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Enhancing Sustainability in Geotechnical Engineering Projects: A Case Study of Old Thaba Nchu Road

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ABSTRACT: The Old Thaba Nchu Road (A56) in the Free State, South Africa, is experiencing significant pavement deterioration primarily due to geotechnical factors. This case study, presented by the Civilab@CUT Research Group, examines the underlying causes of degradation, with a focus on the inadequate drainage system and suboptimal roadbed composition. The existing road structure consists of a single layer of moist silty sand and silty clay, which lacks the necessary strength to support both light and heavy traffic loads. This weakness leads to severe rutting and cracking, particularly exacerbated by the passage of heavy trucks transporting construction materials. Water infiltration is identified as a critical factor contributing to pavement failure. The absence of adequate drainage allows water to accumulate beneath the surface, softening subgrade materials and leading to further structural damage. The study highlights that any repairs made will be susceptible to premature deterioration unless these drainage issues are addressed. Additionally, the analysis reveals that the current pavement structure is inadequate to support the heavy loads imposed by local industries, resulting in fatigue cracking and full-depth fractures that extend into the weathered gravel base. The report advocates for a comprehensive rehabilitation strategy that includes the construction of multiple layers—such as a reinforced roadbed, sub-base, base, and asphalt surface—to ensure long-term durability. This project aims to establish a sustainable framework for road rehabilitation that addresses immediate geotechnical challenges and fosters local involvement and capacity building. By integrating community engagement and digital management tools for monitoring and reporting, valuable insights into sustainable practices in geotechnical engineering within the context of infrastructure maintenance can be contributed.

KEYWORDS: Geotechnical factors, inadequate drainage systems, traffic patterns, community engagement, digital management.

1 INTRODUCTION

Effective road rehabilitation in South Africa relies on structured frameworks designed to ensure sustainable and long-lasting repairs. National policies advocate a systematic, multi-layered approach encompassing design standards, institutional coordination, and capacity building through statutory road coordinating agencies (Department of Transport, n.d.; ALG Global, 2023). The adoption of robust asset management systems helps optimise resource allocation and prioritise interventions based on road condition assessments and economic criteria, ensuring that work is undertaken where it offers the greatest impact (PIARC, 2021).

2 LITERATURE REVIEW

2.1 *Sustainable practices*

Sustainable road rehabilitation and asset management practices are gaining increasing global recognition, particularly as infrastructure networks age and pressures on funding and environmental resources intensify (Milne et al., 2017). In the South African context, the persistent challenge of maintaining rural and peri-urban road networks such as the Old Thaba Nchu Road reflects the complexities of balancing technical, economic, social, and environmental considerations (Department of Transport, n.d.; Petros et al., 2021).

Recent studies emphasise the need for adopting robust frameworks for road rehabilitation, highlighting multi-criteria decision-making approaches that prioritise long-term sustainability over short-term cost minimisation (PIARC, 2021). These frameworks typically incorporate life-cycle costing, socioeconomic impacts, risk assessment, and environmental performance in selecting and designing rehabilitation strategies (Kumar et al., 2019; Park & Kim, 2018).

2.2 *Geotechnical factors*

Geotechnical factors remain a central concern in road performance, particularly where expansive clay subgrades are present. Smith and Jones (2020) noted that improper subgrade characterisation and inadequate drainage are leading contributors to premature pavement failure in highveld regions, while Mshali and Savant (2022) identified effective subgrade stabilisation and layered construction as effective mitigations. Advanced reinforcement techniques, including chemical modification of base materials, have shown to significantly improve resistance to both moisture penetration and cyclic loading (Ng et al., 2018; O'Connell et al., 2021).

2.3 *Community engagement and management tools*

Community engagement and digital management tools are increasingly featured in contemporary literature as means to enhance the sustainability and effectiveness of rehabilitation projects (ALG Global, 2023; Christodoulou et al., 2020). Incorporating local knowledge through participatory processes can lead to more resilient designs that better serve the needs of affected populations. At the same time, digital asset management systems offer improved data-driven prioritisation and resource allocation (Lee & Choi, 2022).

Despite these advances, notable gaps persist in adapting global best practices to specific regional constraints—such as the climatic, geotechnical, and operational characteristics encountered in the Free State. This case study of the Old Thaba Nchu Road thus contributes to current knowledge by analysing the efficacy of a systematic, staged-stabilisation approach within a South African highveld context.

3 METHODOLOGY

This research employs a case study methodology to investigate the sustainability and long-term performance of rehabilitation strategies implemented on the Old Thaba Nchu Road (A56) in the Free State Province. The methodological approach comprises the following stages:

3.1 *Site Assessment and Data Collection:*

A comprehensive site investigation was conducted, which included geotechnical profiling of subgrade soils, traffic and loading analysis, and condition surveys of the pavement and drainage infrastructure. Archival data and project documentation from previous maintenance cycles were also reviewed.

3.2 *Framework Analysis:*

Relevant national and international frameworks and standards for road rehabilitation were analysed to benchmark the adopted practices. These included guidelines from the South African Department of Transport, the World Road Association (PIARC), and various peer-reviewed models of sustainable asset management.

3.3 *Design and Reconstruction Evaluation:*

The technical design and staged reconstruction methodology for the A56 were documented in detail, with attention to material selection, pavement layer configuration, and additive specifications. Laboratory testing results and field performance criteria for the G5 material and chemical additives were assessed. G5 material is a medium-quality granular road construction material classified in South African practice (TRH14/COLTO) that comprises natural gravel or crushed rock and is commonly used as a subbase layer in flexible pavement structures.

3.4 *Performance Monitoring and Impact Analysis:*

Post-reconstruction performance was monitored using key performance indicators, including rutting, surface cracking, drainage efficacy, and community feedback. Economic and maintenance outcomes were compared with original projections and previous conventional interventions.

3.5 *Stakeholder and Community Consultation:*

Interviews and workshops involving local authorities, users, and affected community members gathered qualitative data on the perceived impact, successes, and areas for future improvement.

Through this multi-pronged methodology, the study critically evaluates whether the adopted approach aligns with best practice for geotechnical sustainability and delivers superior outcomes under local Free State conditions.

4 STUDY AREA AND GEOLOGY

The Old Thaba N'chu Road (A56) as shown in Figure 1, is a significant arterial route located to the east of Bloemfontein in the Mangaung Metropolitan Municipality, Free State Province, South Africa. This road, which connects Bloemfontein with Thaba Nchu, forms a major transportation corridor serving communities such as Bloemfontein, Botshabelo, and Thaba Nchu. The surrounding region is characterised mainly by open grasslands and gently rolling terrain, typical of the Highveld plateau, with an elevation between 1,300 and 1,400 meters. The A56 is not only crucial for daily commuting and local economic activity, but also serves as an essential link for rural and peri-urban settlements, facilitating access to goods, services, and economic opportunities.

The A56 traverses a landscape predominantly underlain by sedimentary rocks of the Karoo Supergroup. These rocks are primarily composed of shales, sandstones, and mudstones from the Ecca and Beaufort Groups, deposited in fluvial and floodplain settings within the ancient Karoo Basin (Johnson et al., 2006; Free State Department of Water Affairs, 2010). Intruding through these sedimentary beds are dolerite sills and dykes, dating to the Jurassic period, which form harder ridges and prominent outcrops within the generally flat terrain (Johnson et al., 2006). In the vicinity of Bloemfontein and Mangaung, the geology is dominated by the Adelaide Subgroup of the Beaufort Group, which sometimes contains calcareous nodules and significant fossil assemblages, such as late Permian vertebrates preserved within the floodplain mudstones and minor sandstones (SAHRA, 2020). The weathering of these rock types has produced fertile, reddish soils that support the regional grassland vegetation (Free State Department of Water Affairs, 2010).

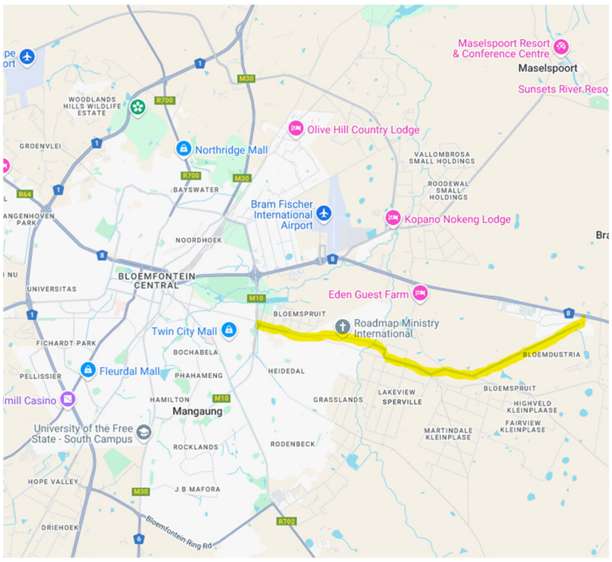

Figure 1. Map of the Old Thaba Nchu Road (A56), east of Bloemfontein.

The geology presents a range of challenges that can accelerate the deterioration of the A56. As discussed, much of the area is underlain by sedimentary rocks of the Karoo Supergroup, particularly shales and mudstones of the Ecca and Beaufort Groups, which weather to form expansive clays. These clays are highly reactive, swelling when wet and shrinking in dry conditions, leading to cyclic ground movements that cause cracking and deformation of road surfaces (Johnson et al., 2006). Additionally, the presence of dolerite sills and dykes introduces abrupt changes in subgrade strength, as dolerite is significantly more resistant to weathering than the surrounding sediments. This variation results in stress concentration zones along the road, manifesting as longitudinal cracks and localised settlement (Johnson et al., 2006). The permeable nature of weathered sedimentary rocks and high groundwater tables further contributes to poor drainage, increasing the risk of water ingress, subgrade weakening, and the formation of potholes and rutting, as shown in Figure 2, especially where less-permeable rock layers perch groundwater (Free State Department of Water Affairs, 2010).

Figure 2. Pavement failure of the A56

When saturated, weathered shales and mudstones rapidly lose shear strength, making road embankments susceptible to slope failures and shoulder slippage after heavy rainfall (SAHRA, 2020). The alternating occurrence of soft sedimentary rocks and rigid dolerite bodies complicates construction and maintenance by causing uneven compaction and differential movement, which can perpetuate pavement distress and maintenance needs (Johnson et al., 2006). Finally, the fine-textured, reddish soil generated by the weathering of these rocks are highly erodible, and heavy rainfall can induce erosion along road shoulders and embankments, undermining pavement support and contributing to ongoing edge and support failures (Free State Department of Water Affairs, 2010).

5 STRUCTURAL DETERIORATION OF THE A56

A forensic assessment of the Old Thaba Nchu Road (A56) has revealed that the original pavement structure consisted of a relatively thin, chemically stabilised base layer—measuring only 150 to 200mm in thickness—constructed directly above highly expansive clays of the Adelaide Group (see Figure 3). This base was surfaced with a notably thick asphalt layer, 80–100 mm in depth, which was intended to enhance load distribution and moisture protection under the region's prevailing climatic and traffic conditions. The design approach reflected the common engineering philosophy at the time, aiming to minimise construction costs while providing sufficient bearing capacity for the forecast traffic volumes and expected rainfall patterns. Chemical stabilisation of the base was selected to improve its resistance to moisture ingress and to increase its structural strength, despite the inherent challenges posed by the reactive nature of the Adelaide Group clays. The substantial thickness of the asphalt was anticipated to counter the effects of seasonal moisture fluctuations and thermal movements, providing a durable surfacing layer to reduce the risk of surface cracking and rutting.

Figure 3. The excavated area of the A56

While this configuration initially provided an effective solution for the traffic volumes predicted during the design period, it did not sufficiently mitigate the risks posed by the active clay subgrade. The limited thickness of the stabilised base allowed seasonal moisture fluctuations to induce significant vertical and lateral movements in the underlying clays, leading to considerable subgrade instability. Over time, these cyclic changes resulted in differential heave and settlement, which manifested as reflective cracking, rutting, and surface distress in the asphalt layer above. The inadequate drainage provisions further enabled water ingress into the pavement structure, amplifying the swelling and shrinking behaviour of the expansive clays.

The situation was worsened by substantial increases in both traffic volume and axle loads, particularly after the opening of the Bloemspruit Quarry in 2017. Heavy quarry trucks (Figure 4) and increased commuter traffic imposed loadings far beyond those envisaged in the original design, accelerating the rate of pavement failure. Consequently, maintenance interventions became more frequent and expensive, while the overall serviceability of the road deteriorated, negatively impacting safety and user satisfaction for both local communities and commercial roadway users. Figure 5 illustrates the location of the Bloemspruit Quarry relative to the A56.


Figure 4. Heavy quarry trucks traveling along the A56

Figure 5. Location of the quarry relative to the A56

The construction of new housing developments adjacent to the A56 has had a profound impact on the road's structural performance and overall functionality (Figure 6). These residential estates have significantly increased local traffic volumes, introducing a constant flow of commuter vehicles, school transport, and service deliveries to what was historically a lower-traffic corridor. The addition of frequent access points, turning movements, and peak-hour congestion has placed added stress on the pavement—stress that was not considered in the original design.

Figure 6. Location of the new housing developments relative to the A56

Compounding these structural challenges, inadequate drainage infrastructure contributed significantly to the road's progressive deterioration. Blocked and undersized drains led to frequent surface water pooling and saturation of the shoulder and subgrade layers (see Figure 7), particularly in low-lying zones underlain by expansive clays. Persistent wet conditions weakened the pavement support, increased the occurrence of potholes and edge breaks, and further hastened the loss of pavement integrity. Overgrown vegetation on the road edges exacerbated these problems by impeding water flow, trapping moisture at the pavement edge, and allowing root intrusion that undermined the shoulders.

Figure 7. Blocked drain, pooling water and overgrown vegetation.

Collectively, these factors, thin subbase overactive clay, escalation of heavy vehicle loading, and inadequate drainage, led to a marked reduction in the functional lifespan of the A56. The observed failures underscored the need for a fundamentally different rehabilitation and reconstruction approach to ensure durable performance in the challenging geotechnical and operational environment characterising this corridor.

6 SUSTAINABLE FRAMEWORK FOR THE REHABILITATION OF THE A56

As the A56 continues to function as the primary arterial route for both long-established and newly developing communities, there is an escalating need for enhanced road capacity and upgraded traffic management infrastructure, including turning lanes, signalisation, pedestrian crossings, and improved signage. The surge in traffic volume, combined with the greater diversity of vehicle types, places mounting pressure on the pavement structure of the A56, which is already weakened by the sustained movement of heavy freight vehicles. In the absence of proactive interventions, the cumulative effects of ongoing residential expansion and intensified usage will further accelerate the deterioration of the roadway, driving up maintenance costs and increasing safety hazards for all users, especially at critical access points. Therefore, it is crucial to implement a sustainable framework for the rehabilitation of the A56, one that addresses current and future demands while ensuring long-term structural performance, safety, and community connectivity. The application of this framework to a section of the A56 assigned to CiviLab@CUT for rehabilitation is discussed in the following paragraphs.

6.1 *Pavement structure*

To rehabilitate the failed section of the A56, a systematic reconstruction methodology was adopted, emphasising high-quality materials and staged stabilisation for long-term performance. Pavement construction commenced with the importation of substantial quantities of high-quality G5 material. The new pavement layers were constructed in increments of 100 mm, following a carefully designed stratification as detailed below:

- 0–620 mm: This foundational layer consists entirely of compacted, neat G5 backfill material, providing a uniform and stable base.
- 620–720 mm: The subsequent layer comprises G5 material chemically modified with 1.5% additive, enhancing resistance to moisture and load-induced deformation.
- 720–970 mm: This section incorporates G5 material stabilised with a soil fix (@CiviLab) product, further improving structural integrity and durability against expansive clay movement.
- 970–1,000 mm: The uppermost layer consists of a 30 mm cold asphalt binder (@CiviLab), offering a moisture-resistant cap and establishing a strong interface with the final asphalt surfacing.

This multi-layer design sequence was selected to optimise performance in challenging subgrade conditions and to ensure lasting structural and functional capacity under increased traffic demands.

6.2 *Community engagement*

Community involvement was a cornerstone of the rehabilitation project on the A56, aligning both with the project's sustainability objectives and broader government priorities for local capacity-building. In this initiative, learners from the Expanded Public Works Programme (EPWP) in the Shannon community played a central role (Figure 8). These learners were carefully selected and trained through a collaborative framework established between the Free State Department of Community Safety, Roads, and Transport and CiviLab@CUT. Their training encompassed both practical road repair skills, such as pothole patching, crack sealing, and surface rehabilitation, as well as soft skills needed for teamwork, communication, and workplace problem-solving.

Figure 8. EPWP learners applying and levelling a fresh asphalt layer during road surfacing operations.

Engaging Shannon's EPWP learners, who were employed at a fixed government rate, not only expedited on-site rehabilitation through the application of local knowledge but also fostered a sense of ownership and accountability among the participants. By working directly on roads used by their own community, learners were empowered to identify context-specific infrastructure challenges, monitor maintenance needs, and contribute to long-term road stewardship. Their participation also provided much-needed employment and marketable technical skills, directly addressing unemployment and enhancing local socio-economic outcomes.

Further, the hands-on involvement of local learners ensured that project outcomes were responsive to community priorities, increased transparency, and improved knowledge transfer for ongoing maintenance. The success of this participatory approach has set a replicable model for future infrastructure initiatives, demonstrating how collaboration between academia, provincial authorities, and local residents can deliver both high-quality technical results and meaningful community upliftment.

6.3 *Digital management tools*

To complement the physical rehabilitation of the A56, a web-based digital management system developed by the Civilab@CUT Research Group was integrated to support real-time monitoring, data collection, and reporting. This tool was designed to address historical issues, including ad hoc maintenance, inadequate defect tracking, and fragmented communication among stakeholders. The system enhances sustainability through increased efficiency, accountability, and local capacity building. Built with Django, PostgreSQL with PostGIS, and Leaflet, the platform functions as a centralised interface where authorised users can submit, visualise, and monitor road maintenance data in real time. Field staff, EPWP learners, and supervisors can upload geo-tagged photos, complete standardised inspection forms, and log various maintenance activities, such as pothole repairs and drainage clearance. Smart forms facilitate quick and standardised data entry in the field. For example, the pothole repair form features dropdowns for the products used, automatically calculates surface area and volume based on length, width, and depth entries, and allows for PDF and photo uploads for documentation. These inputs are stored in a PostgreSQL database and automatically linked to the user's role, submission date, and spatial coordinates.

Each entry is geospatially referenced and displayed on an interactive web map interface, enabling stakeholders to see the exact location of completed repairs and ongoing work along the A56. (Figure 9). The map provides a clear visual record of rehabilitation progress, with real-time layer toggling that enables users to differentiate between completed tasks, pending issues, and recurring problem areas.

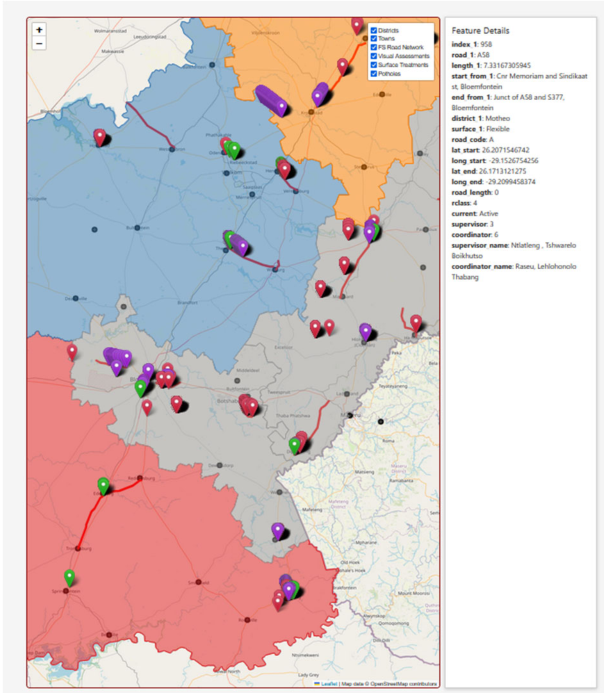

Figure 9. Interactive web map interface visualising the geospatially referenced entries.

This spatial visualisation supports transparent reporting, enhances coordination between field teams and administrators, and allows project managers to monitor the pace and distribution of maintenance activities across the corridor. All submissions are recorded in a searchable, paginated table view, providing a transparent record of progress and allowing export to Excel for further analysis. The platform is fully responsive, with mobile compatibility that facilitates real-time data collection on-site via tablets or smartphones (Figure 10). Field users, including EPWP learners, can complete forms and upload images directly from the construction site. When internet connectivity is limited, submissions are cached locally and automatically synchronised once online access is restored.

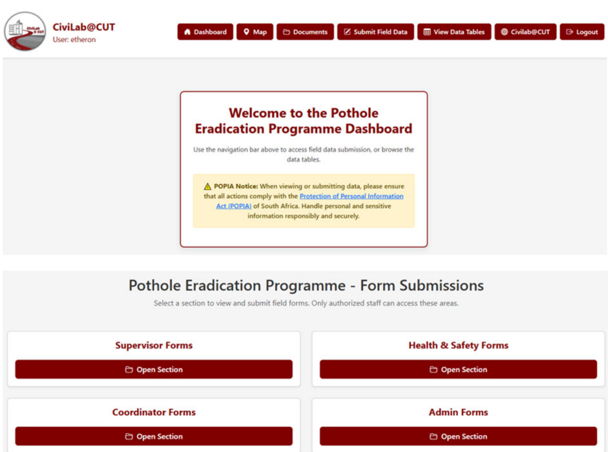

Figure 10. Platform dashboard for field data submission.

The platform is also designed to incorporate additional information layers into the central database, such as geological maps, soil classification data, groundwater depth, and RAMS datasets. These layers can be visualised alongside maintenance records on the interactive map, helping users understand how subgrade conditions and environmental factors relate to observed road failures. For example, recurring defects can be spatially linked to zones of expansive clay or shallow groundwater, facilitating better decisions on drainage design, material selection, and rehabilitation strategies. The inclusion of RAMS data, such as historical repair logs, surface condition ratings, and traffic load trends, provides a comprehensive understanding of asset performance over time. By consolidating technical, spatial, and environmental data into a single platform, the system promotes a holistic, evidence-based approach to sustainable infrastructure management. The platform was designed to be modular and scalable, making it easy to adapt and replicate for other roads or municipal projects by adjusting forms, maps, and datasets. This approach aligns with global best practices in intelligent road asset management while being grounded in local conditions and accessible to users with limited technical expertise. It was therefore straightforward to adapt and implement on the A56.

7 CONCLUSIONS

This research demonstrates the value of an evidence-based, context-specific approach to the sustainable rehabilitation of major arterial roads in South Africa. By integrating robust geotechnical assessment, systematic material selection, phased construction, and stakeholder engagement, the rehabilitation of the Old Thaba Nchu Road (A56) achieved measurable improvements in performance and longevity compared to conventional interventions.

The case study highlights the importance of addressing region-specific challenges, such as expansive clays and increasing heavy vehicle traffic, through tailored engineering and management solutions. The implementation of chemically stabilised G5 bases, strategic layer thickness, and improved drainage design yielded a pavement structure better suited to withstand environmental and operational stresses typical of the Free State Highveld.

Furthermore, the incorporation of digital management systems and community engagement processes contributed to a more inclusive, transparent, and responsive project delivery. While the case is specific to the A56, the findings have broader implications for sustainable road asset management in similar geotechnical and climatic contexts, reinforcing the necessity for ongoing research and adaptation of global best practices for local applications.

8 ACKNOWLEDGEMENTS

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