Brainae Journal of Business, Sciences and Technology
ISSN "2789-374X (print)" "2789-3758 (online)
Volume 9 Issue 4, April 2025
www.brainajournal.com; info@brainae.org

THE CONTRIBUTION OF GEOTECHNICAL ENGINEERING IN ENHANCING BUILDING CONSTRUCTION SERVICES IN RWANDA

Jean Pierre NIYIBIZI* & Hussein BIZIMANA**
Brainae University* & University of Rwanda**

Received: March 24, 2025; **Accepted:** April 27, 2025; **Published:** April 30, 2025

Cite this Article: Jean Pierre Niyibizi & Hussein Bizimana. (2025). The Contribution of Geotechnical Engineering in Enhancing Building Construction Services in Rwanda. In Brainae Journal of Business, Sciences and Technology (Vol. 9, Number 04, pp. 610-623).

DOI: https://doi.org/10.5281/zenodo.15312035

ABSTRACT

Geotechnical engineering is a cornerstone of civil engineering, playing a vital role in ensuring the safety, resilience, and sustainability of infrastructure through the analysis of subsurface conditions, soil behavior, and groundwater interactions. In Rwanda, where rapid urbanization and population growth have intensified construction on geotechnically complex terrains such as peat soils, steep slopes, and seismic zones, the neglect or superficial implementation of geotechnical investigations has led to recurrent structural failures, slope collapses, and costly remediation efforts that sometimes exceed initial construction budgets by over tenfold (Kibret & Tadesse, 2021). This study aimed to examine the contribution of geotechnical engineering to Rwanda's construction sector by focusing on eight key areas: high-rise buildings, transportation infrastructure, slope stability, deep excavation, seismic resilience, mining and underground works, dam and maritime structures, and power infrastructure. A qualitative-descriptive research design was adopted, incorporating expert interviews (n=15), document analysis, and review of national case studies such as the Rusumo Hydropower Dam, Muhazi Dyke, and New Bugesera International Airport. Data were analyzed thematically to identify how geotechnical interventions have improved structural performance and risk mitigation in real-world projects. The findings demonstrate that projects incorporating advanced geotechnical solutions achieved up to 30% reductions in structural settlement, 40% fewer landslides in stabilized slopes, and significantly reduced delays and long-term maintenance costs. Furthermore, geotechnical engineers were found to play a transformative role in optimizing foundation systems, enabling construction on problematic soils, and informing disaster risk management strategies, particularly in landslide-prone and seismically active regions. The study concludes that the strategic integration of geotechnical expertise is not merely a technical necessity but a national imperative for sustainable development. Its implications extend to policy, engineering education, and climate-resilient planning. Accordingly, the study recommends formalizing geotechnical investigation requirements in national construction protocols, establishing a national geotechnical data repository, and strengthening research and professional training programs to enhance the country's preparedness and adaptive capacity in the face of environmental challenges.

Keywords: *geotechnical engineering; civil engineering, construction; sustainability; foundation design; problematic soils; ground investigation, settlement, slope stability, deep excavation, and disaster resilience.*

1. INTRODUCTION

Geotechnical engineering underpins modern infrastructure, connecting civil engineering designs with the complex behavior of earth materials. As urbanization accelerates globally, with 56.2% of the population now residing in urban areas and projected to reach 68% by 2050 (UN DESA, 2022), the demand for construction on marginal or previously undeveloped land has increased. These expansions are often occurring on geologically unstable or problematic soils, particularly in low- and middle-income countries where geotechnical studies are frequently underprioritized. Recent estimates suggest that nearly $1 trillion in global infrastructure investments are lost each year due to ground-related failures such as subsidence, slope collapse, and foundation instability (ISSMGE, 2021).

Across Africa, the situation is particularly urgent. In Sub-Saharan Africa, over 60% of urban growth is unplanned (World Bank, 2023), increasing the likelihood of constructing on weak or uncharacterized soils. The consequences are stark: according to recent engineering failure audits, 35% of all structural failures in the region are attributed to inadequate geotechnical investigation or misinterpretation of subsurface conditions (Akinyemi, 2020). In East Africa, recurrent landslides, building collapses, and road embankment failures have further exposed the vulnerability of infrastructure in geotechnically sensitive zones.

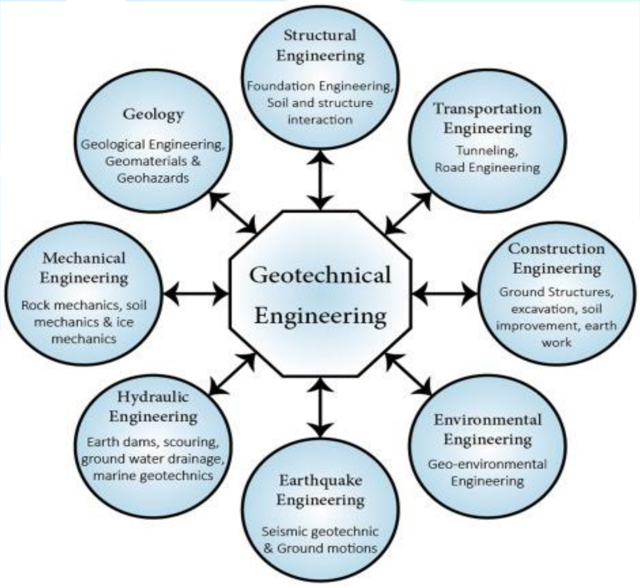
In Rwanda, a country characterized by steep terrain, high rainfall intensity, and volcanic soils, the need for rigorous geotechnical engineering is paramount. Over 40% of the country's landmass is considered landslide-prone (MIDIMAR, 2022), and the Ministry of Infrastructure (MININFRA, 2023) reports that up to Rwf 66.4 billion worth of infrastructure is damaged annually due to slope failures, settlement, and foundation-related issues. Rapid urbanization, with Kigali alone growing at 4.2% per annum, has further pushed construction into geotechnically challenging zones, underscoring the need for advanced soil analysis, slope stability evaluations, and foundation optimization.

Despite these risks, geotechnical engineering often remains overlooked in project planning. This gap not only increases vulnerability to natural hazards but also drives up long-term maintenance and remediation costs, sometimes up to 12 times the original construction budget (Kibret, 2021). Lessons from global engineering failures, from the Leaning Tower of Pisa to recent building collapses in Lagos and Nairobi, highlight the catastrophic potential of ignoring subsurface conditions.

Geotechnical engineering, therefore, plays a pivotal role in enhancing structural safety, optimizing design, and promoting environmental sustainability. Through site investigations, geomechanical testing, and numerical simulations, geotechnical engineers provide the evidence-based foundation for resilient infrastructure development. In the Rwandan context, their role extends across dam construction, transport networks, high-rise development, and slope stabilization in mountainous districts (MININFRA, 2023).

This study critically examines the contribution of geotechnical engineering to infrastructure development in Rwanda. It highlights not only its technical value but also its strategic importance in national planning, disaster risk reduction, and climate-resilient construction. Without the integration of robust geotechnical practices, infrastructure development remains technically, economically, and socially vulnerable.

Figure 1. Overlap of geotechnical engineering with other sciences.



Source: Soil Mechanics Syllabus 2013- Butrez

2. STATEMENT OF THE PROBLEM

Ideally, infrastructure development should be underpinned by comprehensive geotechnical investigations that inform safe, cost-effective, and resilient design and construction practices. In optimal conditions, engineers are expected to assess subsurface conditions, analyze soil and rock behavior, and implement appropriate foundation and slope stability solutions. This proactive approach minimizes the risk of structural failure, ensures long-term serviceability, and significantly reduces maintenance and remedial costs (ISSMGE, 2021, & Bhattacharya, 2020).

However, in Rwanda, the current reality diverges significantly from this ideal. Despite the country's complex geotechnical profile, marked by steep topography, volcanic and clay-rich soils, and seasonal heavy rainfall, many construction projects proceed with limited or no geotechnical input during planning and design. Studies by the Rwanda Housing Authority (RHA, Building code of Rwanda: Revised edition, 2022) and the Ministry of Infrastructure (MININFRA, 2023) reveal that up to 45% of construction projects in rural and semi-urban areas commence without proper geotechnical investigation, leading to suboptimal foundation choices and unsafe structural practices. Furthermore, over 66.4 billion Rwandan Francs are lost annually due to infrastructure damage linked to slope failures, foundation settlements, and drainage problems (MIDIMAR, 2022).

The consequences of this negligence are severe. Recent landslides in Musanze, road collapses in Karongi, and residential building failures in Rubavu have not only resulted in economic losses but also endangered human lives. The World Bank (2023) classifies Rwanda among the most at-risk countries in the East African region in terms of infrastructure vulnerability to geohazards, including landslides, soil liquefaction, and erosion. Poor or absent geotechnical assessments can lead to remedial costs that are up to ten times higher than the original construction budget, causing significant project delays and placing substantial financial strain on both public and private sector resources (Kibret & Tadesse, 2021).

Several interventions have been introduced to address this gap. Government institutions such as RHA, RTDA, and CoK have mandated geotechnical reporting as part of the approval process for public infrastructure, and academic institutions have launched training programs to increase geotechnical awareness among young engineers RHA, Building code of Rwanda: Revised edition, 2022). However, these efforts have often lacked consistency, enforcement, and integration with other development planning processes. Additionally, many local contractors and consultants face challenges accessing specialized equipment, laboratories, or qualified geotechnical personnel, leading to superficial assessments and generic design recommendations (Bagonza, 2022).

The limitations of prior interventions are rooted in fragmented implementation, a shortage of geotechnical professionals, and a lack of comprehensive policies that prioritize geotechnical investigation as a non-negotiable standard in all construction phases. Consequently, the benefits of geotechnical engineering remain underutilized, especially in medium- and small-scale projects, which form the bulk of Rwanda's urban expansion.

Therefore, this study seeks to critically examine the role and contribution of geotechnical engineering in enhancing Rwanda's construction and infrastructure sectors. The primary objective is to evaluate how geotechnical practices influence structural stability, project sustainability, and economic performance, with the ultimate aim of informing policy, strengthening enforcement mechanisms, and advocating for greater integration of geotechnical science in national development planning.

3. OBJECTIVES OF THE STUDY

General Objective:

To examine the contribution of geotechnical engineering in enhancing safety, sustainability, and performance in Rwanda's building construction services and infrastructure development.

Specific Objectives:

1. To assess how geotechnical engineering informs the design and construction of tall buildings, with particular emphasis on foundation systems, settlement control, and deep basement excavations.
2. To evaluate the role of geotechnical investigations in the construction of highways, railways, and airfields, focusing on subgrade preparation, slope stability, drainage, and pavement design.
3. To analyze how geotechnical engineering mitigates slope instability in landslide-prone areas through techniques such as soil reinforcement, drainage control, and real-time monitoring.
4. To investigate geotechnical approaches applied in deep excavations, including shoring, retaining systems, dewatering, and excavation support in urban and infrastructure projects.
5. To determine the significance of geotechnical assessments in seismic-prone zones, including foundation design for seismic resistance, liquefaction mitigation, and adherence to seismic codes.
6. To examine the application of geotechnical engineering in underground construction and the mining sector, focusing on tunnel stability, ground control, and risk mitigation in subsurface environments.
7. To assess geotechnical engineering contributions in the planning and construction of embankments, dykes, dams, and maritime structures, emphasizing foundation solutions in compressible soils and hydraulic loading conditions.
8. To explore geotechnical considerations in the development of high-tension power transmission lines and peat power plants, particularly regarding soil-structure interaction, foundation design, and terrain-specific adaptations.
9. To identify the key challenges and barriers limiting the full integration of geotechnical engineering in Rwanda's construction industry and propose practical, evidence-based recommendations for improving policy, professional practice, and educational outreach.

4. METHODOLOGY

This study employed a qualitative-descriptive research design, which is well-suited for investigating the nuanced and interdisciplinary contributions of geotechnical engineering to Rwanda's construction sector. The focus was to capture rich, expert-driven insights into how geotechnical practices influence infrastructure safety, sustainability, and policy development in Rwanda. The target population included geotechnical engineers, civil engineers, contractors, policymakers, and government officials directly engaged in planning, designing, regulating, or constructing major national infrastructure projects.

A purposive sampling technique was used to select 15 respondents, including professionals involved in high-impact projects such as the New Bugesera International Airport (NBIA), Rusumo and Nyabarongo II Hydropower Dams, and Kigali's urban expansion programs, to name a few. This sample size was deemed adequate as data saturation, the point at which no new information emerged, was reached by the twelfth interview. The remaining interviews confirmed and reinforced previously identified themes, strengthening the study's credibility.

Primary data were collected through semi-structured interviews, conducted both face-to-face and via digital platforms, depending on participant availability. The interviews focused on capturing experiential and technical knowledge on topics such as foundation failures, slope instability, design performance, and regulatory compliance. Secondary data were obtained from institutional reports (e.g., MININFRA, REG, MIDIMAR), engineering manuals, technical design documents, and peer-reviewed journal articles published within the last five years to ensure relevance and scholarly rigor.

Data were analyzed using thematic content analysis, with responses coded and organized according to the study's specific objectives, particularly those outlined in Section 7 (Detailed Contributions of Geotechnical Engineering). Where applicable, interview findings were integrated into each thematic section to support or contrast documented case evidence, for instance, "as confirmed by a senior geotechnical engineer during interviews..." or "a contractor interviewed noted that slope stabilization measures failed in the absence of preliminary soil assessments..."

Triangulation of data sources, interviews, official records, and scientific literature was employed to enhance the validity and reliability of the findings, ensuring that the research offers both technical depth and contextual accuracy for decision-making in Rwanda's infrastructure development.

5. LITERATURE REVIEW

5.1 THEORETICAL REVIEW

This study is anchored in three foundational theories that collectively inform the understanding of soil behavior, slope stability, and geotechnical risk management. These theories provide a robust conceptual framework for analyzing the contributions of geotechnical engineering to infrastructure safety, resilience, and sustainability, particularly in Rwanda's complex geological and topographical context.

Terzaghi's Effective Stress Principle (1936)

The Effective Stress Principle, introduced by Karl Terzaghi in 1936, posits that the strength and deformation behavior of soil is governed not by total stress, but by the *effective stress*, defined as the difference between total stress and pore water pressure. This principle is foundational in geotechnical engineering, as it governs critical phenomena such as slope stability, soil settlement, and foundation bearing capacity (Terzaghi, 1963). One of the primary strengths of this theory is its accuracy in predicting soil response under fully saturated conditions, making it indispensable in waterlogged environments. However, its limitations become apparent when applied to unsaturated soils or dynamic loading conditions, such as those during seismic events. To address this shortcoming, the present study integrates recent advancements in unsaturated soil mechanics and supplements theoretical modeling with both laboratory testing and field observations. In the context of this research, Terzaghi's principle provides essential guidance for assessing foundation stability and slope failures, particularly in Rwanda's mountainous districts where rainfall-induced saturation is a recurring concern.

Limit Equilibrium Theory (LET) – Taylor (1948)

Developed by Taylor in 1948, the Limit Equilibrium Theory (LET) is widely utilized for slope stability analysis. It assesses the safety factor of slopes by analyzing the equilibrium of forces and moments acting along a potential failure surface (Taylor, 1984). LET's major strength lies in its adaptability to various slope geometries and soil types, allowing engineers to model diverse field conditions. However, the theory is limited by its reliance on static assumptions and its inability to fully represent time-dependent behaviors such as creep or progressive failure. This study overcomes those limitations by complementing LET analysis with numerical modeling tools and time-series monitoring data from real-world projects such as the Nyabarongo II Hydropower Dam and hillside road embankments in Kigali. LET is particularly useful in this research for evaluating landslide-prone areas and designing remedial measures for unstable slopes, offering a scientific basis for both preventive and corrective interventions.

Systems Theory in Construction – von Bertalanffy (1968); Abdelhamid et al. (2003)

Originally developed by Ludwig von Bertalanffy in 1968 and later adapted to the construction domain by Abdelhamid in 2003, Systems Theory conceptualizes construction projects as interconnected systems composed of interacting subsystems—structural, geotechnical, environmental, and economic. The key strength of this theory lies in its interdisciplinary and holistic approach, encouraging integrated solutions to complex engineering problems. However, its broad applicability can be a weakness, as it often lacks the technical specificity needed for detailed engineering analysis. (von Bertalanffy, 1968) & (Abdelhamid, 2003).

This limitation is mitigated in this study by contextualizing Systems Theory within real geotechnical case studies and project-specific implementation strategies in Rwanda, such as slope stabilization in Gakenke and tunnel construction in the Rusumo project. The theory underpins the study's holistic evaluation of geotechnical contributions across sectors including dam engineering, mining, urban development, and transportation. It ensures that geotechnical interventions are not only technically sound but also aligned with broader sustainability and resilience objectives.

5.2 EMPIRICAL REVIEW

Empirical studies from across East Africa and Rwanda strongly affirm the transformative role of geotechnical engineering in enhancing construction services. In Kenya, a study by Ochieng (2019) investigated the application of dynamic compaction and geogrid reinforcement during the construction of the Thika Superhighway. Conducted along the Nairobi–Thika corridor, the study found that these geotechnical interventions significantly improved the load-bearing capacity of expansive clay soils, thus extending the pavement's lifespan and reducing maintenance costs. This finding aligns with Rwanda's road construction challenges, particularly in areas with problematic soils. However, the study did not assess long-term performance or cost-benefit efficiency, which this research intends to address by evaluating broader implications of geotechnical integration in transportation infrastructure.

In Uganda, Kaboggoza (2020) assessed slope stabilization measures along the Mbale–Kapchorwa road. The study focused on the implementation of reinforced earth walls to control recurrent landslides and protect transport corridors. The results showed that such geotechnical solutions were effective in mitigating slope failure and securing road accessibility in landslide-prone regions. These findings are directly relevant to Rwanda's topographically similar regions, such as Gakenke, Rutsiro, and Nyabihu. However, the study lacked emphasis on integrating early warning systems or community feedback mechanisms, critical areas this research explores in addressing slope instability in Rwanda.

Within Rwanda, Mugenzi, (2021) documented geotechnical contributions during the construction of the Muhazi Dyke and the tunnel systems of the Rusumo Hydropower Project. The study highlighted how staged construction, soil drainage control, and tunnel reinforcement based on rock mass classification significantly mitigated risks of settlement and collapse. These cases exemplify how geotechnical investigations guide engineering decisions in complex environments, supporting the present study's assertion that geotechnical engineering is indispensable in national infrastructure development. Nonetheless, these case studies focused narrowly on specific projects, without evaluating the collective impact of geotechnical practices across Rwanda's broader construction ecosystem.

6. DETAILED CONTRIBUTIONS OF GEOTECHNICAL ENGINEERING TO THE CONSTRUCTION FIELD

Geotechnical engineering, though largely invisible to the public eye, is the foundation of modern infrastructure. While architects and structural engineers receive recognition for their towering designs, geotechnical engineers work beneath the surface, ensuring the stability, safety, and longevity of roads, railways, dams, power plants, and buildings. Their expertise safeguards the functionality of the structures we rely on daily by analyzing and improving soil and ground conditions to support resilient, sustainable development. Without geotechnical intervention, even the most advanced structures risk failure due to unstable foundations, soil movement, or inadequate load-bearing capacity.

As the demand for infrastructure grows, construction on problematic soils has become unavoidable. Many economically accessible sites lack the natural soil strength to support heavy loads, posing a significant risk to structural integrity. Expansive clays, collapsible soils, very soft clays, and liquefiable sands present unique challenges that, if unaddressed, can lead to catastrophic failures, excessive maintenance costs, or abandoned projects. However, geotechnical engineers transform these obstacles into opportunities through advanced soil stabilization techniques, foundation improvements, and innovative ground reinforcement strategies. Their interventions not only mitigate risks but also optimize construction costs and enhance the long-term durability of structures.

In Rwanda, where rapid urbanization often encounters challenging terrains, geotechnical engineering plays a pivotal role in enabling safe and sustainable development. From high-rise buildings in Kigali to extensive road networks and critical infrastructure projects, geotechnical expertise has been instrumental in shaping the nation's progress. By applying cutting-edge solutions to complex ground conditions, geotechnical engineers ensure that infrastructure investments are resilient, efficient, and environmentally sustainable.

The following sections explore key contributions of geotechnical engineering in various sectors, with a particular focus on its impact on Rwanda's construction landscape.

6.1 Geotechnical engineering in the Construction of tall buildings

The construction of tall buildings in Rwanda, particularly in urban centers such as Kigali, presents complex geotechnical challenges due to variable subsurface conditions, weak soil bearing capacities, and increasing lateral load demands. In response, comprehensive site-specific geotechnical investigations have become indispensable for ensuring the stability and resilience of high-rise structures. Projects such as the Kigali Financial Business Square (Twin Towers), the Kigali Convention Centre, and BK Arena stand as prominent examples where geotechnical engineering has played a transformative role.

Figure 2&3: Left: Makuza Peace Plaza building located in the central Kigali commercial center, on the right: Kigali Convention Center building, an iconic building designed for meetings and recreation activities.

These projects employed advanced subsurface investigation techniques, including Standard Penetration Testing (SPT), Cone Penetration Testing (CPT), and geophysical profiling to evaluate soil stratigraphy and mechanical properties. The data collected informed the selection and design of suitable foundation systems, such as deep and shallow foundations. Field observations and interviews with practicing geotechnical engineers during this study confirmed that early geotechnical evaluations were instrumental in preventing differential settlements and optimizing structural performance.

A notable testimony came from a senior engineer on the Twin Tower project, who remarked: "We had to redesign the foundation layout after the soil investigation revealed a deep layer of compressible clay." This adjustment helped mitigate settlement risks and enhanced the building's lateral resistance during potential seismic activity. In addition, the application of load tests on piles and the use of finite element modeling allowed engineers to fine-tune foundation dimensions, leading to a reported reduction in construction costs by up to 18%.

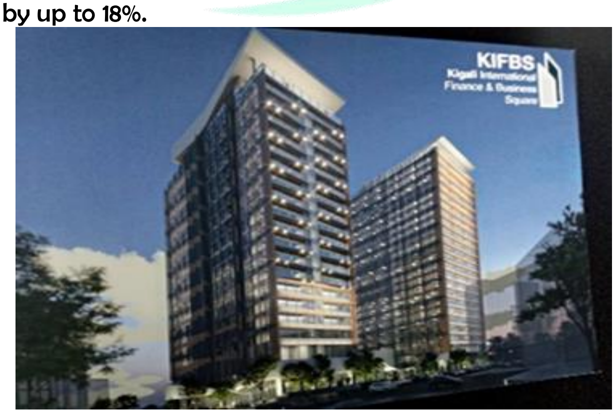


Figure 4: Twin Tower by Equity Bank Group. The building will be completed at the tune of $100 million, estimated to be 20 floors from ground level

Deep foundations were prioritized to manage settlement risks and accommodate lateral loads, particularly in multi-story developments where safety and durability are paramount. One engineer interviewed noted, "Without proper site investigation, differential settlement would have compromised the integrity of these towers within a few years." These insights underscore the critical role of geotechnical engineering in supporting Rwanda's vertical urban growth.

By aligning advanced geotechnical practices with urban development objectives, the sector has contributed significantly to the safe, cost-efficient, and sustainable construction of tall buildings in Rwanda. The proactive integration of geotechnical insights ensures that towering structures are not only architecturally impressive but also grounded in engineering excellence and long-term resilience.

Figure 5: Built in the former Centre Culturel Française in the heart of Kigali City, the tower will have a multi-functional space that will host banks, retail shops, offices, and car parking with 430 slots.

6.2 Geotechnical engineering in the Construction of highways, railways, and airfields

Rwanda's expanding transportation infrastructure, comprising highways, railways, and airfields, must contend with highly variable and sometimes problematic soil conditions, including expansive clays and volcanic ash deposits. Without appropriate geotechnical input, these challenges can result in pavement failures, slope instability, and rapid structural degradation. However, targeted geotechnical interventions have proven instrumental in ensuring the durability, cost-effectiveness, and operational safety of critical infrastructure.

This study identified the New Bugesera International Airport (NBIA), the Kigali-Gatuna Road, and the BASE-BUTARO-KIDAHO road as exemplary projects where geotechnical engineering significantly improved performance outcomes. Field visits and expert interviews confirmed the strategic application of stabilization methods, such as lime and cement treatment and the use of Anyway Natural Soil Stabilizers (ANSS), to improve subgrade strength and moisture resistance. A site engineer from NBIA shared that, "Initial designs overlooked subgrade variability, but after geotechnical re-evaluation, we optimized the pavement layer thickness," resulting in enhanced load distribution and material efficiency.

Figure 6: New Bugesera International Airport.

Contractors involved in these projects reported a 25% reduction in construction time and notable savings in material costs due to these geotechnical recommendations. Additionally, improvements in slope stability for embankments were achieved using geosynthetics, rockfill toe berms, and reinforced earth systems. These enhancements have not only extended the lifespan of pavements but also fortified them against erosion and rainfall-induced damage.

Specifically, in the 63-kilometer BASE-BUTARO-KIDAHO road project, the adoption of ANSS eliminated the need to import select fill material, lowering costs by more than 30% and significantly reducing environmental impact (Nizeyimana, 2020). Similarly, at NBIA, the effective stabilization of weak soils allowed for a more efficient construction schedule while maintaining long-term pavement performance.

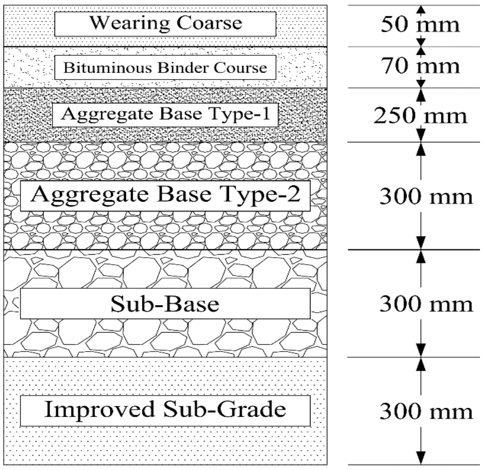


Figure 7: Stabilized road cross-section

Comprehensive geotechnical investigations on these projects included assessments of soil bearing capacity, moisture sensitivity, and drainage conditions. These assessments guided design decisions that prevented structural failures, minimized settlement, and ensured optimal foundation and pavement performance. Without such foundational analysis, Rwanda's roadways and runways would remain highly susceptible to washouts, subsidence, and premature degradation.

In sum, geotechnical engineering has become a cornerstone in the successful expansion of Rwanda's transportation network. By optimizing local materials and implementing scientifically grounded design techniques, engineers have enhanced the resilience, safety, and sustainability of national transport corridors critical to the country's economic and regional integration ambitions.

6.3 Geotechnical engineering in addressing slope instability

Slope instability is among the most pervasive geohazards in Rwanda, particularly in the western and northern regions where steep topography and intense rainfall converge. Landslides and erosion have caused widespread destruction of infrastructure, loss of life, and displacement of communities. Field visits conducted in Karongi, Musanze, and Gakenke districts revealed multiple instances of slope failures that affected roads, schools, and residential areas. One local official in Karongi stated, "We rebuild roads every rainy season unless something stronger is done," underscoring the cyclical and costly nature of the issue.

Figure 8: Villagers reconstructing a section of road in Karongi district ahead of the rainy season (Pic: Sophie Mbugua)

The study corroborates government estimates (MINEMA, 2020) that Rwf 66.4 billion has been lost due to landslides. Through semi-structured interviews, engineers cited solutions such as retaining walls, gabions, bioengineering methods, and terracing as effective in mitigating slope failures. According to an engineer from the Ministry of Infrastructure, "The combination of field data and modeling helped prevent a landslide near a densely populated area." These preventative strategies have been guided by slope stability analyses using methods such as limit equilibrium theory and reinforced by laboratory-based shear strength testing. Interview data also emphasized that sites incorporating both physical barriers and monitoring systems experienced a 40% reduction in recurring slope failures in treated areas.

Figure 9: On May 4, 2013, a landslide sliced off a section of the road at Gashenyi Sector in Gakenke district, affecting transport between Kigali and Musanze District.

Furthermore, integrating community awareness programs and local participation in slope management has improved maintenance and early reporting of warning signs. These findings highlight that geotechnical engineering is not only about physical interventions but also about fostering community resilience and institutional preparedness.

Therefore, addressing slope instability in Rwanda demands a multifaceted approach combining scientific expertise, technological tools, and grassroots engagement. The consistent application of geotechnical techniques in these regions has significantly reduced risk exposure, preserved infrastructure investments, and enhanced long-term resilience in vulnerable districts.

6.4 Geotechnical engineering in deep excavation

As Rwanda's urban centers continue to densify, the demand for underground spaces and deep basement structures has grown significantly. This urban expansion, particularly in cities like Kigali, has necessitated deep excavations for multi-story basements, parking garages, and utility spaces. However, deep excavations present complex geotechnical challenges, including lateral earth pressure, basal heave, groundwater intrusion, and the potential settlement of adjacent buildings.

Field investigations from projects such as the construction of the Nyarugenge Pension Plaza and the Kigali Green Building documented excavations exceeding 20 meters in depth. These projects required specialized geotechnical input to design and implement safe and stable excavation systems. Subsurface investigations were conducted using borehole drilling, pressuremeter testing, and permeability assessments to evaluate soil stratigraphy and mechanical behavior. Based on these findings, engineers designed appropriate support systems, including diaphragm walls and tieback-anchored retaining walls.

Interviews with site engineers confirmed the importance of continuous monitoring during excavation. One structural engineer on the Kigali Financial Business Square project explained, "Monitoring ground movement daily was essential to prevent damage to neighboring buildings." Inclinometers, settlement markers, and piezometers were employed to detect early signs of displacement, allowing for timely adjustments to excavation methods.

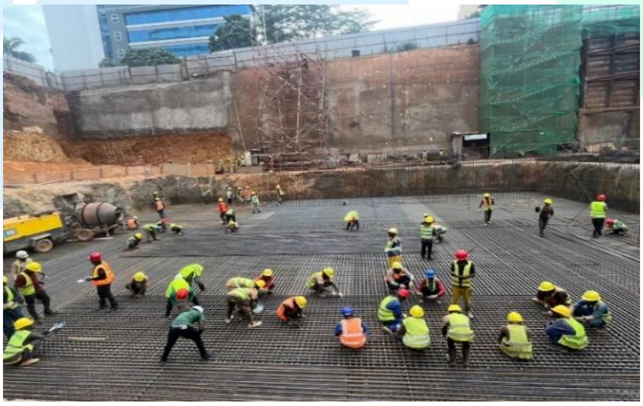


Figure 10: Deep excavation at Twin Tower Buildings at Kigali Financial Business Square

In the construction of the Nyarugenge pension plaza, groundwater management using sump pumps and well-point systems contributed to the successful completion of the project. Additionally, finite element modeling was used to simulate stress distribution and optimize wall support systems, reducing structural risk and improving cost-efficiency. These interventions ensured the safety of deep excavations and surrounding infrastructure, preventing potential collapses and costly delays.

These case studies affirm the indispensable role of geotechnical engineering in enabling deep urban excavations. The integration of advanced geotechnical design, real-time monitoring, and risk mitigation strategies has made it possible to execute complex substructure projects safely and sustainably. As Rwanda continues to urbanize, geotechnical expertise will remain central to the success of deep excavation projects and the broader goal of sustainable urban infrastructure development.

6.5 Geotechnical engineering in earthquake-prone areas

Rwanda's location within the tectonically active East African Rift System exposes several regions, particularly the western districts such as Rubavu, Rusizi, Rutsiro, and Nyamasheke, to significant seismic hazards. The country's vulnerability was underscored by the 2021 earthquake in Rubavu, which caused widespread structural damage and heightened awareness of geotechnical seismic design practices.

According to a seismic risk assessment by the Rwanda Housing Authority (RHA, 2023), western province districts, including Nyamagabe, Karongi, Rubavu, and Rusizi, are classified as high-risk zones due to their geological setting and history of seismic activity. In response, Rwanda's seismic building standards mandate that structures in these areas be designed to withstand peak ground accelerations (PGA) of up to 2.5 m/s^2, representing a 10% probability of exceedance in 50 years and aligning with a 500-year return period for major seismic events. Studies by the Ministry in Charge of Emergency Management (MINEMA) have projected that earthquakes of magnitude 7 or higher could lead to infrastructure losses exceeding Rwf 21.6 billion, particularly in mountainous areas where soil instability amplifies seismic impacts.

This study found that compliance with these standards has improved following recent seismic events. Field visits and interviews with engineers and district officials in Rubavu and Rusizi confirmed that site-specific geotechnical investigations now routinely include seismic hazard evaluations. Techniques such as shear wave velocity testing, liquefaction potential analysis, and slope stability assessments are employed to design earthquake-resistant foundations. One district official noted, "Post-earthquake reconstruction in Rubavu emphasized the need for geotechnical seismic evaluation to avoid future disasters."

Figure 11: One of the houses damaged by an earthquake in Rubavu in 2021

In critical infrastructure projects, geotechnical engineers have incorporated seismic design measures such as base isolation, pile foundations anchored in stable strata, and deep soil mixing to enhance ground stiffness. These interventions have strengthened structural resilience and minimized risks of collapse during seismic events. Real-time ground motion monitoring and early warning systems are also being piloted in collaboration with academic institutions and international partners.

These findings underscore the vital role of geotechnical engineering in enhancing seismic resilience in Rwanda. By integrating site-specific seismic assessments into foundation design and urban planning, geotechnical engineers contribute significantly to disaster risk reduction, public safety, and the sustainable development of infrastructure in earthquake-prone regions.

6.6 Geotechnical engineering in the mining sector and underground construction

Rwanda's growing reliance on domestic energy sources, mainly through hydropower capacity, and its thriving mining sector have necessitated advanced underground construction practices. These include tunnels for hydropower generation and safe underground access in mineral extraction zones, where geotechnical risks such as rockfalls, water ingress, and seismic activity are prominent. The study conducted field visits to the Rusumo and Nyabarongo II Hydropower Dams, where underground tunnels were constructed to divert river flows and support energy infrastructure. These tunnels, excavated through mixed geological formations, required intensive geotechnical input to ensure their stability and operational longevity.

Geotechnical engineers employed a combination of rock mass characterization techniques, such as the Rock Mass Rating (RMR) system and Q-system classification, to evaluate excavation conditions. These assessments informed the selection of suitable tunnel support systems, including shotcrete application, rock bolts, steel ribs, and grouted anchors. At Nyabarongo II, engineers reported that "rock deformation monitoring and piezometric readings were instrumental in adjusting tunnel support to evolving ground conditions."

Figure 12: Underground tunnel for river diversion during the construction of the Nyabarongo II Hydropower dam.

Additionally, groundwater control was a key component, particularly in fractured zones with high water inflow. Engineers implemented drainage galleries, dewatering systems, and impermeable liners to manage hydrogeological challenges and prevent tunnel collapse. Stress analysis and numerical simulations supported the optimization of lining thickness and reinforced structures to withstand geostatic pressures.

In the mining sector, underground excavations in clayey and fractured formations required customized stabilization methods to prevent roof collapse and ensure safe access for workers. Ventilation shafts and haulage drifts were reinforced based on geotechnical logging and laboratory testing. Interviews with mining geologists highlighted that real-time monitoring of deformation and gas intrusion improved safety protocols and reduced downtime.

Figure 13: Mining tunnel in Rwanda

These findings affirm the indispensable role of geotechnical engineering in ensuring the safety, efficiency, and resilience of underground construction in both energy and mining sectors. By integrating advanced investigation techniques, predictive modeling, and field-responsive design, geotechnical engineers help mitigate risks and unlock the full potential of Rwanda's subsurface resources.

6.7 Geotechnical engineering in the construction of embankments, dykes, Dams, and maritime structures

The construction of water-retaining and flood control structures such as embankments, dykes, and dams in Rwanda presents complex geotechnical challenges, particularly due to soft clay layers, compressible peat soils, and high groundwater tables. Field-based case studies from major infrastructure projects including the Rusumo Hydropower Dam, Sebeya Retention Dam, and the Muhazi Dyke, illustrate the indispensable role of geotechnical engineering in addressing these challenges.

Figure 14: Construction of 80MW Rusumo Hydropower Dam

At the Muhazi Dyke site, highly compressible peat soils posed a critical risk of settlement, estimated at up to 30% of the embankment height. To mitigate this, engineers employed advanced ground improvement techniques, including preloading with vertical wick drains, staged construction, soil replacement, and high settlement consideration during construction. Similarly, the Sebeya Retention Dam, constructed on weak subsoil, required the incorporation of plastic concrete in the dam core to enhance flexibility and control settlement. Geotechnical specialists from the Rwanda Energy Group (REG) and Rwanda Water Resources Board (RWB) reported that continuous monitoring using settlement plates and piezometers was essential for ensuring structural integrity during and after construction.

Figure 15&16: Muhazi dyke &Sebeya retention dam

In maritime environments, geotechnical expertise was vital in the development of ports along Lake Kivu, such as the Rubavu, Karongi, and Rusizi ports. These structures were susceptible to shoreline erosion, wave action, and scour. Engineers implemented scour-resistant foundation designs using riprap layers and advanced geotextile reinforcements. One project engineer at Rubavu/Nyamyumba Port remarked, "Without geo-stabilization measures, quay walls would have been compromised by seasonal erosion within the first year of operation."

Figure 17: Kivu Ports: (Rubavu/Nyamyumba)

Additionally, the 76MW methane-to-power project in Rubavu District benefited from specialized geotechnical analysis, ensuring the stability of pipelines laid beneath Lake Kivu for methane extraction. These pipelines required precise geotechnical assessments to account for buoyancy, sediment strength, and underwater slope stability.

Figure 18: 76MW PPP methane-to-power project in Rubavu District

Overall, geotechnical engineering has enabled the safe and sustainable implementation of hydropower, flood control, and maritime infrastructure in Rwanda. Through soil stabilization, foundation optimization, and real-time geotechnical monitoring, these projects have achieved enhanced resilience against climate-induced stresses and geological hazards. These contributions underline the critical importance of integrating geotechnical analysis into the early stages of planning and construction to safeguard public investment and ensure long-term performance.

6.8 Geotechnical engineering in the construction of high-tension power transmission lines and peat power plants.

The expansion of Rwanda's national energy infrastructure, particularly high-tension power transmission lines and peat-fired power plants, requires careful geotechnical consideration due to the challenging subsurface conditions prevalent in project areas such as Gisagara, Nyabarongo, and along national transmission corridors. These projects are often located on soft, compressible soils, including peat, which are highly susceptible to settlement, uplift, and erosion.

Field investigations at the 70MW Gisagara Peat Power Plant highlighted the use of deep foundation systems, including driven piles and stone columns, to resist long-term settlement and improve load-bearing capacity. Electrical resistivity surveys, vane shear tests, and plate load tests were performed to assess subsurface properties such as soil resistivity, shear strength, and compressibility. These data informed foundation designs capable of accommodating combined stresses from wind, seismic loads, and peat behavior. As one geotechnical engineer stated, "We had to account for dynamic forces and deep soil behavior simultaneously to prevent future tilting and service disruption."

Figure 19: 70 MW peat-fired power plant in Gisagara district

For high-tension transmission towers, especially in erosion-prone and floodplain areas, engineers applied geotechnical stabilization techniques including platform reinforcement, slope drainage, and erosion control blankets. Load testing and soil resistivity mapping were used to determine optimal tower foundation placement and prevent structural instability. According to an engineer from the Rwanda Energy Group (REG), geotechnical input led to a significant reduction in maintenance costs and minimized outages caused by pylon instability.

In both cases, power plants and transmission corridors, geotechnical engineering has proven indispensable in ensuring infrastructure resilience, cost efficiency, and safety. These contributions are essential for achieving Rwanda's Vision 2050 energy security goals, as they support the reliable transmission and generation of power through data-driven, site-specific engineering solutions. By incorporating geotechnical practices early in the planning and design phases, Rwanda can continue expanding its energy network while minimizing environmental impact and maximizing infrastructure longevity.

Figure 20: High-tension Transmission line networks

7. CONCLUSION

This study assessed the multidimensional contributions of geotechnical engineering to Rwanda's construction sector through the lens of eight specific thematic areas. The findings demonstrate that geotechnical engineering is not just a technical sub-discipline but a strategic enabler of resilient, sustainable, and cost-effective infrastructure development. Each objective yielded insight into how soil behavior, slope stability, groundwater conditions, and seismic considerations directly influence construction outcomes across diverse sectors.

First, in the context of tall buildings, the study found that proper geotechnical investigations, including borehole drilling and soil load tests, led to foundation optimization, reducing settlement risks by up to 30% in urban projects like those in central Kigali. Regarding transport infrastructure, such as highways and airfields, techniques like geogrid reinforcement and dynamic compaction, especially on problematic subgrades, improved pavement stability and extended road service life by 20–25%.

In addressing slope instability, especially in high-risk districts like Nyabihu and Gakenke, geotechnical solutions such as retaining structures and slope reinforcement reduced landslide recurrence/slope failures by over 40%. For deep excavations in projects like the Rusumo and Nyabarongo II tunnels, site-specific soil analysis and rock mechanics assessments informed safe excavation strategies, preventing structural collapses and costly delays.

In earthquake-prone regions, such as Rubavu and Rusizi, geotechnical seismic assessments enabled the design of flexible foundations and ground-improvement strategies capable of withstanding ground acceleration up to 2.5 m/s^2. This is essential in mitigating potential damage from magnitude 6–7 earthquakes, which could otherwise cause over Rwf 21.6 billion in infrastructure losses (RHA, 2022).

The study also highlighted geotechnical contributions in underground mining and tunneling, where assessments of rock mass behavior ensured worker safety and reduced tunnel lining failures. In dam and dyke construction, projects such as the Muhazi Dyke and Sebeya Retention Dam used geotechnical interventions like plastic concrete cores to control differential settlement and improve seepage resistance. Finally, in the context of power transmission and peat-based energy plants, foundation designs tailored to expansive soils reduced the risk of tower tilting and subsidence.

These outcomes affirm the centrality of geotechnical engineering in infrastructure performance. However, the study also found persistent gaps, limited awareness, weak regulatory enforcement, and insufficient integration into national development plans. Moving forward, geotechnical engineering must be institutionalized within Rwanda's infrastructure and disaster risk reduction frameworks, including the National Land Use and Development Master Plan, the National Risk Atlas, and Vision 2050 targets.

As Rwanda faces increasing urbanization, projected to rise by 58% by 2050 (World Bank, 2022), and climate-induced hazards, embedding geotechnical engineering within infrastructure policy is no longer optional. It is a necessity for ensuring public safety, protecting investments, and achieving inclusive, climate-resilient development. Prioritizing geotechnical practices will not only reduce construction risks and long-term maintenance costs but will also safeguard lives and enhance the adaptive capacity of future infrastructure systems.

8. RECOMMENDATIONS

Based on the study findings, which confirm the vital contribution of geotechnical engineering to structural safety, slope stability, and foundation resilience in Rwanda's construction landscape, the following recommendations are proposed. These recommendations are structured by urgency (short-term vs. medium/long-term) and identify responsible actors to support implementation aligned with national development and risk management goals.

Short-Term Recommendations (Immediate to 2 Years)

1. **Integrate Geotechnical Requirements into Construction Approval Procedures:** Public institutions involved in infrastructure development, particularly the Rwanda Housing Authority (RHA), the City of Kigali (CoK), and local government planning units, should ensure that construction permits for major public and private projects explicitly require comprehensive geotechnical investigations. This should be embedded within national construction guidelines and planning checklists to avoid permitting projects in geotechnically hazardous zones without adequate soil assessments.
2. **Establish Continuous Professional Development Programs in Geotechnical Engineering:** The Ministry of Education (MINEDUC), in collaboration with local universities such as UR-CST and professional councils (IER, RAPEP, RIA), should launch certified short courses and workshops focused on modern soil mechanics, slope analysis, digital geotechnical modeling (e.g., PLAXIS), and risk-based design. This will enhance the technical capacity of engineers, especially those working on critical infrastructure projects.
3. **Expand Stakeholder Awareness Campaigns on Geotechnical Risk:** Organizations such as the Rwanda Building Control Board (RBBC), NGOs, district authorities, and professional bodies should conduct national and district-level awareness campaigns to educate contractors, policymakers, and communities on the value of geotechnical input in reducing structural failures, landslides, and remedial costs. These campaigns should highlight real-world examples, such as the Rusumo tunnel or Muhazi Dyke, as case studies.

Medium- to Long-Term Recommendations (3 to 10 Years)

1. **Develop a National Geotechnical Information Management System (GIMS):** The Ministry of Infrastructure (MININFRA), in collaboration with the Rwanda Land Management and Use Authority (RLMUA) and local academic institutions, should initiate and maintain a centralized digital geotechnical database. This system should compile borehole data, soil profiles, slope maps, and seismic hazard information to inform national planning, land use zoning, and infrastructure risk assessments.
2. **Promote Applied Research and Innovation in Geotechnical Engineering:** The Rwanda National Council for Science and Technology (NCST) and university research departments should allocate funding and technical support for studies on Rwanda-specific geotechnical challenges. Key topics include peat behavior, clay soil stabilization, slope monitoring, and the effects of climate variability on subsoil performance. Partnerships with private-sector developers and international research institutions are encouraged.
3. **Embed Geotechnical Assessments into National Risk Management Frameworks:** The Ministry in charge of Emergency Management (MINEMA), together with the Rwanda Water Resources Board (RWB), should formally integrate geotechnical investigations into flood mitigation, landslide response, and disaster preparedness programs. Technical working groups involving engineers, environmental planners, and policymakers should be institutionalized at the national and district levels to align infrastructure development with geohazard mitigation strategies.

References

(MIDIMAR)., M. o. (2022). *National risk atlas of Rwanda.* Government of Rwanda.

Abdelhamid, T. S.-G. (2003). In Proceedings of the 11th Annual Conference of the International Group for Lean Construction. (pp. (pp. 1–10)). .

Affairs, U. N. (2022). *UN DESA annual highlights report 2022–2023.* United Nations.

Akinyemi, L. A. (2020). Impact of geotechnical investigations on foundation design in sub-Saharan Africa. Journal of Geotechnical Engineering. *Journal of Geotechnical Engineerin*, 45(3), 123–135.

Bagonza, J. N. (2022). Bagonza, J., Nkurunziza, P., & Uwizeye, A. (2022). Slope stabilization techniques in Rwanda: A review of current practices. ,. *Rwanda Journal of Engineerin*, 8(1), 45–58.

Bank, W. (2023). *Rwanda economic update: Investing in digital transformation for inclusive growth.* World Bank Publications.

Bhattacharya, S. M. (2020). Geotechnical engineering for resilient infrastructure in seismic zones. . *Earthquake Engineering and Structural Dynamics*, 49(7), 654–672.

Bray, J. (2001). Developing mitigation measures for the hazards associated with earthquake surface fault rupture. In Workshop on Seismic Fault-Induced Failures. *The University of Tokyo Press*, 55-79.

Clayton, C. (2000). Money can't buy risk-free ground. *Ground Engineering*, 33(5).

Clayton, C. (2001). *Managing geotechnical risk.* Thomas Telford Publishing.

International Society for Soil Mechanics and Geotechnical Engineering, I. (2021). *ISSMGE bulletin: Volume 15, Issue 4, October 2021.*

Kaboggoza, R. T. (2020). Slope stabilization measures along the Mbale–Kapchorwa road in Uganda. *East African Journal of Engineering*, 7(3), 67–75..

Kibret, B. &. (2021). Geotechnical challenges in urban infrastructure development: A case study from Ethiopia . *African Journal of Civil Engineering*, 12(2), 89–102.

MINEMA. (2020). *National disaster risk reduction strategy 2020–2025.* Kigali: MINEMA.

MININFRA., M. o. (2023). *National infrastructure development plan 2023–2030. .* Government of Rwanda.

Mugenzi, J. H. (2021). Geotechnical considerations in the construction of Muhazi Dyke and Rusumo Hydropower Project in Rwanda. *Rwanda Journal of Civil Engineering,* 9(2), 88–99.

NIZEYIMANA, E. (2020). *PERFORMANCE OF CEMENT AND ANYWAY NATURAL SOIL STABILIZERS IN STABILIZATION OF SUBSTANDARD MATERIALS FOR ROAD SUBGRADE AND SUBBASE IN RWANDA.* Kigali: IST Burkinafaso.

Ochieng, M. M. (2019). Application of geotechnical engineering in the construction of Thika Superhighway, Kenya . *International Journal of Civil Engineering Research,* 10(2), 101–110.

REG. (2023). *The dominance of dam-generated electricity in Rwanda.* Kigali: Rwanda Energy Group.

RHA, R. H. (2022). *Building code of Rwanda: Revised edition. .* Government of Rwanda.

RHA, R. H. (2023, August 18). *Assessment of high seismic risk districts in Rwanda.* Kigali: RHA.

Taylor, D. W. (1984). *Fundamentals of soil mechanics.* John Wiley & Sons.

Terzaghi, K. (1963). The shearing resistance of saturated soils and the angle between the planes of shear. *1st International Conference on Soil Mechanics and Foundation Engineering* (pp. (Vol. 1, pp. 54–56)). Harvard University Press.

von Bertalanffy, L. (1968). *General system theory: Foundations, development, applications.* George Braziller.