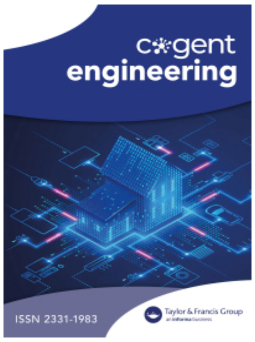

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CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

Geotechnical analysis and stability assessment of a landslide event in Gera Woreda, Ethiopia

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ABSTRACT

This study investigates the geotechnical factors influencing a recent landslide event in Gera Woreda, Ethiopia. The primary objective was to identify the soil properties contributing to landslide occurrence and understand the triggering mechanisms. Field investigations, soil sampling from both affected and unaffected areas, and subsequent laboratory characterization were conducted. The analysis revealed a dominance of fine-grained soils, such as clay and silt, which are susceptible to weakening upon saturation, thereby increasing landslide susceptibility. Rainfall is identified as the primary trigger for the landslide. Numerical stability assessments using the Limit Equilibrium Method (software, Slide™) and the Finite Element Method (software, PLAXIS®) were performed to assess the stability of the slopes. The stability analysis revealed a notable decrease in the factor of safety (FS) under rising groundwater levels. For example, the FS for Slope 1 decreased from 1.42 under dry conditions to 0.73 at a 2 m groundwater depth. Similarly, Slope 2's FS decreased from 2.06 to 1.18 under similar conditions. These results emphasize that rainfall is the primary trigger for landslides in the area. To address this, the study proposes surface drainage systems and the planting of Vetiver grass to improve slope stability. These findings provide critical insights for developing proactive mitigation strategies to protect local communities and infrastructure from landslide hazards.

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1. Introduction

Landslides, a pervasive threat to communities worldwide, inflict significant casualties, infrastructural damage, and economic disruption. These mass movements, triggered by a complex interplay of natural and anthropogenic factors, occur across diverse geographical regions (Haque et al., 2019).

The highlands of Ethiopia, in particular, are prone to landslides, necessitating detailed investigations to mitigate associated risks (Alemayo & Eritro, 2021). Despite the global understanding of landslide triggers, the specific geotechnical factors leading to slope failures in Ethiopia remain underexplored. This study addresses this research gap by focusing on the recent landslide event in Gera Woreda, Ethiopia, with the primary objective of elucidating the underlying geotechnical controls contributing to its occurrence.

Slope failure, often used interchangeably with landslides, occurs predominantly along sloped terrains due to various triggering factors. While natural causes such as water, earthquakes, and volcanic activities significantly influence slope stability (Hack et al., 2007), human activities, including construction practices and land modifications, also play a crucial role in exacerbating landslide risks (Alexander, 1992). Intense rainfall induces an elevation in pore pressure and reduction in the effective stress of the soil, ultimately weakening its shear strength and predisposing slopes to failure (Igwe et al., 2014; Qu et al., 2024; Sengani & Mulenga, 2020; Yang et al., 2018). Besides rainfall, factors such as slope steepness, presence of soft soils over impermeable rocky materials, and deforestation further contribute to landslide occurrences (Ayenew & Barbieri, 2005).

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Ethiopia has a history of landslides, resulting in substantial property damage and loss of lives across the country (Abebe et al., 2010; Asnakew et al., 2019; Broothaerts et al., 2012; Mebrahtu, 2021; Woldearegay, 2013). The concentrated and heavy rainfall concentrated during the July-August monsoon season infiltrates the ground, triggering slope failures across the country (Ayalew, 1999; Gidday et al., 2023; Mebrahtu, 2021). The highlands of Ethiopia, in particular, are prone to landslides, necessitating detailed investigations to mitigate associated risks (Alemayo & Eritro, 2021). Gera Woreda, a small city in Ethiopia, recently experienced a landslide triggered by heavy rainfall, emphasizing the critical need to understand the geotechnical conditions underlying such events (Kabeta et al., 2023). This study hypothesizes that the landslide in Gera Woreda was primarily triggered by the interplay of specific geotechnical factors, including soil composition, permeability, and shear strength, exacerbated by heavy rainfall. To evaluate landslide stability in this context, existing literature provides valuable insights. For instance, studies like (Han et al., 2019) and (Xue et al., 2024) offer methods and perspectives that can be applied to the Ethiopian context. However, these approaches need adaptation to the specific geotechnical conditions in Gera Woreda. This study investigates into the recent landslide event in Gera Woreda, Ethiopia, with the primary objective of elucidating the underlying geotechnical controls that contributed to its occurrence. This study draws upon a master's thesis by Tamiru et al. (2021) which includes detailed geotechnical laboratory testing of soil samples collected from both affected and unaffected areas. These tests were used to characterize crucial soil properties such as composition, permeability, and shear strength. Furthermore, slope stability assessments were conducted using both the Limit Equilibrium Method (software, Slide™) and the Finite Element Method (software, PLAXIS®), providing comprehensive numerical analysis of the slopes under various conditions. As part of the thesis, this paper presents the key geotechnical factors responsible for the landslide and propose targeted mitigation strategies to minimize future landslide risks in this region.

2. Study area

The investigation is centered on Gera Woreda, located in the Jimma zone of Ethiopia's Oromia Regional State (Figure 1). This area is situated about 345 km southwest of the capital, Addis Ababa, and approximately 100 km southwest of Jimma City, the zone's capital. Gera Woreda has a notable elevation range from 1390 m to 2980 m above sea level, featuring rugged volcanic mountainous terrain with a mix of high and low relief hills. The region receives a significant average annual rainfall of 1955.4 mm. Rainfall patterns indicate lower amounts in January, February, and December, while the primary rainy season occurs from May to September, with the heaviest precipitation in June, July, and August.

The topography of Gera Woreda plays a critical role in landslide susceptibility. The area's rugged mountainous terrain, combined with steep slopes and varying elevations, significantly contributes to the risk of landslides, especially in regions with high relief. The presence of fault structures within the region further exacerbates this risk, as these geological features can weaken the structural integrity of the slopes, making them more prone to failure during heavy rainfall or seismic activity.

Gera Woreda is home to a population predominantly engaged in agriculture, with settlements often located on or near steep slopes. The region's history includes several significant landslide events, particularly following periods of intense rainfall. These incidents have resulted in considerable damage to property and infrastructure, highlighting the urgent need for effective mitigation strategies. Figure 1 highlights the specific locations of the landslide-prone areas within Gera Woreda. These locations have been identified based on historical landslide occurrences and the analysis of the area's topography and fault structures. The map provides a clear visual representation of the affected regions.

3. Methodology

This section provides a detailed overview of the comprehensive methodological framework employed to investigate the geotechnical conditions and stability of the Gera Woreda landslide. The methodologies encompassed various stages, including data collection procedures, laboratory testing methods, and numerical analysis techniques

3.1. Data collection procedures

Field surveys were conducted following the occurrence of landslides to assess the extent of the damage and identify areas affected by mass movement. Initial site visits involved engaging with local communities through interviews to gather insights into the circumstances surrounding the landslide event.

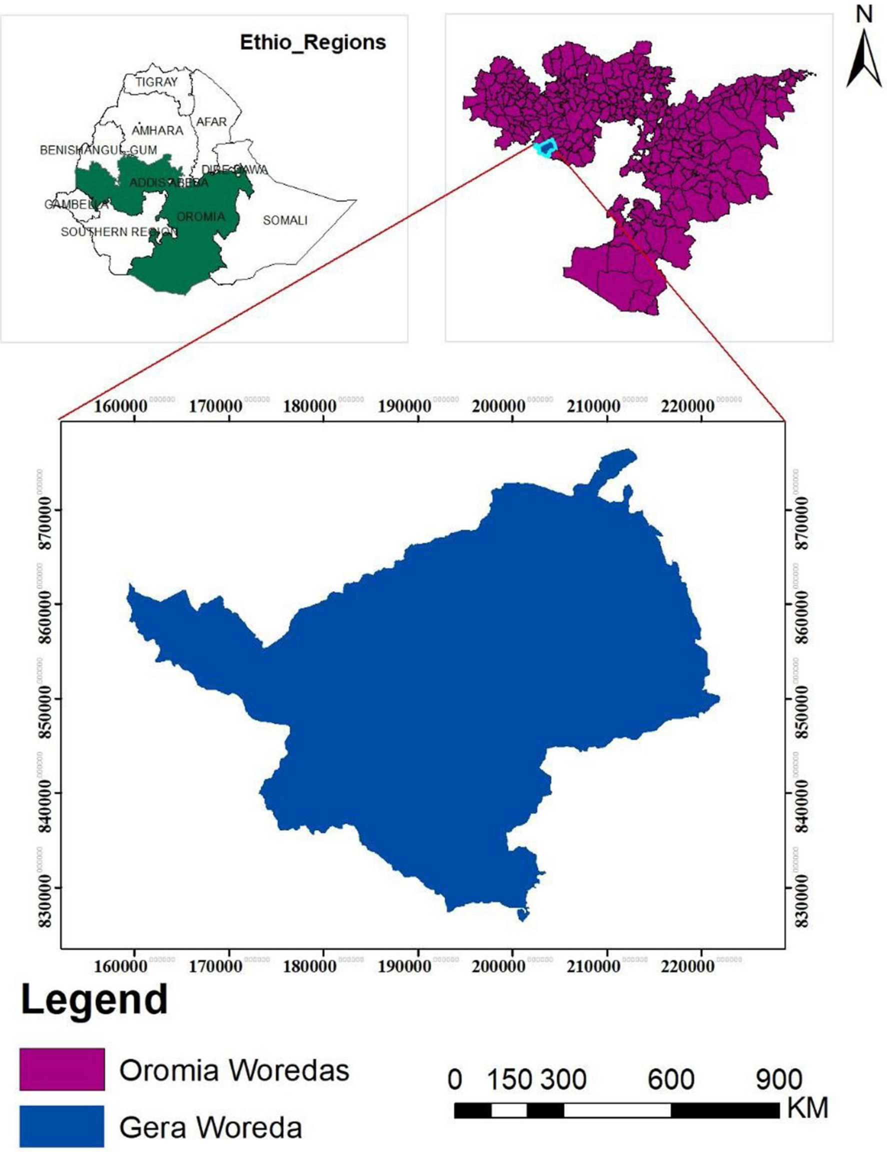


Figure 1. Map of the study area.

Table 1. Site characteristics.

	Condition of the sample	Location			
		E	N	Elevation (m)	Depth (m)
TP1	Affected	196953	857143	2074	1.5 2.8
TP2	Affected	195960	857460	2102	2.4
TP3	Non-affected	195843	857509	2096	2 2.4
TP4	Affected	195898	857363	2089	2.7
TP5	Non-Affected	196243	857045	2095	2 2.7

Informed consent for participation in the study was obtained from all participants, with consent being provided verbally.

Soil sampling was then conducted across both affected and stable soil zones within the study area. A total of five test pits were excavated, considering both disturbed and undisturbed soil samples from areas directly impacted by the landslide and adjacent regions considered stable. Detailed descriptions of the sampled soil types and their respective locations are provided in Table 1. Sample size was justified based on the spatial variability observed in the field, and the selected pits represent key zones within the study area. Additionally, primary data was supplemented via site observations. Furthermore, secondary data, including meteorological records and town demographics, were sourced from meteorological stations and town administrative records.

All identifying details of individual participants have been anonymized to protect their privacy. Written consent to publish these details was obtained from all individuals (or their legal guardians), ensuring full compliance with ethical standards. It is important to note that consent for publication is separate from consent to participate in the study, and written informed consent to publish was specifically obtained.

To summarize the overall methodology, a flowchart (Figure 2) is included, which outlines the key steps from data collection to numerical analysis and the proposal of mitigation measures.

3.2. Laboratory and field tests

Upon collection, soil samples were subjected to a series of laboratory tests to analyze their geotechnical properties. Various laboratory tests were conducted including Atterberg limit tests, triaxial tests, natural moisture content measurements, specific gravity determination, and unit weight measurements. Atterberg limit tests were performed for the determination of the plasticity index, liquid limit, and plastic limit of the soil samples, providing information on their plasticity and moisture susceptibility. Shear strength of the soil were determined from triaxail test. Additionally, natural moisture content measurements, specific gravity determination, and unit weight measurements were carried out to characterize soil permeability and density.

Geophysical tests using Electrical Resistivity Tomography (ERT) were employed in the field to examine subsurface conditions and characterize geological features and potential failure zones. ERT surveys involved the measurement and analysis of electrical resistivity profiles to be analyzed to examine subsurface conditions and characterize geological features and potential failure zones.

3.3. Numerical analysis

Numerical analysis techniques, specifically the Limit Equilibrium Method software and the Finite Element Method software, were utilized to evaluate the stability of slopes and assess the factors contributing to landslide occurrences. Using the geotechnical data obtained from field surveys and laboratory tests, slope stability analyses were conducted to assess the stability of the landslide-affected slopes. The effects of groundwater levels on slope instabilities were analyzed using numerical methods. Both the Finite Element Method and the Limit Equilibrium Method were employed for different water levels.

Finally, based on the findings from field investigations, laboratory testing, geophysical tests, and numerical analyses, key triggering factors for landslides were identified. Subsequently, a series of mitigation measures were proposed to reduce future landslide risks and safeguard communities and infrastructure in the study area

3.3.1. Slope stability analysis methods

The Bishop, Generalized Limit Equilibrium (GLE), and Janbu approaches are commonly used methods for slope stability analysis, each with distinct characteristics and applications. The **Bishop method** is a widely used simplified method that assumes circular slip surfaces and satisfies vertical force equilibrium but only approximates moment equilibrium. It is particularly effective for homogeneous slopes and is computationally less intensive, making it suitable for preliminary analysis.

The **Generalized Limit Equilibrium (GLE) method** is a more comprehensive approach that allows for both circular and non-circular slip surfaces. It satisfies both force and moment equilibrium, making it more accurate and versatile than the Bishop method. GLE is particularly useful in complex slope stability problems where non-circular failure surfaces are expected, such as in heterogeneous soils or slopes with irregular geometry.

The **Janbu method** comes in two forms: the simplified method, which considers only horizontal force equilibrium, and the rigorous method, which also includes moment equilibrium. Unlike the Bishop

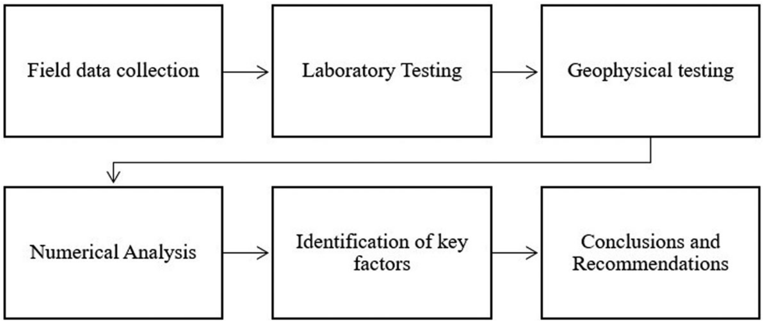


Figure 2. Flowchart of the methodological framework employed in the study.

method, Janbu can handle non-circular slip surfaces, making it applicable to a broader range of soil conditions and slope geometries. The Janbu method is often used when dealing with slopes that have varying soil layers or irregular boundaries, where the assumption of circular slip surfaces may not be valid.

4. Results

4.1. Site observations

The initial site visits provided critical insights into the environmental conditions contributing to the Gera Woreda landslide. The primary observations included visual indicators of ground instability, such as cracks on exposed subsurface profiles and evidence of ground subsidence. The destructive impact on infrastructure, including houses, roads, and utilities, was apparent, forcing residents to relocate (Figure 3). Despite the evident risks, some residents continued to live in precarious housing near the slope's toe, highlighting socio-economic challenges.

The observations indicate ongoing slope movement, particularly exacerbated by seasonal rainfall, which may increase pore pressure and trigger further instability. The continued habitation in high-risk areas underscores the need for targeted relocation and risk mitigation strategies. The presence of a river and springs at the slope's foot suggests a significant hydrological influence on landslide activity, warranting further investigation into regional water dynamics.

4.2. Laboratory test results

4.2.1. Natural moisture

Natural moisture content tests were conducted on eight undisturbed samples collected at various depths. The measured values ranged from 35.67% to 49.04%, reflecting conditions during the dry season. Since these tests were conducted during the dry season, the report acknowledges that the moisture content is likely higher during the rainy season. This fluctuation in moisture content is a crucial factor influencing landslide occurrence. Reduced moisture content during dry seasons can decrease soil cohesion, while increased moisture during rainy seasons can decrease shear strength, both of which contribute to slope instability.

4.2.2. Specific gravity

The specific gravity test, performed on eight samples, yielded values ranging from 2.65 to 2.84, indicating predominantly clay and silty clay soils in the study area. While specific gravity indirectly influences soil properties like cohesion and shear strength, it does not solely determine slope stability.

Figure 3. Land subsidence and effects on residential houses and roads.

However, higher specific gravity soils typically exhibit greater cohesion and shear strength, enhancing slope stability.

4.2.3. Atterberg limits

Atterberg limits tests on eight samples revealed liquid limits ranging from 64.80% to 73.71%, plastic limits from 30.44% to 33.58%, and plasticity indices from 32.45% to 38.17%. These values decrease with depth, indicating varying plasticity behavior under different moisture conditions. Higher liquid limits suggest increased soil plasticity, potentially leading to saturation during the rainy season and heightened landslide susceptibility.

Soil Classification: Based on the Atterberg limits test results, the USCS classification system identified three test pits containing clay soils (CH) and two containing silty soils (MH). These fine-grained soils are particularly susceptible to losing shear strength when saturated, making them more prone to mass movement, especially during periods of heavy rainfall.

4.2.4. Grain size analysis

Grain size analysis revealed that over 92.68% of soils were comprised of fine-grained particles (silt and clay). This composition, combined with their susceptibility to moisture, indicates a heightened risk of slope instability under wet conditions.

4.2.5. Unit weight

The unit weight measurements varied from 1.289 g/cm^3 to 1.481 g/cm^3 for dry density and from 1.844 g/cm^3 to 2.024 g/cm^3 for bulk density. Higher unit weights increase stress and shear forces on slopes, affecting overall stability.

4.2.6. Free swell

Free swell values are 25.00% to 41.67%, suggesting a low level of soil expansiveness. While not highly expansive, these soils may still experience volume changes under varying moisture conditions.

4.2.7. Permeability test

The Falling Head Method revealed low coefficients of permeability ranging from 6.25E-05 to 9.91E-07, consistent with clay and silt soils. Their low permeability contributes to positive pore pressure, soil particle dispersion, and decreased shear strength, increasing landslide susceptibility.

4.2.8. Triaxial test

Triaxial tests were conducted on five soil samples to determine their shear strength parameters using ASTM D 2850 method. These parameters, such as internal friction angle (φ) and cohesion (c) are essential inputs for slope stability analysis. The results of these tests are shown in Table 2.

4.3 Geophysical test

Electrical Resistivity Tomography (ERT) were conducted at three distinct locations in the field, allowing for the determination of subsurface layer presence, thickness, and the depth of landslide-prone areas. Electrical resistivity profiling was employed to visualize subsurface structures and lithological variations. These profiles revealed distinct layers of varying resistivity, aiding in the identification of subsurface lithology and potential landslide zones.

Figures 4–6 shows profiling images varying resistivity layers which indicates indicative of different lithological formations. For instance, profiling along the municipality office (Figure 4) revealed a layer of basaltic tertiary volcanic rock overlaid by sticky clay soil. Similarly, profiling along Muje Bar (Figure 5) indicated moderately fractured tertiary volcanic rock underlying sticky clay soil. Lastly, profiling along the Agricultural Office (Figure 6) showed slightly fractured tertiary volcanic rock overlaid by sticky clay soil. These findings provide critical information for understanding subsurface lithology and identifying areas prone to landslide.

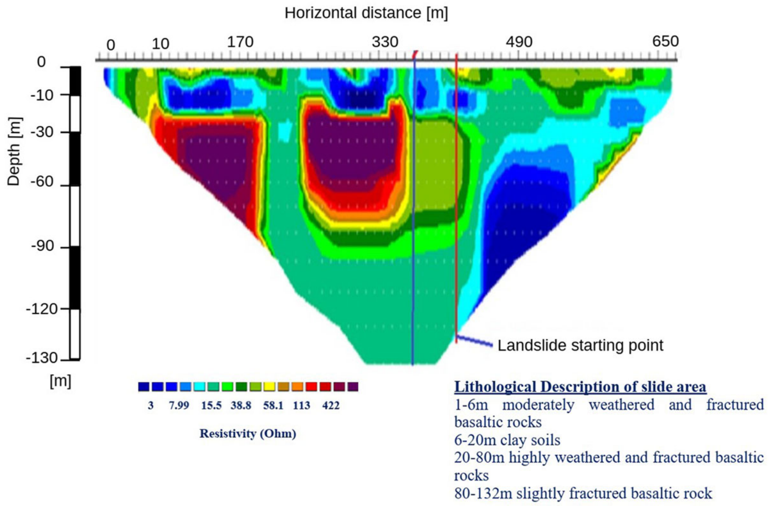
The profiling image from Figure 4 reveals distinct layers of electrical resistivity, aiding in the identification of subsurface lithology and layers. The relatively massive resistivity reading of approximately 422 Ωm suggests the presence of basaltic tertiary volcanic rock at depth. Overlying this rock layer is a zone of very low resistivity, measuring less than 8 Ωm, indicative of sticky clay soil. This interpretation aligns with observations made during fieldwork, providing valuable insights into the composition and depth of subsurface layers.

In Figure 5, the profiling image reveals distinct layers of electrical resistivity, aiding in the identification of subsurface lithology and layers. A relatively massive resistivity reading of about 110 Ωm suggests the presence of moderately tertiary volcanic rock, specifically ignimbrite. This rock layer is overlaid by a zone of very low resistivity, measuring less than 22 Ωm, indicative of sticky clay soil, as observed during fieldwork.

Similarly, Figure 6 presents a profiling image displaying different layers of electrical resistivity.

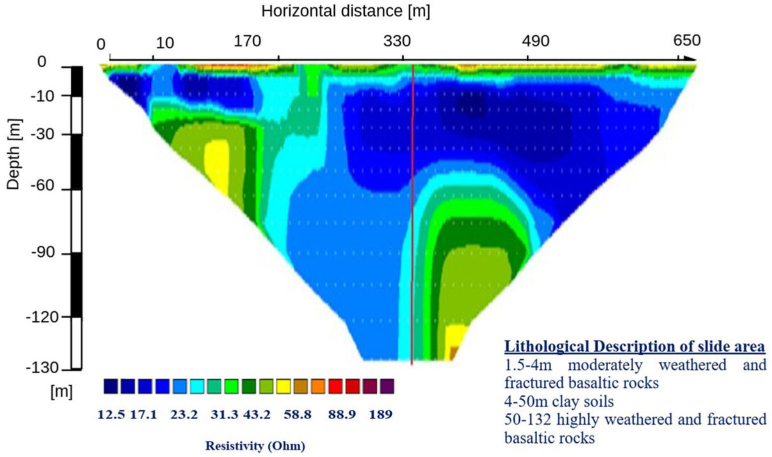
Table 2. The triaxial UU test results.

	Location: TP1, TP2 and TP3@2.4m TP4 and TP 5 @ 2.7m				
Parameter	TP1	TP2	TP3	TP4	TP5
C (Kpa)	47.21	58.26	67.12	25.47	63.58
Ø(Degree)	15.35	20.24	14.04	15.36	8.48



Lithological Description of slide area
1-6m moderately weathered and fractured basaltic rocks
6-20m clay soils
20-80m highly weathered and fractured basaltic rocks
80-132m slightly fractured basaltic rock

Figure 4. Geophysical investigation profiling along municipality office.



Lithological Description of slide area
1.5-4m moderately weathered and fractured basaltic rocks
4-50m clay soils
50-132 highly weathered and fractured basaltic rocks

Figure 5. Geophysical investigation profiling along Muje Bar.

This profile assists in identifying the lateral and depth of subsurface lithology and layers. A resistivity reading of approximately 130Ωm indicates slightly fractured tertiary volcanic rock. Overlying this rock layer is a zone of very low resistivity, measuring less than 10 Ωm, indicating the presence of sticky clay soil, as observed during field observation.

4.4. Numerical analysis of slope stability

4.4.1. Analysis using the finite element method

Factors influencing slope stability were investigated using advanced numerical analyses with the Finite Element Method software. The results provide invaluable insights into the behavior of slopes under varying groundwater table (GWT) conditions, highlighting potential failure mechanisms and critical thresholds. Table 3 summarizes the slope stability results obtained using this method. As indicated in Table 3, when the groundwater table rises from a significant depth to the surface, the stability of the slopes diminishes. This trend holds true for all slopes, including those that were unaffected. The reason for this is that increased moisture content boosts the driving force and reduces the shear strength of soil particles, leading to a lower factor of

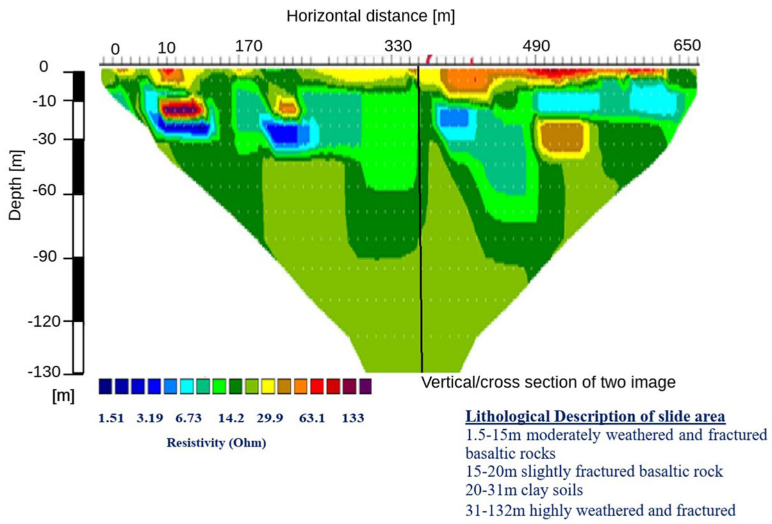


Figure 6. Geophysical investigation profiling along agricultural office.

Table 3. Slope stability summary from finite element method.

Slope	Site condition	Ground water table condition	FS	Deformation (m)
S-1	Unstable	Dry	1.34	$341.03*10^{-3}$
		Saturated partially @10 m BGL	0.90	1.62
		Saturated partially @5 m BGL	0.66	1.82
S-2	Unstable	Dry	1.95	$144.53*10^{-3}$
		Saturated partially @5 m BGL	1.27	$279.29*10^{-3}$
		Saturated partially @2 m BGL	1.10	$952.03*10^{-3}$
		Saturated partially @1 m BGL	0.98	2.87
S-3	Stable	Dry Condition	3.18	$62.85*10^{-3}$
		Saturated partially	2.52	$87.10*10^{-3}$
		Saturated	1.83	$176.58*10^{-3}$

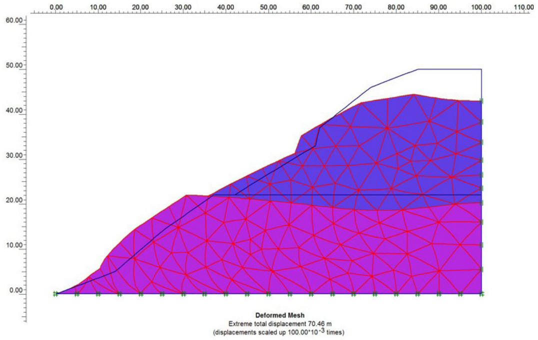


Figure 7. Deformation meshes at GWT -10m.

safety for the slopes. Similarly, deformation also decreases as the groundwater level rises from a great depth to the surface. The deformations in the affected areas were significantly higher in a saturated state, indicating that the stability of the study area is highly influenced by rainfall.

The factor of safety for slope one, as depicted in Table 3, was notably below unity, except for the dry condition. The safety factor values were 1.34, 0.66, and 0.90 for dry, partially saturated at 5 m, and 10 m below the ground surface, respectively (see Figure 7). This difference suggests that increasing water content increases the weight of the soil mass while decreasing its shear strength, leading to landslide occurrences. Furthermore, slope stability decreased by 26.55% and 32.94% when the groundwater table rose from 10 to 5 m below ground level and from significant depths to 10 m below ground level, respectively. Notably, increments in groundwater level up to 5 m precipitated a 50.74% decline in factor of safety compared to stability under dry conditions. Deformation analysis for slope one revealed a substantial increase, soaring from 0.34 to 1.82 m—an 81.26% escalation—when the groundwater table rose to 5 m below ground level from the dry area.

The factor of safety for the slopes exhibited a notable decrease as the groundwater table level increased, as illustrated in Figure 8. Specifically, the safety factor decreased from 1.95 to 1.27 under dry conditions and when the groundwater table was at 5 m, respectively. This decrease signifies a 32.92% reduction when the groundwater level rose from significant depths to 5 m below the surface. Moreover, further increases in the groundwater level in this slope led to a subsequent decrease in the safety factor. Specifically, the safety factor decreased by 48.80% and 43.52% with additional increments of the groundwater table from significant depths to 1 m and 2 m below the ground surface, respectively. In slope 2, deformation analysis revealed that the rise in groundwater level from dry conditions to partially saturated conditions at 2 m increased deformation from 144.53 to 95.2 mm, marking an 84.82% increase.

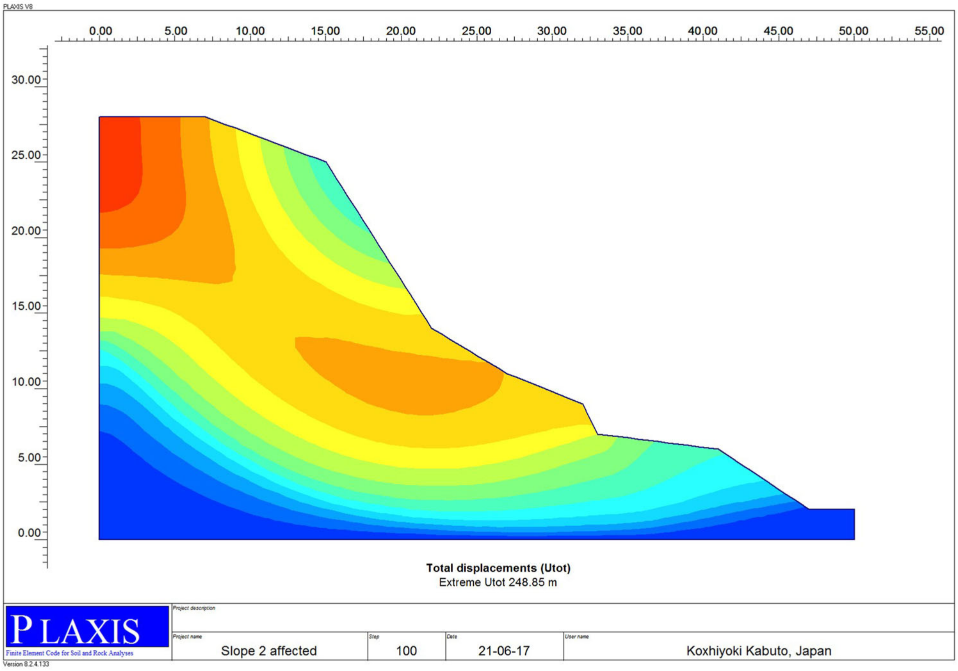


Figure 8. Deformed mesh of slope 2 at GWT -5m.

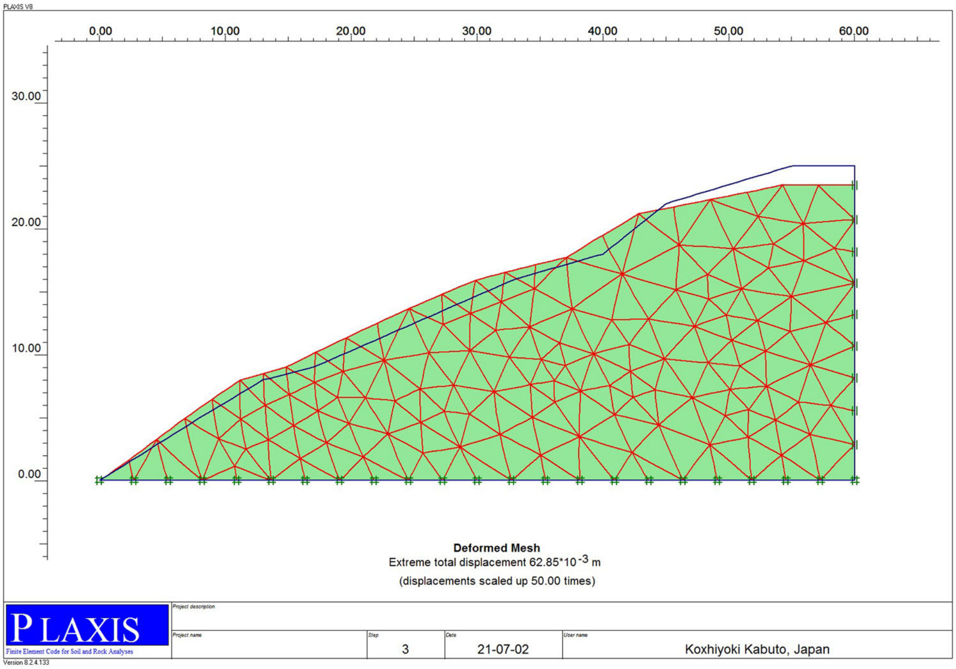


Figure 9. Deformation mesh of unaffected slope in dry conditions.

Regarding the unaffected slope, it featured gentle slopes located on the town's western border, mainly covered by vegetation due to limited human activity. The elevation contrast between the affected and nearby unaffected slopes significantly influenced hydrological dynamics. Notably, the unaffected slope sat above the affected one, aiding in the movement and retention of moisture in the affected slopes, thereby elevating pore pressure.

The slope exhibited marginal stability under saturated conditions and remained stable under other conditions, as depicted in Figure 9. Given the area's susceptibility to landslides, particular attention must be paid to this slope for future endeavors. Although failure was avoided, the rise in groundwater level reduced the numerical values of the safety factor. Specifically, the factor of safety declined from 3.18 under dry conditions to 2.52 under partially saturated conditions, further dropping to 1.83 under saturated conditions, indicating a 42.39% decrease in slope stability due to elevated moisture content. Deformation analysis of slope 3 revealed its sensitivity to failure with increasing moisture content, similar to affected slopes. Additionally, the unaffected slope demonstrated sensitivity to failure under saturated conditions. Changes in groundwater level and the addition of surcharge load affected both the factor of safety and deformation. Consequently, as construction activities and human settlement increase, this slope presents a heightened risk of failure.

4.4.2. Stability analysis using limit equilibrium method

The slope stability analysis under different conditions utilized three well-established Limit Equilibrium Methods (LEMs): Bishop, Generalized Limit Equilibrium (GLE), and Janbu approaches, integrated within the Limit Equilibrium Method software. These methods assessed the factor of safety and depth of the slip surface using the slice method. Meanwhile, the Finite Element Method software simultaneously analyzed the slope under various groundwater conditions to compare results and provide further insights. Table 4 shows the variations in the factor of safety (FS) under various groundwater conditions. For Slope 1, as the groundwater table (GWT) rose from dry conditions to 2 meters below the ground surface, the minimum FS decreased by 47.95%, 48.52%, and 49.93% according to the Janbu, Bishop, and Generalized Limit Equilibrium (GLE) methods, respectively. Notably, the Finite Element Method software produced lower FS values compared to the Limit Equilibrium Method. While all FS values under dry conditions indicated stability (FS $>$ 1), they decreased with rising groundwater levels. This highlights the influence of rainfall in triggering the observed mass movement in the study area, as evidenced by the Finite Element method analysis.

Table 4. Slope stability summary from limit equilibrium method.

Slope	GWT level	Bishop	GLE	Janbu
S-1	2 m	0.73	0.73	0.67
	5 m	0.82	0.83	0.77
	10 m	0.98	0.99	0.91
	Great depth	1.42	1.48	1.35
S-2	0 m	1.18	1.18	1.07
	1 m	1.23	1.23	1.13
	2 m	1.28	1.28	1.19
	5 m	1.47	1.47	1.39
	Great depth	2.06	2.05	1.93
S-3	0 m	2.16	2.16	2.02
	5 m	2.66	2.66	2.52
	Great Depth	3.37	3.37	3.17

The Limit Equilibrium Method results show a decrease in the factor of safety for Slope 2 as the groundwater table (GWT) level increased from dry conditions to fully saturated conditions. According to the Bishop, GLE, and Janbu methods, the FS decreased by 42.72%, 42.50%, and 44.38%, respectively (refer to Figure 10).

Similarly, for Slope 3, the FS calculated using LEM ranged between 2.02 and 3.37 for different conditions. Despite a decrease in FS with increasing groundwater levels, Slope 3 remained stable. However, the declining FS values with rising GWT levels indicate that without proper management, the slope's stability could be compromised, especially considering the susceptibility of the area to landslides. The FS decreased by 36.18%, 35.94%, and 35.94% in the Janbu, Bishop, and GLE methods, respectively, from dry conditions to fully saturated conditions.

Factor of safety values exceeding 1 are generally regarded as safe, whereas values below 1 signify instability. However, FS values slightly above 1 (up to 1.5) can still pose risks. It is important to note that various uncertainties in material investigation, boundary conditions, analysis methods, and numerical approximations can impact the results. In this study, all FS values from both Limit Equilibrium method and Finite Element method were compared to the target stable safety factor of 1.5.

The FS derived from Limit Equilibrium (LE) analysis tended to be overestimated compared to Finite Element (FE) analysis. Specifically, the Bishop Method in LE overestimated FS by 5%–20% in dry and partially saturated conditions, respectively. However, the Janbu method yielded FS values comparable to those computed from Finite Element method. In saturated conditions, discrepancies in FS values may arise from inaccurately calculated stresses in the LE analysis.

4.4.3. Factors contributing to and triggering landslides

4.4.3.1. Rainfall analysis. A comprehensive analysis of rainfall spanning 36 years (1985–2020) was conducted to assess the distribution of rainfall in the Gera area (Figure 11). Around 6.8% of the Chira rainfall station's data were incomplete, but these gaps were filled afterward.

The annual rainfall analysis for Chira shows a steady rise in rainfall across the area beginning in 2014, reaching its peak in 2016 (see Figure 11). Local observations during site visits revealed a corresponding increase in the extent of ground surface cracks

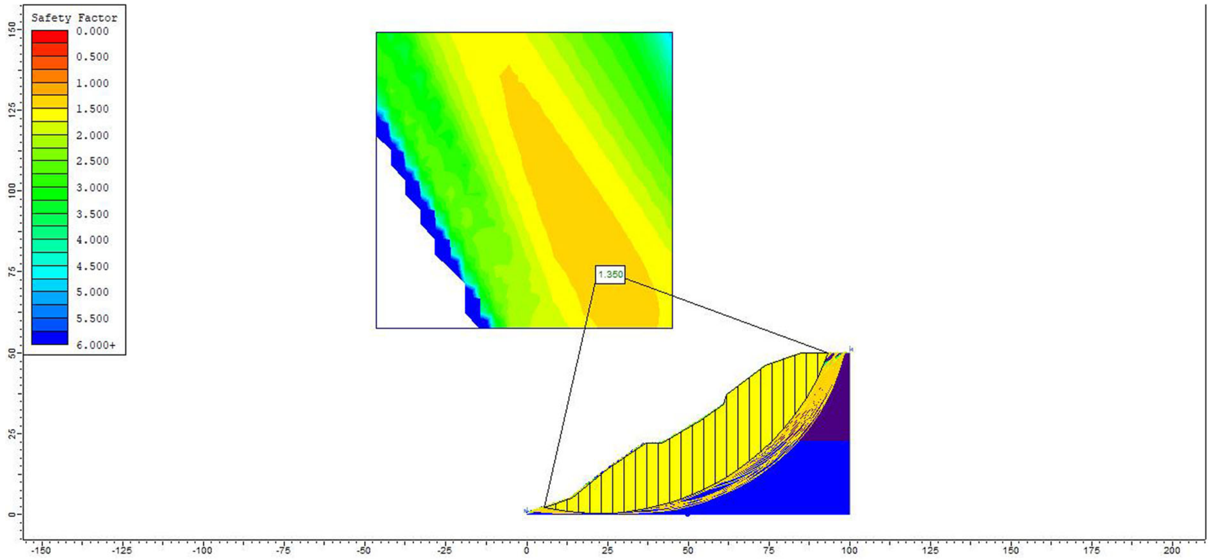


Figure 10. Slope 1 FS in Dry Conditions.

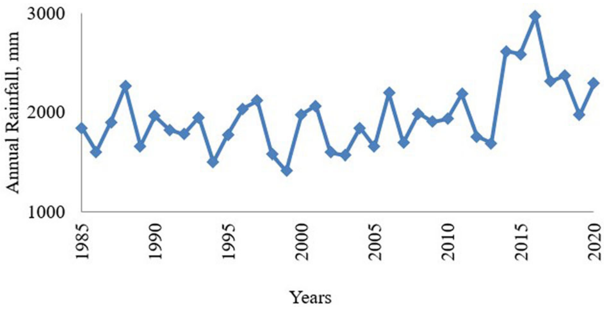


Figure 11. Annual rainfalls Analysis Gera woreda.

following the heavy rainfall experienced in 2016. This intensified rainfall led to a decline in the shear strength of soils, ultimately triggering landslide occurrences in Gera Woreda. The average mean annual rainfall for Chira was recorded at 1955.4 mm, with maximum and minimum rainfall amounts of 2967.8 mm and 1414.1 mm, respectively. These recent rainfall records strongly suggest a correlation with the occurrence of landslide activities.

The monthly rainfall analysis for Gera indicates a consistent occurrence of precipitation year-round, with relatively lower rainfall from January to December. Conversely, the primary rainfall seasons in the region are from May to September, with peak rainfall typically observed in June to August.

4.4.3.2. Status of groundwater and variation in elevation. Groundwater conditions are significantly influenced by rainfall variations and elevation differences. Fluctuations occur due to water infiltration into the ground during rainfall events. Runoff originating from higher elevations and accumulating at lower elevations also contributes to groundwater levels. When runoff infiltrates the soil from higher elevations and accumulates at lower elevations, it increases groundwater levels at those points. The elevation of groundwater consequently amplifies the weight of the soil mass and weakens the shear strength of vulnerable layers. Consequently, the driving force acting on the earth mass exceeds the resisting forces, facilitating landslide occurrences.

In Gera, groundwater levels fluctuate between 6 and 17 m at different locations within the study area. These fluctuations in groundwater levels induce variations in pore water pressure, negatively impacting the stability of the earth mass. As a result, the interaction between weather patterns, which alternate between dry and wet conditions, along with variations in elevation throughout the study area, leads to fluctuations in groundwater levels. These fluctuations serve as one of the factors that trigger landslides in Gera woreda.

4.5. Proposed remedial measures

4.5.1. Surface drainage

Rainfall acts as a primary trigger for landslides in the area, causing fluctuations in groundwater levels and subsequent destabilization of slopes. As indicated in the stability analysis (Table 3), the factor of safety decreases with increasing groundwater levels. Implementing effective surface drainage systems can mitigate these risks by collecting runoff and reducing water infiltration into the subsurface. By minimizing the amount of water seeping into the ground, surface drainage helps enhance slope stability without significantly increasing the driving force.

This measure is not only economically viable but also relatively simple to implement. However, the cost of installation and maintenance, as well as potential challenges such as ensuring proper design and functionality during extreme weather events, must be considered. A case study in Rwanda (Majoro et al., 2020) demonstrated the effectiveness of surface drainage in reducing landslide occurrences in similar terrains, highlighting its practical application in the region.

4.5.2. Planting Vetiver vegetation

Introducing Vetiver grass in Gera woreda is proposed as a remedial measure. This grass can penetrate up to 3 meters into the soil, providing reinforcement that improves the shear strength of affected slopes. Additionally, Vetiver grass is lightweight compared to other vegetation types and does not contribute significantly to the driving force on the slope. The feasibility of this measure is high, given its low cost and minimal maintenance requirements. However, challenges such as the initial establishment period and the need for community involvement in planting and upkeep should be addressed. Examples from Ethiopia (Tsige et al., 2019) show the successful use of Vetiver grass in stabilizing slopes, which could serve as a model for its implementation in Gera woreda.

4.5.3. Proper land use management. Urban expansion observed during site visits emerged as a significant triggering factor for landslides in Gera woreda. Stability analysis and land use land cover assessments highlight stable slopes located at the town's periphery, where human activity is minimal. Ensuring the future safety of these slopes necessitates the implementation of effective land use management strategies in the study area. Without appropriate management practices, the entire town faces an increased risk of landslide incidents. While land use management is a critical and cost-effective measure, it poses challenges such as enforcement, community buy-in, and the balancing of development needs with environmental protection. Successful land use management strategies from regions like Bhutan, where strict zoning and land use policies have reduced landslide risks, could inform similar efforts in Gera woreda.

5. Discussion

The findings of this study underscore the complex interplay between geological composition, soil properties, hydrological factors, and slope stability in determining landslide susceptibility in Gera woreda, southwest Ethiopia. The fractured volcanic rock, overlain by silty and clay soils with high plasticity and low permeability, significantly contributes to landslide risk, especially during elevated groundwater levels, as confirmed by the numerical slope stability analysis. The decrease in the factor of safety with rising groundwater levels highlights the critical role of hydrological conditions in triggering landslides, suggesting that effective groundwater management is essential for mitigation. The study's proposed surface drainage systems demonstrate potential in reducing water infiltration and enhancing slope stability, though their effectiveness may vary with site-specific conditions and long-term performance remains uncertain. However, the study acknowledges limitations, including the assumptions in numerical models and the focus on a specific geographical area, which may limit the generalizability of the findings. Additionally, factors such as seismic activity, vegetation cover, and human interventions, which were not fully explored, could further influence landslide dynamics. Future research should validate these models with field data, incorporate more advanced hydrological and geotechnical models, and explore integrated mitigation strategies that combine engineering solutions with natural stabilization methods for a more comprehensive approach to landslide risk reduction.

6. Conclusion

This study, conducted in Gera woreda, southwest Ethiopia, aimed to conduct a thorough analysis of the factors leading to landslides in the area and suggest viable remedial actions. Through geophysical testing, soil analyses, and numerical stability assessments, key findings emerged. The geological composition of the area, characterized by fractured volcanic rock covered by silty and clay soils, significantly influences landslide susceptibility. Soil properties, including high plasticity and low permeability, exacerbate the risk, particularly during periods of increased groundwater levels induced by heavy rainfall. Numerical analyses demonstrated a decrease in slope stability with rising groundwater levels. For instance, the factor of safety for Slope 1 decreased from dry conditions (FS = 1.34) to partially saturated conditions at depths of 10 m (FS = 0.90) and 5 m below ground level (FS = 0.66), respectively. Similarly, for Slope 2, the factor of safety decreased from dry conditions (FS = 1.95) to partially saturated conditions at depths of 5 m (FS = 1.27), 2 m (FS = 1.10), and 1 m below ground level (FS = 0.98), respectively. These results underscore the critical role of rainfall as a primary triggering factor for landslides. This study contributes to the field by providing detailed insights into the geological and hydrological factors contributing to landslides in Gera woreda, emphasizing the importance of considering both soil properties and groundwater levels in landslide assessments. The findings have significant implications for policy and practice, highlighting the necessity of implementing proactive mitigation strategies, such as surface drainage systems, to manage water infiltration and enhance slope stability. Future research should focus on further refining numerical models and conducting more extensive field investigations to better understand the dynamics of slope stability under varying environmental conditions, as well as exploring the long-term effectiveness of the proposed remedial measures in different geological settings.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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