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SLOPE FAILURE ANALYSIS, CAUSES, AND SUSTAINABLE STABILIZATION MEASURES: CASE STUDY OF MUHANGA-KARONGI ROAD (PK 49), RUTSIRO DISTRICT, RWANDA

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ABSTRACT

Landslides are a critical geohazard in Rwanda's mountainous regions, especially along key transport corridors where slope failures threaten land transport infrastructure, public safety, and economic development. A notable case occurred on May 6, 2018, along the Muhanga–Karongi road (PK 49) in Rutsiro District injured eight people, displaced 40 residents, and disrupted road operations. This study aimed to identify the geotechnical, environmental, and human-induced causes of the failure and recommend effective stabilization measures. A mixed-method approach was employed, including field reconnaissance, soil sampling and laboratory testing, rainfall data analysis, and expert interviews. Results showed that the slope material consisted of over 70% fines, predominantly silty sand, with low cohesion (3.2–4.2 kPa), friction angles between 24.7° and 27.0°, and unit weights ranging from 16.2 to 16.5 kN/m³. The natural slope angle (40°–46°) exceeded the soil's shear resistance, yielding a factor of safety below 1.0. Rainfall data recorded 430.2 mm in April 2018 shortly before the slope failure, intensifying pore pressure and reducing effective stress, while slope cutting further destabilized the site. The study concludes that slope failure resulted from the interplay of saturated silty soils, steep terrain, and construction-related disturbances. Recommended interventions include slope regrading to 2.2H:1V, gabion wall construction with geotextiles, surface drainage installation, and re-vegetation. To enhance long-term resilience, national road agencies should institutionalize mandatory geotechnical investigations and slope stabilization protocols in high-risk areas.
Keywords: *Slope failure, Rainfall infiltration, Shear strength, Geotechnical analysis, PK 49, Slope stability, Landslide hazard, Road infrastructure, Silty soils, Stabilization measures*

1. Introduction

1.1 Background

Landslides represent one of the most pervasive natural hazards globally, particularly in mountainous and tropical regions. Defined as the downslope movement of soil, rock, or debris under the influence of gravity, landslides frequently result in extensive damage to infrastructure, ecosystems, and human lives. According to the United Nations Office for Disaster Risk Reduction (UNDRR, 2021), landslides account for over 4,000 fatalities annually and contribute to global economic losses exceeding USD 20 billion each year. The Food and Agriculture Organization (FAO, 2022) reports that approximately 75% of global landslide fatalities occur in low- and middle-income countries, where rapid urbanization intersects with vulnerable terrain and under-resourced risk mitigation systems.

In Rwanda, landslide risks are amplified by the country's unique physiographic conditions. More than 70% of Rwanda's land area lies on moderate to steep slopes, with elevations exceeding 2,000 meters in parts of the Western and Northern Provinces (MOE, 2022). These regions experience mean annual rainfall above 1,500 mm, rendering slopes highly susceptible to saturation-induced failure. Recent data from the Rwanda Meteorology Agency (Meteo, 2023) show that in May 2023 alone, landslides and floods caused over 130 fatalities, the displacement of hundreds, and extensive damage to road infrastructure and homes in Western Rwanda.

This study centers on the catastrophic slope failure that occurred on May 6, 2018, at PK 49 along the Muhanga–Karongi road in Rutsiro District. This corridor is a strategic route for inter-district trade and mobility in Western Rwanda. The landslide destroyed homes, injured eight individuals, displaced 40 residents, and halted regional transport for days. Despite the recurrence of similar incidents, slope stabilization efforts in Rwanda remain fragmented, underfunded, and often devoid of site-specific geotechnical assessments.

Slope instability is typically triggered by a combination of unfavorable geotechnical and environmental factors. These include weak soil strength parameters (e.g., low cohesion and friction angles), steep terrain, prolonged rainfall, elevated pore water pressures, inadequate drainage, and anthropogenic modifications such as slope cutting or vegetation clearance. In Rwanda's context, the pressure to expand infrastructure on unstable slopes, often without thorough geotechnical assessments, intensifies these hazards.

The present study addresses this critical knowledge and policy gap. Through detailed field surveys, laboratory analysis of soil samples, rainfall data evaluation, and expert interviews, the research investigates the primary drivers of slope failure at PK 49. It aims to produce context-specific recommendations for stabilizing vulnerable slopes along national roads. These findings are intended to inform both engineering design and institutional frameworks, contributing to safer infrastructure development and more robust disaster risk reduction strategies in Rwanda's high-risk, topographically complex regions.

1.2 Statement of the Problem

Under ideal conditions, infrastructure development in mountainous regions like Western Rwanda should be guided by rigorous geotechnical investigations, hydrological modeling, and proactive slope stabilization strategies. Roads traversing steep terrain are expected to incorporate engineered embankments, effective surface and subsurface drainage systems, and retaining structures that safeguard both human lives and economic assets while ensuring year-round connectivity.

However, the current reality diverges sharply from this ideal. On May 6, 2018, a severe landslide struck PK 49 on the Muhanga–Karongi road in Mukura Sector, Rutsiro District. The event resulted in eight injuries, the displacement of 40 residents, the destruction of homes and property, and the disruption of a major transport route. Preliminary observations attributed the failure to cumulative rainfall and unengineered slope cuts during road construction, but no comprehensive geotechnical study was conducted to diagnose the failure mechanisms or guide corrective measures.

The consequences of this gap are significant. According to the Ministry in charge of Emergency Management (MINEMA, 2023), over 221 landslides were reported nationwide in 2022, resulting in more than 130 fatalities and infrastructure losses valued at over RWF 10 billion. Western Rwanda remains disproportionately affected due to its steep terrain and high rainfall. Despite this, many interventions remain reactive and short-term, often involving empirical reshaping of slopes, ad hoc gabion installations, or community reforestation, without adequate design or site-specific data.

Previous mitigation efforts by the Rwanda Transport Development Agency (RTDA) and the Rwanda Environment Management Authority (REMA) have achieved partial success in reducing surface erosion and shallow slope failures. However, their limitations lie in the absence of integrated geotechnical assessments, lack of long-term monitoring systems, and reliance on rule-of-thumb construction practices that overlook local soil behavior, slope geometry, and rainfall thresholds. Consequently, the effectiveness and sustainability of these interventions remain constrained.

This study seeks to bridge this gap by conducting a comprehensive geotechnical analysis of the PK 49 slope failure, integrating field surveys, laboratory testing, rainfall trend analysis, and stakeholder insights. The objective is to identify critical failure triggers, evaluate soil strength parameters, quantify the role of rainfall infiltration, and propose evidence-based stabilization measures. In doing so, the study contributes to building institutional knowledge and informing policy for safer, climate-resilient infrastructure development in Rwanda's landslide-prone zones.

1.3 Research Objectives

The overarching objective of this study is to investigate the underlying causes of the slope failure that occurred at PK 49 along the Muhanga–Karongi road in Rutsiro District and to propose effective, evidence-based stabilization measures suited to the local geotechnical and environmental context.

The specific objectives are:

- To evaluate how the soil properties of the slope material influence overall slope stability.
- To assess the influence of topographical conditions on the likelihood of slope failure.
- To investigate the impact of human activities on the integrity of the slope.
- To analyze the impact of rainfall on the slope failure.
- To develop integrated and sustainable slope stabilization strategies, informed by the interaction of the above factors, for application in similar high-risk areas across Rwanda.

1.4 Study area description

The study site is located in Rwanda's Western Province, specifically in Rutsiro District, Mukura Sector, Kagano Cell, Ntobo Village, and is adjacent to Bigugu Village in Nyarugenge Cell, Rubengera Sector of Karongi District. It lies along the national road NR11 (Muhanga-Karongi), approximately 49 km from Muhanga and 10 km from Rubengera Town at the NR13 junction. The precise geographical coordinates are 2°36'26.44"S latitude and 29°44'12.00"E longitude.

Topographically, the site features steep slopes with elevations ranging from 2,115 m to 2,200 m above sea level and an elevation difference of 80–100 m over a horizontal distance of approximately 200 m. This corresponds to a slope angle of 40°–46°, which is significantly steep and well above safe thresholds for most fine-grained soils under saturated conditions (Mupenzi, 2023). These conditions place the area in a high-risk landslide zone, especially during periods of prolonged rainfall. According to Rahardjo (2018), slopes exceeding 35° on fine-grained soils with weak cohesion are prone to failure under modest hydrological loading. The region's combination of steep slopes, weak soils, and high annual rainfall, often surpassing 1,500 mm (Meteo Rwanda, 2023), amplifies this susceptibility.

Figure 1 below provides a geospatial overview of the PK 49 slope failure location using satellite imagery from Google Earth. The image highlights the terrain's elevation profile and infrastructure proximity, demonstrating the strategic but vulnerable positioning of the road in relation to the slope.

Figure 2 illustrates the physical manifestation of the slope failure captured during a field visit. The photograph shows evidence of toe collapse, surface erosion, and sediment displacement, all typical of rainfall-induced failures in saturated silty soils.

Such failures often begin with tension cracks near the crest and propagate downslope rapidly, especially when drainage is inadequate (Cho, 2024).

Figure 1: PK 49 slope failure location on Google Earth map

Figure 2: slope failure of the case study.

These visual and geospatial data validate the topographical and geological challenges facing infrastructure development in the Western Province. They underscore the urgent need for proactive slope stabilization measures informed by detailed geotechnical assessments.

2. Literature Review

2.1. Theoretical Review

This study is grounded in three foundational theories that collectively inform the scientific understanding and engineering analysis of slope stability, soil behavior, and rainfall-induced geotechnical hazards. These theories form the conceptual basis for assessing slope failure mechanisms and developing stabilization strategies appropriate for Rwanda's steep terrain and intense rainfall patterns. The integration of these models enhances the rigor, applicability, and diagnostic accuracy of the research.

2.1.1 Mohr-Coulomb Failure Criterion – Christian Otto Mohr (1900) & Charles-Augustin de Coulomb (1776)

The Mohr-Coulomb failure criterion is one of the earliest and most widely applied theories in geotechnical engineering. It defines the shear strength of soils as a function of cohesion (c) and internal friction angle (ϕ), represented by the linear equation:

$$\tau = c + \sigma \tan(\phi)$$

where τ is shear strength and σ is normal effective stress. The theory is instrumental in understanding how soil resists sliding along potential failure planes.

The major strength of the Mohr-Coulomb model lies in its simplicity and practical utility, it enables direct interpretation of laboratory test results, such as direct shear and triaxial compression tests. However, its limitations include the assumption of a linear failure envelope and its inability to model complex, non-linear, or strain-softening behaviors, particularly in heterogeneous or weathered soils.

In this study, these weaknesses are addressed by using site-specific direct shear test data combined with field observations of actual failure surfaces. The theory is applied to quantify soil strength parameters at PK 49 and to evaluate how reduced shear strength, especially under saturated conditions, contributed to the 2018 slope failure.

2.1.2 Limit Equilibrium Method (LEM) – Bishop (1955); Morgenstern & Price (1965)

The Limit Equilibrium Method (LEM) evaluates slope stability by analyzing the balance of driving and resisting forces or moments along a potential failure surface. It provides a safety factor (FOS), where failure is imminent if FOS < 1. LEM variants include Bishop's Simplified Method and Morgenstern-Price Method, each with different assumptions on inter-slice forces.

The strength of LEM lies in its adaptability to different slope geometries, soil conditions, and loading scenarios. It remains the standard analytical tool in engineering practice for preliminary and design-stage slope assessments. Its main weakness, however, is its static nature, which does not account for progressive failure, time-dependent deformation, or hydrological variation during rainfall events.

This limitation is mitigated in this research through the incorporation of temporal rainfall analysis and pore pressure considerations using historical precipitation data. LEM is applied to evaluate the factor of safety under pre- and post-failure conditions at the PK 49 slope, providing a rational basis for proposed stabilization measures.

2.1.3 Effective Stress Principle – Karl Terzaghi (1936)

Terzaghi's Effective Stress Principle asserts that the behavior of saturated soils is governed not by total stress but by the effective stress:

$$\sigma' = \sigma - u$$

where σ' is the effective stress, σ is the total stress, and u is the pore water pressure. This principle underpins the analysis of slope failure, especially where rainfall-induced pore pressure is a critical concern.

The strength of this theory is its foundational role in explaining how water affects soil strength, settlement, and slope performance. It is particularly valuable in saturated or near-saturated soils. However, it does not adequately address unsaturated soil behavior or rapid changes in hydraulic conditions during intense rainfall.

To address this, the present study complements the theory with rainfall monitoring data and analysis of water content and soil suction relationships. The principle is used to interpret how rising pore pressures from 430.2 mm of rainfall in April 2018 reduced effective stress in the slope at PK 49, ultimately triggering failure.

2.2. Empirical Review

Empirical research from Rwanda, East Africa, and global contexts corroborates the multi-factorial nature of slope failure, especially in tropical highland environments. In Karongi District, Rwanda, Sobio (2019) conducted a detailed geotechnical assessment and found that poorly graded silty soils with low cohesion and plasticity were highly prone to landslides. However, the study lacked slope geometry evaluation and anthropogenic factors. Building on this, the present research integrates soil strength testing with topographical profiling and human activities analysis to provide a more comprehensive understanding of slope behavior.

Bizimana (2015) examined landslide mitigation practices in Northern and Western Rwanda, recommending bioengineering and drainage control. However, his work relied heavily on qualitative observations without laboratory validation. In contrast, this study employs laboratory tests, including direct shear, Atterberg limits, and grain size analysis, to propose evidence-based engineering interventions.

Mugisha (2021) explored how slope angle, rainfall, and land use changes contribute to instability in Nyabihu District. While the study identified slope gradients above 35° as high-risk, it did not assess soil strength or perform safety factor evaluations. Our study extends this by calculating friction angles and cohesion values to quantitatively evaluate slope vulnerability.

Kayumba (2022) investigated the impact of infrastructure construction on slope failures in the Southern Province, revealing that inadequate drainage and slope cutting were responsible for over 60% of slope instability cases. However, the research lacked numerical modeling. This gap is addressed here through the integration of mechanical soil analysis with hydrological data.

Mupenzi (2023) reviewed RTDA-led stabilization efforts and found that many gabion walls failed due to improper design and lack of reinforcement. Our research complements these findings by recommending reinforcement with geotextiles and matching wall dimensions with local geotechnical profiles.

Recent global research confirms the strong link between rainfall infiltration and slope failure in steep, silty terrains like PK 49 in Rwanda. Studies by (Yang, 2023) & (Hung, 2018) showed that prolonged rainfall raises pore water pressure and reduces shear strength, triggering landslides. In regions like Yunnan and Chongqing in China, similar slope failures occurred due to heavy rainfall and terrain disturbance, conditions mirrored at PK 49, which saw 430.2 mm of rainfall in April 2018.

Furthermore, investigations by (Cho, 2024) & (Joe, 2020) emphasized the destabilizing effects of unengineered slope cutting and inadequate drainage. These conditions, also present at PK 49, intensified infiltration and structural weakness. Collectively, these studies reinforce the need for integrated geotechnical planning and proper drainage in managing slope stability, particularly in high-risk areas like Western Rwanda.

In summary, prior studies confirm that rainfall, weak soils, slope angle, and human activity interact to cause landslides. However, most existing work either lacks field-based laboratory testing, integration of multiple risk factors, or quantitative slope safety evaluations. This research addresses those deficiencies by applying an interdisciplinary methodology to the PK 49 case, offering replicable stabilization strategies.

3. Methodology

This study adopted a case study research design to investigate the geotechnical, hydrological, and anthropogenic factors contributing to the slope failure at PK 49 along the Muhanga–Karongi road in Rutsiro District, Rwanda. The research population included the slope site, affected residents, and technical personnel from governmental agencies such as the Rwanda Transport Development Agency (RTDA) and Meteo Rwanda. A purposive sampling strategy was employed to select 15 key informants, comprising civil engineers, geotechnical engineers, geologists, local field technicians, and residents with direct experience of the landslide, ensuring triangulated insights into both technical and community perspectives. The number of respondents was deemed sufficient to reach data saturation, as recurring themes emerged by the tenth interview, with the remaining responses confirming the established trends. Qualitative data were collected through semi-structured interviews and direct field observations of slope geometry, drainage conditions, and visible signs of instability. Quantitative data were obtained through laboratory testing of ten soil samples collected from different elevations and orientations of the failed slope. Tests included natural moisture content, grain size distribution (sieve and hydrometer analyses), Atterberg limits, unit weight, and direct shear strength measurements (cohesion and internal friction angle). Rainfall records were sourced from Meteo Rwanda's Rubengera station to analyze cumulative precipitation trends preceding the failure. All data were processed using Microsoft Excel and subjected to thematic and comparative analysis to correlate observed field conditions with laboratory and rainfall data. This integrated methodological approach provided a comprehensive diagnosis of slope failure mechanisms and informed the formulation of evidence-based stabilization measures appropriate for the local geotechnical and climatic context.

4. Results and Discussion

Slope failure occurs when gravitational forces acting downslope exceed the shear strength of the slope materials, resulting in instability. Field observations at PK 49 in Rutsiro District confirmed significant signs of slope movement, including soil cracks, displaced materials, and vegetation displacement. These observations were further validated through interviews with district engineers and residents, many of whom indicated that similar failures had occurred in nearby areas during previous rainy seasons.

Multiple geotechnical and environmental factors were found to influence the failure, including soil properties, slope geometry, human activities, and rainfall. These factors are discussed below, incorporating findings from laboratory testing, field visits, and qualitative interviews.

4.1 Soil properties and slope stability

Soil stability is highly dependent on its physical and mechanical properties, particularly water retention and permeability. Fine-grained soils such as silts and clays tend to retain more water, leading to saturation and a reduction in shear strength. (Aubeny, 2004) As confirmed by a geotechnical engineer interviewed during the study, "the dominance of fine particles in the soil along this slope means it can quickly become saturated under rainfall, reducing its cohesion and triggering instability."

4.1.1 Natural moisture content of soil material

Moisture content is a fundamental parameter in slope stability analysis, as it influences both the weight and shear strength of soil. Elevated moisture increases pore water pressure, reduces matric suction, and weakens interparticle bonding, all of which lower the soil's effective stress and stability. This is particularly critical in residual soils of tropical highlands like Rwanda, where rainfall is intense and prolonged (Chen, 2021). The natural moisture content test was conducted on ten representative soil samples collected from various elevations along the PK 49 slope. The goal was to quantify in situ saturation levels and assess potential contributions to slope failure.

Table 1: Natural moisture content results

Sample N°	1	2	3	4	5	6	7	8	9	B
Wet sample	63.5	87	48	82	85	77	90	72.5	92.5	70.5
W tare	13	14.5	14.5	12	14	14	14	14	14.5	13.5
W dry Sample	56.5	75	43.5	68.5	78	55	73.5	63	80	66.5
W Water	7	12	4.5	13.5	7	22	16.5	9.5	12.5	4
Dry sample	43.5	60.5	29	56.5	64	41	59.5	49	65.5	53
M. Content %	16.1	19.8	15.5	23.9	10.9	53.6	27.7	19.4	19.1	7.5
Average (%)	21.3									

The average moisture content across all samples was 21.3%, indicating moderate saturation, but several individual samples exceeded 25%, with sample 6 reaching a critical 53.6%. This suggests the presence of highly localized zones of saturation within the slope body conditions that substantially increase the likelihood of pore pressure build-up during heavy rainfall (Rahardjo, 2018). These findings are consistent with the rainfall conditions observed at PK 49, where cumulative rainfall of 430.2 mm in April 2018 likely pushed soils near or beyond saturation limits, triggering the landslide.

The spatial variability in moisture values also aligns with field observations of differential saturation along the slope, supporting the assertion that rainfall-induced increases in soil weight and reductions in effective stress were major contributing factors to failure. According to (Mupenzi A. U., 2023), moisture content exceeding 25% in silty clays in Rwanda's Western Province significantly compromises slope integrity. Therefore, the observed values validate the need for targeted drainage interventions to mitigate water retention and reduce landslide risk.

4.1.2 Grain size distribution

Grain size distribution is a critical parameter in geotechnical engineering that influences a soil's permeability, drainage characteristics, and shear strength. To assess these characteristics, both sieve analysis and hydrometer tests were conducted on soil samples collected from the PK 49 slope failure site. The goal was to understand the textural composition and its influence on the slope's susceptibility to instability.

The results revealed that over 70% of the soil passed through the #200 sieve (0.075 mm), confirming that the material is predominantly composed of fine particles, particularly silts and clayey silts. The computed coefficients, uniformity coefficient (Cu) and coefficient of curvature (Cc), were outside the 1–3 range typically associated with well-graded soils, classifying the material as poorly graded. According to the Unified Soil Classification System (USCS, 1986), the soil falls under inorganic silts and silty clays of low plasticity.

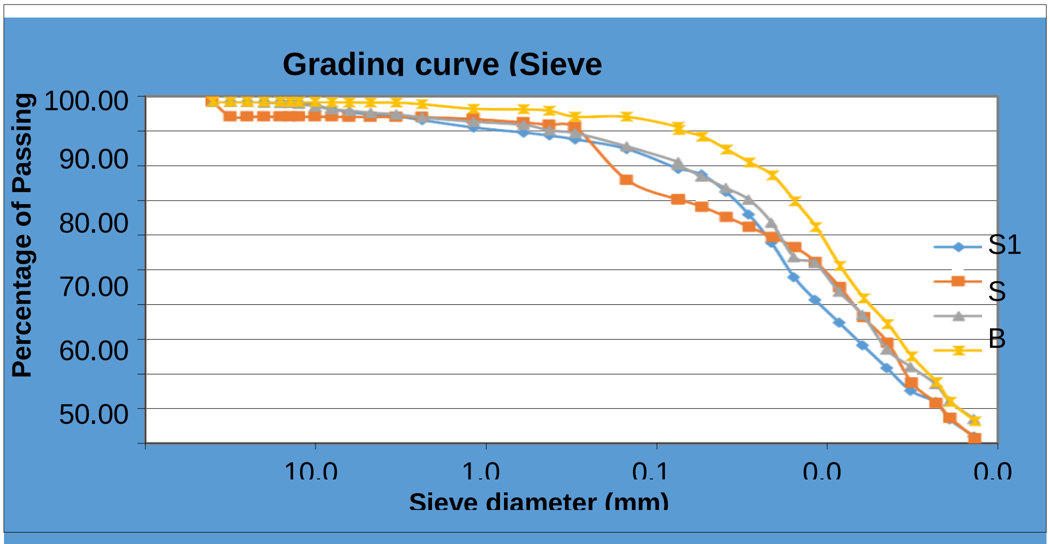

Figure 3: sieve analysis curve

The dominance of fine-grained particles in the soil has substantial implications for slope stability. Fine soils such as silts and clays have low permeability and tend to retain more water under unsaturated conditions, increasing pore water pressure during rainfall events (Hung, 2018). This accumulation of water reduces effective stress and diminishes shear strength, leading to higher susceptibility to slope failure. In contrast, coarse-grained soils, which drain more freely, typically exhibit better stability due to higher internal friction and reduced water retention (Aubeny, 2004).

One technician interviewed during the field visit observed, “These fine soils are highly prone to saturation and sliding, particularly when left unreinforced.” This insight aligns with Rahardjo (2018), who demonstrated that silty soils in tropical regions often experience rapid slope failure when exposed to intense or prolonged rainfall. The combination of low grading quality, poor drainage characteristics, and minimal cohesion makes the slope material at PK 49 inherently unstable.

4.1.3 Atterberg limits

Atterberg limits are crucial indicators of soil consistency and plasticity, used to classify fine-grained soils and assess their behavior under changing moisture content. The plastic limit and liquid limit help determine whether the soil can deform without cracking or crumbling, which is essential for understanding slope response to hydrological stress.

At the PK 49 slope site, attempts to determine the plasticity index using the Casagrande apparatus were unsuccessful. As shown in Figure 4, the soil failed to form a cohesive groove and instead flowed out uncontrollably, demonstrating non-plastic behavior.

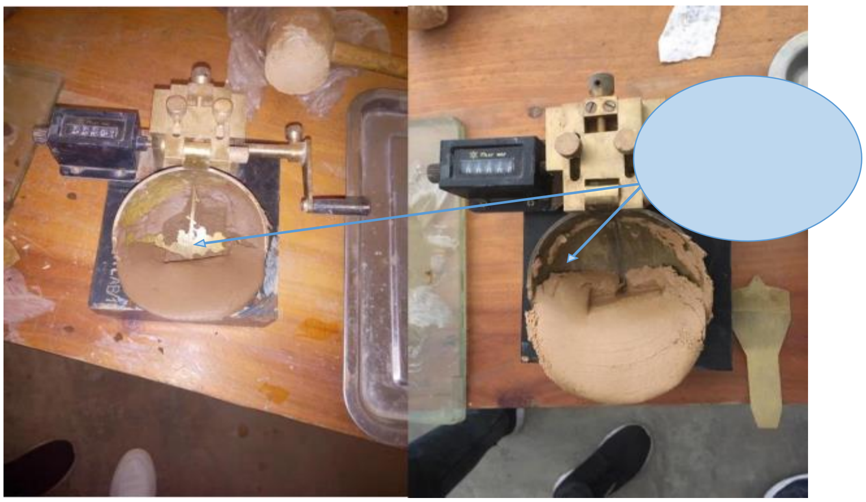

Figure 4: Liquid Limit Test Result.

This result is typical of soils composed predominantly of silt with low clay content. According to Chen (2021), silty soils with insufficient clay minerals lack the electrochemical bonding that provides plasticity and cohesion under variable moisture conditions. As a result, such soils have reduced resistance to deformation and exhibit poor load-bearing capacity, particularly during saturation.

The non-plastic nature of the slope material has direct implications for slope stability. Rahardjo (2018) found that tropical residual soils with minimal plasticity were prone to slope failures even under moderate rainfall due to their inability to absorb and redistribute pore water pressure. In the case of PK 49, the absence of plasticity means the soil cannot strain or bind adequately under hydrological loading, accelerating the saturation process and increasing the likelihood of landslide initiation.

This behavior supports the observed slope failure during the 430.2 mm rainfall event in April 2018. As infiltration occurred, the soil's lack of plastic cohesion allowed for rapid saturation and structural weakening, ultimately leading to the mass movement recorded on May 6, 2018.

4.1.4 Shear strength parameters

Shear strength is one of the most critical parameters in slope stability analysis, comprising two main components: cohesion (c) and internal friction angle (ϕ). These values help determine the soil’s ability to resist sliding along potential failure surfaces. For slopes with limited cohesion, such as the PK 49 site, the contribution of frictional resistance becomes especially important under saturated or disturbed conditions.

The direct shear tests performed on two representative soil samples revealed cohesion values of 3.2 kPa and 4.22 kPa, and internal friction angles of 24.7° and 27.0°, respectively. These results are summarized in Table 2 and visually corroborated in Figure 5, showing the composition and texture of the high-silt soil observed in the field.

Table 2: Direct shear test results summary.

Sample N°	**Direct Shear test**	
	C (KPa)	ϕ (degrees)
1)	4.22	27.01
2)	3.2	24.7

Figure 5: High Silt Soil at PK 49

The findings indicate a dominance of silty material with minimal clay content, which weakens cohesive bonding. While the moderately high friction angles provide some resistance to sliding, the low cohesion renders the slope vulnerable under external disturbances like rainfall infiltration or seismic activity. These results align with Rahardjo (2018), who demonstrated that cohesionless soils experience rapid shear strength loss during pore pressure increases, particularly under tropical rainfall conditions.

The Federal Highway Administration (FHWA, 2019) emphasizes that in the absence of cohesion, maintaining a factor of safety (FoS) above 1.3 becomes essential to account for fluctuating hydrological conditions. In the case of PK 49, where the slope inclination ranges from 40° to 46°, and the internal friction angle peaks at 27°, the FoS is estimated to be below 1.0, signaling a critically unstable condition. This underscores the need for reinforcement structures and drainage interventions to compensate for the deficient cohesive strength.

Moreover, the field engineer interviewed observed that "in soils with low cohesion, even moderate pore water pressures can significantly undermine stability." This highlights the importance of coupling geotechnical evaluation with slope protection planning, especially in high-risk regions such as Western Rwanda.

4.1.5 Unit weight

Unit weight, also known as bulk density, is a critical geotechnical parameter that represents the weight per unit volume of soil, including both solids and pore spaces. It plays a pivotal role in evaluating slope stability, as it directly influences the gravitational driving force acting on a slope. Higher unit weight increases the downslope force, thereby reducing the factor of safety in steep terrain (Zhou, 2020).

Table 3 presents the unit weight values derived from two representative soil samples collected from the PK 49 site. The results show dry densities of 1.68 g/cm³ and 1.65 g/cm³, corresponding to unit weights of 16.5 kN/m³ and 16.2 kN/m³, respectively. These values fall within the range typical for medium-dense silty sands, suggesting moderate compaction.

Table 3: Unit weight test results summary

Sample No	Dry Density (g/cm³)	Unit Weight (kN/m³)
1)	1.68	16.5
2)	1.65	16.2

While these values indicate that the slope material is moderately dense, the accompanying low cohesion (3.2–4.2 kPa) and non-plastic behavior observed in prior tests reduce the soil's ability to resist shear under saturated conditions. Field observations confirmed the presence of loose, silty layers, particularly susceptible to saturation and deformation. Interviewed contractors and field engineers emphasized that "compaction alone cannot compensate for weak soil cohesion in such rainy environments," a sentiment aligned with findings by (Mupenzi A. U., 2023) who noted similar slope vulnerabilities in Western Rwanda.

These findings suggest that despite moderate unit weights, the combined effect of high rainfall, low cohesion, and steep slope angles severely undermines slope stability at PK 49. Rainwater infiltration not only increases the pore water pressure but also raises the soil mass, intensifying the gravitational force and heightening the risk of landslides (Rahardjo, 2018); (Chen, 2021).

4.2 Topography and slope stability

Topography plays a central role in slope stability, especially in mountainous regions like Rutsiro District, where steep terrain amplifies gravitational stress on slope materials. At PK 49, field measurements revealed slope angles ranging from 40° to 46°, which significantly exceed the internal friction angles of the local soil (24.7° to 27°). This disparity suggests a factor of safety below 1.0, indicating a critically unstable condition (Rahardjo, 2018).

The elevation at the site ranges from 2,115 m to 2,200 m above sea level, with an elevation difference of approximately 80–100 m over a 200 m slope length. These characteristics reflect a highly convex topography, known to increase downslope gravitational forces and decrease slope stability. As confirmed by a district geotechnical officer during interviews, "The steep incline here, coupled with poorly drained slopes, creates conditions where saturated soil can't hold its weight."

Furthermore, visual inspection revealed minimal vegetation cover and exposed silty soils along the failure plane. Sparse ground cover facilitates surface runoff and erosion, further destabilizing the slope. Similar findings were reported by (Zhou, 2020), who demonstrated that deforested, convex slopes in tropical regions exhibit accelerated erosion and reduced stability due to lack of root reinforcement.

The presence of silty, non-plastic soils and steep gradient aligns with regional studies in Western Rwanda by (Mupenzi A. &., 2023) who identified topographic steepness as a major landslide trigger in areas with weak geological formations and high rainfall.

These topographic and geomorphologic traits at PK 49, when coupled with hydrological saturation and mechanical disturbances, act as primary drivers of slope failure.

In conclusion, the steep and elevated topography at PK 49 plays a pivotal role in the instability observed. When combined with poor vegetation cover and the soil's limited shear strength, the risk of failure is significantly heightened, especially during prolonged rainfall events.

4.3 Human activities and slope stability

Human-induced modifications are a critical factor in slope failure, particularly when slope geometry is altered without adequate engineering controls. At PK 49, the most prominent anthropogenic trigger was undercutting at the slope's toe during road construction. This excavation activity, conducted to accommodate the roadway alignment, disrupted the natural equilibrium of the slope and removed key resisting forces at the base—known in slope mechanics as toe support.

Figure 6: Evidence of Failure Induced by Slope Cutting at PK 49

As shown in Figure 6, exposed and steeply cut slopes were clearly visible during the field visit, lacking any structural reinforcement or protective facing. This type of undercutting increases the driving moment while reducing the resisting moment of the slope system. In effect, it lowers the factor of safety, making the slope highly vulnerable to even moderate hydrological loading, such as rainfall infiltration.

Furthermore, field interviews revealed that the slope had been stripped of vegetation due to construction activities. Vegetation plays a dual role in stabilizing slopes by providing root cohesion and facilitating surface water interception. The absence of ground cover at PK 49 led to increased surface runoff and infiltration, further weakening the soil matrix. One resident noted, "Since the clearing for road construction began, we've seen more water rushing down the hill and the land breaking apart after every major rainfall," highlighting the cumulative impact of unplanned development.

These observations are supported by Chen (2021), who found that slope failures in East Asia were predominantly linked to poorly engineered cuts and loss of vegetation, both of which increase pore water pressure and reduce shear strength. In Rwanda, similar findings were reported by Mupenzi (2023), who documented multiple landslides following infrastructure works that lacked proper geotechnical planning and slope stabilization measures.

Overall, the PK 49 slope failure illustrates how construction-related slope modification, if left unreinforced and unmonitored, can compromise slope integrity and escalate failure risk, especially in steep, rainfall-prone terrains like Western Rwanda.

4.4 Rainfall and slope stability

Rainfall is widely recognized as a primary natural trigger of slope failures, especially in topographically steep and hydrologically sensitive environments like those found in Western Rwanda. At PK 49, the combination of fine-grained soils and high annual rainfall created ideal conditions for slope instability. During prolonged rainfall, water infiltrates through the soil profile, elevating pore water pressure and reducing effective stress, thereby weakening the soil's shear strength and triggering mass movement (Rahardjo, 2018; Cho, 2024).

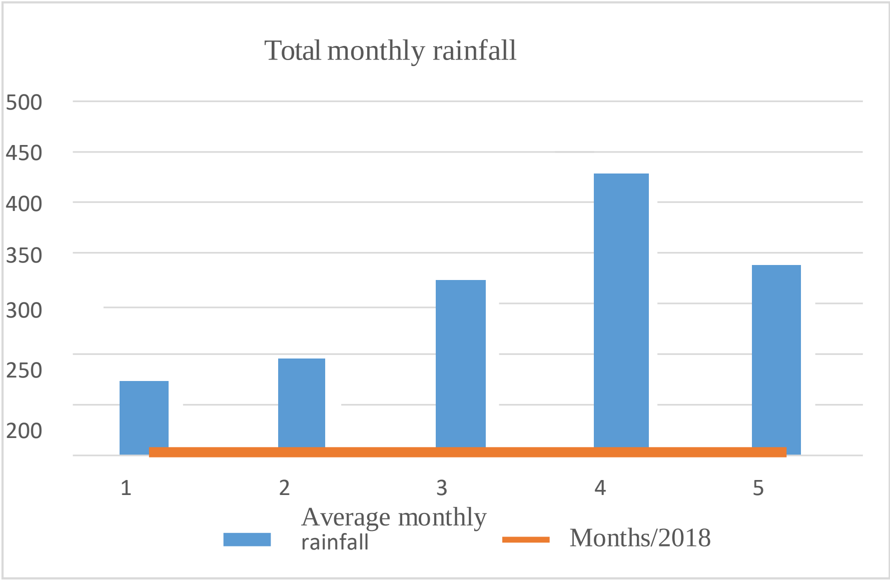

Figure 7: Cumulative rainfall from January to May 2018

Source: (Meteo Rwanda, Rubengera Station)

Analysis of rainfall data from the Rubengera Meteorological Station revealed that cumulative precipitation in April 2018 reached 430.2 mm, the highest monthly total in the first half of the year. This figure far exceeds the regional monthly average, confirming that the slope failure on May 6, 2018, occurred under extreme hydrological conditions. According to a resident interviewed during fieldwork, "The ground had been wet for weeks before the hill collapsed; it just couldn't hold any longer." This anecdotal evidence aligns with rainfall thresholds identified by Yang and Huang (2023), who found that landslide initiation in tropical hill slopes often occurs after cumulative monthly rainfall exceeds 350 mm.

Silty clay soils prevalent at PK 49 possess high water retention capacities. Once saturation is achieved, additional infiltration causes a rapid increase in pore water pressure, significantly decreasing shear strength. Field observations showed early signs of surface runoff, minor rill erosion, and evidence of ponding near the slope toe. These hydrological stressors were exacerbated by the absence of effective surface drainage infrastructure, as confirmed by RTDA field personnel. As Cho et al. (2024) noted, the lack of surface runoff control is a recurrent failure point in landslide-prone infrastructure corridors.

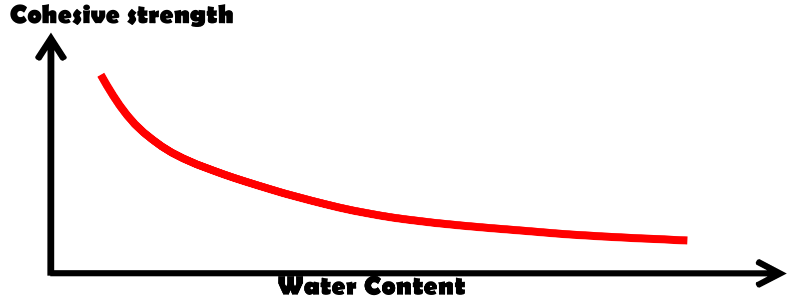

Figure 8: Effect of water content on cohesive strength of clayey silt soil. -EZ Pdh, 2025

As Figure 8 demonstrates, an inverse relationship exists between water content and cohesive strength. This is especially critical in clayey silt soils, where moisture variation can dramatically weaken interparticle bonding. According to Mupenzi (2023), saturated silty soils in Rwanda may lose up to 50% of their original shear strength while experiencing a 20–30% increase in unit weight. These changes result in a greater gravitational load on the slope, compounding the destabilizing effect of rainfall.

In conclusion, the April 2018 rainfall acted as the primary trigger of the PK 49 landslide by elevating pore pressures beyond the slope's structural capacity. The absence of engineered drainage, combined with weak soil properties and steep slope geometry, rendered the site highly susceptible. These findings underscore the need for integrating hydrological modeling into slope design and for mandating rainfall-trigger thresholds in infrastructure development policies for high-risk terrains.

5. Stabilization Measures

Slope stabilization involves the implementation of strategic engineering techniques aimed at enhancing the stability of slopes and preventing future failures. The primary objectives include minimizing erosion, reducing water infiltration, and improving the factor of safety through both structural and non-structural interventions. Drawing on site-specific data and validated research, this section outlines practical, evidence-based recommendations to improve slope resilience at PK 49.

5.1 Slope geometry modification to reduce the slope angle

Modifying slope geometry is a fundamental geotechnical strategy to enhance stability by minimizing shear stress and adjusting the slope to a safer configuration. Field measurements at PK 49 revealed slope angles ranging between 40° and 46°, which significantly exceed the soil's internal friction angle of 24.7°–27°, resulting in a factor of safety estimated to be below 1.0 (Rahardjo, 2018). Under such steep conditions, gravitational forces dominate, and failure is likely, especially in silty soils with low cohesion.

A recommended stabilization measure is the implementation of slope benching at a ratio of 2. 2H:1V, which corresponds to an approximate slope angle of 23°. This regrading substantially reduces the downslope driving force and increases the resisting force by aligning slope geometry with the soil's shear strength. Bench slopes also allow surface runoff to be better managed by disrupting water concentration along long, steep profiles.

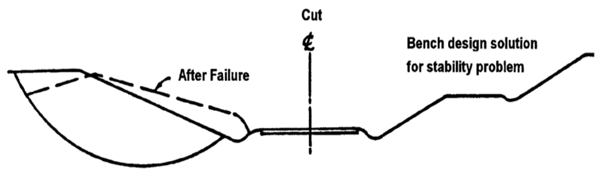

Figure 9: Deep-seated slope failure (left) and bench slope design (right) to ensure long-term stability- EZ Pdh, 2025

As shown in Figure 9, the existing slope failure at PK 49 is deep-seated and typifies conditions where slope angles exceed the mechanical capacity of the soil. On the right, the proposed bench design demonstrates how reducing slope steepness improves stability and accommodates hydrological control infrastructure such as interceptor drains or vegetated benches. This intervention is consistent with slope stabilization practices documented by Chen (2021), who observed that benching significantly improved the factor of safety in tropical, rain-fed hilly terrains similar to Rwanda's Western Province.

Additionally, Yang and Huang (2023) emphasized that slope angles exceeding the critical friction angle without mechanical reinforcement result in catastrophic failures under wet conditions. Modifying geometry not only enhances safety but also reduces long-term maintenance costs and failure risk, making it a sustainable option for infrastructure resilience.

5.2 Gabion retaining wall construction with geotextile to keep a bank of earth from sliding

Gabion retaining walls are a proven slope stabilization solution, particularly effective in regions with high rainfall and silty, low-cohesion soils, such as PK 49. These structures are composed of modular, stone-filled wire mesh baskets that provide both mechanical resistance to slope movement and passive drainage through their porous configuration. Their flexibility and cost-efficiency make them suitable for rural infrastructure development, especially where conventional reinforced concrete walls are economically or logistically unfeasible.

In the context of PK 49, gabion walls serve a dual purpose: they retain the unstable soil mass and permit the dissipation of pore water pressure, thus reducing hydrostatic build-up behind the wall. Interviews with RTDA field technicians revealed that past installations in the area failed primarily due to the absence of geotextile base reinforcement and inadequate toe support. To address these shortcomings, the proposed design integrates nonwoven geotextile layers beneath and behind the gabion structure, which help to distribute stress more uniformly, improve bearing capacity, and filter fine soil particles, preventing internal erosion or piping (Mupenzi, 2023).

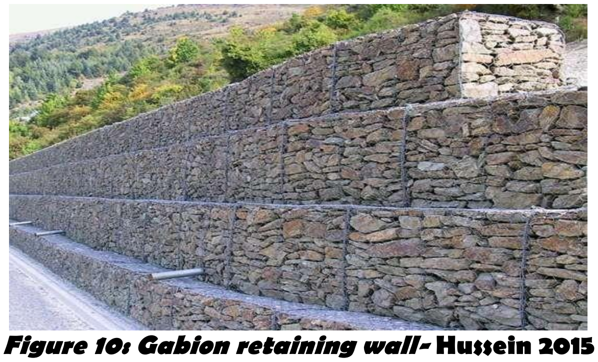

***Figure 10: Gabion retaining wall-* Hussein 2015**

As shown in Figure 10, the proposed retaining system includes a 6-meter-high, stepped gabion wall aligned with the slope base. The structure incorporates horizontal layers of geotextile fabric between basket levels and at the interface with the natural slope. This configuration has been validated in similar tropical terrains, where the combined use of gabions and geotextiles has significantly improved slope performance during rainfall-induced stress events (Cho et al., 2024). Moreover, Joe et al. (2020) demonstrated that reinforced gabions show 40–60% higher resistance to sliding and overturning compared to non-reinforced installations.

In addition to mechanical improvements, the use of locally available stones and ease of installation make gabions a sustainable and community-friendly intervention. When correctly anchored and reinforced, they offer long-term durability, particularly in regions like Western Rwanda where rainfall, slope angle, and weak soils intersect to produce frequent landslides.

5.2.1 Surface Drainage Systems

One of the primary triggers of the PK 49 slope failure was excess pore water pressure resulting from unregulated surface runoff. Surface drainage measures such as lined ditches, intercepting drains, and catchwater channels are essential to prevent water from infiltrating the slope.

Longitudinal drains should be constructed along the crest and at the base of the slope. These systems significantly reduce infiltration and help maintain soil suction, a key factor in resisting slope failure (Rahardjo, 2018). Interviews with RTDA engineers revealed that the absence of such drainage systems in previous road sections had accelerated slope degradation.

5.2.2 Vegetative Cover for Erosion Control

Vegetation plays a critical role in reinforcing shallow soils through root systems and reducing surface erosion. Establishing vegetative cover using grasses and shrubs is a proven, low-cost, and sustainable approach to slope stabilization. In silty soils such as those at PK 49, vegetation increases evapotranspiration and binds soil particles, enhancing surface stability (Zhou, 2020).

Local stakeholders noted that deforestation for road construction had removed natural stabilizers, exacerbating erosion. Reintroducing vegetation would not only provide mechanical anchorage but also reduce raindrop impact and runoff velocity, complementing structural interventions.

6. Conclusion and Recommendations

6.1 Conclusion

This study investigated the geotechnical and environmental factors contributing to slope failure along the Muhanga–Karongi road (PK 49) in Mukura Sector, Rutsiro District. Quantitative and qualitative analyses revealed that the slope failure was primarily triggered by cumulative rainfall, which reached 430.2 mm in April 2018, just a few days before the landslide event. This intense precipitation led to elevated pore water pressure and reduced shear strength in the soil.

Laboratory findings confirmed that the slope material was predominantly inorganic silty clay of low plasticity with more than 70% fine particles. The soil exhibited an average natural moisture content of 21.3%, confirming near-saturated conditions. Atterberg limits tests indicated non-plastic behavior, highlighting the absence of clay cohesion. Direct shear tests revealed low cohesion values (3.2–4.2 kPa) and moderate internal friction angles (24.7°–27.0°), while unit weights ranged from 16.2 to 16.5 kN/m³, suggesting moderate compaction but low resistance to saturation.

Topographic analysis of the site confirmed an average slope angle between 40° and 46°, far exceeding the internal friction angle and thus resulting in a factor of safety estimated to be below 1.0. Human activities, particularly unreinforced slope cutting during road construction, were found to be the key initiator. These interventions destabilized the slope toe and altered natural water drainage patterns, further accelerating failure.

Field evidence, coupled with stakeholder interviews, reinforces the critical need for integrating geotechnical investigations into national infrastructure development policy. The lack of pre-construction soil assessments and inadequate slope reinforcement measures directly contributed to the failure observed at PK 49. This case highlights how early geotechnical analysis, including soil strength characterization, rainfall risk modeling, and terrain profiling, can inform better engineering design and reduce long-term maintenance costs.

To enhance national resilience against future landslides, findings from this case study should inform Rwanda's infrastructure planning frameworks under agencies such as RTDA and MININFRA. Geotechnical risk assessments should be mandated during the feasibility stage of road construction projects, particularly in mountainous districts. Implementing evidence-based design strategies such as slope benching, gabion walls, drainage systems, and vegetation reinforcement is vital to ensuring the long-term stability and safety of road networks in Rwanda's high-risk zones.

6.2 Recommendations

To mitigate future slope failures and improve infrastructure resilience, the following prioritized and stakeholder-specific recommendations are proposed:

Short-Term Recommendations (High Priority):

- **Mandate Slope Stabilization Studies:** The Rwanda Transport Development Agency (RTDA), in collaboration with MININFRA, should enforce slope stability assessments as a prerequisite for road design approvals in high-risk zones.
- **Install Surface Drainage Infrastructure:** District-level authorities, guided by RTDA, should design and construct proper drainage systems to divert surface runoff away from slope faces, reducing saturation and erosion risk.
- **Construct Gabion Retaining Structures:** Contractors working on the Muhanga–Karongi road should install gabion walls reinforced with geotextiles at the toe of the slope to restore lateral support and reduce sliding potential.

Medium-to-Long-Term Recommendations:

- **Institutionalize Geotechnical Monitoring:** The Ministry of Infrastructure (MININFRA) should establish a geotechnical risk monitoring unit to oversee slope stability in all mountainous regions, with periodic inspections and early warning systems.
- **Capacity Building and Technical Training:** The Government of Rwanda, in partnership with local universities and engineering boards, should develop continuous professional development programs focused on slope stabilization techniques, geotechnical investigations, and landslide risk reduction.
- **Promote Vegetative Slope Reinforcement:** The Rwanda Environmental Management Authority (REMA), in partnership with local cooperatives and environmental NGOs, should lead afforestation and grassing campaigns on vulnerable slopes to enhance cohesion and minimize surface runoff.
- **Develop National Guidelines for Slope Design:** The Rwanda Standards Board (RSB), in collaboration with engineering experts, should draft national standards and guidelines for slope design and stabilization, based on local soil types, rainfall patterns, and terrain classifications.

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