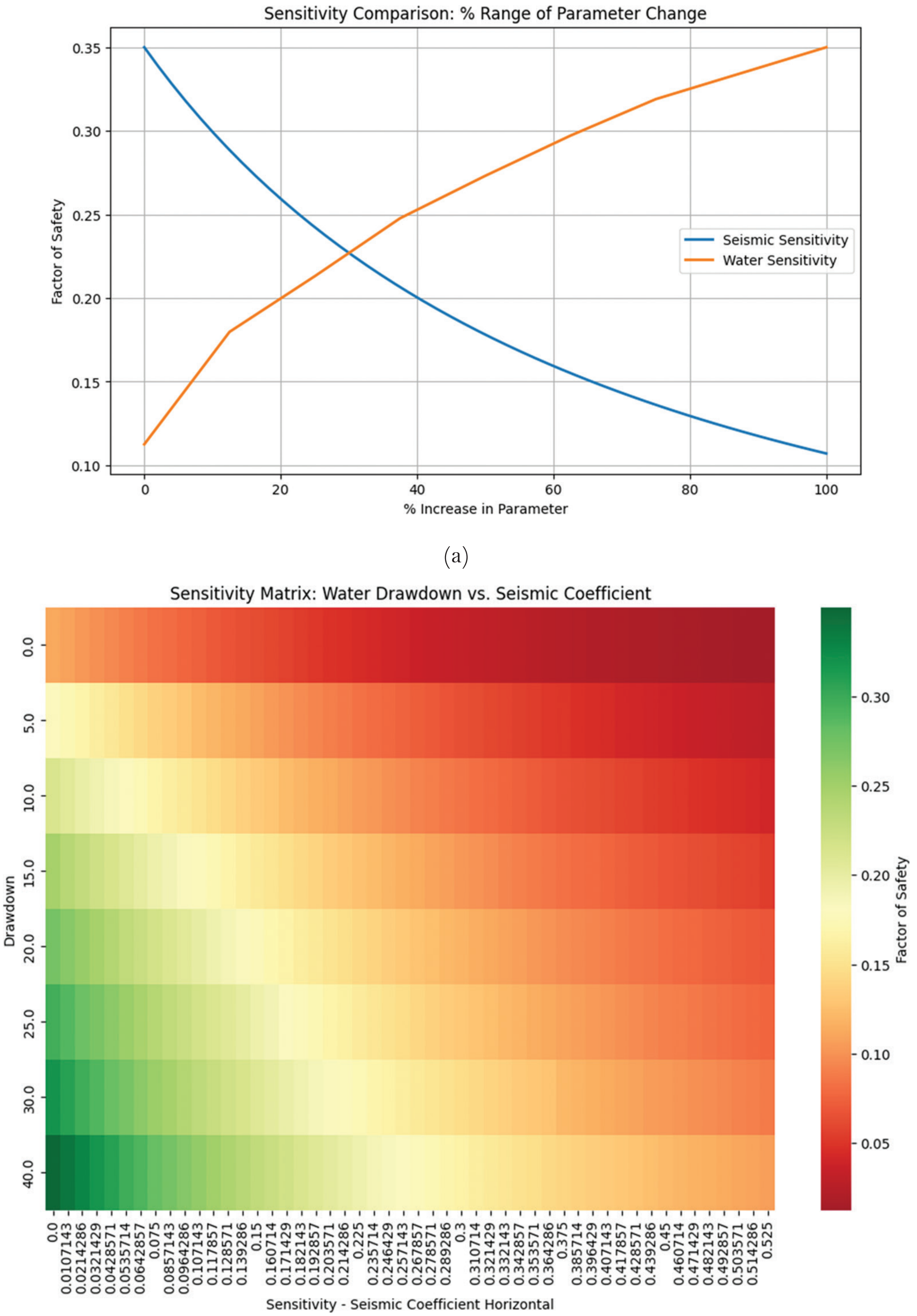
Figure 5: Sensitivity of FoS to Seismic Coefficient (Horizontal) and Water Table Conditions (a) Bishop Simplified method (b) Janbu Simplified Method

Figure 6 (a), (b), and (c) presents three graphical representations illustrating the sensitivity of the FoS to variations in seismic coefficient and water table drawdown. These figures provide a comparative understanding of how different controlling parameters influence slope stability. The sensitivity comparison plot (Figure 6a) shows the percentage change in the FoS as the seismic coefficient and water table drawdown increase. The curve representing seismic sensitivity indicates a decreasing trend in FoS with increasing seismic coefficient. This occurs because higher seismic coefficients introduce greater horizontal inertial forces that increase the driving forces acting on the potential failure surface. Consequently, the stability of the slope decreases as seismic loading intensifies (Y.-L. Chen et al., 2020). The water sensitivity curve shows that the FoS increases as the water table lowers. A decrease in groundwater level reduces pore water pressure, which increases the effective stress and shear strength of the soil, improving slope stability. This highlights the importance of groundwater control measures, such as drainage systems, in landslide-prone areas.

The heatmap (Figure 6(b)) further illustrates the combined effect of seismic coefficient and water table drawdown on slope stability. The color gradient represents variations in the FoS across different combinations of these parameters. The heatmap indicates that higher FoS values occur at larger water table drawdown levels and lower seismic coefficients, represented by green to yellow colors. Conversely, lower FoS values are observed when the seismic coefficient increases and the groundwater level remains high. This interaction confirms that both parameters jointly influence slope behaviour, and their combined effect can significantly alter the stability conditions (Y.-L. Chen et al., 2020; He et al., 2023; Qu et al., 2023; Wu et al., 2020).

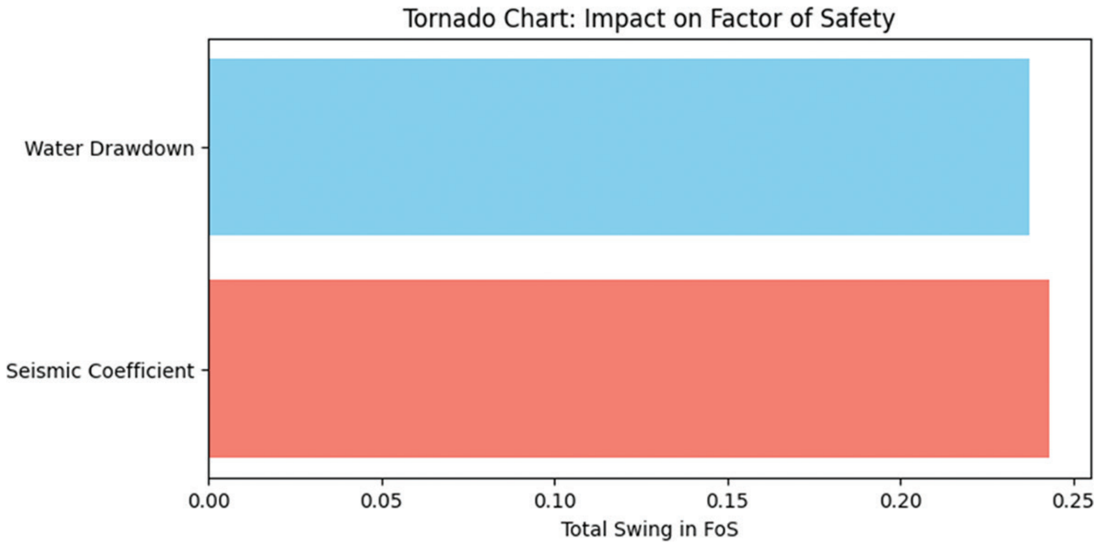
The tornado chart (Figure 6(c)) summarizes the relative influence of the analysed parameters on slope stability. The chart indicates that the seismic coefficient has a slightly greater impact on the variation of the FoS compared to water table drawdown. This result suggests that seismic loading acts as a dominant destabilizing factor in the slope system (Y.-L. Chen et al., 2020; He et al., 2023; Wu et al., 2020). However, groundwater conditions also play a significant role by modifying pore water pressure and effective stress within the soil mass.

Overall, the sensitivity analysis demonstrates that the FoS is highly dependent on both seismic forces and groundwater conditions. Increasing seismic loading reduces slope stability, while lowering the groundwater table improves stability by reducing pore pressure. Therefore, proper consideration of seismic hazard and groundwater management is essential for accurate slope stability evaluation and for designing effective mitigation strategies in landslide-prone regions.


Sensitivity Comparison: % Range of Parameter Change
Factor of Safety
0.35
0.30
0.25
0.20
0.15
0.10
0
20
40
60
80
100
% Increase in Parameter
Seismic Sensitivity
Water Sensitivity
Sensitivity Matrix: Water Drawdown vs. Seismic Coefficient
Drawdown
0.0
5.0
10.0
15.0
20.0
25.0
30.0
40.0
0.0
0.0107143
0.0214286
0.0321429
0.0428571
0.0535714
0.0642857
0.075
0.0857143
0.0964286
0.107143
0.117857
0.128571
0.139286
0.15
0.160714
0.171429
0.182143
0.192857
0.203571
0.214286
0.225
0.235714
0.246429
0.257143
0.267857
0.278571
0.289286
0.3
0.310714
0.321429
0.332143
0.342857
0.353571
0.364286
0.375
0.385714
0.396429
0.407143
0.417857
0.428571
0.439286
0.45
0.460714
0.471429
0.482143
0.492857
0.503571
0.514286
0.525
Sensitivity - Seismic Coefficient Horizontal
Factor of Safety
0.30
0.25
0.20
0.15
0.10
0.05

(a)

(b)



(c)

Figure 6: Sensitivity Analysis of Slope Stability Parameters (a) Sensitivity comparison, (b) heatmap chart, (c) Tornado chart

4. Conclusion

This study investigated the stability of the creeping landslide located at Kuiyadaha village in Baitadi District, Nepal, with particular emphasis on understanding how seismic loading and groundwater conditions influence slope stability. The laboratory test results indicate that the slope materials possess moderate shear strength, with internal friction angles ranging from 15.58° to 18.43° and cohesion values between 9.29 kN/m^2 and 11.45 kN/m^2. These parameters reflect the limited resistance of the soil mass to shear deformation, which partly explains the gradual and continuous movement observed in the study area, particularly during the monsoon season.

The slope stability analysis clearly shows that groundwater conditions play a critical role in controlling the FoS. Under dry conditions, the slope maintains relatively higher stability because effective stress remains high and shear strength is governed mainly by cohesion and internal friction. However, under fully saturated conditions, the FoS decreases significantly due to the increase in pore water pressure, which reduces effective stress and weakens the soil along potential failure surfaces. This finding highlights the strong influence of rainfall infiltration and groundwater accumulation on landslide activity in mountainous terrains.

The sensitivity analysis further demonstrates that seismic loading acts as a major destabilizing factor for the slope. As the horizontal seismic coefficient increases, the FoS consistently decreases, indicating that earthquake-induced inertial forces significantly increase the driving forces along the potential failure surface. The results confirm that the slope becomes increasingly vulnerable under higher seismic loading, particularly when groundwater levels remain high.

At the same time, the analysis shows that groundwater drawdown has a stabilizing effect on the slope. Lowering the groundwater table reduces pore water pressure and increases effective stress, which enhances the shear strength of the soil mass and improves the FoS. The graphical comparisons, including the sensitivity curves, heatmap, and tornado chart, collectively reveal that both seismic forces and groundwater conditions strongly influence slope behavior, with seismic loading exerting a slightly greater impact on stability.

Overall, the findings of this research emphasize that the stability of the Kuiyadaha landslide is highly sensitive to the combined effects of seismic loading and groundwater conditions. While seismic forces increase the likelihood of slope failure, proper groundwater management can significantly improve slope stability. Therefore, incorporating seismic considerations together with effective groundwater control measures such as drainage systems and water management strategies is essential for reliable slope stability assessment and for developing sustainable landslide mitigation practices in seismically active and rainfall-prone mountainous regions like the Himalayas.

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