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Digital Twin Concept for the Safe and Economic Design and Management of Rock Slopes

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Abstract Technological improvements including the routine use of aerial photogrammetry, semi-automatic rock mass characterization, three-dimensional slope stability modelling and ground-based radar monitoring (i.e. mapping, modelling and monitoring) can now be rapidly applied to develop a continuously improving digital twin in parallel to a rock slope excavation sequence for civil and mining engineering projects. This is critical for reconciling the effectiveness of geotechnical models for predicting future slope stability (or instability) by reducing uncertainty in ground conditions as excavations progress. This paper presents a framework and case studies to describe the application of a manual digital twin approach with multiple layers of monitoring. Monitoring systems used to manage safety risks were developed in response to uncertainties in ground characterization and limitations in slope stability analysis and design, i.e., to address known or perceived residual risks prior to excavation. Fast data collection and analysis permits comparison of the three-dimensional model with observed slope conditions as a form of reconciliation and allows for critical geological structures to be added to the geotechnical model as excavations progress.

Keywords slope stability, empirical methods, 3D analysis, photogrammetry, monitoring, digital twin

Introduction

Rock slope failures on man-made and natural slopes include slope instability, rock falls and landslides, as well as debris flows and shallow landslips in weathered rock.

Socioeconomic consequences of rock slope failures include direct costs such as removing the failed rock debris and stabilizing the slope, and a wide range of indirect costs. Indirect costs may include:

- Civil engineering: potential losses of life, damage to vehicles and injury to passengers on highways and railways, traffic delays, business disruptions, loss of tax revenue due to decreased land values, and flooding and disruption of water supplies where rivers are blocked by slides
- Mining engineering: potential losses of life, damage to mining equipment and injury to mine personnel, mine production delays, impairment or sterilization of mineral resources, reputational damage, and mine or mining company closure.

Between 2004 and 2016, a total of 55,997 fatalities were recorded globally from 4,862 individual, non-seismic slope failures including landslides (Froude and Petley, 2018). Slope failure occurrence triggered by human activity such as construction, illegal mining and hill cutting is increasing. Froude and Petley (2018) identified that the majority of landslides that were not initiated by rainfall or earthquakes, were triggered by human activity such as:

- Mining (232 multi-fatality; 67 single fatality events)
- Construction (170 multi-fatality events; 140 single fatality events)
- Illegal hill cutting (60 multi-fatality events; 27 single fatality events).

In both civil and mining engineering projects, it is practically impossible to assess the stability of rock slope cuttings and benches in real-time, using analytical approaches such as kinematics, limit equilibrium or FEM/DEM (numerical) modelling. The rate of excavation advance is usually too fast for this.

Since rock slopes are excavated in existing and natural geological formations, which usually have limitations with respect to site investigations, significant uncertainty and variability inevitably exists in the estimation or calculation of resting forces. Uncertainty in slope design primarily stems from the inherent natural variability of ground conditions, i.e. geological and engineering geological uncertainty and anomalies (Hoek and Diederichs, 2006). Figure 1 describes rock slope design uncertainty associated with the geotechnical components and is based on a similar concept for tunnelling scenarios by Paraskevopoulou and Boutsis (2020).

The idea of a “digital twin” was born at NASA in the 1960’s as a “living model” of the Apollo mission (Allen, 2021). In response to Apollo 13’s oxygen tank explosion and subsequent damage to the main engine, NASA employed multiple simulators to evaluate the failure and extended a physical model of the vehicle to include digital components. This “digital twin” was the first of its kind, allowing for a continuous ingestion of data to model the events leading to up to the accident for forensic analysis and exploration of next steps. A digital twin can simply be described as ‘the simulation of the physical object itself to predict future states of the system’ (Gabor et al. 2016).

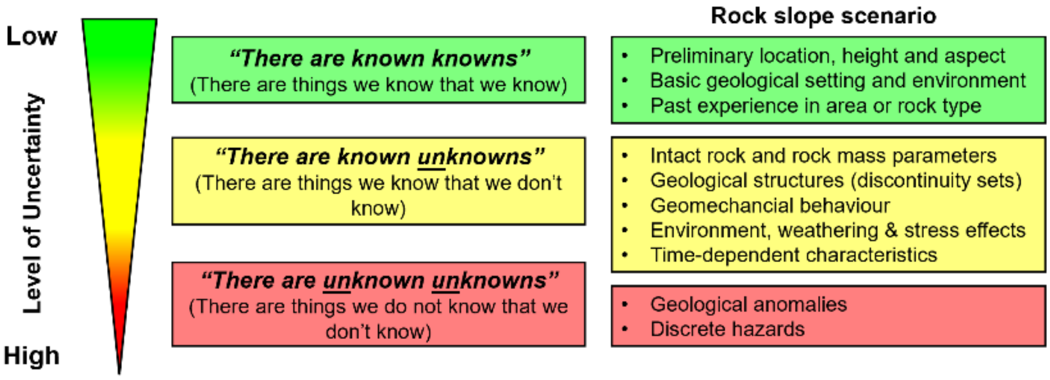

Figure 1 Design uncertainty in association with the geotechnical engineering components for a rock slope scenario

Continuous technological improvements for mapping including aerial photogrammetry and laser scanning, modelling (faster 3D analysis techniques) and monitoring (e.g. satellite InSAR and ground-based radar) facilitate the development and routine updating of digital twin models for rock slope stability (Bautista et al. 2023). As excavations progress and geological and geotechnical data becomes available, digital twin models are updated to reduce uncertainty and improve design reliability.

This paper discusses the key elements required for developing and applying a digital twin approach for the design and management of rock slopes.

Frameworks for the Design of Rock Slopes

Rock slope design has been considered an iterative process in civil and mining engineering projects for 50 years since Hoek and Londe (1974) developed the closed-loop framework shown in Figure 2.

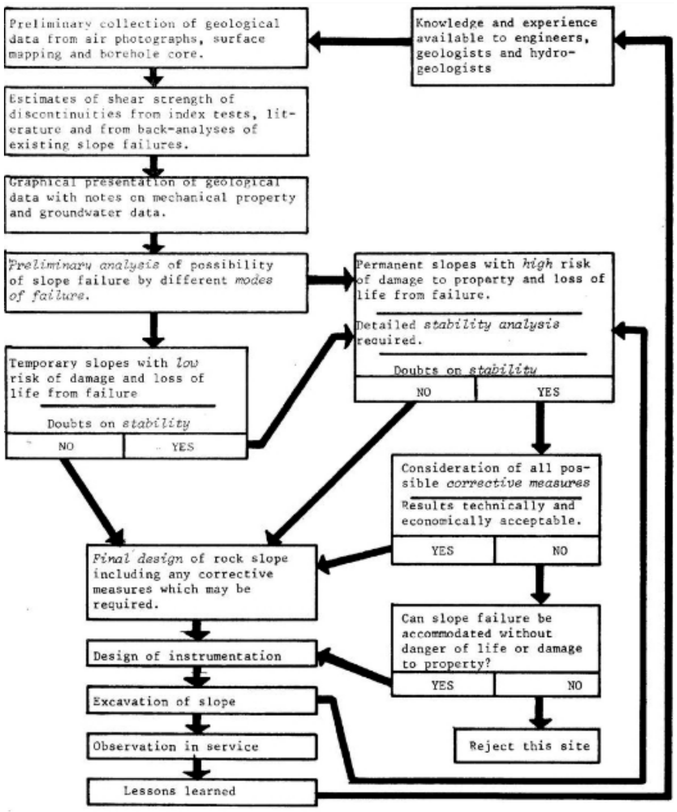

Figure 2 Rock slope design flow chart (Hoek and Londe, 1974)

The flow chart in Figure 2 has a robust initial design process, which is followed by monitoring and observing slope performance during excavation, and feeding back observations, lessons learned and new data into improving the design. Similar frameworks for the design of rock slopes have been adopted in civil and mining engineering with guidance provided by Wyllie and Mah (2004).

In the late 2000's, divergence occurred between rock slope design in civil and mining engineering applications with the development of guidelines for open pit slope design (Read and Stacey, 2009) as part of the mining industry funded LOP Project. This was followed by an update to rock slope engineering guidance for civil engineering applications by Wyllie (2018).

The resultant slope design process in Figure 3 for open pits by Read and Stacey (2009) includes an iterative process for considering mine planning and risk evaluation prior to excavation. However, unlike its predecessors, Figure 3, does not have a clear feedback loop for improving and optimizing the design based on monitoring, new data, slope performance, etc.

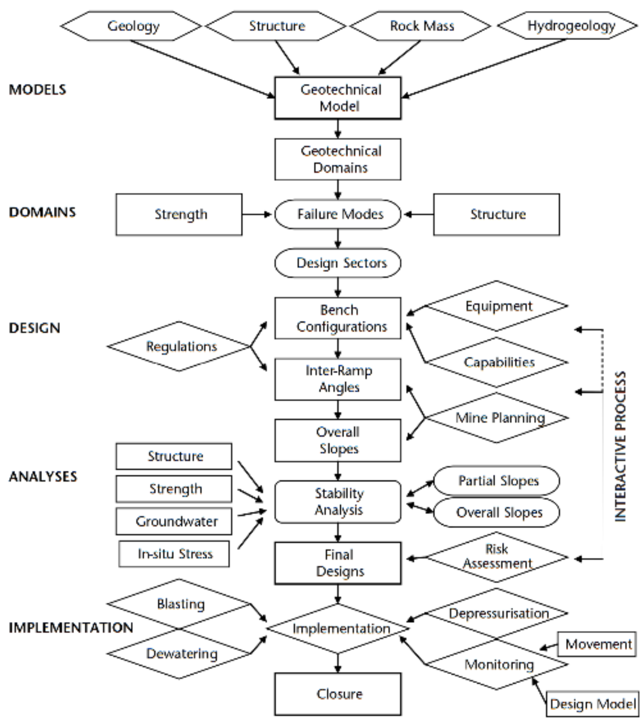

Figure 3 Open pit slope design process (Read and Stacey, 2009)

Rock slope design and management in civil and mining engineering applications are quite different in terms of:

- The design life of a civil engineering slope could be in excess of 100 years, whilst a slope in an open pit mine could range from a few months to a year or two in the case of individual benches and inter-ramp slopes, to several years for larger slopes.
- Risk exposure in civil engineering slopes involves the public (e.g. several thousands of people or more per day on roads, highways and railways) with very little or no access control and without routine monitoring instrumentation. In open pit mining, access is strictly controlled (e.g. typically less than 100 mine workers per day) with several options for additional control measures including monitoring instrumentation.
- Prior to design, site investigations for civil engineering slopes may be limited to outcrop mapping and little or no drilling for understanding subsurface conditions. On the contrary, mineral deposits are extensively drilled to understand the economical feasibility of deposit extraction. Arguably there should be a lower level of uncertainty in a mining engineering project than in civil engineering; however, geological and geotechnical conditions around a mining project are often significantly more complex.

Despite the abovementioned differences, uncertainty related risks described in Figure 1 effect the safe and economic design and management of rock slopes in both civil and mining engineering projects in a similar manner.

By adopting the framework for slope design and management in Figure 4, uncertainty and risk can be reduced and proactively managed through a continuous improvement process that manages safety and has capacity to optimize slope design to add economic value.

Figure 4 Continuous Improvement Framework for Safe and Economic Rock Slope Design and Management

The continuous improvement framework in Figure 4 can be incorporated into a Ground Control Management Plan (GCMP) or Slope Management Plan (SMP) with detailed processes for each component. By way of example, various elements of the 'Geotechnical Model' could be described in further detail, as could the process for their development and their limitations:

- Lithological, weathering and alteration model
- Structural model (major, medium and minor)
- Rock mass model
- Groundwater (pore pressure) model.

Understanding the limitations of a geotechnical model and rock slope design can be used to define the risks.

Hazard and Risk Definition

Ground failure and fall of ground are terms used to generalize various geotechnical hazards in surface mines, including (Bar et al. 2022):

- Rock slope failure: sub-bench, bench scale and larger failures, landslides, etc. (e.g. plane failure, wedge, toppling, step-path or complex failure mechanism, etc.).
- Rock fall: single or multiple rocks or boulders moving down a slope.

For rock slopes, the above hazards are associated with safety (public or mining), economic, environmental and reputational risks.

Risk Management Framework

Critical control measures are the equipment, systems, procedures, and policies that an organization uses to prevent injuries and death (Ross, 2017).

Figure 5 presents a framework of five critical control measures that can be used for managing fall of ground risks (Bar et al. 2022).

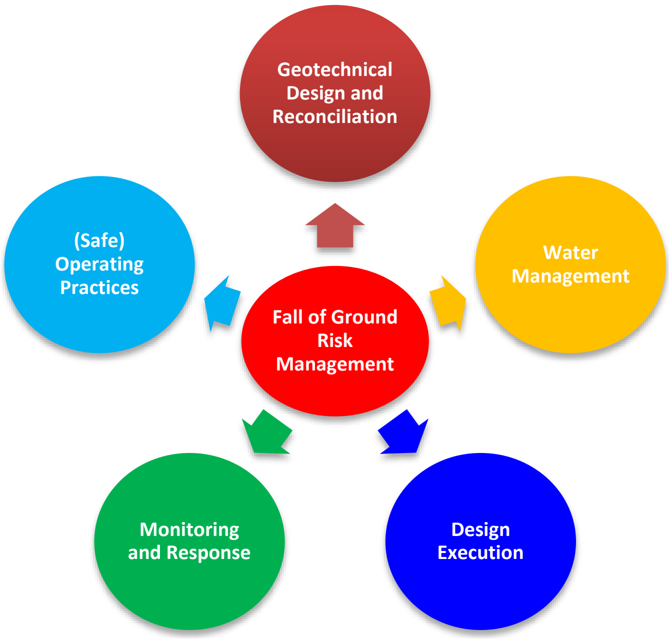

Figure 5 Fall of Ground Risk Management Critical Control Measures

Critical Control Measures

The use of multiple control measures provides redundancy for ensuring safety in the event that one control measure becomes ineffective, safety is maintained through the others.

By implementing the five critical control measures in Figure 5 as part of a GCMP or SMP, the continuous improvement framework for the safe and economic design and management of rock slopes (Figure 4) is followed during excavation.

Rock fall risks can be managed using Safe Operating Practices and Design Execution. By way of example, prescribed standoff distances may be used for personnel on foot to reduce their exposure to rock fall risks, and rock slopes can be excavated and scaled to remove loose rocks and debris that have a potential to fall (Bar et al. 2022).

Rock slope failure safety risks are managed through a combination of Slope Monitoring and Response using instrumentation such as radar and prisms to identify instabilities and remove personnel from the line-of-fire prior to collapse (Bar et al. 2022). Geotechnical Design and Reconciliation, and Water Management also contribute significantly by reducing the likelihood of failure.

Economic risks associated with rock slope failures are primarily reduced by Geotechnical Design and Reconciliation, which requires the use of the continuous improvement framework in Figure 4. This process helps reduce uncertainty in the geotechnical model and better understand potential failure modes as study phases and excavations progress. Water Management to enable and maintain slope depressurization assists in improving stability and facilitates slope optimization in wet climates and below the water table.

Failure Modes

Rock slope failures are rarely circular, spherical or ellipsoidal. In a recent review of over 500 rock slope failures in open pit mines, rock mass and circular failure modes accounted for only 10% and 8% of the database, respectively (McQuillan and Bar, 2024). The vast majority and remaining 82% were structurally-driven failures such as planar, wedge, toppling or step-path mechanisms.

For the design of rock slopes, it is critical to ensure that reasonable failure modes are investigated based on the geotechnical model. Quite simply, assessing for rotational (circular or near-circular) failure modes is considered inadequate in the context of real world, physical outcomes.

Since most failure modes in rock slopes are structurally-driven and may involve one or more geological faults or other persistent singularities, which are almost certainly oblique (i.e. not perfectly parallel) to the slope, stability should be assessed in three dimensions (3D). Rock slope failure modes should be assessed using 3D analysis method in a geotechnical design review process in the case of any of the following conditions (McQuillan and Bar, 2023):

- Non-linear slope geometry.
- Spatially or laterally varying geological and hydrogeological conditions.
- Spatially varying material strengths, including anisotropic material behaviour in the same unit.
- Singularities and persistent geological structures, striking and intersecting up to 50° from the slope orientation.
- Highly variable 2D results within close spatial proximity to each other.

Digital Twin Processes

The continuous improvement framework in Figure 4 is compatible with the digital twin concept; where input parameters (e.g. geotechnical model) are routinely updated as additional information becomes available during design stages.

Assessing rock slope failure modes, stability analysis and design using a digital twin can be undertaken using different levels of complexity from empirical methods to analytical approaches and numerical models.

Empirical Methods

Empirical methods can be used to evaluate the stability of excavations at the rate of excavation.

Methods such as slope mass rating, SMR (Romana, 1985; 1995), and Q-slope (Bar and Barton, 2017) can be used to quickly assess the stability and expected performance of slopes and provide advice on appropriate slope angles using design charts.

When geo-referenced, these empirical methods can serve as rudimentary digital twins, which can be updated several times per day as excavations progress.

Analytical and Numerical Methods

Compared with empirical methods, analytical and numerical approaches require more time for data collection, analysis & interpretation (site investigations), geotechnical model updates (e.g. developing wireframes for new geological faults) and 3D slope stability analysis.

Aerial photogrammetry and laser scanning have a pivotal role in large area rapid data collection for understanding geological structure and its potential impact on slope stability. Bar et al (2020) and Bautista et al (2023) demonstrate how aerial photogrammetry can be used to update a structural model for major and medium faults in a local area in less than a day, i.e. enabling a geotechnical model and 3D slope stability analysis update immediately thereafter.

Similarly, slope deformation monitoring data showing unexpected movements can be used to initiate a geotechnical model update and review of 3D slope stability analyses (Bautista et al 2023), i.e. initiate a digital twin update following the continuous improvement framework in Figure 4.

3D Slope Stability Models – Basis of Digital Twin

A 3D slope stability model can be considered the basis of a modern digital twin, or as the simulation of the physical rock slope in a mining or civil engineering excavation and its future state. Commonly used 3D stability analysis approaches include limit equilibrium method (LEM), finite element method (FEM), finite difference method (FDM) and distinct element method (DEM).

Planning Long-Term Excavations – Hazard Identification

A large coal mine in the Americas that operates multiple open pits simultaneously was planning an expansion of one of these pits, which was 3 x 4.5 km in size with pit slope heights reaching 300 m. These pits exploit over 50 individual coal seams within an interbedded stratigraphical sequence comprising sandstone, siltstone and claystone.

Table 1 presents material properties adopted for the 3D LEM models using Slide3 software (Figure 6). The rock mass and defect properties are well understood after several decades of site investigations, previous 2D LEM analyses and mining activities. The rock masses are moderately anisotropic with an anisotropy index (R_c) ranging from 3 to 4 (Ramamurthy, 1993). Directionally dependent shear strengths were applied to account for the anisotropy formed by continuous bedding planes as described by Bar and Weekes (2017). For 3D LEM analysis, a linear transition from bedding to rock mass shear strength was applied with parameters A and B set to 15° and 30°, respectively (i.e. the 3D LEM model applies bedding shear strengths within 15° of the bedding plane orientation, and then linearly transitions to rock mass strength).

The structural geology is quite simple with minor folding of the stratigraphic sequence. Despite the simplicity, shears have developed on the contacts of the coal and its adjacent units as a result of folding. These shears present themselves in the form of thin, very weak clay seams. These are considered in the slope stability models as weak layers or interfaces.

The groundwater model was developed based on vibrating wire piezometers (VWPs). It assumes a 3D phreatic surface equal to the ground or excavation surface and uses H_u coefficients to assign pore pressures to match actual data observed in the VWPs.

The 3D LEM model was tested on existing slopes and predicted two multi-bench failures as shown in Figure 7. The upper modelled failure had actually occurred and was identified with the radar, whilst the lower had not occurred, indicating a reasonable model output with potential for some degree of conservatism.

The 3D LEM models were used to forecast stability conditions for the life-of-mine (long-term excavations) design considering the excavation sequence at different time steps to identify potential hazards and their significance as shown in Figure 8.

Table 1 Rock Mass, Defect and Pore Pressure Properties for coal mine

Material	Rock Mass					Discontinuity		Anisotropy			Groundwater
	γ kN/m³	UCS MPa	GSI	m_i	D	c' kPa	φ' °	R_c	A	B	H_u
Sandstone	25	27	60	13	0 - 0.7	0	27	4.0	15	30	0.79 - 0.88
Siltstone	24	13	51	11	0 - 0.7	0	21	3.1	15	30	0.79 - 0.88
Claystone/Shale	24	10	46	7	0 - 0.7	0	15	3.5	15	30	0.79 - 0.88
Coal	14	15	51	16	0 - 0.7	0	23	3.0	15	30	0.79 - 0.88
Clay Seam	-	-	-	-	-	10	15	-	-	-	0.85 - 1.00
Fault Zone	20	-	-	-	-	20	22	-	-	-	0.85 - 1.00

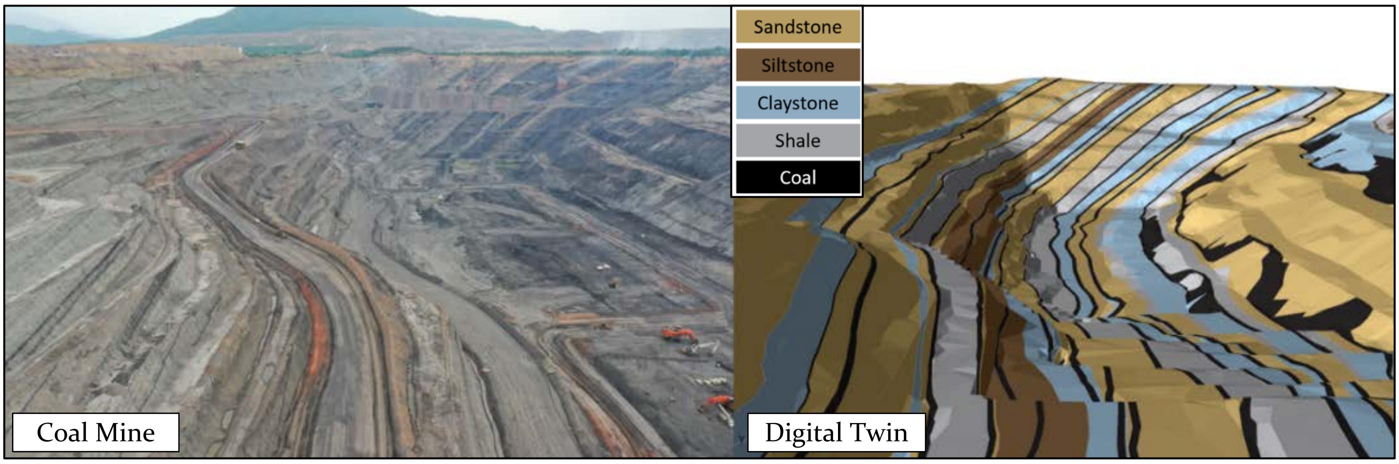

Figure 6 Photograph of coal mine slopes (reality) versus 3D LE model geometry developed in Slide3 software (digital twin) by Rocscience Inc (note: phreatic surface and clay seam interfaces not shown for clarity).

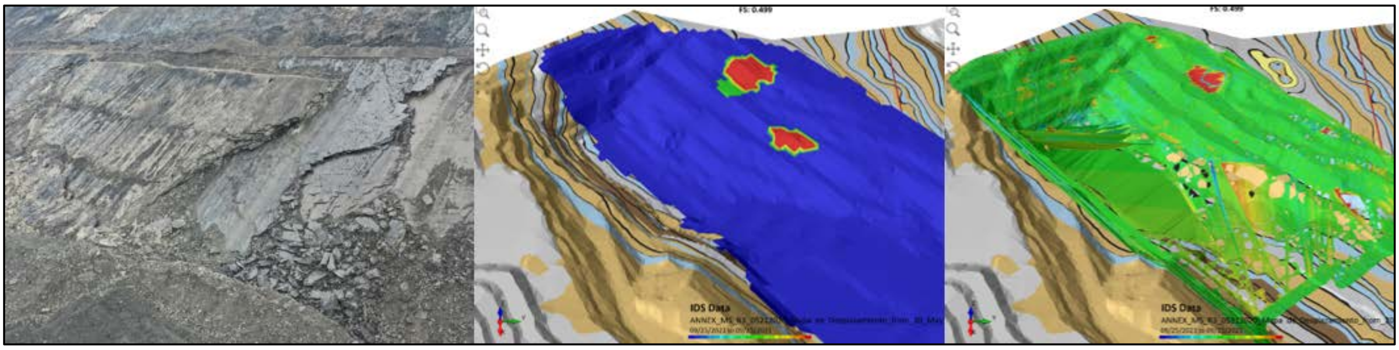

Figure 7 Left to right: Photograph of 30m high failure; 3D LE model outputs (Factor of Safety map: red indicates FoS<1): two multi-bench failures; IDS radar data showing the deformation hotspot associated with the failure in the photograph.

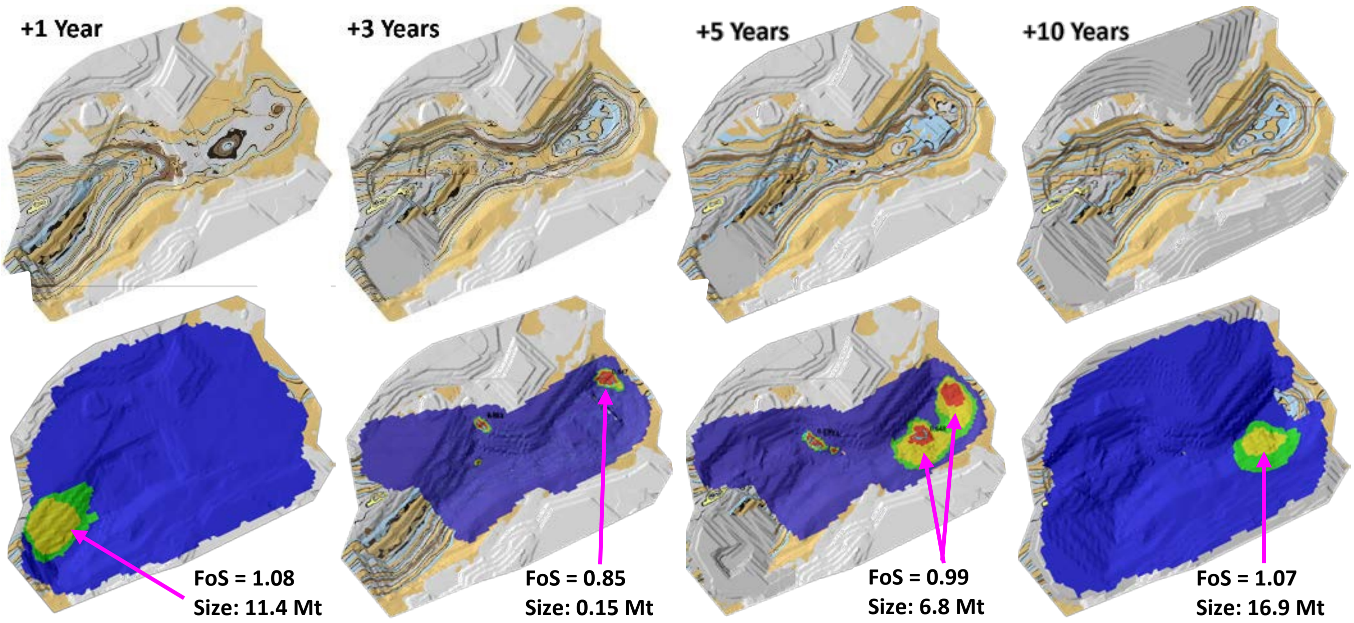

Figure 8 Top: Mine design time horizons with pit progressing from west to east, dumps enlarging and an in-pit dump being constructed. Bottom: Lowest FoS areas and size of modelled failure mechanisms.

For the near future, 1 to 3 years, a relatively large volume low FoS area (FoS≈1.1) was identified as well as a few small volume potential failures (FoS<1). These risks can be managed either through minor design changes, which will result in reduced coal recovery, or risk acceptance and the use of the monitoring and response control measure to continue as planned.

Later in the mine plan, between 3 and 10 years, significantly larger failure volumes were identified (FoS<1). Such failures (>6 million tonnes) would have significant consequences that are likely to impact the economic feasibility of the pit and need to be managed through design (e.g. shallower slope through unloading and additional overburden removal, or a step-in and loss in coal recovery). However, since these risks are several years away, there is time available for additional site investigations and analysis to further refine the geotechnical model and minimize the impacts of the design changes.

Assessing Optionality – Risk versus Reward

A large gold mine in the Americas that operates a single, large open pit, which is 3 x 2 km in size with pit slopes reaching 300 m. The pit is hosted within highly anisotropic and weak Carbonaceous Sediments, which overly various, relatively isotropic volcanic and volcanoclastic rocks.

The Carbonaceous Sediments are up to 100 m thick in the upper portion of the slope and have been host to several ductile slope instabilities, generally involving sliding on bedding planes and sub-parallel faults.

Several of the instabilities within the Carbonaceous Sediments have been back analysed using 3D LEM, FEM and FDM models to derive and calibrate material properties shown in Table 2.

3D LEM models were used as a digital twin due to their ease of updating for the purpose of assessing optionality. Future slope designs with different inter-ramp slope angles (IRA) ranging from 16 to 33° for the Carbonaceous Sediments were assessed (Figures 9 & 10).

Table 2 Rock Mass, Defect and Pore Pressure Properties for gold mine

Material	Rock Mass					Discontinuity		Anisotropy			Groundwater
	γ kN/m³	UCS MPa	GSI	m_i	D	c' kPa	ϕ' °	R_c	A	B	H_u
Carbonaceous Sediments	26 - 27	<10 - 18	35 - 50	8	0 - 0.7	6 - 8	12 - 18	2 - 3	15	30	0.69 - 1.00
Volcanics	27 - 28	30 -70	50 - 60	10	0 - 0.7	-	-	-	-	-	0.61 - 0.85
Fault Zone	24	-	-	-	-	2 - 7	17 - 24	-	-	-	0.85 - 1.00

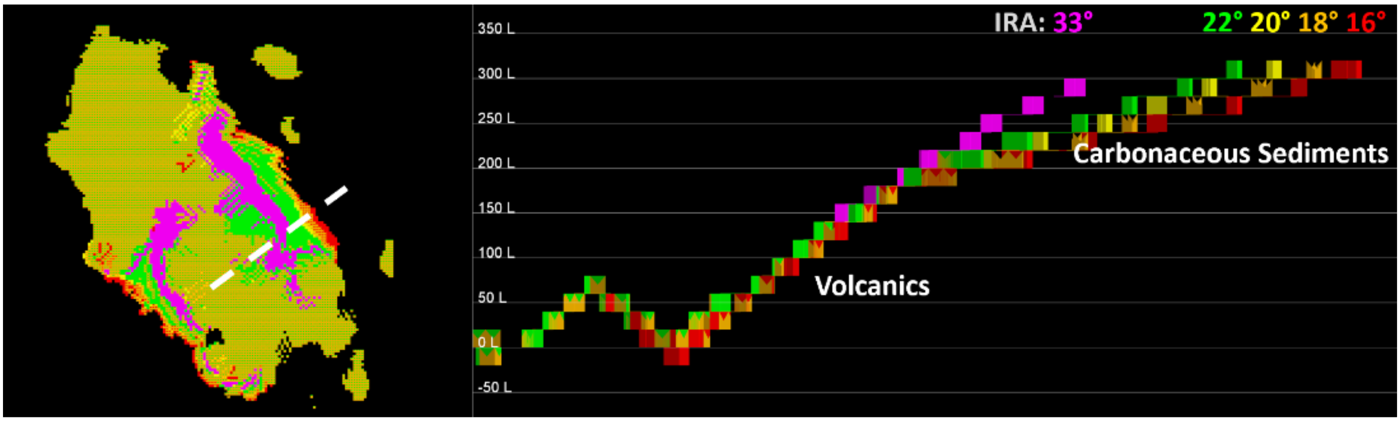

Figure 9 Assessing Optionality: Different IRA within Carbonaceous Sediments using simplified slope design geometry

Five 3D LEM models were developed in Slide3 software to assess the stability of each different conceptual IRA slope design within the Carbonaceous Sediments from Figure 9.

Figure 10 presents 3D LEM model results showing FoS (Factor of Safety) and potential failure volumes in Mt (million tonnes). These optionality assessments illustrate potential risks (low FoS) and consequences (failure volumes) which can be used in a semi-quantitative risk assessment.

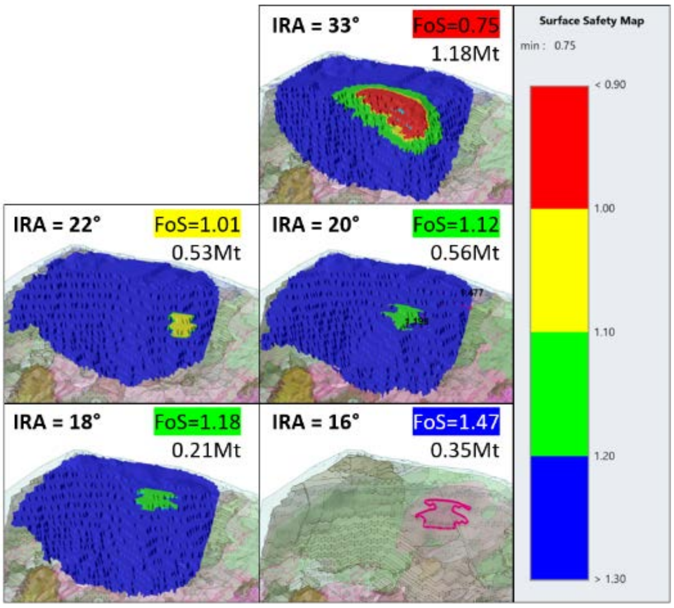

Figure 10 Optionality Assessments of Risk (FoS and Potential Failure Volume) versus Reward (IRA) using 3D LEM (Slide3)

Based on the optionality assessments in Figure 10, a slope design may be chosen based on the risk appetite of the project, and the availability and robustness of critical control measures (Figure 5) required to manage potential safety and economic consequences.

Hazard Management – Slope Depressurization

A large copper mine in Central Asia that operates a single, large open pit, which is 2.5 x 2 km in size with pit slope heights reaching 400 m.

The pit is hosted in relatively isotropic intrusive and volcanic rocks; however, it has a series of persistent fault sets as shown in Figure 11. These fault sets, in combination with pore pressure have the potential to form unstable wedges that can impact inter-ramp slopes on future pit stages.

3D LEM models were used as a digital twin to understand potential failure mechanisms and the impact of pore pressure on slope stability for future design stages (Bar and Zlobin, 2024). The 3D LEM models were also validated using 3D FEM (RS3 software by Rocscience) to check for complex failure mechanisms, including toppling associated with some of the fault sets.

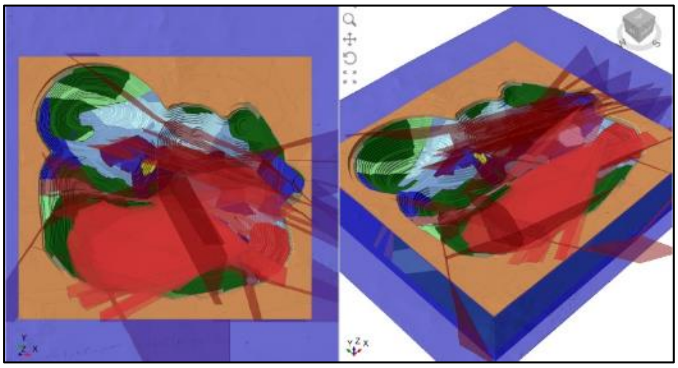
Figure 11 Geological faults (red) intersect pit slopes and groundwater table (blue) in 3D LEM model (Slide3)

Figure 12 identifies three wedges with a low FoS (<1) using 3D LEM for the future south wall under current pore pressure conditions, which are understood from a network of VWPs (vibrating wire piezometers). Currently the slopes are not actively dewatered or depressurised, i.e. water reporting to the bottom of the pit is captured in sumps and pumped out.

With a 25% reduction in pore pressure, which can be achieved through either targeted horizontal drains, vertical pumping wells, or a combination of both; Figure 13 demonstrates a significant improvement in FoS whereby two of the three wedges are stabilized. These negate the need for a shallower slope angle, which would result in significant additional excavation costs.

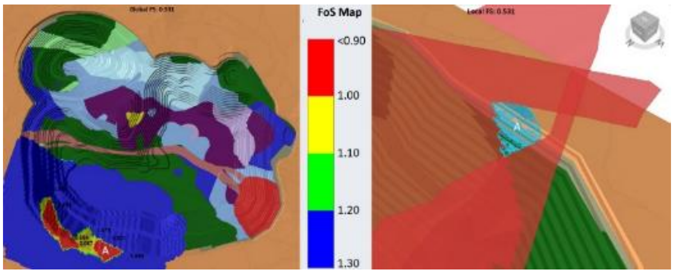

Figure 12 3D LEM model identifying 3 wedges on future south wall with FoS<1.0 with current pore pressure conditions.

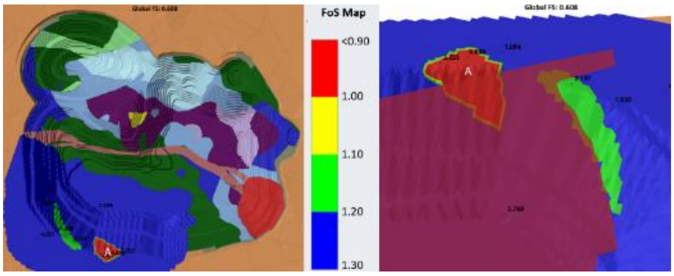

Figure 13 3D LEM model identifying only 2 wedges with improved FoS on future south wall with 25% reduction in pore pressure

A 3D FEM model was utilized to validate the failure mechanisms identified by 3D LEM, and confirmed the wedge risk on the south wall as shown in Figure 14. It also identified a ductile deformation with movement upward along faults on the central north slope in response to unloading from excavation. No toppling mechanisms were identified elsewhere in the proposed slope design.

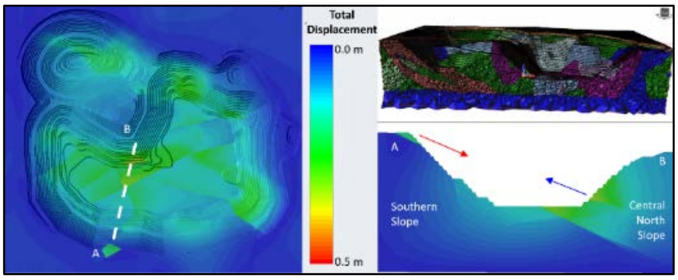

Figure 14 3D FEM model validating wedge mechanism on future south wall from 3D LEM models (Bar & Zlobin, 2024).

Key Findings and Future Developments

Rock slopes can be managed safely and excavation costs can be optimized by adopting a framework with multiple critical control measures as well as a digital twin to continuously improve the design as ground conditions become apparent.

The use of digital twins, particularly combining both empirical and analytical and numerical methods, facilitates the routine application of processes to reduce uncertainty in rock slope engineering. It also helps identify and manage many (but possibly not all) 'unknown unknowns' (geological anomalies or discrete geological faults – e.g. non-daylighting faults). The digital twin process can incorporate:

- Mapping: acquisition and analysis of structures mapped from in-pit face mapping, laser scanning and aerial photogrammetry as excavations progress.
- Modelling: the basis of a digital twin: developing and updating of three-dimensional LEM, FEM, FDM or DEM slope stability models to predict and reconcile slope performance.
- Monitoring: acquisition and review of real time, ground-based, interferometric synthetic aperture radar (Gb-InSAR) with full pit coverage for safety and model validation.

Depending on resourcing for a project, digital twins can be updated for various time horizons including long-term designs (life-of-mine, or life-of-project), individual pushbacks, 2-year plans and even quarterly plans for large open pit mines.

In its current form the digital twin process remains a relatively manual process; however, it is envisaged with ongoing improvements in technology and software integration, the digital twin process for rock slope design and risk management will be automated by 2030.

The use of a digital twin concept for the safe and economic design and management of rock slopes should see a return to similar practices in civil and mining engineering applications.

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