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The Jwaneng underground project: an overview of numerical modelling as a design tool

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Abstract

The Debswana Diamond Company (DDC) Jwaneng mine in Botswana is a large open pit diamond operation extracting 3 kimberlite pipes and has been in production since 1982. Open pit operations will cease in 2036, and studies are being undertaken to transition the mine to an underground operation.

The Jwaneng underground project (JUP) is complex as it needs to consider 3 kimberlite pipes and there are many challenges and complexities. The study is currently at a pre-feasibility level and considers a range of mining methods over the 3 kimberlite pipes and different mining phases. The Jwaneng mine is structurally complex, with many large geological structures and a variable rock mass of strengths ranging from weak kimberlites (~25 MPa) to very competent dolomites (>250 MPa). Initially, mining of kimberlite wedges (Phase 1) on the pit walls will occur from underground and will be done using blasthole open stoping (BHOS) and sublevel retreat (SLR). A transition from this unconfined environment to a confined underground environment occurs below the pit (Phase 2), with extraction using sublevel caving (SLC) and block caving (BC).

DDC has made significant efforts to develop the geotechnical model (geology, structural, rock mass, and hydrogeology) and the stress field as key design inputs. Numerical modelling has been used to evaluate a range of mine designs and design variations, including SLR/SLC drive spacing, BC height, access and infrastructure stand-offs, zone of influence, etc.

Both FLAC3D (finite volume) and Abaqus (finite element) software were used as part of the design process and to allow the project team to make key design decisions. Various sensitivities for a range of input parameters were researched to understand what the models are sensitive to and to identify uncertainty. Results from the numerical modelling will be presented and summarised.

Keywords: *numerical modelling, design, sublevel caving, sublevel retreat*

1 Introduction

The Debswana Diamond Company (DDC) Jwaneng mine in Botswana is a large open pit diamond mine extracting 3 kimberlite pipes. Open pit operations will cease in 2036. Studies are currently underway to transition to an underground mining operation by the time open pit mining ceases, and this is known as the Jwaneng underground project (JUP). It is anticipated that underground mining will be undertaken using a combination of blasthole open stoping (BHOS), sublevel retreat (SLR), sublevel caving (SLC) and block caving (BC) methods. Mining will extend to a depth of 1,000 m below surface and will include excavations within competent country rock and weak kimberlite rock.

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2 Jwaneng mine setting

2.1 Location

Jwaneng mine is situated approximately 160 km southwest of Botswana's capital city, Gaborone, in the eastern part of the Kalahari Desert. It was discovered in the Naledi Valley, southern Botswana, in 1972. In July 1982 the mine went into production, becoming fully operational in August of the same year (Gabanakgosi et al. 2018).

2.2 Geology

The Jwaneng mine country rock stratigraphy comprises Paleoproterozoic sedimentary rocks of the Pretoria Group within the Transvaal Supergroup. The uppermost stratigraphic units are the aeolian Kalahari Sands, as well as pedogenic calcretes (CALC). These units are underlain by various formations comprising a complex assemblage or mixture of laminated shales (LS) carbonaceous shales (CS), quartzitic shales (QS) and siltstones. Below these are carbonates or dolomites (DM) of the Malmani Subgroup West (Beukes 2006). Various dolerite (DOLR) sills and dykes are also present. The country rock geology is further described by Dunn et al. (2022a).

Jwaneng mine exploits a diamond-bearing kimberlite complex of 3 main pipes named the south (S), centre (C) and north (N) pipes. The 3 pipes are associated with steep (~80°) and relatively smooth sides. The contacts with the country rock are typically very sharp. The upper portions of the pipes were dominated by reworked volcaniclastic sediments with shallow dipping bedding structures. This is underlain by the main pipe infill, which is typically dominated by broadly massive volcaniclastic kimberlite (VK) with bedded pyroclastic and volcaniclastic units preserved in the north pipe. There is also a range of breccias (Dunn et al. 2022a).

The north pipe facies within the underground horizon are the VK(N) and the pyroclastic kimberlite PK(N) facies. The south pipe consists of the VK(S) and the autolithic VK [AVK(S)] facies. The centre pipe comprises the VK(C) and 3 breccia units which represent zones of relatively little kimberlitic material. The country rock breccia (CRB) units CRBQS(C) and CRBDM(C) are dominated by QS and DM respectively. Kimberlitic material content in these units is generally less than 5%. The kimberlite rich breccia with DM [KBWDM(C)] unit comprises of DM clasts in relatively more kimberlitic material than the other breccias (5–50%).

2.3 Structural setting

The Jwaneng mine structural setting is complex, and the structural model is updated as new information becomes available. Jwaneng mine is dominated by northeast-southwest striking faults with a strong normal dip-slip shear sense component. These faults are downthrown to the southeast and compartmentalise the shallow to intermediately northwest-dipping strata into structural domains, each with a unique rock fabric (Barnett 2009). It has been suggested (Creus et al. 2017) that there have been at least 3 deformational events. The litho-structural model is regularly updated, with the most recent update done in late 2025. There are 160 faults in the 2025 update of the litho-structural model.

2.4 Geotechnical setting

The country rock lithologies range from relatively weak LS units of poor-to-fair rock mass quality to highly competent DM units of good rock mass quality. The various kimberlite facies range from weak VK to moderate strength PK to highly variable breccia units. The kimberlite facies have varying degrees of durability and weatherability, depending on the proportion of swelling clays present. The uniaxial compressive strength (UCS), elastic modulus (E_i) and rock mass indices (rock mass rating 1989 – RMR_{89}; geological strength index – GSI_{SRK}; Q' – Q-system) and classification are summarised in Table 1 (Dunn & Kebatsetse 2024).

There are 3 well-defined joint sets consisting of 2 steep-dipping sets and a shallower dipping bedding set. There is also an occasional fourth set which is flat dipping. The faults are generally considered benign, with widths less than 1 m and a limited damage zone.

The kimberlite contacts' rock mass quality presents as a minor downgrade to typical rock mass values in all kimberlite pipe. It is assessed to be less competent, and contacts are also noted to be water-bearing, with most of them being wet (Dunn & Kebatsetse 2024).

The current understanding of the stress field is a vertical major stress (σ_V), with the major horizontal stress (σ_H) of 0.94*σ_V orientated northwest-southeast and a minor horizontal stress (σ_h) of 0.58*σ_V (Dunn & Kebatsetse 2024; Wang et al. 2025).

Table 1 Summary of rock intact properties, and rock mass indices and classification (Dunn & Kebatsetse 2024)

Rock type	Uniaxial compressive strength (MPa)	E_i (GPa)	RMR_{89}	GSI_{SRK}	Q'	Rock mass class
CALC	74	35	77	79	42.0	Good
LS	48	25	63	46	2.6	Poor–fair
CS	119	39	67	51	3.5	Poor–fair
QS	232	63	72	56	4.8	Fair
CS2	309	74	80	66	17.3	Good
DM	250	99	83	71	20.7	Good
DOLR	266	77	74	53	7.8	Fair
VK(C)	31	6	73	74	7.1	Fair–good
VK(N)	40	7	69	73	4.0	Fair–good
VK(S)	26	8	73	74	6.1	Fair–good
PK(N)	59	11	73	74	7.5	Fair–good
AVK(S)	28	18	75	75	14.4	Good
CRBDM(C)	96	46	81	74	25.7	Good
CRBQS(C)	87	37	64	43	15.5	Good
KBWDM(C)	20	11	78	69	21.4	Good

3 Jwaneng underground project

3.1 Overview

Studies into the underground potential at Jwaneng mine have been undertaken since the early 2000s. Various studies were completed in 2017 and 2019, and the underground focus increased during the 2020 extended concept study, which eliminated further open pit cutbacks as an alternative.

The JUP has been divided into 3 stages (Figure 1):

- exploration access (EA)
- Phase 1 underground mining
- Phase 2 underground mining.

The EA provides access for the Phase 1 underground mining and importantly also provides access for additional resource drilling for the resource upgrade of the deeper extents of the kimberlite pipes (Phase 2) and the collection of additional geoscience data at depth.

The EA component was fast-tracked and a feasibility study (FS) was completed in late 2023. Mine development commenced in May 2024 and about 8,000 m of development has been completed. The JUP is currently in the pre-feasibility study (PFS) stage for the Phase 1 mining; The PFS stage A (PFS-A) was completed in 2024, and the PFS stage B (PFS-B) is ongoing. It is anticipated that the FS for Phase 1 mining will commence in early 2027.

Whilst current studies are focused on the Phase 1 underground mining, Phase 2 underground mining must be considered as decisions on long-term infrastructure and mining logistics need to be made. All studies consider the Phase 2 mine design, even though the geoscience models may represent a lower level of confidence.

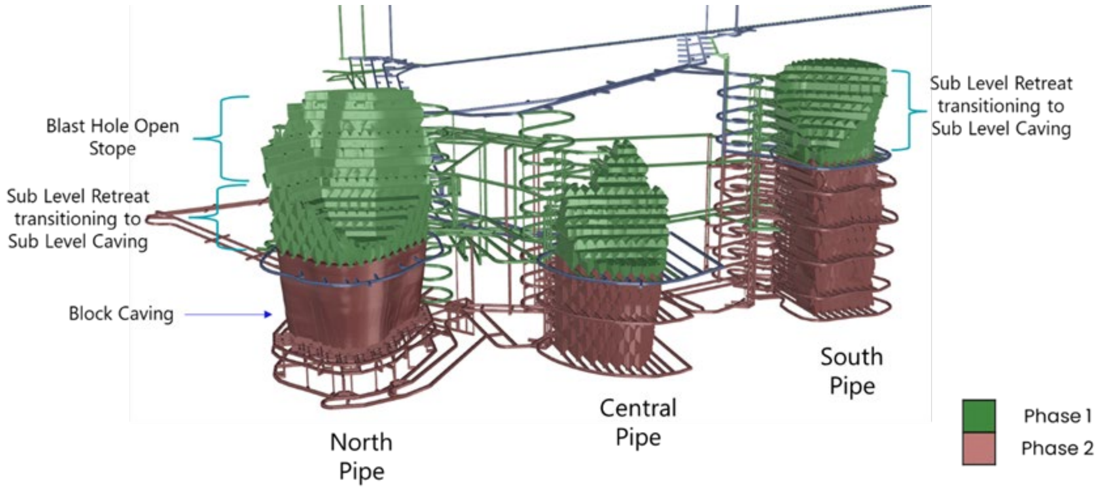

Figure 1 Kimberlite pipes and mining phases

3.2 Proposed mining methods

A range of mining methods has been considered for the Jwaneng underground mine, including:

- blasthole open stoping (BHOS)
- sublevel retreat (SLR)
- sublevel caving (SLC)
- block caving (BC).

The options for the PFS-B going forward are summarised in Table 2.

Table 2 Mining methods per mining phase and kimberlite pipe

Mining	North pipe	Centre pipe	South pipe
Phase 1	BHOS and SLR	SLR	SLR
Phase 2	BC	SLC	SLC

4 Design approach

Debswana undertakes the underground mining studies in accordance with the Anglo-American investment development model (IDM) guidelines. From a mining geotechnical perspective, the following approach is adopted:

- extensive geoscience (geology, geotechnical and hydrogeology) data collection
- development of comprehensive geoscience models

- design guidance developed using benchmarking and empirical rules
- design analysis using empirical, analytical and numerical modelling
- review at various levels (internal, consultants, geotechnical review board, etc.).

The focus of this paper is the application of numerical modelling for the JUP studies. Typically, the design is an iterative process with the mining engineers.

4.1 Design inputs

There are a range of inputs which support the design work for the JUP. A brief overview of those applicable to the numerical modelling follows.

4.1.1 Geotechnical model

The geotechnical model at Jwaneng mine comprises several separate models as shown in Figure 2. The geotechnical model is regularly reviewed and updated as new data becomes available and understanding of the geotechnical environment evolves. Some investigations are carried out as part of the ongoing open pit operations whilst others are conducted specifically for the underground mining studies. Ultimately all learnings, regardless of where the investigations are conducted, are consolidated into the official geotechnical model. As the stress field is an important consideration in underground mine design it has been included in the geotechnical model development for the underground studies.

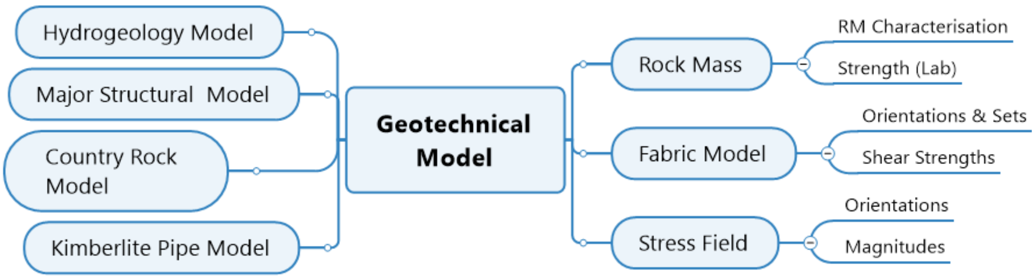

Figure 2 Geotechnical model components (Dunn & Kebatsetse 2024)

Development of the geotechnical model is undertaken in-house and is guided by the geotechnical review board (GRB), which is an important part of the Debswana technical assurance process. The geotechnical model and its various components are described in Dunn & Kebatsetse (2024).

The spatial models (litho-structural and kimberlite pipes) form the basis of the numerical model. Rock mass properties are derived from rock mass characterisation and classification plus intact properties from laboratory testing. Discontinuity properties (faults and joints) are derived from laboratory shear testing and discontinuity characterisation.

The in situ stress regime has been assessed using several in situ stress measurements (Dunn et al. 2022b) and through a detailed back-analysis (Wang et al. 2025).

4.1.2 Design parameters

Geotechnical design guidance was developed as an input into the mine designs which are evaluated using numerical models. These guidelines are based on previous numerical modelling (PFS-A) and empirical design methods and rules which are considered a starting point. These include:

- layout rules
- stand-off distances
- excavation dimensions
- SLR/SLC ore drive spacing

- BC undercut and production level layout
- inter-level spacing
- sequencing rules
- indicative ground support.

5 Numerical modelling

Numerical modelling is regularly used as a design tool across the DDC mining operations for both open pit and underground design.

5.1 Numerical modelling philosophy

Advanced 3D modelling has been undertaken for the Jwaneng open pit for several years and a degree of calibration has been achieved with a commensurate level of reliability that makes it a useful invaluable slope design tool. Open pit slope stability is generally influenced by discontinuities (bedding, joints and faults) and this dominant failure mechanism is well represented in the numerical models.

For the underground mine the failure mechanisms will be different and will be controlled by the rock mass strength and stress redistribution. Numerical models for the JUP are largely uncalibrated. They are used to undertake comparative assessment between different design options, evaluate sensitivity to key parameters and understand the possible extents of deformation, and to better understand potential risks.

Whilst the models are largely uncalibrated, they can be compared to experience from similar mining situations and compared with empirical estimations, analytical models and benchmarks. This is important when analysing and interpreting the model outputs.

5.2 Previous numerical modelling

Numerical modelling has been used for the JUP going back to early studies in 2006 and is summarised in Table 3. The level of confidence and reliability of the inputs (strength properties, stress field, domains, spatial models, etc.) have been systematically improved as more data has been collected, analysed and incorporated into the geotechnical model. Improvements and learnings from each numerical modelling program are taken into the next study stage.

Table 3 Summary of previous numerical modelling for the Jwaneng underground project

Year	Code used	Description of work
2006	Abaqus	The objectives of this analysis were to appreciate the following issues: • conduct a back-analysis of the premier undercut collapse as a test of fitness for the purpose of Abaqus three-dimensional non-linear finite element (3D NL-FE) models • assess the influence of underground mining on the global stability of the pit • assess the deformation at the planned shaft location • provide an initial estimate of deformation in the block cave areas.
2013	FLAC3D	Assessment of the zone of influence (ZOI) assuming block caving across all 3 kimberlite pipes
2021	FLAC3D	Extended concept study modelling program. Assessment to assess the ZOI with an updated (2019) litho-structural model and updated mine designs reflecting SLR, SLC and BC combination
2023	FLAC3D	PFS-A modelling program undertaken to assess ZOI, potential dilution, SLR/SLC drive stability and stability of infrastructure. Updated (2022) litho-structural model and

Year	Code used	Description of work
		updated kimberlite facies domains. Sensitivity analysis undertaken on various stress fields, groundwater inputs and material properties using the shear strength reduction

5.3 Pre-feasibility stage B numerical modelling scope of work

For the JUP Phase 1 mining PFS-B, a decision was made to complement the ongoing FLAC3D (finite volume) (ITASCA 2023) with Abaqus (finite element) numerical modelling as a due diligence cross-check and to ensure we are using all appropriate modelling technology.

The numerical modelling program for the PFS-B was scoped to include the following:

- assessment of different SLR/SLC drive spacing (15, 18 and 21 m) for both Phase 1 and Phase 2 mining, considering both stability and rock flow
- assessment of the BC production level and undercut stability
- extending the height of BC from 170 to 220 m (production level 50 m deeper)
- assess the impact of mining on underground accesses and infrastructure
- dilution assessment and recovery analysis
- kimberlite ground support design
- assess the ZOI and subsidence zone
- various sensitivities (material properties, fault and contact properties, stress field, etc.).

This scope of work allowed for design decisions to be made as part of an iterative design process between the numerical modellers, geotechnical engineers and mining engineers.

5.4 Modelling comparisons

As part of the design study work, comparisons have been made between the FLAC3D and Abaqus approaches and modelling outcomes.

5.4.1 Modelling approach

With FLAC3D a mine-scale model is developed using a hybrid methodology combining FLAC3D and gravity flow using MassFlow (ITASCA 2025), which can capture slope failure progression and stress redistribution affecting underground workings. This approach does not explicitly include the ore drives and underground infrastructure, but it provides the evolution of the mining advance and the emerging slope conditions. The model results from the mine-scale model are then used in a finer zone model (detailed model) adequate to evaluate tunnel closures and induced strains. This represents a multiscale model approach aimed at optimising running times, since the hybrid approach is computationally intensive. A strain softening Hoek–Brown constitutive model (IMASS in Ghazvinian et al. 2020) is used in the analyses.

For the Abaqus modelling, a strain softening dilatant discontinuum finite element model following the Levkovitch Reusch and Flow Slover (LR4-FS4) framework, with a generalised Hoek–Brown yield criterion was used. The LR4 constitutive framework (Levkovitch et al. 2010) is applied to forecast the mechanical behaviour of the rock mass and geological structures. The FS4 flow solver used for the flow simulation is a physics-based particle flow simulation adapted by Beck Engineering for mine-scale flow simulation applications, allowing the evolution of realistic cave phenomena at high resolution (Drover et al. 2022).

5.4.2 Deriving inputs

Both consultancy groups were provided with the same rock mass characterisation and laboratory testing database. This data was used to derive the material properties for the numerical modelling using different approaches.

For the FLAC3D modelling, the intact Hoek-Brown parameters, unconfined compressive strength (σ_{ci}) and the material constant for intact rock (m_i) were estimated from UCS and triaxial compression tests using the Bayesian regression approach (Bozorgzadeh et al. 2018) recommended by Hoek & Brown (2019). A 35th percentile value is typically used to account for rock mass variability and weaker zones, and mean value is used when a shear strength reduction is applied. A more conventional approach was adopted for the Abaqus modelling, and the median values are used for the Hoek–Brown parameters and the other intact properties.

Consequently, slightly different inputs were derived because of the different approaches used. This is not considered a major issue as the consultants are experts in the software they are using, and they understand what inputs work best with the constitutive model being used in their models. Using different methods to derive input parameters is not unique, and many consultants have different approaches. There is no accepted standard industry approach; all is that is required is a reasonable process that is justifiable and auditable.

5.4.3 Initial model and results

The initial modelling commenced with the mine design alternatives developed in the PFS-A. Following the initial modelling, guidance was provided to the mining engineers with respect to SLR/SLC drive spacing, stand-off distances for long-term access infrastructure, extended BC height, and alternative undercut and production level designs for the extended BC, etc. This guidance was then used to develop an updated PFS-B mine design with further refinements part of an ongoing process.

5.4.4 Results comparison

When different numerical modelling approaches are used there will likely be questions around whether the results are comparable. Both consultants were requested to produce plans and sections (20 m ahead of faces) for specific mining levels and quarterly mining steps for the following outputs:

- major principal stress (σ_1)
- minor principal stress (σ_3)
- plastic strains.

The stress field, litho-structural models and mining geometry were the same. These were then systematically compared with each other. The expectations were that modelled stress levels would be similar and of the same order of magnitude, although some differences in plastic strains were expected due to different constitutive models and slightly different material input properties.

It was expected that there would be small differences in the modelled stresses due to the following factors:

- slightly different input of the extraction sequence
- mesh sizes and density in the model
- differences in contouring algorithms and settings.

These comparisons indicated that the modelled stress levels between the FLAC3D and Abaqus models were similar as expected, as shown by examples in Figures 3 and 4. Differences were observed for plastic strain between the FLAC3D and Abaqus models, with higher plastic strains observed in the Abaqus models as shown by the example in Figure 5. Generally, the plastic strains were less than 3%, with localised areas of higher strain for the uncalibrated models.

From both models it was concluded that induced stresses are insignificant for Phase 1 mining, although they do increase with depth, potentially becoming an issue in the deeper part of Phase 2 mining. A similar trend is seen with plastic strain, which increases in response to increasing stresses with depth.

The ZOI predictions from both models were also compared and they are similar and largely constrained to the open pit due to the very competent DM surrounding the kimberlite pipes at depth. The FLAC3D prediction extends a distance beyond the open pit crest, but this is largely due to a shear strength reduction (SSR) = 1.5 being applied, whereas it was not applied in the Abaqus model.

From this analysis it was concluded that whilst there were differences in the modelling approach, constitutive models and derived input parameters for the FLAC3D and Abaqus models, they were comparable and similar conclusions could be drawn from the results.

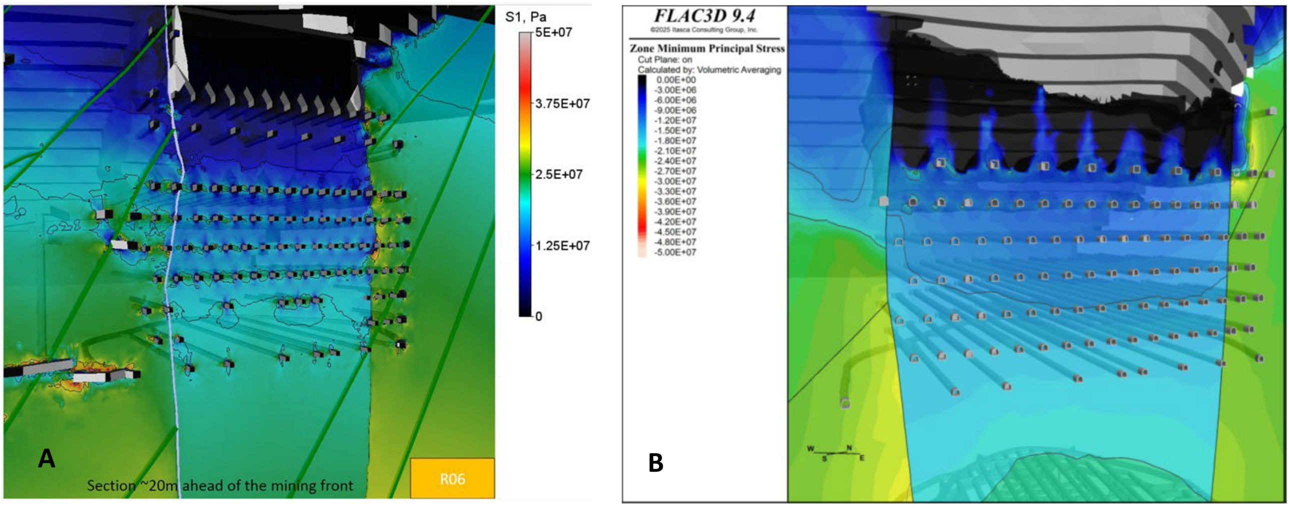

Figure 3 Principal stress sections (north pipe – Y2038-Q3 [18 m]). (a) Abaqus; (b) FLAC3D

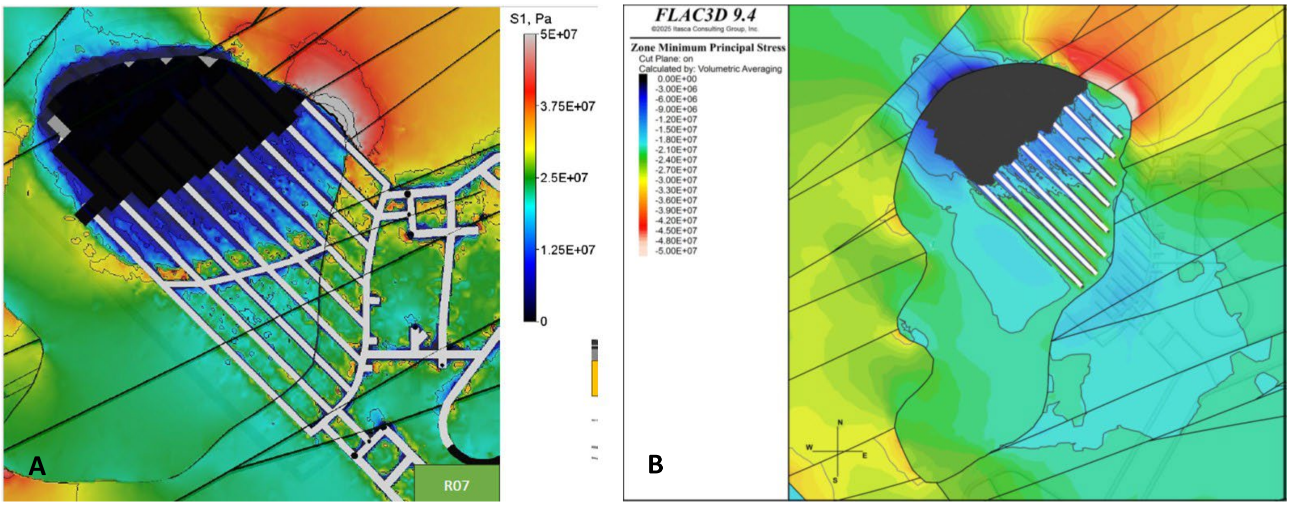

Figure 4 Principal stress sections plan (centre pipe [L300] – Y2027-Q2 ([21 m]). (a) Abaqus; (b) FLAC3D

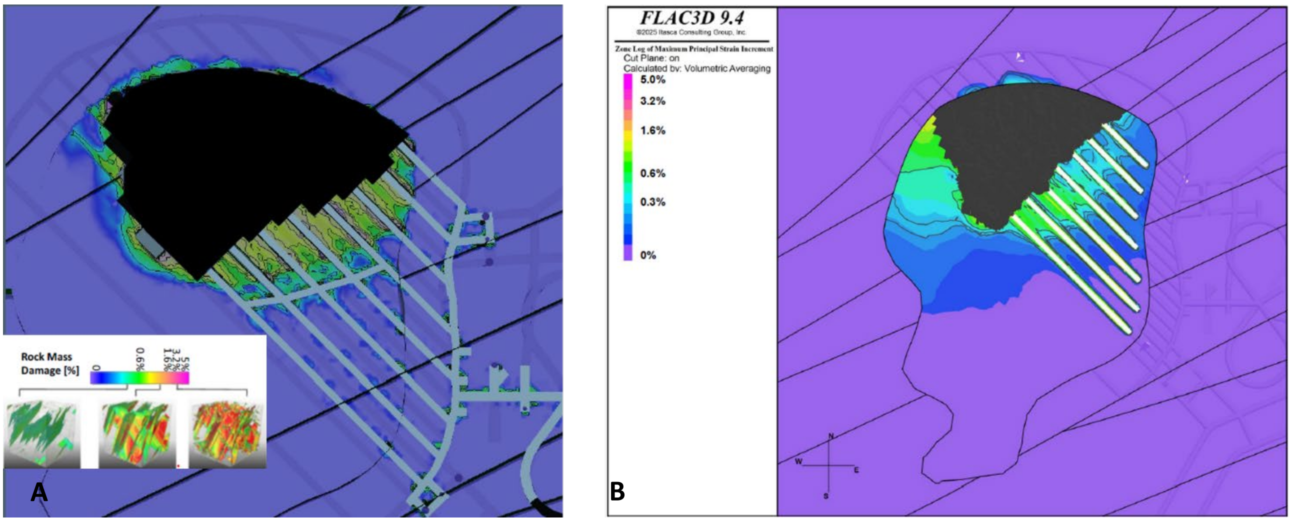

Figure 5 Plastic strains plan (centre pipe [L200] – Y2040-Q4). (a) Abaqus; (b) FLAC3D

5.5 Sensitivity analysis

Several sensitivity analyses were undertaken as part of the PFS-B design process. This is in addition to the various sensitivities on the stress field that were undertaken in the 2023 studies. The sensitivities were undertaken in response to questions raised by the GRB and to understand what impacts drive stability within the kimberlite pipes and larger-scale deformations (ZOI). Sensitivities are also used to better understand uncertainties in the model inputs (geotechnical model) and pose 'what if' questions.

The shear strengths on the major faults were varied and increased, as was the kimberlite contact strength, to understand what impact this has on the transfer of stress into the pipes. Kimberlite properties (m_i, E_i and strength) were all varied to assess the impact on drive closure and stability.

In FLAC3D, the sensitivities were evaluated by coupling a mine-scale model to a sub-model to assess the impacts. In Abaqus, the sensitivities were undertaken using mine-scale models. Table 4 is a summary of the sensitivities undertaken for the current study.

Table 4 Summary of sensitivity analysis options

FLAC3D	Abaqus
Variable fault strength	Reduced geological strength index values for kimberlite
Increased kimberlite contact strength	Variable uniaxial compressive strength for kimberlite based on density block model, i.e. density used a proxy
VK(C) m_i reduced to 5 from 7	Increased maximum horizontal stress to 1.3
Elastic modulus (E_i) (30%reduction)	Increased kimberlite contacts and variable fault shear strengths
SSR = 1.3 on kimberlite strength (strength reduction)	
More brittle post-peak response produced by halving the critical strain (eps_crit)	

Whilst changes were observed in all models (as expected) for the various sensitivity analyses, some of the changes were minor and not considered significant. For increased fault shear and kimberlite contact shear strengths, both models showed increased transfer of stress, but this did not have a significant impact on SLC drive stability or the ZOI.

Sensitivities for m_i and E_i indicated a moderate impact with more small increases in modelled deformation (higher closures) for the SLC drives. Reducing E_i has more impact on SLC drives than m_i. The largest impact on SLC drive stability was due to the reduction in rock mass strength by applying a SSR = 1.3 and by reducing the post-peak critical strain (Alvarez et al. 2026).

The various sensitivity studies undertaken in the PFS-A and in the current PFS-B have been useful to understand what inputs are more critical, and to better understand the impact of uncertainty on mine designs and thus plan future work accordingly.

6 Conclusion

Numerical modelling has been applied as a design on the Jwaneng underground mine studies since 2006. The numerical modelling is used to guide and assess mine designs. The JUP is in a study phase, so the models are largely uncalibrated, but they are extremely useful to compare design options, and to assess impacts and potential risks. Results from the numerical modelling have been used to make key design decisions such as oredrive spacing, extending the BC height and BC production level layout.

For the PFS-B a decision was made to use 2 numerical modelling consultants applying different codes (FLAC3D and Abaqus) and approaches. It was accepted that there would likely be some differences in the results. The results were compared and it was found that the modelled stresses were similar and comparable. There were some differences in the modelled plastic strains, driven by differences in how inputs are derived and the different constitutive models used. Overall, the same trends could be identified and both approaches were useful in guiding design decisions for the study.

Sensitivity studies are used to understand what impacts both drive scale and mine-scale stability. These allow for a better understanding of uncertainty in the geotechnical model and the impact this has the mine design. Sensitivity analysis allows for 'what if' scenarios to be assessed so that we better understand where to focus our data collection and analysis efforts.

The sensitivity analyses confirmed that small changes in m_i had a minor impact on drive deformation and that reducing elastic modulus had a larger impact. Variable fault shear strength and increased kimberlite contact strength resulted in increased transfer of stress, but this did not have a significant impact on the drive stability or the ZOI. The largest impacts were for reduced rock mass strength and reduced post-peak critical strain. Further work is required in evaluating the post-peak critical strain properties.

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