



Digital Innovations in Slope Stability: Addressing South Africa's Unique Challenges

*Keshia Myburgh¹ and Salona Naidoo²

¹ AECOM Australia (Pty) Ltd, Brisbane, Australia, *keshia.myburgh@aecom.com

² Atkinsréalis UK Limited, salona.naidoo@atkinsrealis.com

Abstract. Slope stability in South Africa presents unique challenges, significantly influenced by the country's critical infrastructure and distinctive geological features. The road network is a lifeline for communities, connecting citizens to essential destinations such as workplaces, schools, healthcare facilities. Detours are often located at considerable distances and the lack of alternative routes highlights the need for reliable and safe slopes. It is therefore imperative to minimize road closures due to rock falls and ensure the stability and safety of existing roadways. Designing effective solutions for unstable road slopes is challenging due to access constraints and adverse conditions that hinder data collection, which often results in conservative designs. Innovative methods are therefore required to obtain reliable, and up-to-date data when on-site surveys cannot be achieved. This paper discusses the use of advanced digital technology for remote 3D mapping of road slopes, enabling the efficient design of over 50 No. rock slopes within a short timeframe. By integrating topographical surveys, LiDAR scans, and drone photogrammetry, 3D digital twins of slopes were created that allowed for remote investigation and multiple virtual site inspections, reducing the need for physical presence. These virtual replicas provided accurate geometric representations, aiding in geotechnical assessments and constructability evaluations. The paper also demonstrates the use of Seequent's Leapfrog software allowed for interpolation of joint measurements in inaccessible areas. Additionally, the integration of Leapfrog, Context Capture by Bentley Systems and Global Mapper by Blue Marble Geographics enhanced the development of detailed construction drawings and accurate material measurements.

Keywords: Slope Stability, Digital Innovation, Digital twin

1 Introduction

In South Africa, the road network is crucial for daily commutes and overall mobility, connecting communities to key destinations. The importance of a reliable road network cannot be overstated, as it underpins the country's economic growth and development and disruptions to the transport assets proves detrimental. The effectiveness of the country's transportation system is however significantly impacted by rockfalls and slope failures, particularly due to its complex geology and diverse climate. The varied rock formations, steep gradients and limited geometric alignment space create an

inherently unstable environment, especially susceptible to rock falls and landslides, posing substantial risks to road users and infrastructure.

Data collection for slope stability design is challenging due to access constraints, such as high elevations, steep topography, dense vegetation, increased traffic volumes, and the presence of bends and blind spots within mountain passes. Due to these constraints, it is often difficult for practitioners to assess rockfall hazards and risks, based on investigations conducted from within the road corridor, (Field and Hunter, 2024). As a result, designers often rely on assumptions or incomplete data, leading to risks being poorly understood resulting in either qualified or overly conservative designs.

Overcoming these challenges necessitated innovative methods of retrieving reliable, detailed and up-to-date data where on-site investigations could be partially achieved. This included specialized approaches, such as advanced assessment techniques, safeguarding measures, and proactive maintenance strategies. Acknowledged by roads authorities, collaborative and integrated design approaches were implemented to engage various stakeholders in planning, design, and construction of slope stability systems in the country. By integrating conventional data collection procedures with advanced digital technologies, 50 No. rock slopes, mainly located within mountainous terrain, were successfully designed within a short period. This involved creating 3D digital twins of slopes that allowed for remote investigation and data recording, facilitating multiple virtual site inspections minimal physical site visits. Joint readings were extrapolated from accessible areas to inaccessible regions using advanced geospatial software. The integration of the 3D reality modeling software, advanced geospatial software and powerful GIS software facilitated construction drawing development, and accurate material measurements. These approaches demonstrated how digital advances enable effective, safe data collection, streamline data extrapolation, enhance data accuracy, and provide valuable insights for decision-making and planning.

2 Challenges with Data Collection

Rockfalls can originate at various heights within constructed cuts and natural slopes. Many roads in South Africa traverse challenging escarpments with rugged landscape and dense vegetation (**Fig. 1**). These hard-to-reach areas introduce substantial intricacy, making it difficult to accurately assess rockfall hazards and risks from road level. The complex geometry of mountain passes, characterized by steep inclines, sharp turns, narrow paths and uneven surfaces, complicates navigation and hazard assessment. Additionally, variations in joint orientation along bends and curves create discrete areas where discontinuity planes daylight towards the road or intersects to form wedges. Increased traffic volumes and reduced visibility due to bends and blind spots pose additional safety risks for professionals conducting surveys.



Fig. 1. General view of slopes within mountainous terrain

South Africa's unique geology, characterized by its uniformity in plan and its variety in structure and composition (Gregory, 1927), adds another layer of complexity. Approximately two thirds of the country's surface comprise strata of the Paleozoic–Mesozoic Karoo Supergroup, that exhibits unique weathering patterns. One of the major engineering geological problems associated with slope failures within the Karoo Supergroup the slaking and disintegration in Mudstones, which undermines more resilient overlying rock like siltstone or sandstone. Over time, the undermining expands beneath the competent rock until the cantilever strength of the overlying and now overhanging rock is breached. This process can lead to catastrophic failures with very little warning, posing potentially life-threatening conditions as noted by Price, North-Coombes, and Damhuis (2005). Several areas along the cuttings were therefore either difficult or dangerous to access due to the ever-present threat of rock falls.

In addition, geological processes like folding and faulting create variations in lithology and formations over short distances, resulting in diverse and intricate geological structures. These variations required robust solutions, especially in areas where contact zones between different rock types exhibit significant differences in properties and where intrusive igneous formations such as dolerite dykes cut through existing rock layers, further enhancing geological diversity.

Several unique factors in the South African context complicate data collection:

- Safety of personnel on site in high-crime or volatile areas poses significant safety risks to personnel due to unrest and violence being prominent.
- Strict regulations made it challenging to obtain permissions for flying drones in public spaces or over road works, involving complex regulatory and safety requirements.
- The presence of baboons in certain areas posed safety risks to fieldworkers, as they displayed aggressive behavior when encountered.
- The behavior of animals such as goats influenced slope stability indirectly due to their digging activities that loosen soil and rocks, contributing to instability.

- Limited road shoulder space along highways restricts parking and staging areas for survey equipment and personnel, and procuring flagmen for lane closures is challenging due to their limited availability and long lead times.
- Landownership challenges caused delays in assessments and surveys due to restricted access to critical areas outside the road reserve that still impact the roadway.
- Specialized abseiling and the use of hydraulic cranes for data collection face challenges such as safety risks, high costs, logistical difficulties in accessing and operating on steep or unstable slopes, and the need for extensive training of personnel.

3 Systematic Design Approach

A systematic design approach was implemented to ensure thorough investigation and effective stability design of 50 No. slopes across South Africa. Through this process multiple customized solutions for each site were designed. These solutions were then evaluated against a set criteria including client requirements, constructability, viability, cost effectiveness and maintenance. The chosen designs were refined through simulation and modeling, feedback and collaboration between various stakeholders. The methodology as described below, was meticulously documented to ensure clarity, traceability, and continuous improvement throughout the projects' lifecycle.

- **Desk Studies** comprised reviewing all available information for each slope, including consulting aerial and satellite imagery, survey data, drone photogrammetry, regional geology, previous investigation, inspection, monitoring, and incident reports.
- **Surveys** included conventional topographical surveys, combined with LiDAR scans to extract the desired data for analyses.
- **Drone Photogrammetry** captured high resolution images of each slope used for production of detailed photogrammetric models by generating 3D meshes with photo-derived textures from site imagery.
- **Field Investigations** included a phased approach. Initial site walk-over inspections allowed for assessments of geotechnical conditions, failure mechanisms and initial evaluation of mitigation measures. Subsequent investigations included discontinuity survey and geotechnical mapping. In situ testing was done to obtain rock strength, reliance on tactile assessments rather than laboratory testing.
- **Stability Analysis** that followed a systematic approach which includes kinematic analysis, limit equilibrium analysis and finite element modelling.
- **Stability Options**, multiple options for addressing geotechnical instability per slope were provided drawing on effective slope stabilization methods, construction sequence, constructability, feasibility, and maintenance. The process also included estimating quantities and construction costs.

4 Development of 3D Digital Twins

A slope digital twin is an effective way to establish a “mirror” relationship with its physical counterpart (Shu-yu et al., 2024). These models are able to continuously learn

from actual observations, such as site investigation data and slope performance records, thereby consistently enhancing their performance (Liu et al., 2022). 3D replicas of each slope were created following the summarized sequence depicted in Fig. 2.

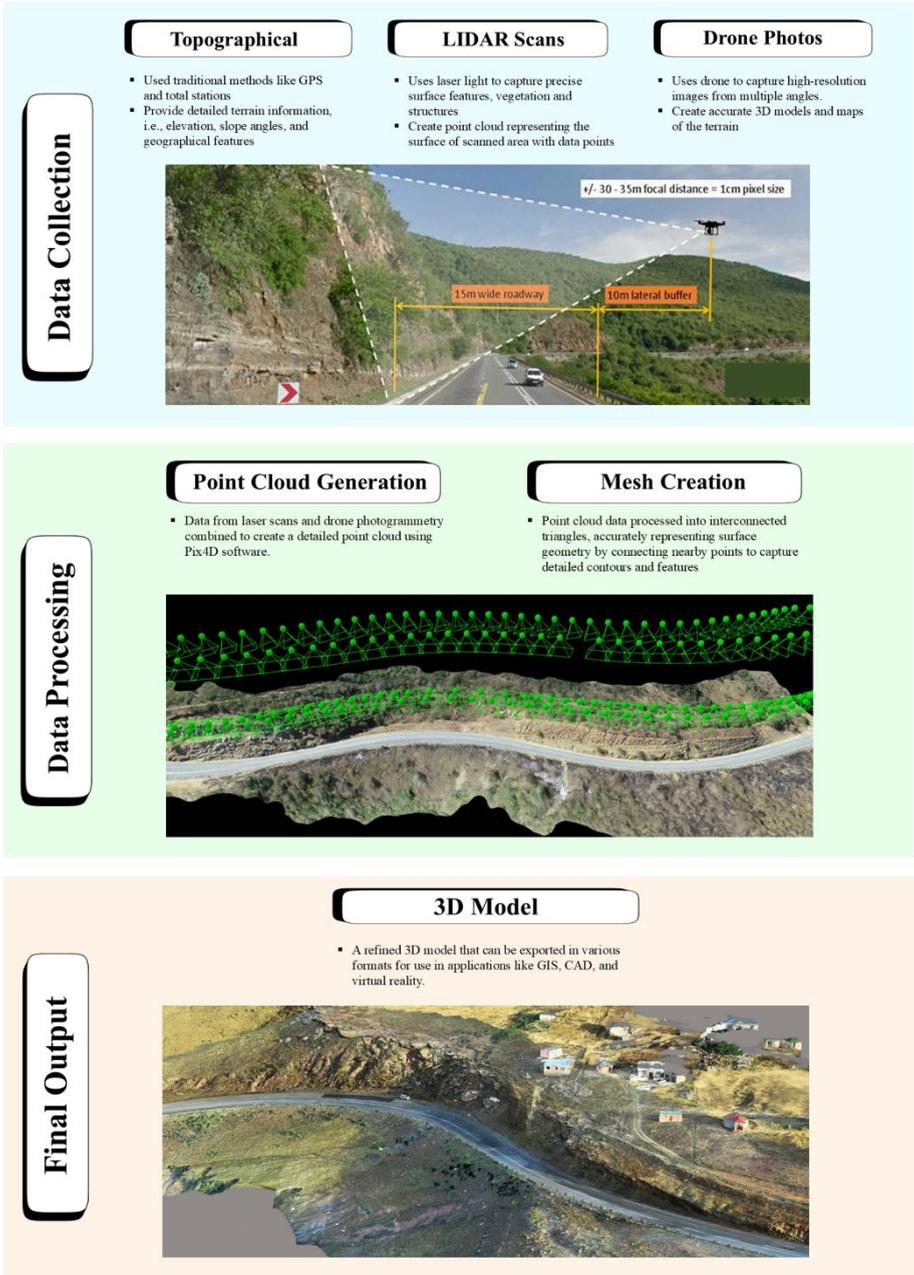


Fig. 2. Process followed to create digital replicas of each slope

5 Extrapolating Joint Measurements from Leapfrog

Discontinuity data offers in-depth insights into the mechanical behavior, strength, and stability of a rock mass. Accurate interpretation of discontinuities within a rock mass requires substantial data with representative spatial distribution (Ribeirinho et al., 2019). On steep, high slopes, traditional on-site measurements are nearly impossible. Seequent's Leapfrog software was utilized to extrapolate joint orientation data from accessible areas to inaccessible portions of the slope. This process supplemented field measurements and produced a comprehensive dataset that accurately represents the actual conditions along the entire slope, which is essential for stability analysis.

The 3D models were imported to Seequent's Leapfrog 2023.2 software, where joint and bedding orientations were generated using the software's 'structural modelling function'. Discontinuity data was extrapolated by placing structural "disks" along pre-defined joint planes to measure their dip and dip direction. These disks were aligned with the joint planes, and their orientation relative to the slope geometry was recorded using a compass with a clinometer within the software (**Fig. 3**). Field and joint measurement were used to validate joint measures taken using Leapfrog.

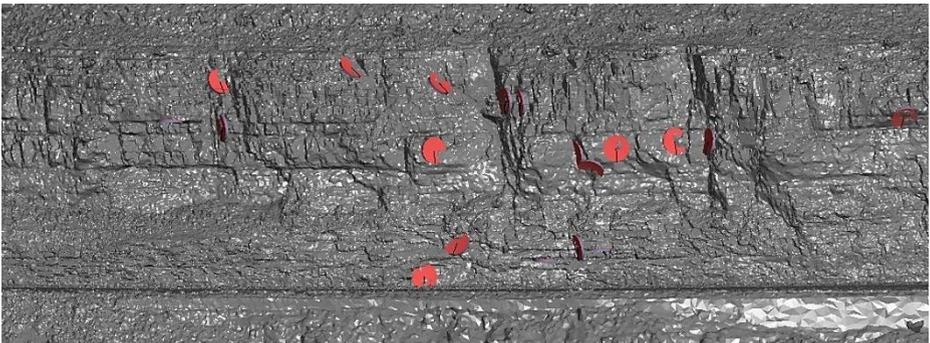


Fig. 3. Structural "disks" aligned with pre-defined joint planes to obtain joint orientation data from various areas on the slope

6 Utilization of Digital Tools

The integration of various digital tools significantly expedited the stability design of 50 rock slopes. Detailed discussions on the application of these tools throughout the project lifecycle are provided in the sections below.

6.1 Desk Studies

Survey data, high-resolution drone photos and 3D models were used understand slope locations and gain insight into parameters, such as major joint set orientations, slope heights, lengths, catch ditch widths. Virtual site visits identified potential high-risk or unstable areas and provided valuable information on failure mechanisms within

the rock mass. An example of a rock slope with interbedded mudstone and sandstone intersected by a dolerite dyke is shown in **Fig. 4**. Shadows from the overhangs formed in the sandstone are seen on the cut face.

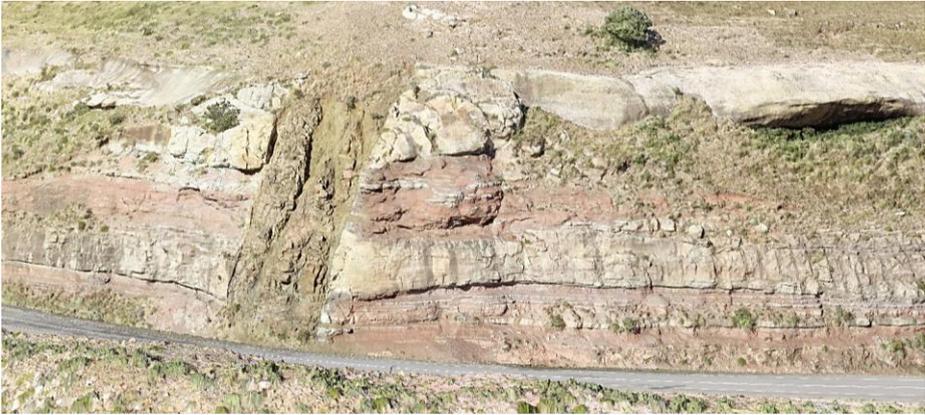


Fig. 4. Image from 3D model showing the geology and shadows from sandstone overhangs

Remote inspections enabled robust analysis, fostering a comprehensive understanding of slope conditions prior to fieldwork. This proactive approach allowed teams to focus on gathering the most critical and relevant data, improving efficiency on site.

6.2 On-Site Investigations

Preliminary slope parameters and initial geotechnical assessments were verified on site using printed or digital versions of the 3D models. Annotated geotechnical defects were overlapped onto these models (**Fig. 5**) and the occurrence and spatial distribution of discontinuities and structural features observed on the slopes were noted.

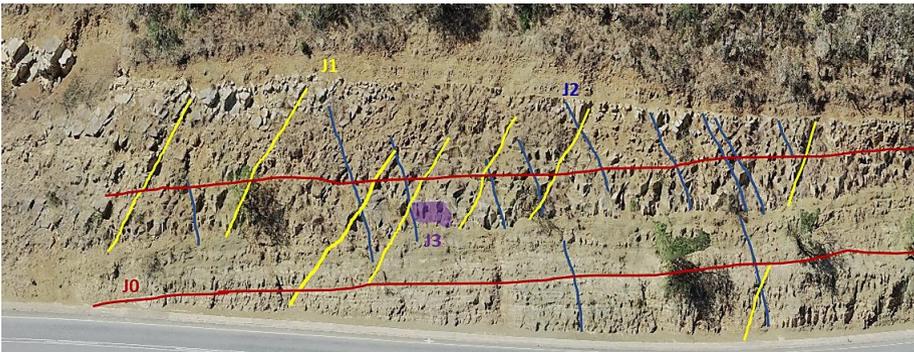


Fig. 5. Major joint sets extrapolated through visual inspection on site

The use of 3D models streamlined field investigations, increased the efficiency and accuracy of data collection, improving design confidence.

6.3 Stability Analysis and Design

The following sections provides details on how these digital tools were used during stability analysis and design.

Kinematic Analysis

As discussed in Section 5, Leapfrog was used to supplemented field discontinuity measurements to create a comprehensive dataset representing the entire slope. This enhanced statistical analysis by reducing the impact of outliers, allowing designers to identify joint sets with greater confidence and leading to more accurate analysis and identification of potential failure modes.

The digital replicas accurately depicted the slopes' physical characteristics, including geometry and structural features, allowing designers to confirm slope parameters for kinematic analysis. These detailed representations of geological structures and slope geometries enabled verification of failure mechanisms and allowed for sensitivity analyses under various conditions, such as changes in water levels, slope angles, slope heights, traverses etc. **Fig. 6** depicts an example of planar failure identified on Rocscience's DIPS software (left) and how the 3D models were used to investigate and confirm failure planes within the rock mass.

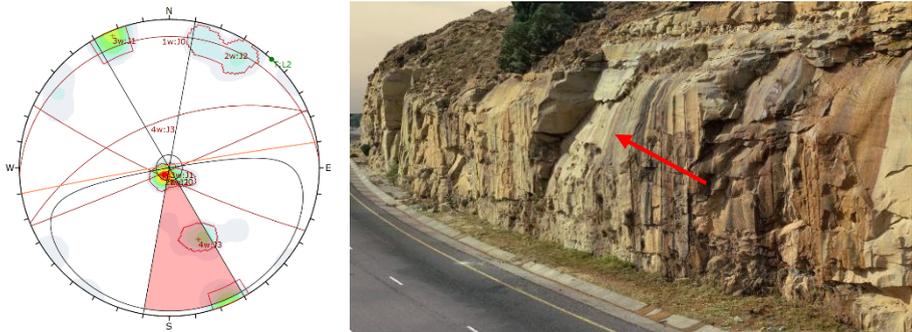


Fig. 6. Planar failure identified via kinematic analysis (left) and confirmed on the 3D model (right)

Stability Analysis

Limit Equilibrium Analysis and Finite Element Analysis were performed using Rocscience® software, which requires input of parameters such as slope geometry, material strength, joint data, applied forces, water pressure, and existing failures for reliable stability analysis. The 3D models were used for measuring wedge dimensions, heights along various sections of a slope, catch ditch widths and joint spacing and persistence. Sensitivity analyses were also carried out observing their effects on the Factor

of Safety (FoS) for construction and design life, thereby supporting practical construction sequencing.

The use of digital tools enhanced stability analysis by accounting for the three-dimensional nature of slope failures, which often involve complex interactions between different parts of the slope. In this regard, dimensions of a tension crack within a rock slope (width, length, distance from slope crest) could be measured accurately and used in the stability analysis (Fig. 7).



Fig. 7. Digital slope twins allowed measurement of structural and geotechnical mechanisms on the slope face

Options Analysis and Design

The visual output of 3D models facilitated effective communication of findings and recommendations to all stakeholders. This was crucial for decision-making, gaining support for necessary interventions, and ensuring smooth collaboration and efficient project delivery within a short timeframe. A minimum of three stability options per slope were proposed, and the use of 3D models allowed for comparison of different design options based on criteria such as effectiveness, constructability, cost, environmental impact and maintenance. The preferred stability design option was then selected based on its ability to meet these criteria while ensuring the highest level of safety and feasibility. For instance, maintaining slope infrastructure in South Africa is uniquely challenging due to theft and vandalism, especially near townships or rural communities. Design for steel draped mesh and steel anchored mesh systems had to be amended to at least 3 m above the slope toe to prevent theft or vandalism of the base anchor cable.

In addition, stability designs considered a Factor of Safety (FoS) that provided a safety margin for uncertainties in material properties during construction. The digital twins allowed for detailed constructability evaluations and facilitated in development of construction sequences that ensured contractor safety on site and met regulatory standards.

Through remote inspections of inaccessible crest and summit areas, drainage designs could be customized and project battery limits also adjusted. Fig. 9 shows an example where the proposed crest drains were located in areas with gradients steeper than 30% that was not easily accessible to general construction equipment and concrete delivery trucks.

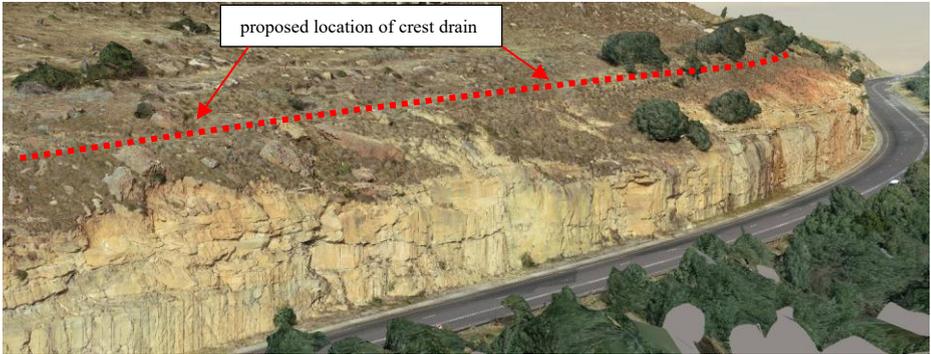


Fig. 8. Overview along slope summit where crest drain was proposed

Each stability option proposed included a program and construction quantity estimates. The integration of the 3D models, Leapfrog, Context Capture and Global Mapper® improved confidence in material quantity estimates for construction. Specific examples of achieving higher confidence in material measurements and quantities included calculated surface areas for shotcrete (measured using Leapfrog in Fig. 9) or pinned steel mesh or systematic rock bolts specifically tie-in to existing infrastructure (surface area measured using Global Mapper in Fig. 10).

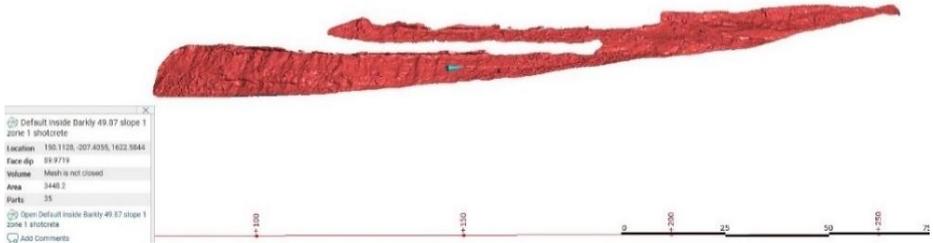


Fig. 9. The surface area where shotcrete is proposed measured in Leapfrog



Fig. 10. Global Mapper used to measure the area where steel mesh was proposed

Compilation of Construction Drawings

3D models provided a comprehensive view of each slope, allowing drafters to visualize structures from multiple angles and relate various stability options to specific areas on a slope, e.g., shotcrete applied to material that weathers more rapidly and rock bolts applied to more competent rock (**Fig. 11**). This data helped identify potential design issues early on, allowing for quick changes and efficient design iterations. This flexibility was crucial for accommodating design modifications and client feedback.

Ultimately, Comprehensive construction drawings serve as the primary communication tool between designers and builders, clearly conveying design intent, dimensions, materials, and techniques. The detailed drawings allowed contractors to accurately estimate the quantities of materials and labor required, that lead to precise project budgets and reduced cost overruns. These well-coordinated drawings minimize conflicts between different trades, streamline the construction process, and prevent costly delays.



Fig. 11. Extract from construction drawing

6.4 Construction Phase

During the slope construction period, the digital twin system was utilized to intelligently screen unstable blocks on and above the slope face. **Fig. 12** shows large wedges precariously held in place along the slope crest and on the slope face.

More importantly, before mobilizing to site, contractors could gain a general understanding of the area, as slopes were often located in rural areas with nearby clusters of housing on relatively flat terrain, situated as close as 20m from the cutting's edge (**Fig. 12**). This understanding helped contractors plan effectively by assessing potential risks and incorporating these into their Safe Work Method Statements. Consulting these twin replicas enabled proactive risk management by informing local communities of construction activities and ensuring minimal disruption and maximum safety.



Fig. 12. Unstable wedges identified on slope face and houses near edge of the cutting

7 Conclusion

Addressing the unique challenges of slope stability in South Africa required a deep understanding of geological and geotechnical properties, combined with innovative digital technologies and geotechnical expertise. By reducing site visits and enabling remote data access, digital tools have streamlined stability design and enhanced safety. Integrated methods such as kinematic analysis, Limit Equilibrium analysis, and Finite Element analysis along with the application of digital technology have led to customized solutions that consider environmental impact, aesthetics, and maintenance.

The success of these approaches in South Africa highlights their potential for application in other countries and regions facing similar challenges. By adapting these methods to local conditions, regions worldwide can benefit from improved slope stability management. The integration of digital tools and advanced geotechnical techniques can lead to safer, more efficient infrastructure projects, reducing the need for extensive on-site investigations and enabling remote monitoring. This global applicability underscores the importance of continued innovation and collaboration in the field of geotechnical engineering, paving the way for more resilient and sustainable infrastructure solutions across diverse landscapes.

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