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A sensitivity analysis of a Landslide to assess the influence of shear strength parameters and groundwater conditions on slope stability of Kaande Landslide

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Abstract

Slope instability is a persistent geohazard in the hilly regions of Nepal, with the Kaande landslide area in Kaski District being particularly vulnerable. This study evaluates the sensitivity of key geotechnical parameters controlling slope stability at the Kaande landslide using numerical modeling. Slope stability analyses were performed in Phase2 using the Mohr Coulomb failure criterion. Field investigations involved detailed slope profiling and soil sampling through open pit tube sampling, followed by laboratory testing to determine cohesion, internal friction angle, and unit weight. Gradation analysis classified the soil as SM–SC. A sensitivity analysis was conducted by varying cohesion, internal friction angle, and Groundwater Table (GWT) conditions individually while keeping other parameters constant. Analyses were carried out for three representative slope sections, and slope failure was identified at a Strength Reduction Factor (SRF) of 1. The relative influence of each parameter was quantified using coefficients of determination. Results show that slope stability is most sensitive to changes in the internal friction angle, with critical values of 28.93°, 29.04°, and 26.41° for Sections 1, 2, and 3, respectively. GWT variation was identified as the second most influential factor, while cohesion had a comparatively minor effect due to its low magnitude in SM–SC soils. The study concludes that frictional resistance and groundwater conditions are the primary controls on slope stability at Kaande. These findings provide a practical basis for designing effective slope stabilization and groundwater management measures in similar geological and geomorphological settings across Nepal.

Keywords

Slope stability; Sensitivity analysis; Phase2 numerical modeling, Mohr Coulomb failure criterion

1. Introduction

Landslides are one of the most common and damaging natural hazards in mountainous areas, especially in the Himalayas. This is mainly because steep slopes, heavy rainfall, and weak ground conditions occur together, making the land highly unstable [1]. In Nepal, landslides caused by intense monsoon rainfall have repeatedly led to loss of lives, damage to houses, and destruction of roads and hydropower facilities [2]. These repeated impacts highlight the importance of using reliable methods to assess slope stability.

Kaski District, located in Gandaki Province, experiences high rainfall and has complex ground conditions, which makes it particularly prone to both shallow and deep landslides. In this setting, more than 75% of the total yearly rainfall in Nepal occurs during the summer season [3, 4]. Intense rainfall is widely recognized as the primary factor that triggers slope failures in the country [5-7]. Most of these events take place every year during the monsoon period and lead to considerable loss of lives and damage to property across Nepal [8-10].

Slope failures often cause serious damage to civil engineering structures such as roads, bridges, and other infrastructure [11]. In Nepal, landslides occur due to a combination of several factors, including geological conditions, slope shape, physical processes, and human activities [5, 12-16]. A landslide is defined as the movement of soil, rock, and vegetation downslope under the force of gravity, as well as the landform that results from this movement [17].

Many studies around the world have shown that slope failure is mainly controlled by three groups of factors: material strength, slope geometry, and water conditions [18]. Among these, shear strength parameters such as cohesion and friction angle are often the most important. Unit weight also matters because it controls the driving force acting on a slope. Groundwater is often the main trigger, as it reduces strength and increases pressure inside the slope during rainfall [19].

In recent years, computer-based methods have become widely used in slope stability studies. Finite element method (FEM) tools allow engineers to model complex ground conditions more realistically than older limit equilibrium methods. One widely used FEM tool is Phase2, developed by Rocscience. Phase2 uses the Shear Strength Reduction (SSR) method to calculate the factor of safety by slowly reducing material strength until failure occurs [20, 21].

Sensitivity analysis using FEM tools has gained attention because it helps deal with uncertainty. Studies from different regions have shown that slope safety is often most sensitive to friction angle and GWT, while cohesion and unit weight may play a smaller but still important role [22]. Sensitivity analysis is especially useful in landslide prone regions where field data are limited.

In Nepal, landslides are a common problem due to young geology, steep slopes, and strong monsoon rainfall. Several studies have mapped landslide areas and linked them to rainfall patterns [10, 23]. Research has shown that about 80% of annual rainfall in central Nepal occurs during the monsoon months, leading to frequent slope failures. Pokhara Valley in Kaski District receives the highest rainfall in Nepal because of the strong uplift of moist air by the Annapurna range.

Although landslides in Kaski District are widely reported, detailed slope stability studies of major active landslides remain limited. The Kaande landslide, one of the largest and most active landslides in the Phewa watershed, has not been adequately analyzed to understand how variations in key strength parameters such as cohesion and friction angle, along with changes in groundwater level, influence its stability. Most previous studies have focused mainly on landslide mapping and general triggering factors, rather than examining the sensitivity of slope stability to these critical parameters that vary with rainfall and seasonal conditions. In addition, the application of Phase2 for sensitivity based slope stability analysis is still rare in Nepal, particularly in the Himalayan region, which limits the use of advanced numerical tools to clearly identify the controlling factors of slope failure and to support effective landslide mitigation planning.

This study investigates how existing ground conditions and variations in cohesion, friction angle, and GWT level influence the slope stability of the Kaande landslide using Phase2 finite element modeling. The objectives of the research are to evaluate the current stability condition of the Kaande landslide under present ground and groundwater conditions and to assess the sensitivity of slope stability to changes in cohesion, friction angle, and groundwater level in order to identify the most critical parameters controlling slope failure.

2. Methodology

2.1 Study area

The landslide area extends from the crown at about 28°16′38.54″ N and 83°48′42.69″ E, with an elevation of around 1908 m, down to the toe located near 28°16′45.73″ N and 83°49′04.35″ E at an elevation of about 1619 m. From side to side, the landslide spreads from one margin at 28°16′38.28″ N and 83°48′58.57″ E, with an elevation of roughly 1730 m, to the opposite margin at 28°16′47.69″ N and 83°48′51.48″ E, where the elevation is about 1776 m. Overall, the landslide measures approximately 597 m in length and about 397 m in width. The map of the study area is shown in Figure 1.

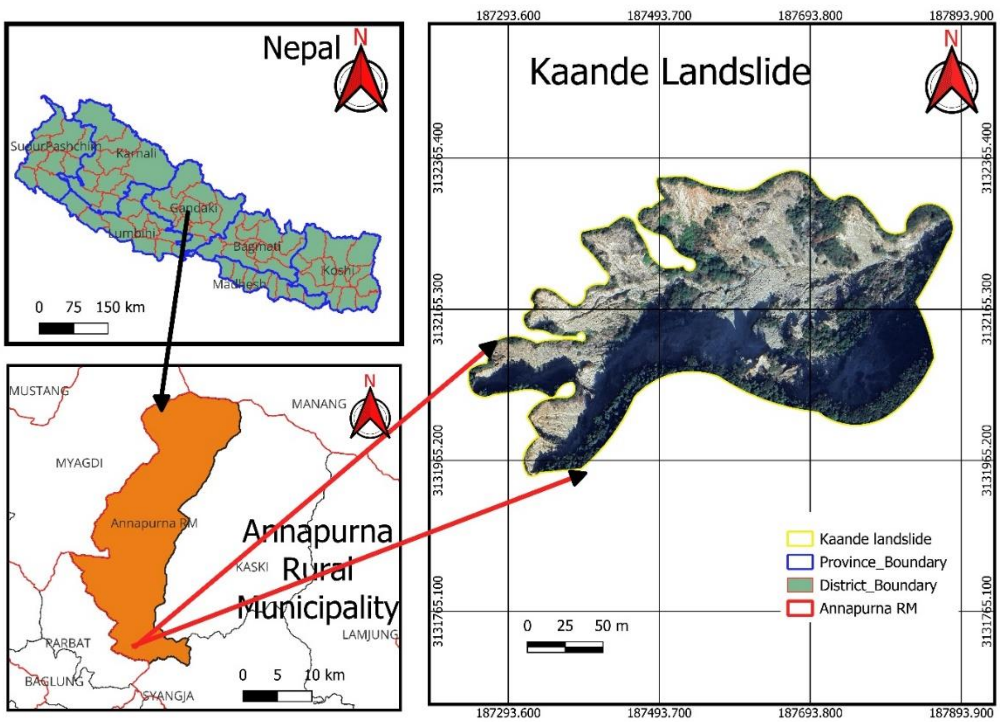


Figure 1: Study area map of Kaande Landslide, Kaski, Gandaki Province, Nepal

The Kaande landslide exhibits a steep and complex slope profile, which plays a key role in its high instability. Along the main direction of movement, the slope descends from the crown at approximately 1908 m to the toe at 1619 m, resulting in a vertical drop of 289 m over a horizontal distance of 597 m. This gives an average longitudinal slope of around 48%, or roughly 25–26°, indicating a steep incline typical of landslide-prone areas in mountainous terrain. Such a steep slope naturally increases the gravitational driving forces acting on the slope mass, making it highly susceptible to movement, particularly during periods of heavy rainfall when pore water pressures rise and the shear strength of the soil and weathered rock is reduced.

Laterally, the slope varies from 1730 m on one side to 1776 m on the opposite side over a width of approximately 397 m. This gives a gentler lateral slope of about 11–12°, which, while less steep than the longitudinal slope, still influences the overall stability. The combination of steep longitudinal and moderate lateral slopes suggests that any movement along the main failure direction could propagate laterally, potentially widening the affected area. This lateral component also affects the distribution of stresses within the slope and the way water infiltrates during rainfall events, which can further destabilize the slope.

A detailed site visit was conducted to study the Kaande Landslide in Kaski District, Nepal. The main purpose of this visit was to collect essential survey information, review existing reports, identify sampling locations, and obtain soil samples for laboratory testing and analysis. The study area of the Kaande Landslide is illustrated in Figure 1.

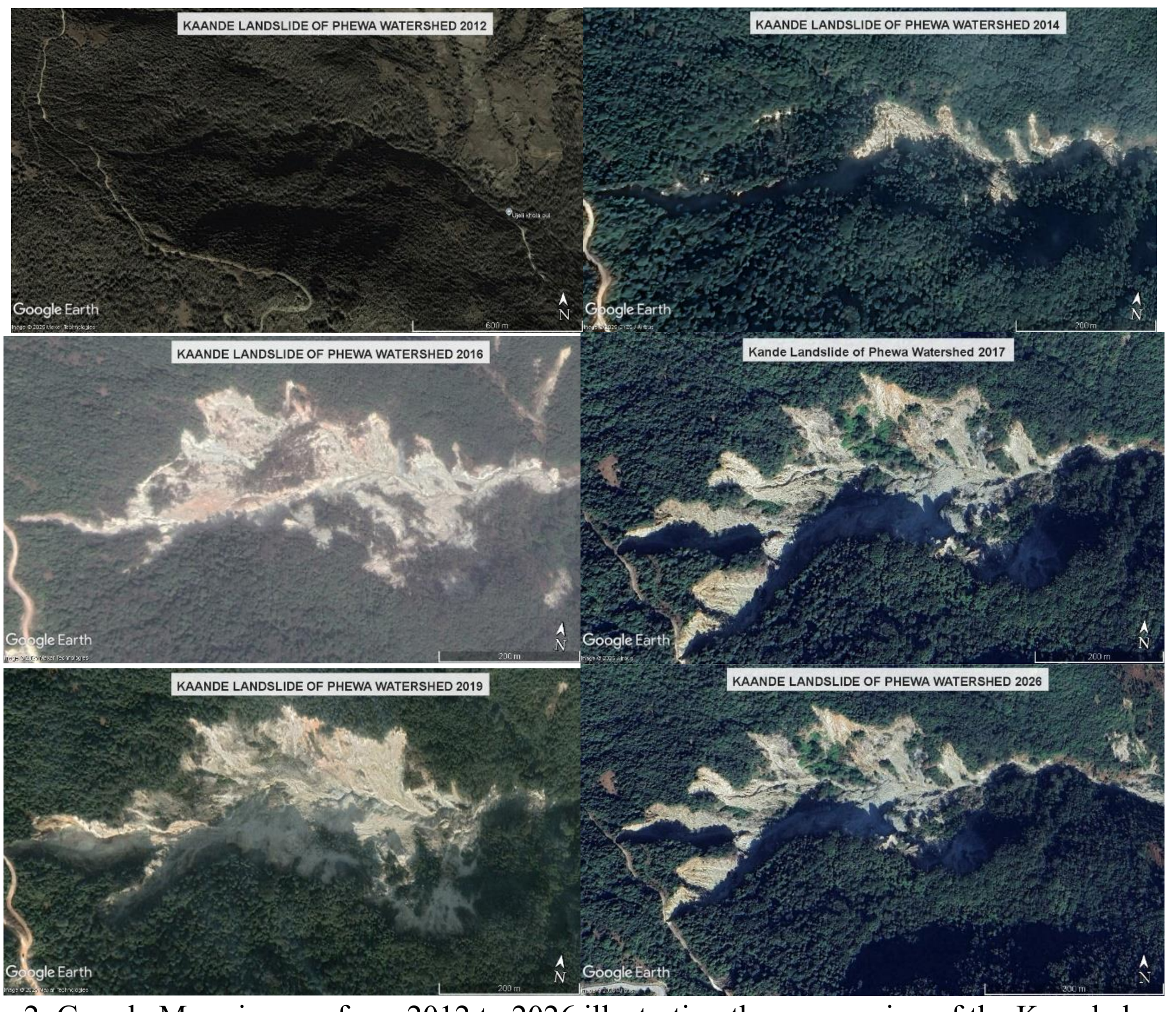


Figure 2: Google Maps images from 2012 to 2026 illustrating the progression of the Kaande landslide in Kaski District.

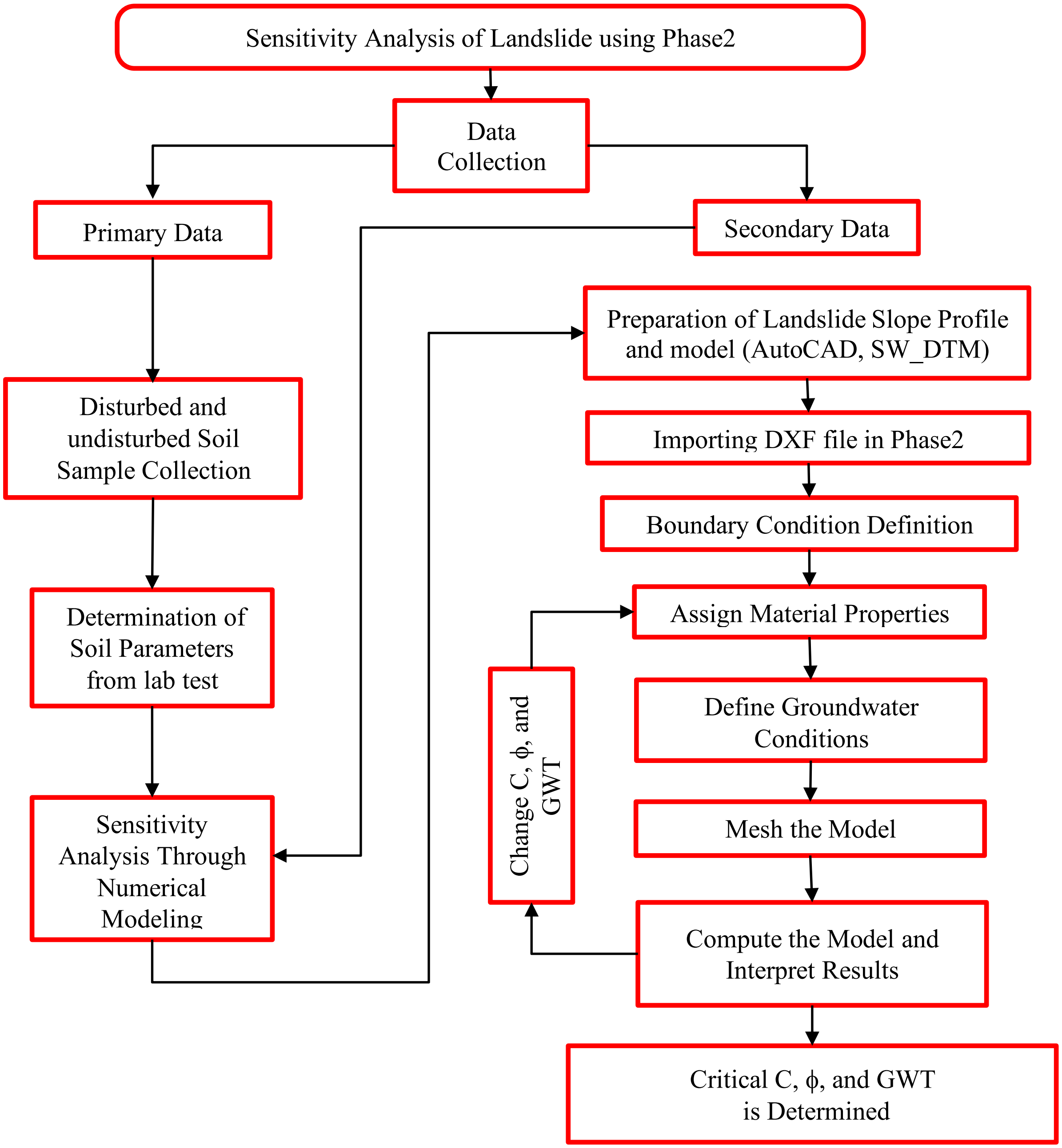


Figure 3: Workflow for the numerical and computational analysis

Google map of Kaande landslide is shown in Figure 2 from 2012 to 2026, showing the sequence of landslide occurrence before and after slope failure. To ensure a systematic assessment of the slope materials, a structured workflow was followed, as shown in Figure 3. For the purpose of analysis and modeling, the landslide site was divided into three sections. From each section, both disturbed and undisturbed soil samples were collected using a thin-walled tube sampler through the open-pit method. These samples were then prepared and tested in the laboratory to determine their geotechnical properties, including grain size distribution, and shear strength using direct shear tests.

The results from these tests provided the fundamental input parameters for numerical modeling, thereby directly linking the laboratory characterization of the soil to the slope stability assessment of the landslide.

Slope profiles of the landslide were first prepared using AutoCAD and SW_DTM to represent the geometry of the slope sections in a clear and accurate manner. These profiles were then imported into Phase2, where meshing and material mapping were carried out to simulate the slope conditions observed in the field. The numerical model was developed as a two-dimensional plane strain problem. Boundary conditions were applied by fixing the base and side of the model, while the remaining slope is free to move. Different researchers have emphasized that, in professional geotechnical practice, the depth of a numerical or physical model must be sufficiently large to prevent the fixed base boundary from influencing the formation and development of the failure surface [24, 25]. In the finite element model of the Kaande landslide, Kaski, Pokhara, Nepal, the bottom boundary of the model (minimum 64m below ground surface) was placed at the lowest elevation of the slope profile, extending below the landslide toe to represent the stable underlying ground. The base boundary was fixed in both horizontal and vertical directions ($U_x = 0$, $U_y = 0$) to prevent rigid body movement of the entire model [24, 25]. This boundary condition arrangement follows common practice in finite element slope stability analysis to reduce boundary effects and obtain realistic factor of safety values.

Geotechnical parameters obtained from laboratory testing were assigned to the model materials. These included cohesion (c), internal friction angle (φ), and unit weight (γ). The values of cohesion and friction angle were taken directly from laboratory test results for each section of the landslide, while unit weight was assigned based on the corresponding sampling. Sensitivity analysis was carried out using the laboratory test results as the base condition. In the first step, cohesion was varied while all other parameters were kept constant to evaluate its effect on slope stability. Next, the friction angle was varied independently, with all other parameters unchanged, to determine the corresponding SRF. Finally, groundwater conditions were analyzed by lowering the water table from a fully saturated state up to 10 m drawdown and calculating the SRF for each case. Through this step-by-step approach, the critical shear strength parameters controlling the stability of the slope were identified.

3. Results and Discussion

The particle size distribution curve indicates that the Kaande landslide material is a well-graded soil consisting of a wide range of particle sizes, predominantly sand with a significant amount of fines (silt and clay), and minor gravel content. Based on this gradation, the soil can be classified as SM or SC type depending on the plasticity of the fines as shown in Figure 4. The soil is predominantly SM–SC with less than 5% fines. Therefore, under dry conditions, shear strength is mainly governed by frictional resistance and mechanical interlocking between sand particles. Since pore water pressure is absent in dry conditions, the friction angle is fully mobilized, resulting in adequate shear strength [26, 27]. Although the fines content is relatively low (≈5%), their presence slightly reduces the permeability compared to clean sand by partially filling the pore spaces. Under prolonged or intense rainfall, infiltration may exceed drainage capacity, leading to temporary pore water pressure buildup [28]. This reduces effective stress and shear strength, contributing to rainfall-induced slope instability, particularly under saturated conditions [29].

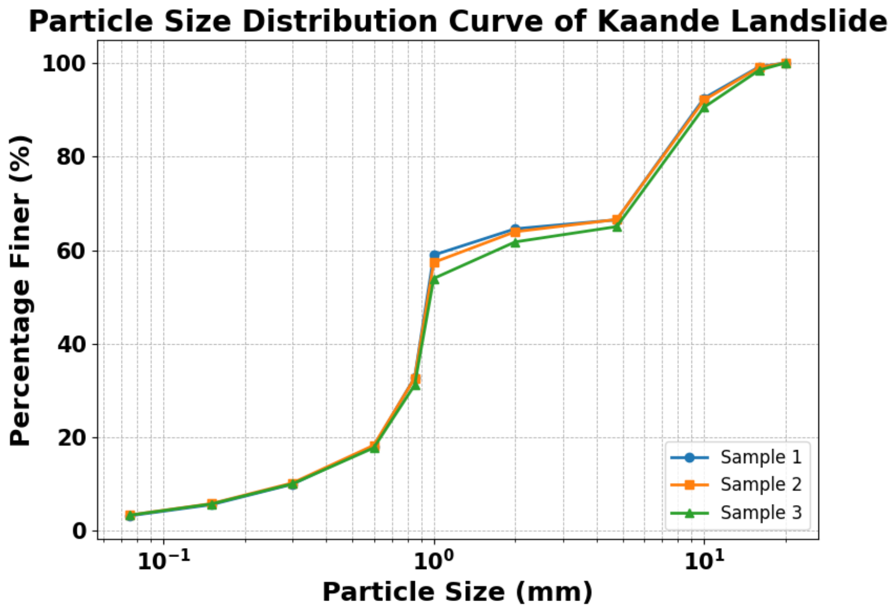


Figure 4: Grain size distribution characteristics of the collected soil samples

The results of the direct shear test show that the soil samples cohesion and internal friction angle conform to the Mohr Coulomb failure criterion, demonstrated by a linear relationship between normal stress (x-axis) and shear stress (y-axis) (Figure 5). Scatter in the data points suggests variability in soil composition, which may influence the accuracy of stability assessments. Soils exhibiting lower cohesion values (1.961-3.537 kN/m²) and smaller friction angles (31.3°–32.129°) provide reduced shear strength, thereby increasing the susceptibility of slopes to failure [30, 31].

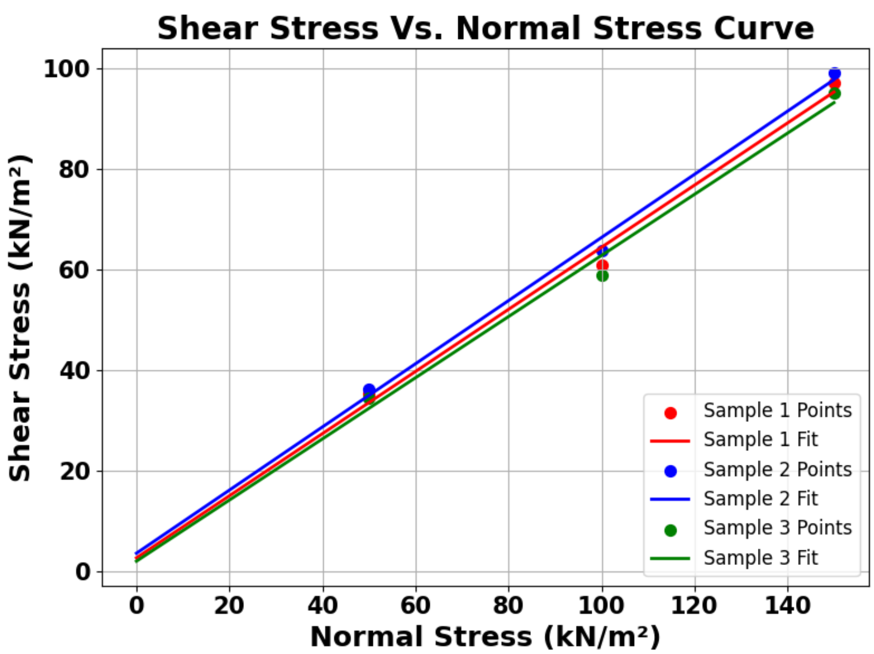


Figure 5: Shear strength parameters obtained from laboratory direct shear testing

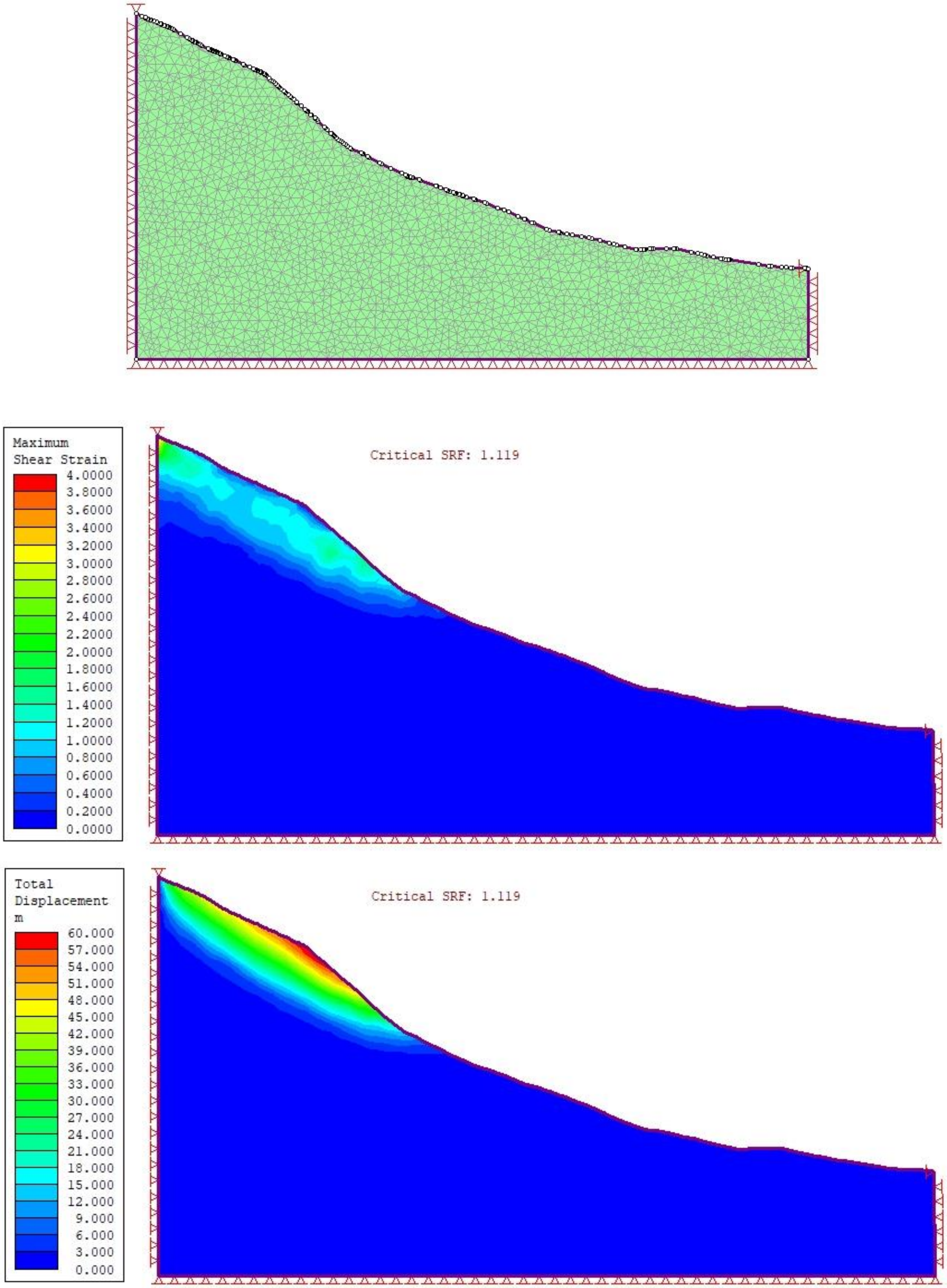


Figure 6: Model with material assignment and messing, Distribution of the potential maximum shear strains and Distribution of total displacement corresponding to c = 2.65 KPa and an internal friction angle of 31.708° for Section 1

A sensitivity analysis was conducted to evaluate the influence of key geotechnical and hydrological parameters on slope stability using Phase2 (Figure 6). The SRF was used as the stability indicator. Cohesion was varied from 0 kPa to 18.037 kPa to assess its contribution to overall stability while keeping all other parameters constant and then only model was computed in Phase2 for analysis. The model results show a corresponding increase in SRF as cohesion increased. The slope exhibited marginal stability at lower cohesion values, while higher cohesion significantly improved the factor of safety. This demonstrates that even modest increases in cohesive strength can substantially influence slope performance.

The slope of each Cohesion vs SRF curve provides important insight into the sensitivity of slope stability to changes. Steeper curves indicate that small variations in cohesion can cause significant changes in the SRF, reflecting high sensitivity, whereas gentler slopes suggest lower sensitivity. The critical cohesion points, highlighted on the graph, represent the minimum cohesion required for the slope to reach a stable condition (SRF = 1). As shown in Figure 7, all three soil samples exhibit relatively gentle slopes, indicating low sensitivity of SRF to cohesion changes. Importantly, the critical cohesion values for Sample 1 (≈0.06 kPa), Sample 2 (≈0.31 kPa), and Sample 3 (≈0.24 kPa) are all lower than the cohesion values measured in laboratory tests. This implies that the slopes are inherently stable under current soil conditions, and small reductions in cohesion are unlikely to compromise overall slope stability. These findings highlight the significant impact of cohesion on slope behavior and demonstrate that the existing soil strength is sufficient to maintain stability [30, 32].

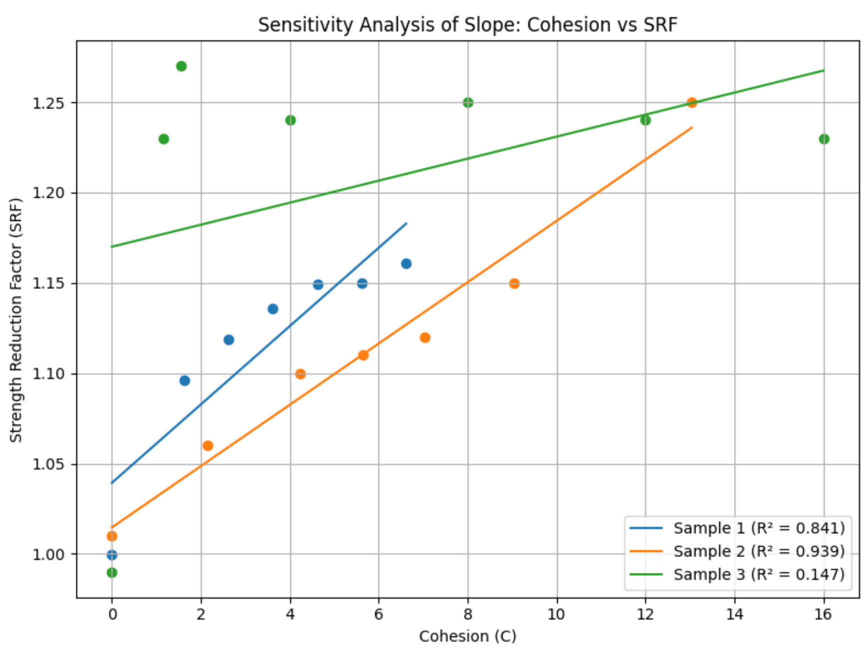


Figure 7: Sensitivity analysis of slope for Cohesion Vs SRF for three soil sample

The internal friction angle (ϕ) was varied from 21.707° to a maximum value of 42.128° for all three samples, while keeping other parameters constant, and then modeling was done in Phase2 for determine the corresponding SRF value. The results indicate a progressive increase in SRF with increasing friction angle, confirming the strong dependence of slope stability on shear strength parameters. Higher ϕ values enhanced the shear resistance of the slope material, leading to improved stability conditions.

Analysis of the SRF versus friction angle in Figure 8 reveals that the SRF increases with increasing friction angle for all three soil samples. The steepness of each SRF curve reflects the sensitivity of slope stability to friction, a steeper curve indicates greater sensitivity, where even small variations in friction angle result in significant changes in SRF. The critical friction angles required to achieve SRF = 1 are approximately 28.93° for Section 1, 29.04° for Section 2, and 26.41° for Section 3. So the friction angle is the critical parameter for the evaluation of slope stability analysis [32, 33].

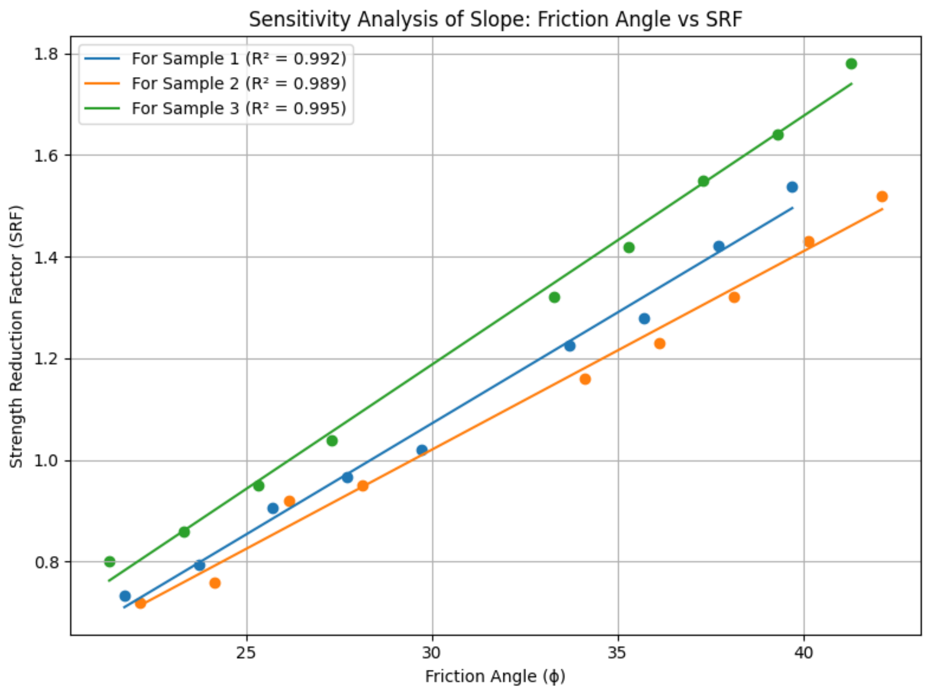


Figure 8: Sensitivity analysis of slope for Friction Angle Vs SRF for three soil sample

To assess the hydrological influence on slope stability, the GWT was gradually lowered from a fully saturated condition to 30 m below the ground surface. During the analysis of all three samples, the remaining material parameters were kept constant, while the GWT was reduced stepwise. At each stage, the corresponding SRF was determined from the model results. The results show that lowering the GWT increased the SRF. This behavior reflects the reduction in pore water pressure and the associated increase in effective stress, which enhances shear strength and slope stability. The fully saturated condition produced the lowest SRF values [34], highlighting the critical role of GWT in slope failure mechanisms. Figure 9 illustrates how the SRF changes with decreasing GWT for the three soil samples at the Kaande landslide site. Each sample shows a distinct response, reflecting differences in their sensitivity to groundwater changes. The critical reduction in GWT, corresponding to SRF = 1, represents the threshold at which the slope would become unstable: approximately -24.55 for Sample 1, -23.68 for Sample 2, and -162.00 for Sample 3. Steeper curves indicate that slope stability is more sensitive to changes in the GWT, indicating even small variations in GWT can significantly affect the slope's stability [33, 35, 36].

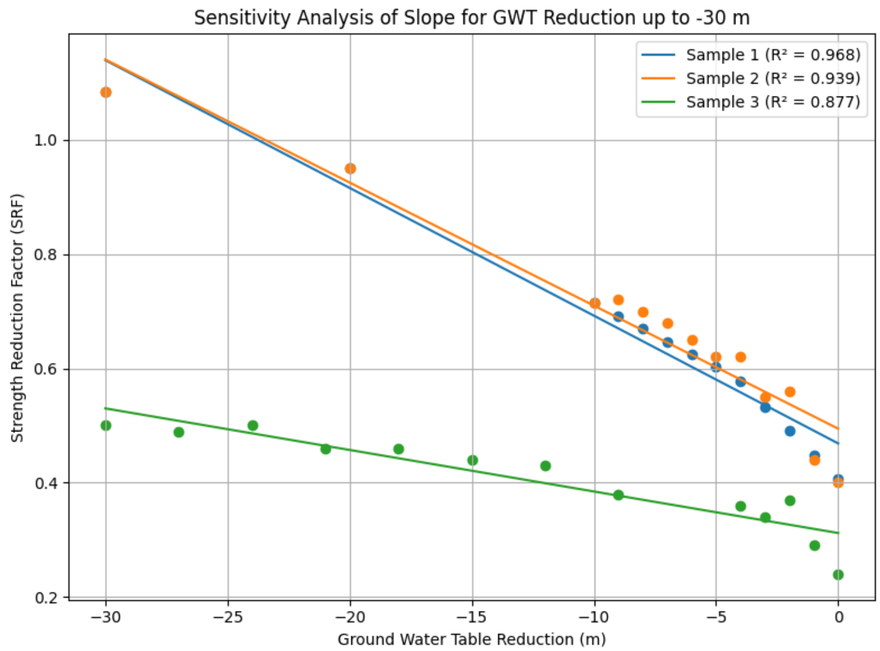
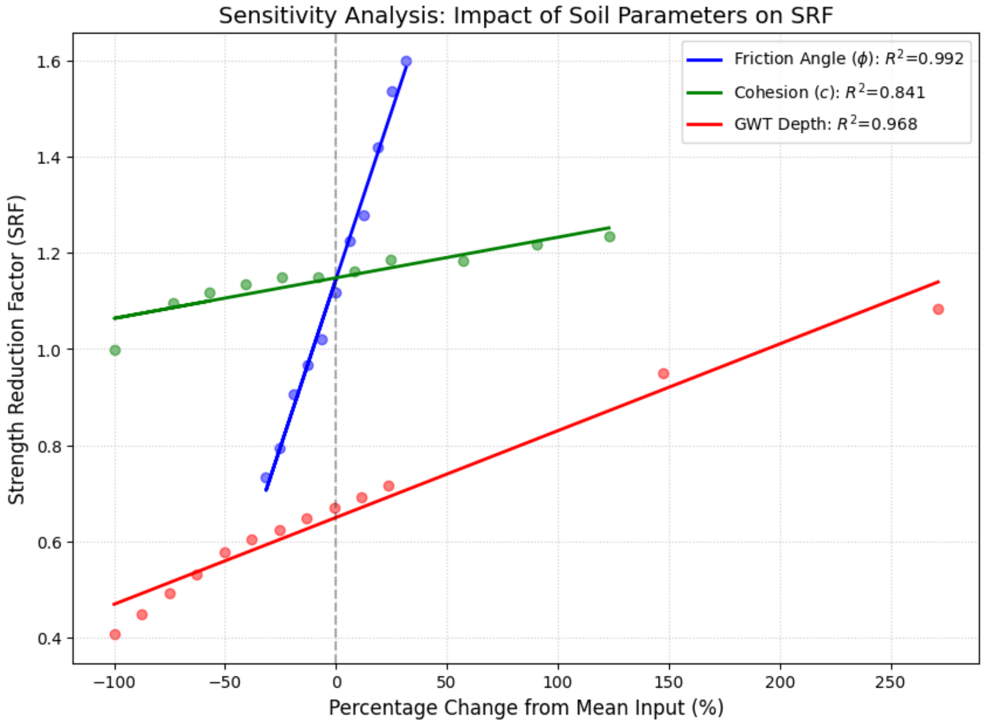


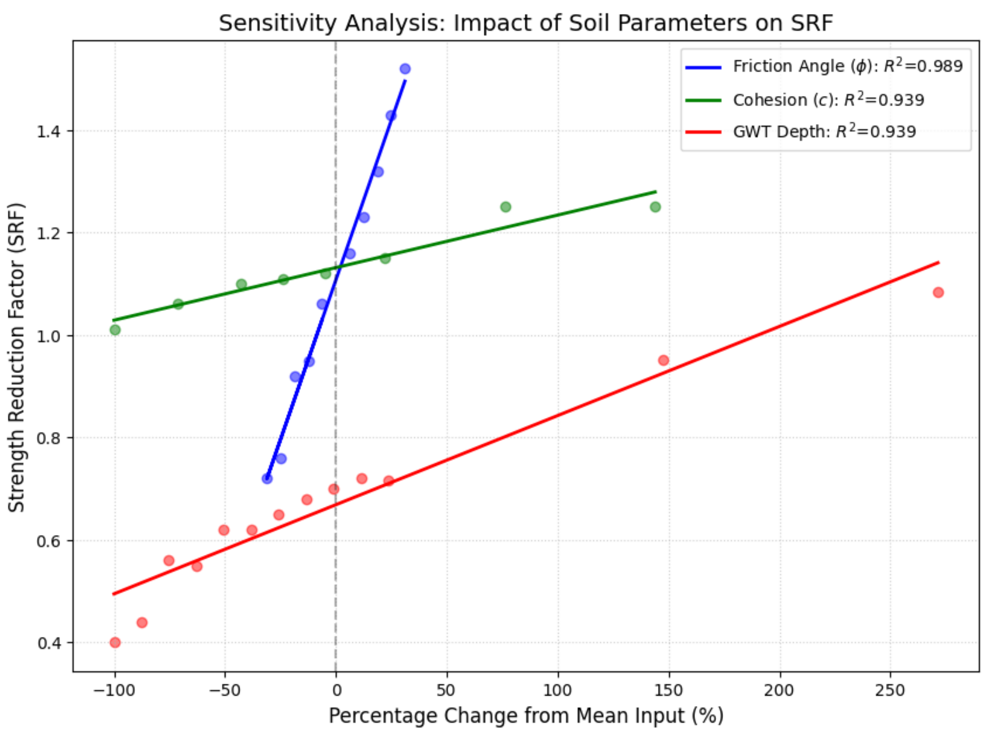
Figure 9: Sensitivity analysis of slope for GWT reduction Vs SRF for three soil sample

The sensitivity analysis based on the coefficient of determination (R^2) demonstrates clear differences in how key geotechnical parameters influence slope stability across the three soil samples as shown in Figure 10. Among all variables, the friction angle consistently shows the strongest relationship with the SRF, with R^2 values ranging from 0.989 to 0.995. This indicates that variations in internal friction almost entirely control the changes in slope stability, making friction angle the most critical parameter for all analyzed cases. GWT depth reduction also exhibits a strong correlation with SRF (R^2= 0.877 to 0.968), highlighting the important role of pore water pressure and saturation in reducing effective stress and destabilizing slopes [33]. In contrast, cohesion shows variable influence, while it contributes significantly in Samples 1 and 2, its very low R^2 value in Sample 3. The analysis shows that the slope's stability is more sensitive to friction angle and groundwater conditions than to cohesion. The low R^2 value for cohesion (0.147) for sample 3 indicates that small changes in cohesion have little effect on the SRF under the modeled conditions, while other factors such as internal friction angle or groundwater depth dominate slope stability. Overall, the sensitivity ranking derived from this analysis identifies friction angle as the dominant controlling parameter, followed by groundwater conditions, with cohesion playing a secondary and soil dependent role in slope stability behavior. This observation is consistent with previous studies showing that friction angle plays a dominant role in determining shear strength and factor of safety in both Finite Element Method and strength reduction based numerical analyses [37].



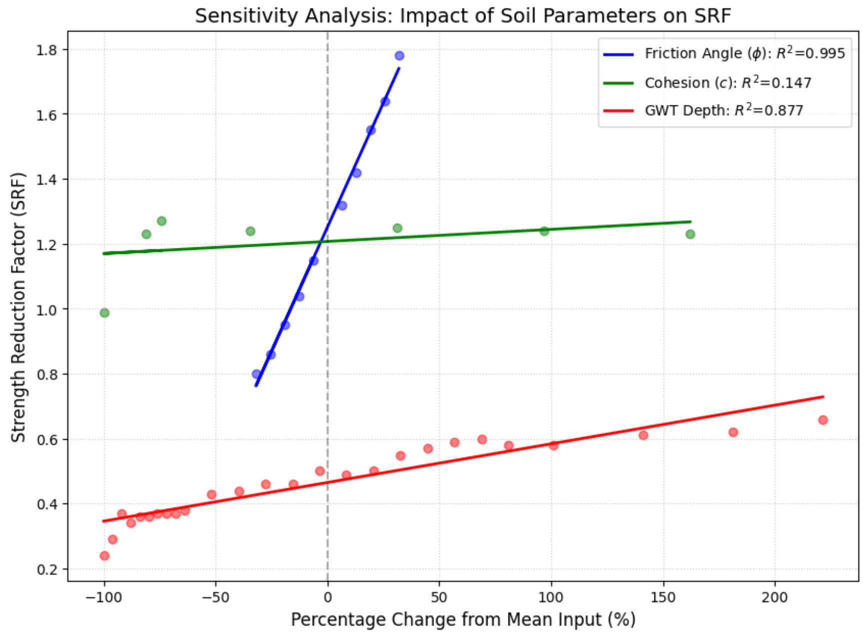
Sensitivity Analysis: Impact of Soil Parameters on SRF
Friction Angle (ϕ): R^2=0.992
Cohesion (c): R^2=0.841
GWT Depth: R^2=0.968
Strength Reduction Factor (SRF)
Percentage Change from Mean Input (%)

(a)



Sensitivity Analysis: Impact of Soil Parameters on SRF
Friction Angle (ϕ): R^2=0.989
Cohesion (c): R^2=0.939
GWT Depth: R^2=0.939
Strength Reduction Factor (SRF)
Percentage Change from Mean Input (%)

(b)



(c)

Figure 10: Comparison of the influence of friction angle, cohesion, and GWT on slope stability across three soil samples based on R^2 values (a) Sample 1 (b) Sample 2 and (c) Sample 3

4. Conclusions

The sensitivity analysis of the Kaande landslide slope using Phase2 has provided valuable insights into the stability behavior of the slope under varying geotechnical parameters. The analysis was conducted using the Mohr Coulomb failure criterion, which effectively captured the shear strength behavior of the slope material. Gradation analysis identified the soil as SM-SC type, indicating a silty sand to clayey sand composition, which significantly influences the mechanical behavior and overall stability of the slope. Notably, the cohesion values of the soil were relatively low in comparison to the internal friction angle, highlighting the predominant role of friction in maintaining slope integrity.

The results of the sensitivity analysis revealed that variations in the friction angle had the most pronounced impact on slope stability across all three sections studied. Changes in cohesion, while still relevant, had a comparatively smaller effect on the factor of safety. Additionally, reduction in the GWT emerged as the second most critical factor influencing slope behavior, indicating the importance of pore water pressures in destabilizing the slope. These findings underscore the necessity of considering both shear strength parameters and hydrogeological conditions when evaluating landslide prone areas.

Overall, the study demonstrates that for the Kaande landslide site, the slope stability is highly sensitive to frictional properties of the soil, with cohesion and GWT reduction serving as secondary but still significant factors. This understanding can guide targeted mitigation strategies, such as slope reinforcement, drainage improvement, or soil stabilization, prioritizing parameters that most significantly influence slope safety. The Phase2 based analysis provides a robust framework for future stability assessments and risk management in similar soil slopes.

Conflicts of Interest Statement

The author declares no conflicts of interest for this study.

Data Availability Statement

The data supporting the findings of this study are presented in the manuscript. Additional data will be provided upon request.

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