

Does a Factor of Safety of 1.2 mean anything? The hidden drivers of FoS variability in open pit slopes

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ABSTRACT

The stability of open pit slopes is often described as being controlled primarily by geological conditions and input parameters. A common industry perspective is that, provided input data are robust, the resulting Factor of Safety (FoS) can be considered meaningful and broadly comparable regardless of the numerical method or constitutive model applied. This perspective overlooks a critical reality: the physics and assumptions embedded within analysis software and constitutive formulations can fundamentally alter the outcome, even when geometry and material inputs remain identical.

This paper challenges the prevailing 'it's all about the inputs' view by demonstrating that, even when geometry and primary geotechnical characterisation (eg laboratory testing, rock mass classification, and structural interpretation) are held constant, different analysis tools and constitutive formulations can produce widely different FoS values – in some cases ranging from below 1.0 to above 2.0. Using two real-world case studies, we show how differences in material representation, post-peak behaviour, strength degradation, solver mechanics, and failure detection criteria drive these variations. In several scenarios, the modelling framework exerts greater influence on FoS than plausible variation in geological parameters.

By systematically comparing outcomes across commonly used geomechanical tools, this study highlights the risks of relying solely on software defaults or assuming model equivalence. The findings question commonly accepted interpretations, such as treating FoS = 1.2 as a reliable and transferable indicator of stability. We argue that appropriate model selection is foundational to defensible slope design and present a practical framework for evaluating constitutive suitability and understanding tool limitations in open pit applications.

INTRODUCTION

Factor of Safety (FoS) has long been the central quantitative metric used to assess the stability of open pit slopes. It is embedded in design workflows, regulatory frameworks, and operational decision-making, with commonly adopted design acceptance criteria typically ranging between FoS = 1.2 and 1.3 for inter-ramp and overall slopes (higher for more critical locations like below the ramp etc). In practice, FoS is often treated as an objective and transferable indicator of stability, provided that geological interpretation and material inputs are considered sufficiently robust.

A substantial body of published slope stability literature places primary emphasis on the characterisation of input parameters, such as geological structure, rock mass classification, and laboratory-derived strength properties, while providing limited discussion of the influence of modelling framework, constitutive formulation, or numerical implementation. For example, Hoek and Bray (1981) and Hoek, Carranza-Torres and Corkum (2002) focus extensively on rock mass characterisation and empirical strength estimation using GSI-based approaches, forming the basis for many modern design workflows, yet do not address how different constitutive implementations may influence stability outcomes. Similarly, Wyllie and Mah (2004) present comprehensive guidance on slope stability analysis centred on parameter selection and failure mechanisms, with limited consideration of solver-dependent behaviour. Duncan (1996) highlights the importance of parameter selection and variability in limit equilibrium analysis, but treats the method itself as a stable and reliable framework. More recent studies, such as de Bruyn *et al* (2025), continue this trend by comparing stability outcomes across multiple sites while focusing primarily on geological inputs and disturbance factors, without explicitly examining the role of constitutive models or numerical

assumptions. Even in comparative studies of slope stability methods, such as Cheng, Lansivaara and Wei (2007), the emphasis is placed on differences in calculated FoS rather than on how underlying constitutive behaviour or solver mechanics influence those differences. Collectively, these works reflect a prevailing practice in which FoS is interpreted primarily as a function of input data quality, while the influence of modelling framework and constitutive assumptions remains comparatively underexplored. Advances in numerical modelling over the past two decades have increasingly challenged the assumption that FoS is independent of the modelling framework used to compute it. The widespread adoption of continuum-based methods and shear strength reduction (SSR) techniques has shown that FoS is not a unique property of a slope, but an emergent result that depends on how failure is defined, how strength degradation is implemented, and how numerical instability is identified.

This raises a fundamental question: what does it truly mean to declare a slope ‘stable’ at $\text{FoS} = 1.2$?

This paper addresses that question using two real-world case studies. Rather than advocating a single modelling approach, we demonstrate that FoS is strongly influenced by constitutive representation and numerical framework, and argue that explicit consideration of these factors is essential for defensible slope design.

WHAT DOES ‘FACTOR OF SAFETY’ ACTUALLY MEAN?

In classical slope stability analysis, the Factor of Safety (FoS) is defined as the ratio of resisting forces (or shear strength) to driving forces acting along a potential failure surface, as typically evaluated using limit equilibrium methods (LEM). Within this framework, FoS represents a kinematic stability margin, where values greater than unity indicate that available shear strength exceeds that required for equilibrium. This definition forms the basis of commonly adopted design thresholds, such as $\text{FoS} \approx 1.2$ for open pit slopes.

In contrast, in continuum-based analyses using shear strength reduction (SSR), FoS is defined as the factor by which material strength parameters must be reduced to induce numerical instability or failure within the model, following the strength reduction framework described by Dawson, Roth and Drescher (1999). While both approaches aim to quantify a margin of stability, they are conceptually different: LEM FoS is derived from force equilibrium along an assumed failure mechanism, whereas SSR FoS emerges from the interaction between constitutive behaviour, stress redistribution, and the numerical failure criterion (Griffiths and Lane, 1999). As a result, FoS is not a single, objective property of a slope but a method-dependent measure, and values obtained from different analysis approaches are not strictly equivalent and must be interpreted within the context of the modelling framework used to derive them.

Arndt and Vakili (2024) frames this clearly by emphasising that SSR/SRF-based FoS is not simply ‘inputs $\rightarrow$ FoS,’ but depends on solver behaviour, definitions of failure, and numerical implementation choices. For example, *implicit* and *explicit* solvers do not even share a common failure trigger: implicit SSR commonly uses non-convergence as the indicator of failure, whereas explicit solvers often rely on displacement/velocity/kinetic energy response to identify instability.

Even when the reduction rule is formally the same (eg reduce c and $\tan \phi$ by SRF), the physical meaning depends on the constitutive model:

- A perfectly plastic Mohr–Coulomb model with constant dilation behaves fundamentally differently under progressive yielding than a strain-softening model.
- Models that include anisotropy, post-peak degradation, or stiffness softening can shift both the *mechanism* and the *SRF at instability*.

This is why ‘SSR FoS’ is better understood as: the strength reduction factor at which the adopted constitutive model and numerical formulation first satisfy the selected instability or failure criterion.

WHAT DOES IT MEAN TO ‘VALIDATE’ A SLOPE STABILITY MODEL?

In geotechnical engineering, numerical models are routinely used to support design decisions, yet the concept of model validation is often applied inconsistently. In many slope stability studies, validation is implicitly assumed once a model produces a Factor of Safety (FoS) above an accepted

threshold. However, achieving a target FoS does not, in itself, demonstrate that a modelling approach can realistically represent slope behaviour or failure mechanisms.

Model validation, in its strict sense, requires demonstrating that a modelling framework is capable of reproducing observed behaviour under known conditions. For slope stability problems, this extends beyond matching a single FoS value and instead requires the ability to replicate key aspects of real slope response, including deformation patterns, failure mechanisms, spatial extent of damage, and, where applicable, the timing or progression of instability.

Back-analysis as the basis for validation

Back-analysis of documented slope failures remains the most defensible method for validating slope stability models. In this context, validation involves applying a modelling approach to a slope for which the failure mechanism, geometry, deformation history, and geological controls are reasonably well constrained, and demonstrating that the model can reproduce those observations using plausible material parameters.

Critically, this requires more than demonstrating that a model becomes unstable at some point during strength reduction. A validated model should, at a minimum:

- reproduce the observed failure mechanism (eg sliding, toppling, combined modes).
- predict deformation patterns that are consistent with monitoring data or post-failure mapping.
- localise damage in regions consistent with observed failures.
- produce FoS values that are consistent with the observed stability state of the slope (ie stable slopes should yield FoS values greater than unity, whereas slopes that have failed or are actively failing should yield FoS values less than or close to unity).

FoS is a scalar quantity, whereas slope behaviour is inherently spatial and kinematic. Two models may report similar FoS values while predicting fundamentally different deformation mechanisms or failure volumes. Conversely, a model may reproduce realistic deformation patterns while producing a different FoS. Without validation against observed behaviour, FoS alone cannot confirm that a modelling framework captures the true mechanics of failure.

Limited validation of commonly used methods in hard rock slopes

It is important to distinguish between the extensive validation history of slope stability methods in soil and soft-rock engineering, and their application to large-scale hard rock open pit slopes. Limit equilibrium methods combined with Mohr–Coulomb constitutive behaviour have been widely validated for embankments, cut slopes, and natural slopes in soils and weak rock, where failure mechanisms are often relatively shallow, continuous, and governed by low confinement conditions. In these contexts, numerous documented case histories demonstrate that LEM-based FoS values, when interpreted appropriately, can provide realistic and reliable indicators of stability.

However, this validation base does not readily extend to hard rock open pit slopes. Large open pit failures typically involve complex three-dimensional mechanisms, strong confinement effects, stress redistribution during excavation, brittle fracture, progressive damage, and scale effects that are not naturally captured by traditional LEM formulations or by perfectly plastic Mohr–Coulomb representations. In such settings, failure surfaces are rarely predefined or continuous in the classical sense assumed by LEM, and deformation often develops progressively through cracking, yielding, and localisation rather than sudden global collapse.

Continuum-based analyses using linear or bilinear Mohr–Coulomb or linearised Hoek–Brown models, where the nonlinear Hoek–Brown strength envelope is approximated by an equivalent linear Mohr–Coulomb envelope over a selected stress range, face well-recognised limitations when applied to hard rock slopes. While such models can identify regions of yielding or global instability under strength reduction, they often do not reproduce realistic post-peak deformation, progressive failure, or damage localisation consistent with observed hard rock slope behaviour, particularly in situations where confinement-dependent strength and stiffness degradation play a critical role. As a result, although LEM and conventional constitutive models are widely trusted and routinely applied

in open pit slope design, their ability to represent real hard rock slope failure mechanisms is often assumed rather than demonstrated. This gap between widespread application and limited published validation highlights the need for explicit back-analysis of hard rock failures when interpreting FoS values derived from these methods.

More advanced formulations, such as strain-softening Hoek–Brown and Itasca’s Improved Model for Advanced Strain Softening (IMASS), have been developed to address some of these limitations; however, their application in practice remains less standardised. Strain-softening Hoek–Brown models are implemented in multiple forms across different software platforms, typically requiring selection of softening laws and parameters for which limited published guidance exists, leading to variability in application and results. IMASS similarly represents a significant development in incorporating anisotropy and strain softening, but publicly available methodologies for parameter derivation and calibration remain limited, and published validation through case studies is relatively sparse. In addition, its treatment of anisotropy relies on Mohr–Coulomb-type formulations along weakness planes, inheriting some of the associated limitations. As a result, despite their potential, these models are not yet as widely or consistently applied in open pit slope design practice, and they do not fully resolve the broader challenges of representing confinement-dependent strength, progressive failure, and deformation localisation in hard rock slopes.

Lessons from IUCM validation studies

In contrast, the development of the Improved Unified Constitutive Model (IUCM) placed explicit emphasis on validation through back-analysis of documented case histories. Ford, Lucas and Vakili (2020) presented several open pit case studies in which the IUCM was applied to reproduce observed slope behaviour, including deformation patterns, failure mechanisms, and regions of damage. Importantly, these studies reported both successful replications and cases where the model was unable to accurately reproduce observed behaviour, providing transparency regarding the model’s limitations.

However, the authors also noted that many of the case studies were subject to confidentiality constraints, which limited the level of detail that could be published regarding geology, material parameters, structural models, and mine-scale geometry. While sufficient information was provided to demonstrate the general validity of the approach, full disclosure of inputs and assumptions was not always possible, restricting the ability of third parties to independently interrogate or reproduce the analyses.

SOFTWARE AND CONSTITUTIVE MODELS COMPARED

To investigate the extent to which Factor of Safety (FoS) is influenced by modelling framework rather than input data, this study compares results obtained using a subset of widely adopted slope stability software and constitutive models. The tools and models selected reflect current industry practice in open pit slope design, particularly in hard rock mining, and represent the approaches most commonly relied upon for both operational and long-term design decisions.

The objective of this comparison is not to provide an exhaustive review of all available software or material models, but to focus on those that dominate practice and therefore underpin the majority of published FoS-based slope assessments.

Software platforms considered

The following categories of software are included in this study.

Limit equilibrium methods (LEM)

Limit equilibrium methods remain the most widely used class of tools for open pit slope design. In this study, commonly used industry software packages, including Slide2 and Slide3, are considered as representative LEM implementations. These tools compute FoS by satisfying global force and/or moment equilibrium along assumed failure surfaces. While efficient and well established, LEM inherently relies on predefined kinematic assumptions and does not explicitly simulate stress redistribution, deformation, or progressive failure.

Continuum-based numerical tools

Continuum-based numerical modelling tools are widely used to complement or extend LEM analyses, particularly for deep pits, complex geometries, and stress-sensitive problems. The following platforms are considered as representative of common practice:

- **FLAC/FLAC3D** (explicit finite difference method).
- **RS2 and RS3** (implicit finite element method).
- **Abaqus** (implicit and explicit finite element method).

These tools enable stress–strain-based analyses and allow FoS to be derived using the shear strength reduction (SSR) method. As discussed earlier, the interpretation of FoS in these frameworks depends strongly on solver type (implicit versus explicit), numerical controls, and the definition adopted to identify instability or failure.

Constitutive models considered

Across the software platforms listed above, this study focuses on two constitutive modelling approaches that represent the most commonly applied and the most contrasting philosophies in current open pit slope practice.

Mohr–Coulomb (elastic-perfectly plastic)

The Mohr–Coulomb (MC) model remains the most widely used constitutive model in both LEM and continuum-based analyses of open pit slopes. It is characterised by a linear strength envelope, constant stiffness, and elastic-perfectly plastic behaviour. In numerical applications, peak strength parameters are typically derived from laboratory testing or from linearised approximations of nonlinear criteria such as Hoek–Brown.

Despite its simplicity and computational efficiency, the MC model does not inherently account for confinement-dependent strength, progressive damage, stiffness degradation, or post-peak softening. As a result, its application to large-scale hard rock slopes relies heavily on the assumption that peak strength parameters alone provide a sufficient representation of rock mass behaviour.

Inclusion of the Improved Unified Constitutive Model (IUCM)

In addition to the conventional Mohr–Coulomb model, this study includes the **Improved Unified Constitutive Model (IUCM)** (Vakili, 2016). The IUCM was developed to address several recognised limitations of traditional MC-based representations in hard rock slope applications, particularly where confinement dependency, anisotropy, progressive damage, and stiffness degradation influence large-scale behaviour.

The IUCM incorporates a continuous representation of rock mass strength, confinement-dependent post-peak behaviour, evolving dilation, and stiffness softening, and has been implemented within continuum-based numerical frameworks. While its adoption is not yet as widespread as MC-based models, it has been applied in a growing number of complex geomechanical problems and validated against selected underground and open pit case histories.

For the purposes of this study, the IUCM is included as a **contrast case** to conventional modelling approaches, allowing assessment of how a more physics-informed constitutive formulation influences:

- predicted deformation patterns
- failure mechanisms
- derived FoS values under otherwise identical modelling conditions.

CASE STUDY 1 – BACK-ANALYSIS OF A HARD ROCK OPEN PIT SLOPE FAILURE

Case study context

This case study relates to a hard rock open pit operation in Western Australia that experienced a multi-batter slope failure in early 2021. Prior to the failure, the pit had undergone multiple slope design iterations driven by geotechnical stability assessments and independent review. The case has previously been presented at a high level to illustrate the economic implications of advanced numerical modelling; however, the present paper focuses specifically on the geotechnical modelling approaches, assumptions, and interpretation of Factor of Safety (FoS).

To preserve confidentiality, the name of the operation has been removed. All geological, material, and modelling information presented here is derived from a detailed post-failure investigation and numerical back-analysis report.

Pre-failure slope design based on 2D limit equilibrium analysis

Initial slope designs for the hanging wall were assessed using **two-dimensional limit equilibrium methods (LEM)** implemented in **Slide**. These analyses formed the primary basis for early design decisions and independent engineering opinion.

The 2D LEM results indicated marginal stability for the proposed hanging wall geometry, with computed FoS values approaching or falling below commonly adopted acceptance criteria. In response, the slope design was modified by:

- reducing the overall hanging wall slope angle
- introducing a wide geotechnical decoupling berm.

These design changes were implemented explicitly to increase FoS as calculated by the 2D LEM analyses. While effective in meeting FoS targets, the resulting design had a substantial adverse impact on the mine plan and project economics. An example of the original and modified designs derived from 2D LEM is shown in Figure 1.

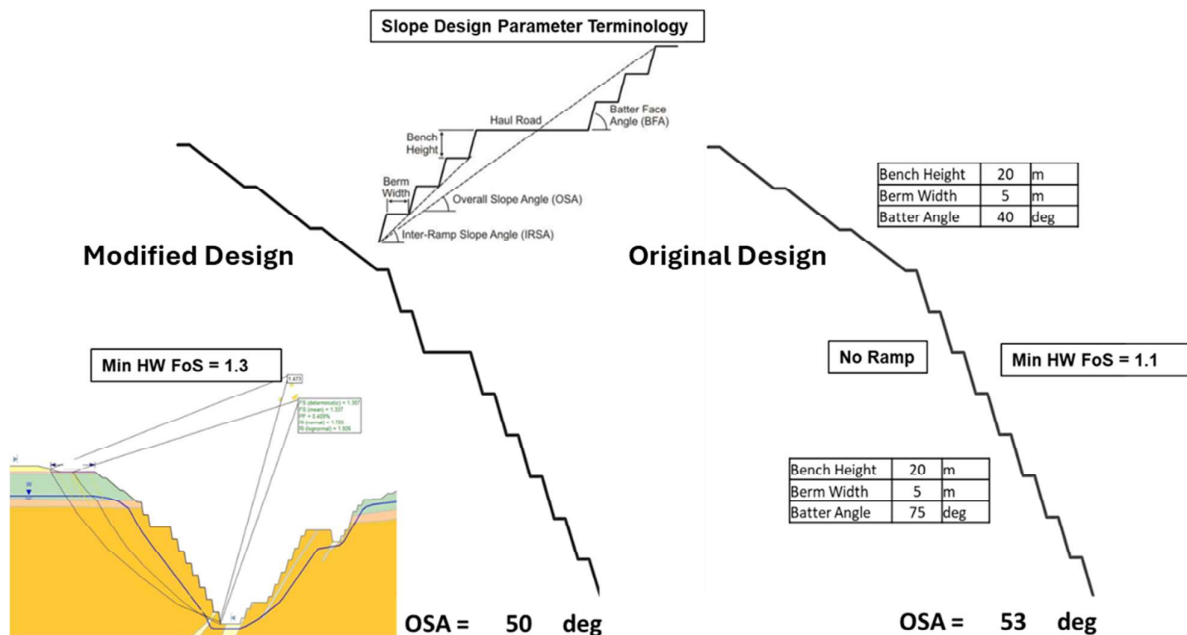


FIG 1 – Original 2D LEM-driven slope design.

Redesign informed by continuum modelling and spatial FoS interpretation

While the 2D LEM approach satisfied conventional FoS criteria after geometric modification, it did not explicitly account for three-dimensional stress redistribution or progressive rock mass behaviour. To investigate these effects, three-dimensional continuum modelling was undertaken.

Following concerns regarding the economic impact of the conservative 2D LEM-based design, three-dimensional continuum modelling was undertaken using **FLAC3D with the IUCM**. These analyses explicitly simulated excavation sequencing, three-dimensional pit geometry, and stress redistribution effects not represented in the 2D LEM framework.

The IUCM analyses indicated that, for the same geometry and material inputs, the hanging wall exhibited a **global FoS exceeding 1.5**, suggesting that the decoupling berm and slope flattening were not required to maintain overall stability. On this basis, the slope was redesigned to remove the geotechnical berm and reinstate steeper overall slope angles.

Importantly, although the global FoS was high, the IUCM results revealed **significant spatial variability in stability**. A localised zone of reduced FoS (approximately **1.2**) was identified on the **north-facing wall**, associated with weaker saprolite and transitional materials and reduced confinement near the crest. This spatial distribution of FoS is illustrated in Figure 2.

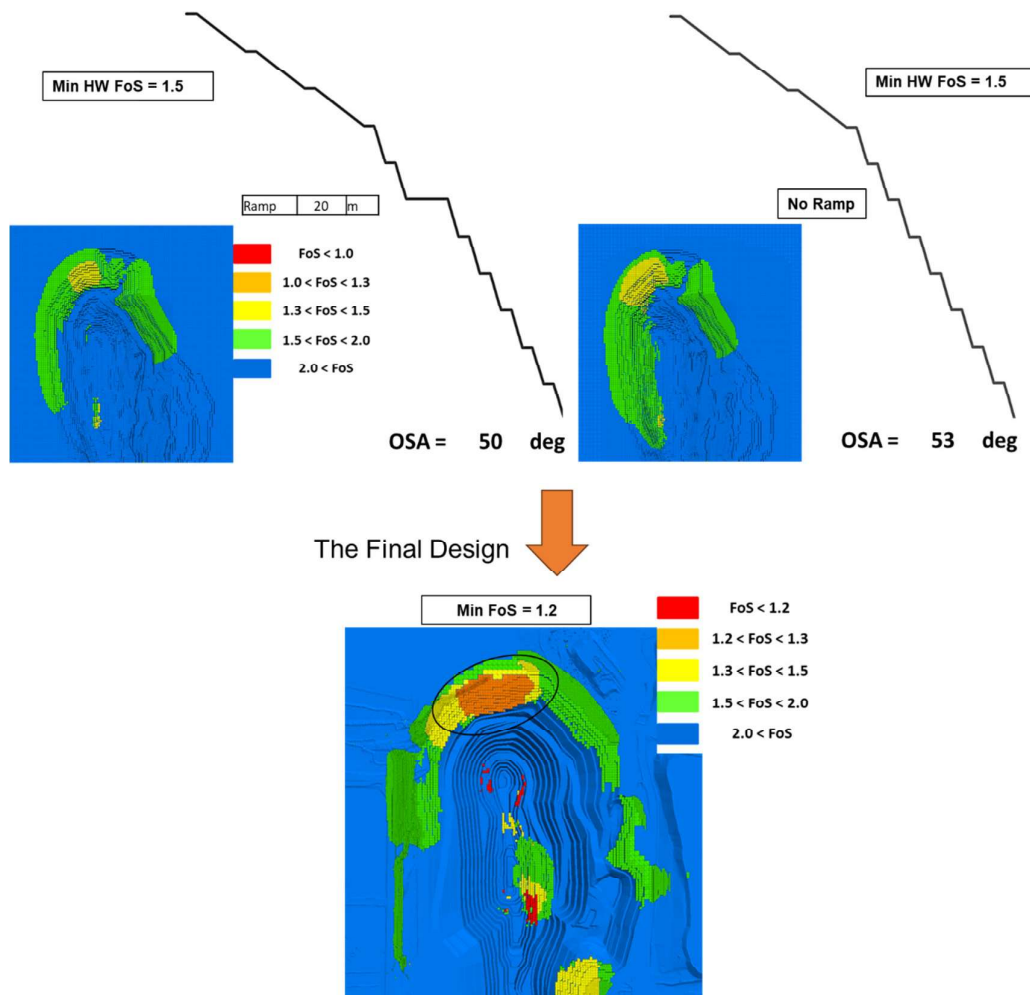


FIG 2 – IUCM-based redesign and spatial FoS distribution.

Post-failure pit geometry used for comparative modelling

In addition to the pre-failure design and back-analysis described in sections 'Pre-failure slope design based on 2D limit equilibrium analysis' and 'Back-analysis as the basis for validation', respectively, a separate modelling exercise was undertaken to directly compare FoS outcomes using different

constitutive formulations under controlled conditions. This comparison was performed using a later pit geometry, corresponding to a pit surface developed after the failure event.

Accordingly, the results presented in this subsection do not represent a back-analysis of the historical failure. Rather, they provide a method comparison study, intended to isolate the influence of constitutive model selection on computed FoS for a subsequent pit design stage.

The comparison was conducted using FLAC3D and included two constitutive formulations:

- Mohr–Coulomb (MC), representing standard industry practice.
- The Improved Unified Constitutive Model (IUCM), representing a confinement-dependent rock mass formulation.

Geometry, zoning, groundwater assumptions, boundary conditions, and excavation state were held constant between the two models.

Analysis methods and modelling assumptions

In order to isolate the effect of rock mass behaviour, the modelling strategy intentionally retained the **Mohr–Coulomb formulation for the laterite and saprolite domains** in both simulations. These units behave predominantly as soil-like weathered materials, and Mohr–Coulomb can provide a reasonable first-order representation of their strength behaviour.

The key difference between the two simulations therefore lies in the representation of the **transitional and fresh rock domains**:

- In the baseline model, these units were represented using Mohr–Coulomb with linear strength envelopes as defined in Table 1.
- In the IUCM model, these units were represented using confinement-dependent, anisotropic, and strain-softening behaviour as defined in Table 2.

TABLE 1
Mohr–Coulomb material for Case Study #1.

Domain	Density (t/m ³)	Mass Young's modulus (GPa)	Friction (°)	Cohesion (MPa)	Tensile strength (MPa)
Laterite	1.78	0.25	31	0.085	0.035
Saprolite	2.56	0.25	31	0.085	0.035
Transitional	2.56	1.3	33	0.436	0.005
Fresh rock	2.75	5.7	56	2.0	0.35
Shale	2.75	4.5	42	1.2	0.35

TABLE 2
IUCM material properties for Case Study #1.

Domain	Density (t/m ³)	Intact Young's modulus (GPa)	UCS (MPa)	GSI	miMax	miMin	Anisotropy factor	Residual friction (°)	Residual cohesion (MPa)
Laterite									
Saprolite									
Transitional	2.56	11	12	35	16	8	5.0	38	0
Fresh rock	2.75	11	113	60	16	8	3.25	45	0
Shale	2.75	11	62.5	55	6	3	3.25	45	0

MC model used with same parameters as Table 1

This approach ensures that differences in FoS arise from the constitutive treatment of hard rock, rather than from changes in soil-like material behaviour. Figure 3 shows a comparison of Mohr–Coulomb (MC) and Hoek–Brown (HB) strength envelopes for the transitional, fresh rock, and shale domains, plotted in principal stress space (σ_1 – σ_3) for confinement up to 2 MPa. The MC envelopes are derived from the parameters in Table 1, while the HB curves are based on the rock mass properties in Table 2.

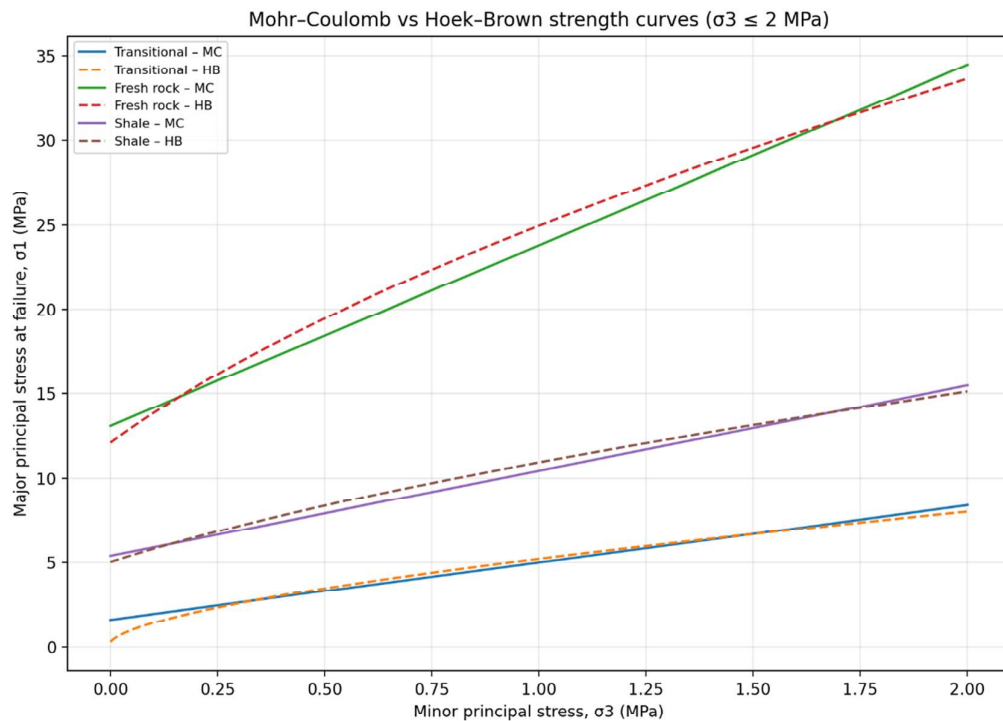


FIG 3 – Comparison of Mohr–Coulomb and Hoek–Brown strength envelopes in σ_1 – σ_3 showing differences for Case Study #1.

The IUCM formulation was adopted to assess the influence of confinement-dependent strength and progressive degradation on the predicted stability response. Adopted domains are shown in Figure 4, MC parameters in Table 1 and IUCM parameters are summarised in Table 2, note these properties.

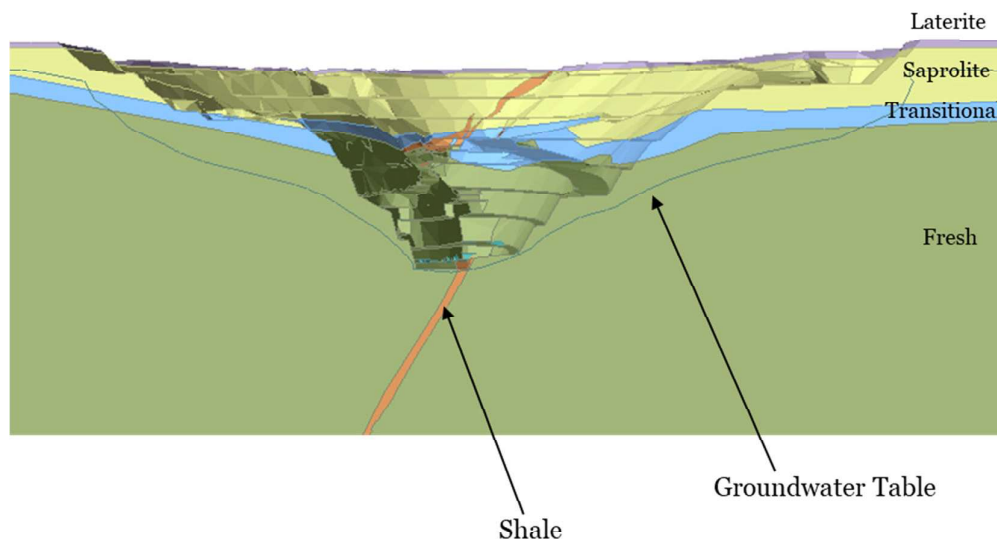


FIG 4 – Material domains for Case Study #1.

Comparison of FoS distributions – Mohr–Coulomb versus IUCM

Figure 5 presents the FoS distributions obtained using Mohr–Coulomb and IUCM for the post-failure pit geometry.

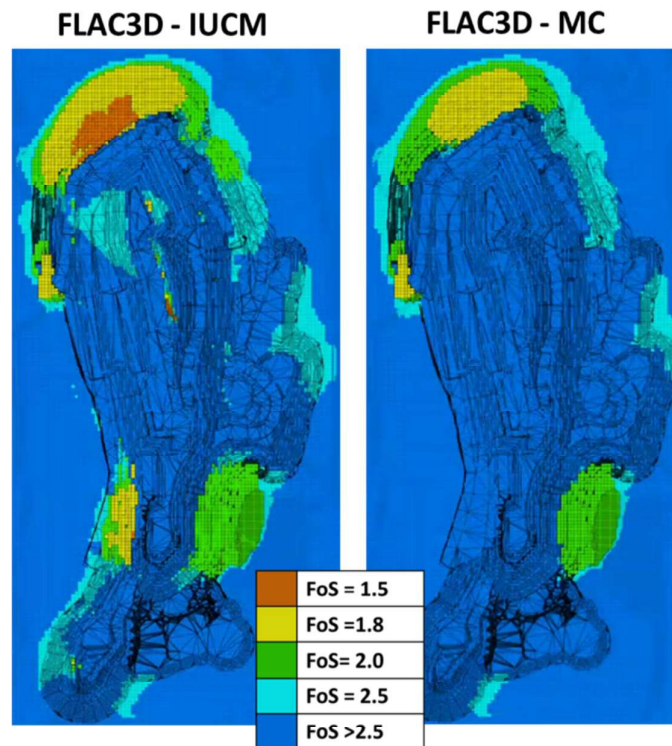


FIG 5 – FoS comparison between Slide3, FLAC3D Mohr–Coulomb (MC), and FLAC3D IUCM.

The IUCM model produced the lowest minimum FoS across all analyses, with a minimum value of approximately $\text{FoS} = 1.5$. In contrast, the Mohr–Coulomb model predicted higher FoS values across most slope segments, including extensive regions with FoS exceeding 2.0.

A key observation is that the Mohr–Coulomb results indicate high stability within the competent rock units, with FoS values remaining elevated across much of the fresh rock slope. In contrast, the IUCM results show meaningful FoS reductions extending into these hard rock domains.

Although Mohr–Coulomb behaviour was intentionally retained for the laterite and saprolite domains in both simulations, the results indicate that FoS differences are not confined to the hard rock units alone. Figure 5 shows that adopting the IUCM formulation for the transitional and fresh rock domains modifies the overall stress redistribution and deformation response of the slope system, resulting in **measurable changes in FoS within the cover sequence**, including saprolite and transported materials.

Interpretation of constitutive influence on global response

The divergence between Mohr–Coulomb and IUCM results reflects fundamental differences in how rock mass behaviour is represented.

The Mohr–Coulomb formulation assumes a linear strength envelope and elastic-perfectly plastic response, without explicit representation of:

- confinement-dependent brittle strength loss
- progressive damage accumulation
- stiffness degradation
- or post-peak strain localisation.

In contrast, the IUCM explicitly incorporates confinement sensitivity and progressive post-peak degradation in rock mass behaviour. As a result, IUCM predicts reduced stability in rock units where stress redistribution and confinement changes influence strength mobilisation.

Importantly, although the soil-like materials were treated identically in both models, changing only the basement rock constitutive behaviour influenced the overall pit response. This indicates that constitutive model selection in hard rock does not merely affect local behaviour, but can alter the global stability field.

Key outcomes from the comparative modelling

The comparative modelling exercise conducted on the post-failure pit geometry demonstrates the following:

- FoS values are strongly dependent on constitutive model selection, even when geometry, material zoning, groundwater conditions, and boundary conditions are unchanged.
- The IUCM model produced the lowest minimum FoS (≈ 1.5) among the models tested, despite identical treatment of the saprolite and laterite units in both simulations.
- Differences in FoS are not confined to the hard rock domains. Although Mohr–Coulomb behaviour was retained for the soil-like units in both models, adopting IUCM for the transitional and fresh rock altered the stress redistribution and deformation compatibility of the entire slope system, resulting in measurable FoS differences within the overlying cover sequence.
- The most pronounced divergence occurs within competent rock, where the Mohr–Coulomb model predicts consistently higher FoS values relative to IUCM. This suggests that linear elastic–perfectly plastic formulations may overpredict stability in confinement-dependent hard rock environments.
- Constitutive representation of the basement rock mass materially influences not only local rock slope behaviour, but also the global stability field, including the response of weathered and soil-like units.

CASE STUDY 2 – STEEP HARD ROCK SLOPES SUCCESSFULLY MINED UNDER PREDICTED IUCM PERFORMANCE

Case study context

The second case study is drawn from a deep, structurally controlled hard rock open pit mine in South Australia that was successfully mined to completion at a depth exceeding 360 m. The pit included steep overall slope angles and highly persistent, unfavourably oriented discontinuity sets, raising concerns regarding the potential for large-scale instability.

Lucas, Vakili and Hutchison, (2020) describe the geotechnical setting and slope stability challenges of this mine, with particular emphasis on the west wall, which was undercut by a widely spaced but highly persistent joint set dipping into the excavation. In addition to structural controls, concerns were raised regarding the influence of mining-induced stress redistribution due to the depth and three-dimensional confinement of the pit geometry.

Unlike many published case histories where modelling is limited to FoS values, this mine provides an opportunity to compare predicted stability and deformation patterns against extensive monitoring data collected throughout mining.

Early assessments and conventional stability predictions

Prior to adopting advanced three-dimensional modelling, the mine was assessed using multiple conventional stability methods. A summary of these earlier predictions indicates substantial variability in computed stability outcomes:

- Empirical assessments suggested FoS values as low as approximately **0.85**.

- Two-dimensional limit equilibrium (LE) analyses produced FoS values in the range of approximately **0.8 to 1.1**.
- Two-dimensional finite element analyses (RS2) produced FoS values in the range of approximately **1.0 to 1.2**.

These results collectively implied that the slope configuration was either unstable or marginally stable, and that mining to the proposed steep design would involve a high risk of large-scale failure.

IUCM modelling and predicted feasibility of aggressive slope designs

To address uncertainty in the conventional assessments, the mine adopted three-dimensional numerical modelling using FLAC3D. Lucas *et al* (2020) report that multiple phases of 3D modelling were undertaken between 2015 and 2019, focusing on larger-scale stability and deformation mechanisms rather than purely on slip-surface FoS calculations.

The Improved Unified Constitutive Model (IUCM) was selected due to its ability to represent confinement dependency, progressive damage accumulation, and anisotropic rock mass response under higher stress conditions.

The IUCM modelling predicted that the mine could successfully excavate steep walls with an acceptable Factor of Safety against large-scale instability, and that mining-induced stress would not trigger deep-seated failure mechanisms. Based on these results, the mine proceeded with the aggressive steep wall design.

Validation through monitoring and observed deformation behaviour

A key strength of this case study is that the numerical modelling was validated against extensive monitoring data sets. Lucas *et al* (2020) report that the mine employed routine laser scanning and that modelled displacements showed good agreement with observed displacement patterns and magnitudes.

The modelling was able to reproduce:

- the spatial distribution of displacement along the west wall
- the structural influence on movement mechanisms
- the magnitude of observed displacement development over time.

The mine was ultimately excavated to the final pit design, which Lucas *et al* (2020) report as being consistent with modelling predictions indicating FoS values greater than approximately 1.1.

Later comparative study – Slide3 versus IUCM (SlopeX plugin)

Following completion of the mine, a separate study was conducted to compare FoS outcomes between 3D limit equilibrium analysis (Slide3) and IUCM-based numerical modelling implemented using the SlopeX plugin for FLAC3D.

This comparison was performed on a simplified representation of the pit and rock mass domain geometries. Simplification was necessary because Slide3 required reduction of geometric complexity to achieve a workable limit equilibrium model, whereas the FLAC3D-based SlopeX workflow was capable of incorporating more complex surfaces and internal zoning. To ensure comparability, the simplified Slide3 geometry was replicated in FLAC3D and analysed using IUCM. Material domains are shown in Figure 6, model inputs for Slide3 are listed in Table 3 and for IUCM in Table 4.

For the comparative analysis between Slide3 and IUCM in Case Study 2, a generalised Hoek–Brown (HB) formulation was adopted within the Slide3 model. This was done to ensure that the underlying strength representation was as consistent as possible with the IUCM framework, which is fundamentally based on Hoek–Brown-type behaviour. In this context, HB parameters were derived from the same rock mass characterisation used for the IUCM model, allowing a more direct comparison between the two approaches. This represents an intentional departure from the earlier discussion of typical industry practice, where Mohr–Coulomb formulations are more commonly

applied. The use of HB in this case was therefore aimed at minimising differences arising purely from strength representation, so that the comparison more clearly reflects differences in modelling framework and failure simulation.

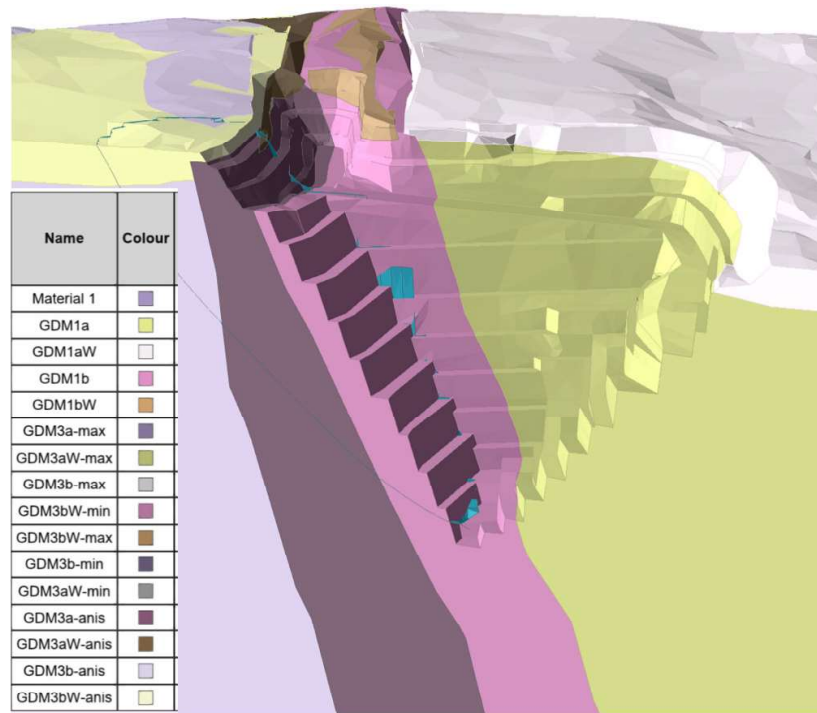


FIG 6 – Material domains for Case Study #2.

TABLE 3
IUCM material properties for Case Study #2.

Name	Colour	Unit weight (MN/m ³)	Water surface	Failure criterion	Cohesion (MPa)	Phi (°)	UCS of intact rock (MPa)	Tensile cut-off type	GSI	mi	D
Material 1		0.02	Water Table	Mohr Coulomb	0.001	35					
GDM1a		0.0333	Water Table	Generalised Hoek–Brown			48	None	80	10	0
GDM1aW		0.0333	Water Table	Generalised Hoek–Brown			40	None	70	10	0
GDM1b		0.0284	Water Table	Generalised Hoek–Brown			48	None	69	10	0
GDM1bW		0.0284	Water Table	Generalised Hoek–Brown			40	None	60	10	0
GDM3a-max		0.0274	Water Table	Generalised Hoek–Brown			33	None	55	10	0
GDM3aW-max		0.0274	Water Table	Generalised Hoek–Brown			29	None	50	10	0
GDM3b-max		0.0274	Water Table	Generalised Hoek–Brown			18	None	40	10	0
GDM3bW-min		0.0274	Water Table	Generalised Hoek–Brown			12	None	50	10	0
GDM3bW-max		0.0274	Water Table	Generalised Hoek–Brown			50	None	50	10	0

Name	Colour	Unit weight (MN/m ³)	Water surface	Failure criterion	Cohesion (MPa)	Phi (°)	UCS of intact rock (MPa)	Tensile cut-off type	GSI	mi	D
GDM3b-min		0.0274	Water Table	Generalised Hoek–Brown			12	None	40	5	0
GDM3aW-min		0.0274	Water Table	Generalised Hoek–Brown			19.3	None	50	5	0
GDM3a-anis		0.0274	Water Table	Generalised Anisotropic							
GDM3aW-anis		0.0274	Water Table	Generalised Anisotropic							
GDM3b-anis		0.0274	Water Table	Generalised Anisotropic							
GDM3bW-anis		0.0274	Water Table	Generalised Anisotropic							

TABLE 4
IUCM material properties for Case Study #2.

Domain	Density (t/m ³)	Ei (GPa)	Sigci (MPa)	Mi max	Mi min	Anisotropy factor	Dip (°)	Dip direction (°)	GSI
Weathered domains									
GDM1a-w	3.4	45	40	10	n/a	n/a	n/a	n/a	70
GDM1b-w	2.9	40	40	10	n/a	n/a	n/a	n/a	60
GDM3a-w	2.8	40	29	10	5	1.5	74	103	50
GDM3b-w	2.8	25	18	10	5	1.5	74	103	40
Fresh domains									
GDM1a	3.4	69	48	10	n/a	n/a	n/a	n/a	80
GDM1b	2.9	53	48	10	n/a	n/a	n/a	n/a	70
GDM3a	2.8	53	33	10	5	1.5	74	103	55
GDM3b	2.8	53	18	10	5	1.5	74	103	40

Results of the sensitivity analysis for Massive hard rock is shown in Figures 7 and 8 and for soft and highly jointed rock shown in Figure 9. The study demonstrated that differences between Slide3 and IUCM based model could be significant, particularly under massive rock mass conditions. The results suggested discrepancies in minimum FoS of up to approximately 100 per cent in some scenarios, and substantial differences in predicted failure volume and location.

The Hoek–Brown disturbance factor (D) was applied consistently in both the Slide3 and IUCM (FLAC-based) models, ensuring that equivalent rock mass strength conditions were represented across the comparative analyses.

None of the sensitivity cases presented are intended to represent the design case in terms of absolute FoS values, as the comparative models incorporate geometric and material simplifications, including the treatment of groundwater conditions. However, the dry, anisotropic case with D = 0 most closely reflects the material characterisation adopted in the design model.

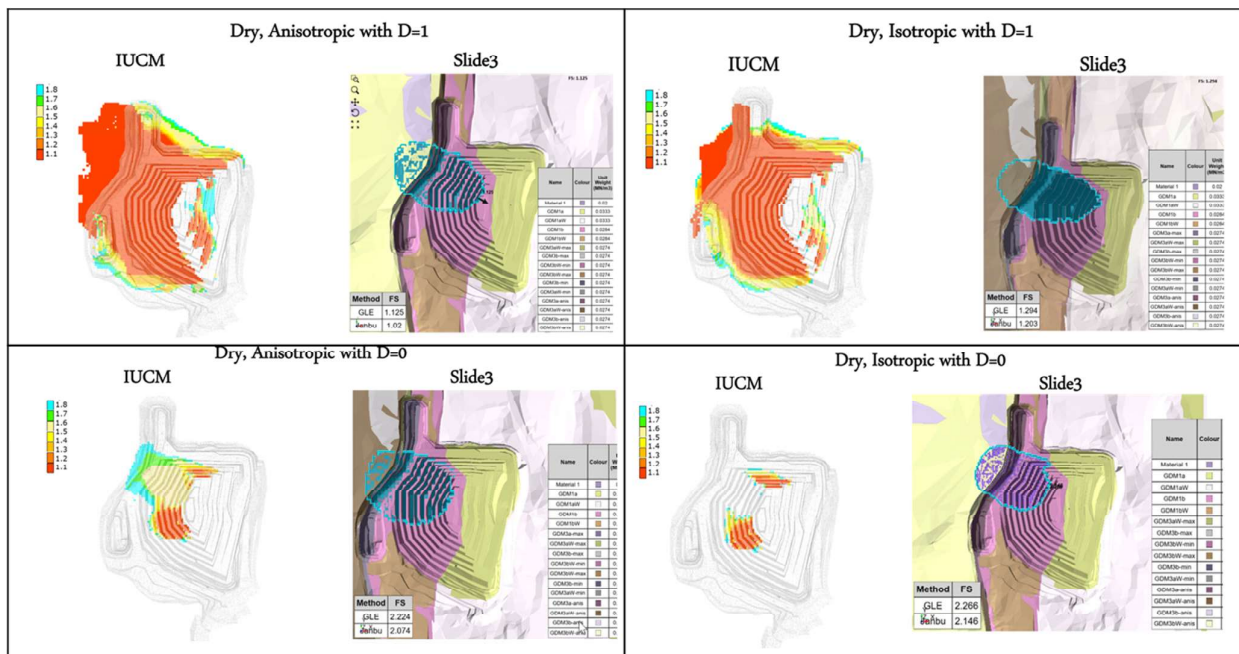


FIG 7 – Comparison between IUCM and Slide 3 for Massive Hard Rock with Varying property changes (Case Study #2 and Dry conditions).

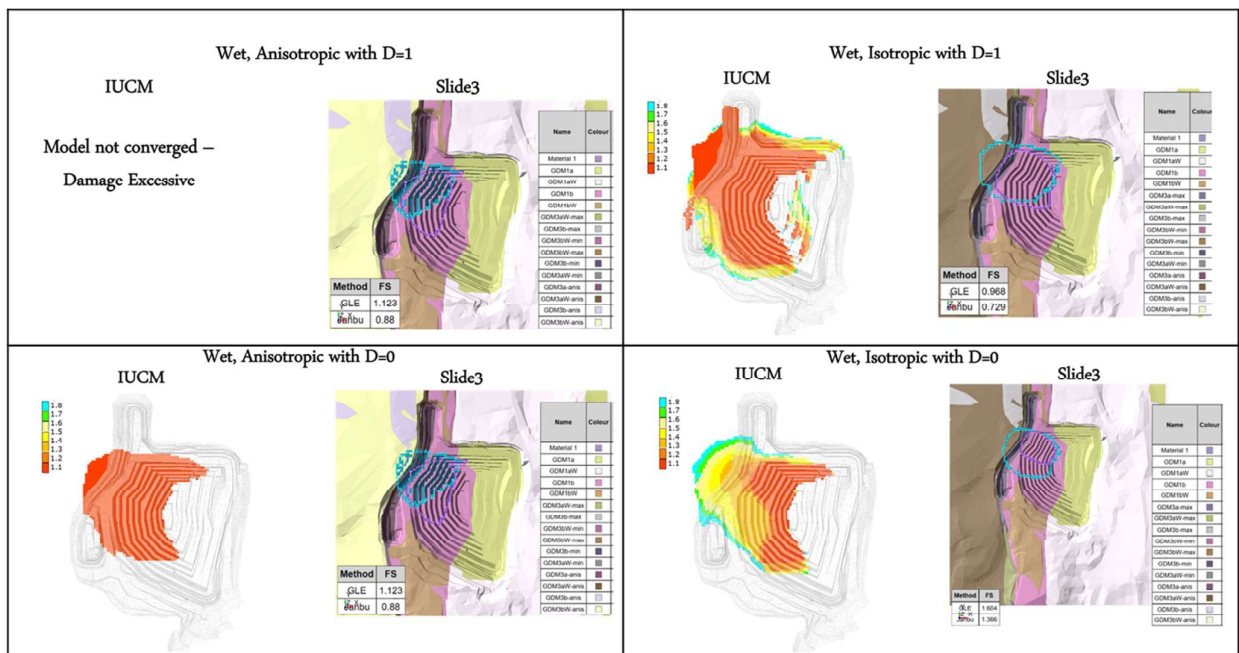


FIG 8 – Comparison between IUCM and Slide 3 for Massive Hard Rock with Varying property changes (Case Study #2 and Wet conditions).

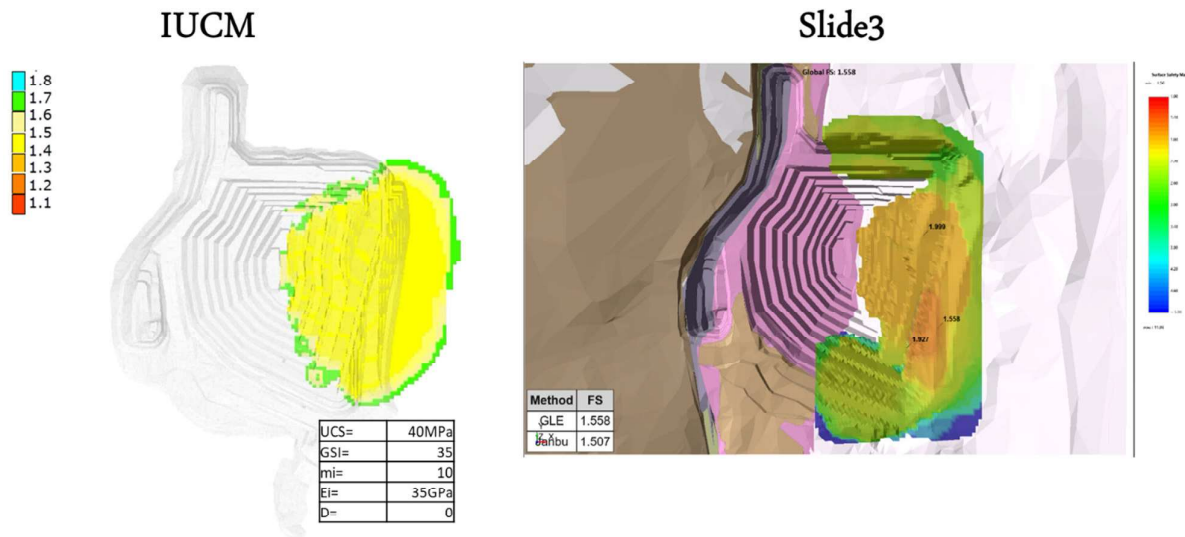


FIG 9 – Comparison between IUCM and Slide 3 for highly jointed and soft rock with varying property changes (Case Study #2 and Dry conditions).

A key finding from this comparative exercise was that agreement between methods improved when a circular or soil-like failure mechanism was expected, while divergence increased when the stability mechanism depended on progressive rock mass damage or confinement-controlled behaviour. A summary of the FoS for varying conditions between the two approaches are in Tables 5 and 6.

TABLE 5

Minimum FoS for multi-batter failure in massive rock mass.

	Dry						Wet					
	Iso			Aniso			Iso			Aniso		
	D=0	D=0.7	D=1	D=0	D=0.7	D=1	D=0	D=0.7	D=1	D=0	D=0.7	D=1
IUCM	1.1	<1	<1	1.1	<1	<1	<1	<1	<1	<1	<1	<1
Slide3D	2.2	1.7	1.3	2.1	1.5	1.1	1.6	1.4	<1	1.5	1.1	1.1
Difference	100%	70%	30%	91%	50%	10%	60%	40%	0%	50%	10%	10%

TABLE 6

Minimum FoS for multi-batter failure in highly jointed and weathered rock mass.

	Dry Iso D=0
IUCM	1.4
Slide3D	1.5
Difference	7%

Recent reanalysis using updated pit shell and stress field

A more recent reanalysis of the pit was undertaken using an updated pit shell and an updated *in situ* stress field interpretation. This modelling included a direct comparison between Mohr–Coulomb and IUCM constitutive representations using consistent geometry and boundary conditions (see Figure 10 for MC parameters and comparison with HB in σ_1 - σ_3 space).

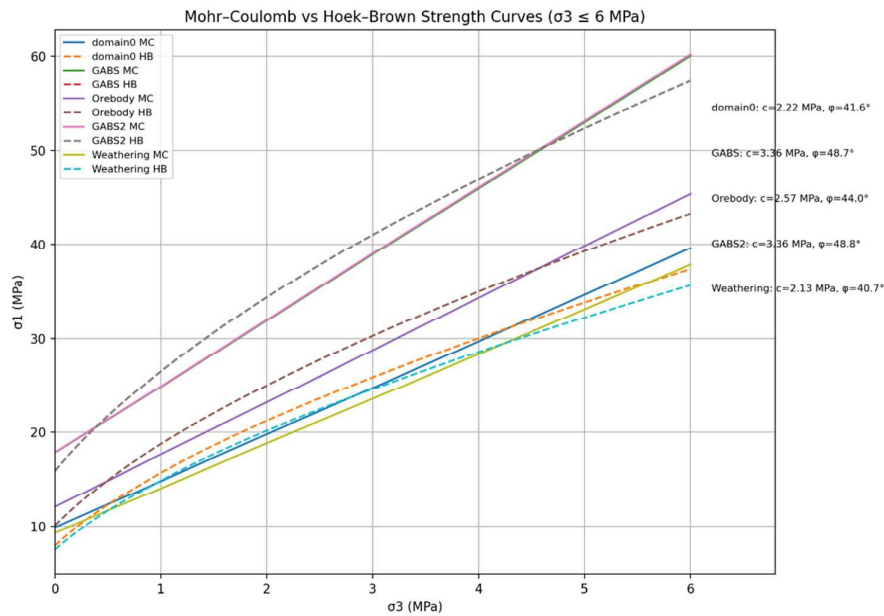


FIG 10 – Comparison of Mohr–Coulomb and Hoek–Brown strength envelopes for Case Study 2 materials in σ_1 - σ_3 space.

The results of this updated analysis are presented in Figure 11, which shows that the Mohr–Coulomb formulation produced high FoS values with limited sensitivity in competent rock domains, while IUCM predicted a more differentiated FoS distribution and lower minimum FoS values. Notably, IUCM predicted meaningful stability gradients extending into hard rock regions, whereas Mohr–Coulomb produced predominantly high FoS values across the pit.

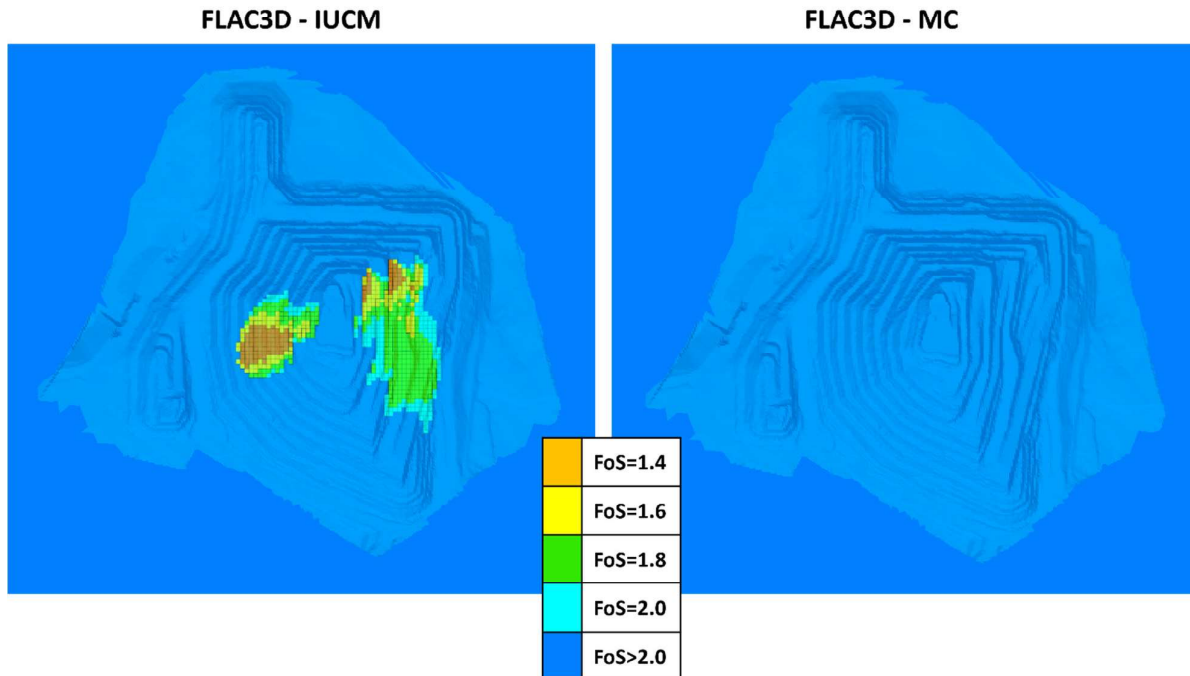


FIG 11 – Updated pit reanalysis comparing FoS distributions obtained using Mohr–Coulomb and IUCM under consistent geometry and updated stress field conditions.

This finding is consistent with Case Study 1 and supports the conclusion that constitutive model selection can materially alter not only local stability predictions, but the entire system response, including cover sequence behaviour and global FoS distribution.

Implications for FoS interpretation

Case study 2 highlights a key contradiction within common slope design practice. Conventional methods (empirical, LE, and 2D FEM) indicated marginal or unstable slope conditions, while the IUCM-based 3D modelling predicted acceptable stability and deformation behaviour. The mine proceeded with aggressive steep slopes and was successfully completed, with laser scanning monitoring confirming that observed deformation mechanisms and magnitudes were consistent with numerical predictions.

The results demonstrate that FoS should not be interpreted as an absolute and transferable measure of stability across modelling frameworks. Instead, the meaning of FoS depends on whether the analysis method can realistically represent:

- confinement-dependent rock strength mobilisation
- stress redistribution during excavation
- structural control and anisotropy
- progressive damage accumulation
- deformation compatibility at slope scale.

This case study therefore provides one of the rare published examples where a confinement-dependent constitutive model, combined with three-dimensional explicit modelling of structures, not only predicted a defensible FoS but also successfully predicted slope deformation trends that were validated through ongoing monitoring.

CONCLUSIONS

This study demonstrates that the Factor of Safety (FoS) is not an intrinsic property of a slope, but a model-dependent outcome governed by the numerical framework and constitutive assumptions used in its calculation.

Across two real-world open pit case studies, identical geometries and comparable material characterisation produced materially different FoS values depending on the modelling approach adopted. These differences arise from variations in analysis methodology (limit equilibrium versus continuum), the numerical definition of failure, and the representation of rock mass behaviour within the constitutive model.

In Case Study 1, Mohr–Coulomb and IUCM formulations applied within the same numerical platform produced significantly different FoS distributions, despite identical treatment of soil-like materials. Differences in hard rock constitutive behaviour influenced stress redistribution and, in turn, the global stability response of the slope system.

In Case Study 2, conventional empirical methods, limit equilibrium analysis, and 2D FEM predicted marginal or unstable conditions, whereas the original 3D IUCM design model-incorporating full geometric, structural, and groundwater complexity-predicted acceptable stability and deformation behaviour. The mine was subsequently excavated to completion, with monitoring confirming the predicted deformation response. It is noted that the lower SRF values observed in later IUCM sensitivity analyses correspond to simplified comparison models and were not used as the basis for design assessment.

These findings lead to several key conclusions:

- FoS values derived from different modelling frameworks are not directly comparable.
- Constitutive model selection can influence FoS to a degree comparable to, or greater than, reasonable parameter variation, even when models are calibrated to the same underlying geotechnical data set. While the derivation of model parameters introduces an additional source of variability, the results presented here demonstrate that differences in constitutive formulation alone can lead to substantial divergence in predicted FoS.
- Validation against observed deformation behaviour and failure mechanisms is essential when interpreting FoS values.

- An FoS value such as 1.2 does not have a universal meaning independent of the modelling assumptions used to derive it.

FoS should therefore be interpreted as a model-conditioned stability indicator rather than an absolute measure of safety. Defensible slope design requires explicit consideration of model-form uncertainty, constitutive representation, solver behaviour, and validation against observed performance, alongside traditional parameter sensitivity analysis. Without this broader perspective, numerical results risk reflecting the assumptions of the modelling approach rather than the true mechanics of the slope.

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