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Ground support in kimberlite: design and implementation challenges

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Abstract

The Jwaneng mine is a large open pit diamond mine extracting 3 kimberlite pipes. Studies are underway to transition to an underground operation by the time open pit mining ceases. Underground mining will be done using a combination of blasthole open stoping and sublevel retreat, sublevel caving and block caving mining methods. All these mining methods require significant tunnel development within the kimberlite pipes.

Kimberlites are highly variable and can range from competent to very weak rocks depending on the facies. The kimberlite rocks in this study have intact strengths in the 20 to 60 MPa range; there are also kimberlite breccias which have a kimberlite matrix and country rock clasts in varying proportions and have highly variable intact strength.

Kimberlites and kimberlite breccias rock masses are extremely difficult to classify using widely used classification systems such as the Bieniawski (1989) rock mass rating (RMR_{89}) system, Q-system (Barton et al. 1974) and geological strength index (GSI) (Hoek 1994). This is typically due to the absence of open joints resulting in high rock mass ratings, whilst for the breccias, the high variability between matrix and clasts is problematic. The kimberlites have swelling clays (smectite) present in varying proportions depending on the facies. An increase in the smectite proportion increases the weatherability and swelling potential (squeezing ground) in the kimberlites. Underground mining will cause stress changes on the kimberlite tunnels resulting in ongoing deformation. These issues present both design (characterisation and classification) and implementation challenges such as ongoing deterioration and the need for thin skin liners (Bartlett & Nesbitt 2000).

Ground support practices at other kimberlite underground mines in South Africa, Canada and Australia have been reviewed as part of the design process. A combination of mine experience (precedent), empirical methods, and numerical modelling were used to assess ground support requirements. An attempt to account for swelling (squeezing) ground was made by adjusting the stress reduction factor (SRF) in the Q-system. Numerical modelling was used to assess likely deformation of the kimberlite tunnels and the required ground support load.

Keywords: *Kimberlite, ground support design, characterisation, swelling clays, squeezing ground*

1 Introduction

The Debswana Diamond Company Jwaneng mine is situated approximately 160 km west of the capital city of Gaborone in Botswana. It is a large open pit diamond mine extracting 3 kimberlite pipes. Open pit operations will cease in about 2036. Studies are currently underway to transition to an underground mining operation by the time open pit mining ceases; this is known as the Jwaneng Underground Project. 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 (CR) and weak kimberlite rock.

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The Jwaneng mine CR stratigraphy comprises Paleoproterozoic sedimentary rocks of the Pretoria Group within the Transvaal Supergroup. The upper-most stratigraphic units are the aeolian Kalahari Sands, as well as pedogenic calcretes (CALC). These units are underlain by various formations, comprising of a complex assemblage or mixture of laminated shales (LS) carbonaceous shales, 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 CR geology is further described in Dunn et al. (2022).

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 CR are typically 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 kimberlite (PK) and volcaniclastic units preserved in the north pipe. There are also several breccias in the centre pipe (Dunn et al. 2022).

The north pipe facies within the underground horizon are the VK(N) and the 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 CR 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%).

The Jwaneng mine structural setting is complex, and the litho-structural model is updated as new information becomes available. The most recent update was done in late 2025. There are 160 faults in the 2025 update of the litho-structural model.

The CR 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 geotechnical setting and stress regime are described in Dunn & Kebatsetse (2024).

2 Challenges with kimberlite

Kimberlite is an igneous rock, a rare variant of peridotite, and is mostly known as the main host matrix for diamonds. They are essentially volcanoes and they mostly occur as pipes with the characteristic carrot shape; there are more irregular shapes and dykes and sills.

There are different types of kimberlite or facies, and these are associated with different styles of magmatic activity. They are quite variable in mineralogy and physical properties. There are also kimberlite breccias with varying proportions of kimberlite matrix with CR.

There are external contacts between kimberlite and CR and internal contacts between different kimberlite and breccia facies. The contacts are also variable and are zones of weakness and external contacts are often associated with water.

Kimberlite rocks and associated breccias at Jwaneng mine pose various challenges from a geotechnical and mining perspective. This is also true of kimberlites at other diamond mines.

2.1 Variable strength

Kimberlites have a varied mineralogical makeup and consequently they have a variable intact strength. Figure 1 shows uniaxial compressive strength (UCS) data from several kimberlite mines globally. The Jwaneng data is shown in red. There are variations between different types of kimberlites and considerable variations within each type. The average UCS values of the Jwaneng kimberlite rage from 20 to 60 MPa. This will present challenges at mining depths up to 1,000 m.

Some kimberlites are sensitive to water, and care needs to be taken when sampling and in preserving the samples. The preservation of samples is important to prevent degradation (drying out or being exposed to additional water) and preserving the in situ moisture contact for laboratory testing.

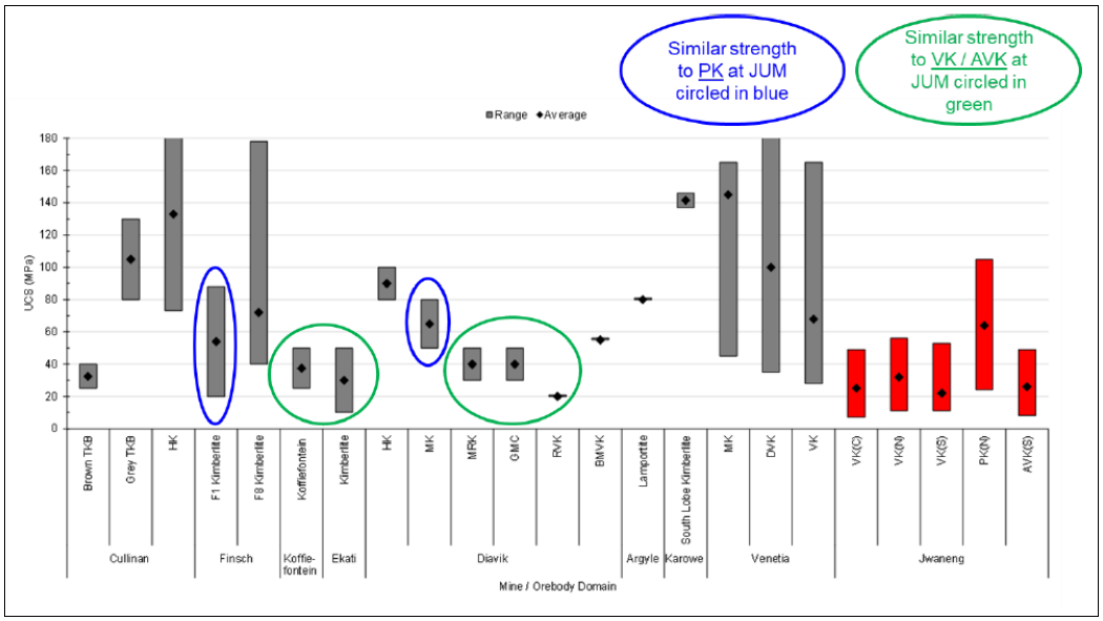


Figure 1 Kimberlite uniaxial compressive strength (UCS) comparisons

Breccias also have highly variable UCS and are difficult to sample; either you are sampling the kimberlite matrix (low strength) or CR clasts which could have a high UCS. Consequentially, the laboratory UCS results are highly variable. There are scale issues and ideally you need larger samples to capture both matrix and CR clasts, which is not practical. Any failures during laboratory testing would likely occur through the weaker material. A synthetic rock mass approach has been used to model UCS tests for the breccias. The inputs are based on the understanding of the kimberlite and CR clast intact properties and the relative proportions of these in different types of breccia.

2.2 Rock mass characterisation and classification

Kimberlites and kimberlite breccia can be difficult to characterise and classify using common rock mass classification system such as Bieniawski (1989) rock mass rating system (RMR_{89}), the Q-system (Barton et al. 1974; NGI 2025) and the geological strength index (GSI) (Hoek 1994; Hoek & Brown 1997) etc. At Jwaneng a version of GSI developed by SRK Consulting (GSI_{SRK}) is used. The GSI_{SRK} estimation is based on the use of the Laubscher (1990) rock mass rating system (RMR_{90}) fracture frequency (FF) and joint condition ratings, each with a maximum of 40 points (Contreras 2012). These systems are focused on assessing the conditions of open joints.

There are generally very few open joints observed in the kimberlite core at Jwaneng, and low FF and high rock quality designation (RQD) (Deere 1964) are typically recorded, as shown in Figure 2. This results in relatively high rock mass classification falling in the fair to good rock mass classes based on several classification systems. This is different to field exposures in the open pit where joints are observed in the kimberlite (Figure 3).

With the breccias, the issue is the degree of variability, with the kimberlite matrix in the fair to good rock mass classes and the CR clast often falling in the good rock mass class. Behaviour will be controlled by the weak kimberlite matrix. Approaches such block-in-matrix (Bimrocks) as described by Medley (1994) have been assessed, and work on improving the characterisation and classification of breccias is ongoing.

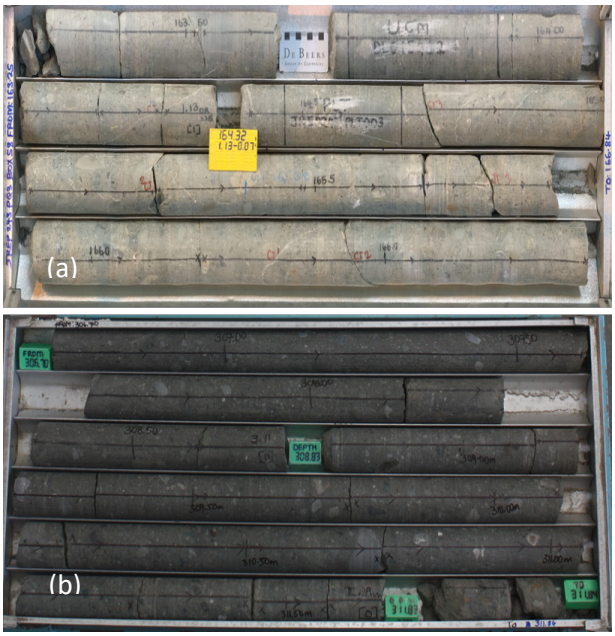


Figure 2 Core photos of typical (a) volcaniclastic kimberlites and (b) autolithic volcaniclastic kimberlites showing few open joints, high rock quality designation, and low fracture frequency

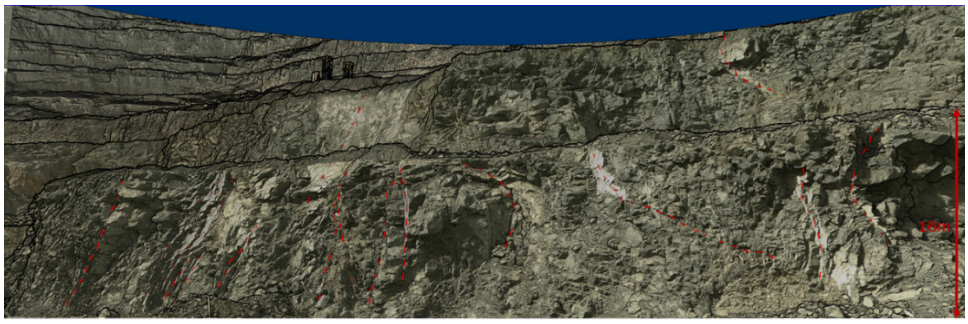


Figure 3 Open pit kimberlite exposure with joints

Table 1 is a summary of the UCS, elastic modulus (E_i) and various rock mass classification indices for kimberlite and kimberlite breccia facies at Jwaneng mine.

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

Rock type	UCS (MPa)	E_i (GPa)	RMR_{89}	RMR_{90}	GSI_{SRK}	Q'	Rock mass class
VK(C)	31	6	73	64	74	7.1	Fair–good
VK(N)	40	7	69	63	73	4.0	Fair–good
VK(S)	26	8	73	64	74	6.1	Fair–good
PK(N)	59	11	73	65	74	7.5	Fair–good
AVK(S)	28	18	75	66	75	14.4	Fair–good
CRBDM(C)	96	46	81	73	74	25.7	Good
CRBQS(C)	87	37	64	42	43	15.5	Good
KBWDM(C)	20	11	78	64	69	21.4	Good

UCS = uniaxial compressive strength; E_i = intact elastic modulus; RMR_{89} = Bieniawski (1989) rock mass rating system; RMR_{90} = Laubscher (1990) rock mass rating system; Q' = Q-system; GSI_{SRK} = geological strength index adapted by SRK.

2.3 Swelling clays

Clay minerals from the breakdown of serpentine and other silicate minerals in the presence of water and aqueous solutions (Bartlett & Nesbitt 2000) form in the kimberlite. Some of these are swelling clays (smectite group) and are present in various proportions in different kimberlite facies.

The swelling clays pose significant engineering challenges because of their ability to absorb water and expand, generating high swelling pressures, rapid strength loss, and structural degradation. Morkel (2006) found that increasing smectite content increases weatherability. The presence of swelling clays (Kebatsetse et al. 2026) presents the following challenges for SLC and BC mining:

- squeezing ground when exposed to water
- time dependent deterioration of the rock mass
- weak rock mass due to presence of clays
- drilling difficulties in squeezing ground
- 'sticky' ore which can cause hang-ups in ore passes and difficulties on conveyors
- secondary fragmentation effects with more fines being produced
- the increased potential for fines generation increases the mud rush risk.

Testing at the Council for scientific and Industrial Research (CSIR) of the Cullinan kimberlite showed that swelling in kimberlite could result in swelling pressures in the order of 30 MPa (Bartlett & Nesbitt 2000). Borejszo & Bartlett (2002) state that volume changes of as much as 18% have been measured as the kimberlite is saturated with water.

At Jwaneng, work has been ongoing in assessing the proportions of swelling clays in the various kimberlite facies. X-ray diffraction (XRD) analysis is used to identify the percentage of smectite group clays within the kimberlite facies samples. It has been proposed that hyperspectral scanning be used to obtain a continuous record of the smectite content, as opposed to point data.

In addition, several standard durability tests are undertaken, these include the field weathering test, slake durability index, accelerated weathering index and Duncan swell index. Results from these tests have been compared to the smectite percentage results obtained from the XRD analysis.

Kebatsetse et al. (2026) draw the following conclusions from this analysis:

- swelling clay content is highest in the AVK(S) and lowest in the PK(N) with trace amounts in the breccias
- the general smectite trend is: AVK(S) > VK(S) > VK(C) > VK(N) > PK(N)
- the smectite content correlates with the various durability indices, i.e. high smectite content relates to low durability as well increased weatherising and swelling potential.

These conclusions align with the Morkel (2006) findings that the increased smectite content results in increased weatherability (loss of durability). Understanding the swelling clay proportions and spatial distribution is important for ground support design, scheduling and rehabilitation planning. It is also a valuable input into fragmentation assessments and for assessing mud rush potential and vulnerability.

2.4 Water sensitive

Kimberlites can be very sensitive to water due to the high clay content. This has implications for the following:

- core drilling: core deterioration and hole squeezing
- sampling from core drilling and sample preservation
- underground production drilling: dry drilling needed, but it creates dust issues

- ground support issues such as shotcrete adherence, grouts etc
- need for a thin skin liner (TSL) in high smectite content kimberlites to prevent exposure to water.

There are several sources of water that can impact the kimberlite:

- groundwater within the rock mass and on geological structures
- ingress of water from surface through shafts portals and open pit / underground mine interaction
- water from underground production activities
- humidity.

Wilson et al. (2007) note that 'weathering' degradation of the tunnel rock surface appears to be greatly exacerbated in the presence of free water and that even under apparently 'dry' conditions, degradation from humidity continues to occur albeit at a slower rate. Figure 4 shows clay rich kimberlite core that has been exposed to water.



Figure 4 Degradation smectite rich kimberlite exposed to water

It is common to encounter water on the kimberlite–country rock contacts, and these should be targeted for dewatering. Morton (2022) highlights the importance of understanding sources of water and flows paths, and the need for early dewatering in underground kimberlite mines. Management of surface water and underground groundwater inflows is critical for underground mining in kimberlite. It is necessary to manage the water associated with production activities. This means limiting the amount of water used and maintaining effective drainage so that ponding on the floor is avoided etc.

Water has the effect of degrading the rock mass and influences stability, caving and ground support design. It is important to account for both the current and future groundwater conditions when using classification systems such as Q, RMR_{89} and the Laubscher (1990) mining rock mass rating (MRMR) for ground support design.

3 Ground support design

Aspects pertaining to the ground support design in kimberlite are outlined in subsequent sections with specific consideration of the Jwaneng underground mine.

3.1 Ground support requirements and considerations

Bull & Page (2000), state that the ground support for SLC production tunnels has 2 primary functions: (1) to protect personnel and equipment and (2) to provide support of the brow to facilitate optimum operating conditions (draw profile and access for charging). The ground support must work when the brow has freedom to move and must resist strong blasting disturbance (Laubscher et al. 2017).

For BC ground support, it is necessary to cater for the undercut, production level tunnels and drawpoints. The service life of the BC production level tunnels and drawpoints is considerably longer than for SLR and SLC tunnels. Protection of drawpoint corners is important and heavy rigid ground support is needed at drawpoint brows (Laubscher et al. 2017).

Ground support design in the Jwaneng kimberlite will need to consider:

- SLR / SLC and BC mining
- changing stress conditions and high stress in BC
- weak rock mass with low intact strength and mining of ~25 MPa kimberlite at up 1,000 m depth
- presence of swelling clays:
    - weatherability and degradation when exposed to water
    - squeezing (chemical) behaviour.
- very poor conditions expected at contacts (internal and external)
- sensitive to water (dry production drilling, water management etc).

3.2 Design approach

A multifaceted approach has been adopted for the design of the ground support in kimberlite that considers:

- precedent (experience from other kimberlite mines)
- empirical methods
- numerical modelling.

There is a strong emphasis on developing ground support designs that are practical and have worked under similar rock mass and loading condition to those expected at Jwaneng underground mine.

Whilst various design methods were considered, they typically consider the rock mass conditions expected and deformations that will likely results from mining-induced stress changes. None of the design methods explicitly consider the squeezing behaviour that is associated with swelling clays.

3.2.1 Precedent

During the earlier studies kimberlite ground support patterns for 3 types of ground conditions:

- Type 1: PK(N) and Breccias (poor to fair)
- Type 2: VK and AVK (poor to very poor)
- Type 3: contacts (very poor).

The conditions or rock mass classes listed above are lower than those in Table 1 as they have been downgraded to account for water and stress influences, as well as kimberlite conditions observed in the Jwaneng open pit.

When initially defining the ground support patterns for kimberlite, the following additional aspects were considered:

- simplicity – the system should be based on a few elements (based on resin bolts, cable bolts, fibre reinforced shotcrete [FRS], mesh and straps)
- TSL required on kimberlite with high smectite content
- spiling may be required on some contacts (needed at other sites)
- shotcrete arches are also a possibility in some conditions.

From initial benchmarking, ground support systems that had been successfully implemented at several South African, Canadian and Australian SLC and BC diamond mines were identified. Two ground support approaches were considered; one was a FRS based approach used on Canadian mines (Ekati and Diavik); the other was mesh based as used on several South African mines (Finch, Cullinan and Venetia). There was considerable overlap between the 2 approaches.

Both approaches had been successfully applied (trial and error) and in many cases the choice of which system was applied came down to preferences and mine site constraints. The basis of design and design methodology used in deriving the ground support systems was not well documented in the literature.

3.2.2 Empirical

Several empirical systems were applied in assessing the proposed ground support and these included the Q-system and the RMR_{89} system. The Q-system is widely used in ground support design in mining and civil tunnels, although it should be noted the database on which it is based is predominantly in civil applications, and does not explicitly include kimberlites; however, the Q-system does include weak rock masses.

The RMR system has been used for excavation and ground support design and has been extensively used in weak rock masses in Nevada. The MRMR system has been used in many underground mining projects including kimberlite mines. Laubscher (2000) outlines a range of ground support patterns for different conditions in cave mining.

The Q-system allows potential swelling behaviour to be accounted for the application of the stress reduction factor (SRF). A SRF of 7.5 (moderate swelling pressure) was applied and this reduces the Q-rating value and rock mass class (very poor for swelling units). A joint water rating of 0.66 (medium inflow) was also applied to account for the effect of water on kimberlite. The design is based on 25^{th} percentile (P25) Q-value but other values were considered; precedent was also considered. There was a reasonable correlation between the Q-system ground support requirements and the proposed ground support.

3.2.3 Numerical modelling

Both simple 2D finite element modelling and advanced 3D numerical modelling were considered in the ground support design. The approach was to assess the possible performance of the proposed ground support. The modelling did not include mesh but focused on FRS, resin bolts and cable bolts.

3.2.3.1 RS2 modelling

The RS2 (Rocscience 2023) finite element code was used to model ground support in AVK(S), the weakest kimberlite (SRK 2024). The model considered 4.5 by 4.5 m tunnels spaced 13.5 m part skin to skin. The ground support was modelled as follows:

- Rockbolts were modelled as bolts that are fully grouted and bonded over their full length.
- Cable bolts were modelled as fully bonded plain strand cables.
- FRS was modelled as a reinforced concrete liner with a UCS of 40 MPa at 28 days.

No bolts yielded and the maximum axial force in any bolt was below yield capacity at 160 kN, while the resin grout annulus around bolts only yielded locally in some places. The fibrecrete liner did not show yielding, and the models do not show stability issues in the rock pillar between the 2 kimberlite drives.

It should be note that this was preliminary modelling and did not consider the full loading cycle associated with SLC mining. The modelling was done to gain some understanding of how numerical modelling could assist in the design of ground support in kimberlite.

3.2.3.2 FLAC3D

Subsequently, the proposed ground support was modelled by Itasca Consulting using FLAC3D (ITASCA 2023). Sub-models were used to explicitly model 2 ground support patterns in SLC tunnels in 2 types of kimberlites. It was assumed that a TSL would be applied and swelling behaviour would likely be limited (Alvarez et al 2026).

The following simplified ground support was modelled:

- Type 1: 50 mm FRS and 1.2 × 1.2 m Bolts (2.4 m)
- Type 2: 100 mm FRS, 1.0 × 1.0 m Bolts (2.4 m) and 7 cable bolts (4.5 m and 17.8 mm diameter) per ring

The FRS is modelled by non-linear shell elements. Behaviour in tension is strain softening based on fibre properties. Connections to the rock is assumed to be rigid. Resin bolts and cable bolts are modelled as cable elements (only axial strength) and are considered as passive support. In this type of elements, failure in grout/rock interface is allowed. The Type 1 support was modelled in the north pipe at the 350 level. Type 2 support was modelled in the centre pipe VK which was weaker and at great depth at the 150 level. The depth difference between the north pipe and centre pipe tunnels was 200 m.

For the rockbolts and cable bolts the utilisation ratio (force/ yield force) and plastic strain were used as evaluation criteria. In the case of shotcrete (FRS), 3 stages were defined according to the evolution of the stress versus tensile strain curve corresponding to serviceability, cracking formation and rehabilitation.

The ground support performance was based on the relatively short life of the SLC tunnels and support yielding is allowed if the ultimate strain limits are not reached. In the north pipe with Type 1 support only limited bolt yielding (10%) was noted with minimal damage to the FRS. In the centre pipe with Type 2 support there was increased bolt yielding (70%) and some damage to the FRS.

The modelling has captured differences in the performance of different ground support types for different kimberlites and at different depths. These initial results are promising and provides an indication of how the ground support patterns will perform. This approach does not account for the squeezing behaviour that is likely due to the presence of swelling clays.

3.2.3.3 Abaqus modelling

Ground support modelling was also undertaken by Beck Engineering using Abaqus (Dehkhoda 2026). Sub-models were used to evaluate ground support for SLC and BC mining. The analyses focus on the weakest kimberlite domains, namely VK(S) for the SLC at 250 level and VK(N) for the block cave at 100 level, together with the kimberlite–country rock contact, where the highest support demands are anticipated.

The ground support modelled was as follows:

- SLC: 50 mm FRS, Mesh, 50 mm FRS over the mesh a with 2.4 m resin bolts on 1.0 m spacing with 7 cable bolts (4.5 m and 17.8 mm diameter) per ring
- BC: 50 mm FRS, Mesh, 50 mm FRS over the mesh a with 2.4 m resin bolts on 1.0 m spacing with 7 cable bolts (6.0 m and 17.8 mm diameter) per ring.

Rockbolts and cable bolts were explicitly built into the sub-model as ‘beam elements’ with elastoplastic properties. Mesh and fibrecrete are modelled as shell elements and as one compound with homogenised elastoplastic properties. The thickness of the shell is selected based on the fibrecrete thickness and the shell properties were selected based on the combined mesh–fibrecrete system response (Dehkhoda 2026).

Accumulated axial strain in the rockbolts and cable bolts resulting from mining-induced ground deformation within the SLC and BC work areas was assessed. Damage to the surface support (fibrecrete and mesh composite) was assessed using the maximum in-plane principal strain within the excavation shell.

As mining progresses in the SLC work areas, excavation closure and rock mass deformation mobilise axial loading within the support elements. Localised zones of elevated strain develop where shear bands form due to stress relaxation and interaction between adjacent mining levels. The magnitude of rockbolt and cable bolt deformation increase as the mining front approaches and the depth of the yielded rock mass increases.

Within the block cave production areas, the rockbolts and cable bolts become progressively mobilised as mining advances and ground deformation develops around the extraction level. The highest axial strains are concentrated at excavation intersections and in areas adjacent to the kimberlite contacts, where stress redistribution and differential ground movement are greatest.

Overall, the modelling indicates that the surface support experiences moderate damage at approximately 25–75 mm of closure and significant damage at closures of approximately 75–135 mm. These deformation thresholds provide guidance for planning inspections, rehabilitation and replacement of surface support during mine operations (Dehkhoda 2026).

4 Ground support implementation challenges

There are a range of implementation challenges that need to be considered when designing ground support in kimberlite tunnels.

- Smaller tunnels (4.5 by 4.5 m) are used to assist with stability, and this requires smaller equipment.
- Applying TSL in smectite rich kimberlite – this requires relatively small volumes and needs to be integrated with FRS equipment.
- FRS fibres ending up in kimberlite ore causing processing issues.
- How much squeezing will occur and the need for serviceability criteria:
    - not necessarily an issue in SLR /SLC drives which have a limited life
    - will be an issue in BC extraction level and rehabilitation will likely be needed.
- Advance must be limited and this impacts the development schedule:
    - 3 m per blast in fair ground conditions
    - 2 m or less in very poor ground conditions.

Extensive ground support is needed, this means slow cycle times; typically, the following applies:

- scale
- apply TSL
- apply FRS / Mesh
- install resin bolts / straps
- install cable bolts.

The ground support cycle is even slower if spiling or shotcrete arches are needed. Understanding smectite proportions and spatial distribution has an impact on advance rates, scheduling and for estimating ground support costs.

Many diamond mines have downscaled or closed and the number of experienced people available with kimberlite development experience has reduced. This skills gap needs to be considered in the development

schedule and needs to be mitigated by appropriate training and user-friendly grounds support patterns and cycles that are not overly complicated.

5 Ground support practices on underground kimberlite mines

Ground support practices at various kimberlite SLR, SLC and BC mines were reviewed. The examples which follow are primarily focused on SLR and SLC. Similar ground support patterns would be used in a BC undercut, but ground support would be upgraded for a BC production or extraction level and would include thicker FRS, mesh, strapping of drawpoint corners and longer (6.0 m) cable bolts.

5.1 Canada

Typical ground support in Canadian kimberlite underground mines is summarised in Table 2 (Jakubec et al. 2024). Burns (2023) outlines ground support used at Diavik for open stoping; instead of resin bolts, 2.4 m PM12 Swellex bolts are used, and mesh is limited to the backs with 50 mm of shotcrete applied on the walls and shoulders. In some areas this was upgraded to 2.4 m PM24 Swellex and an additional 50 mm of shotcrete was applied over the mesh installed in the backs.

Table 2 Example ground support patterns used on Canadian sublevel caving (SLC) kimberlite mines

Ground support (GS) type	GS layer	Canada – SLC ground support patterns		
		Surface support	**Bolt type**	**Bolt spacing (m)**
Type 1: PK and Breccia (poor to fair)	1	50 mm FRS (40 MPa) applied floor-floor	2.4 m resin bolts (22 mm diameter)	1.2 by 1.2 m
Type 2: VK and AVK (poor to very poor)	1	TSL and 50 mm FRS (40 MPa) applied floor-to-floor		
	2	Weld mesh applied floor-to-floor (5.6 mm strand)	2.4 m resin bolts (22 mm diameter)	1 by 1 m
	3	50 mm FRS (40 MPa) applied floor-to-floor	4.5 m single strand cable bolt (17.8 mm)	7 per ring; rings 2 m apart. 3 cables in back and 2 in each sidewall
Type 3: contacts (poor to very poor)	1	50 mm FRS (40 MPa) applied floor-to-floor		
	2	Weld mesh applied floor-to-floor (5.6 mm strand)	2.4 m resin bolts (22 mm diameter)	1 by 1 m
	3	50 mm FRS (40 MPa) applied floor-to-floor with Osro straps	6.0 m single strand cable bolts (17.8 mm)	7 per ring; rings 2 m apart. 3 in back and 2 in each sidewall

5.2 South Africa

The approach in South African kimberlite underground mines was different with weld mesh being used as the surface support and shotcrete applied from the floor to 1.8 m above the floor to protect the mesh from loader damage. Typical ground support in South African kimberlite underground mines is summarised in Table 3.

Table 3 Example ground support patterns used on South African sublevel caving (SLC) kimberlite mines

Ground support (GS) type	GS layer	South Africa – SLC ground support patterns		
		Surface support	**Bolt type**	**Bolt spacing (m)**
Type 1: PK and Breccia (poor to fair)	1	Weld mesh applied to 0.4 m above floor (5.6 mm strand)	2.4 m resin bolts (22 mm diameter)	1.2 m by 1.2 m
	2	6 m traverse tendon straps	4.5 m single strand cable bolt (17.8 mm)	5 per ring; 3 cables in back and 1 in each sidewall
	3	50 mm shotcrete applied to 1.8 m above floor		
Type 2: VK and AVK (poor to very poor)	1	5 mm TSL and 50 mm FRS applied floor-to-floor		
	2	Weld mesh applied floor-to-floor (5.6 mm strand)	2.4 m resin bolts (22 mm diameter)	1 m by 1 m
	3	50 mm Shotcrete applied to 1.8 m above floor	4.5 m single strand cable bolt (17.8 mm)	7 per ring; rings 2 m apart. 3 cables in back and 2 in each sidewall
Type 3: contacts (poor to very poor)	1	5 mm TSL and weld mesh applied to 0.4 m above floor (5.6 mm strand)	2.4 m resin bolts (22 mm diameter)	1 m by 1 m
	2	6 m traverse tendon straps	4.5 m Single strand cable bolt (17.8 mm)	5 per ring; 3 cables in back and 1 in each sidewall
	3	50 mm shotcrete applied to 1.8 m above floor		

5.3 Australia

Fernandez et al. (2011) outline how squeezing ground was managed at the Argyle Diamond Mine (ADM), a BC in Western Australia. Table 4 is a summary of the ground support patterns for different rock mass conditions in 4.4 by 4.4 m tunnels. These ground support patterns are supplemented by 6.0 m cable bolts and Osro straps when deemed necessary

Table 4 Ground support patterns at Argyle Diamond Mine (after Fernandez et al. 2011)

Regular support	Medium support	Heavy support
Fibrecrete: First pass: 50 m thick, sprayed from floor-to-floor	Fibrecrete: First pass: 50 m thick, sprayed from floor-to-floor	Fibrecrete: First pass: 50 m thick, sprayed from floor-to-floor Second Pass: 50 mm thick, sprayed on walls (to cover mesh and bolts' plates) up to 2 m height
Bolts (fully encapsulated): • 9 bolts × 2.1 m long, resin bolts per ring at 1.2 m spacing • ring spacing: 1.4 m	Bolts (fully encapsulated): • 9 bolts × 2.1 m long, resin bolts per ring at 1.2 m spacing • ring spacing: 1.4 m • Mesh: installed from shoulder to shoulder	Bolts (fully encapsulated): • 9 bolts × 2.1 m long, resin bolts per ring at 1.2 m spacing • ring spacing: 1.4 m • Mesh: installed from shoulder to shoulder

5.4 Ground support comparisons

There are similarities in the ground support patterns used in Australia, Canada and South African diamond mines. Resin bolts are generally used, but at Argyle they used a 2.1 m bolt instead of a 2.4 m bolt. In some situations at Diavik (Canada), Swellex bolts were used. Bolt spacing is similar across all 3 regions.

The Canadian and South African practice is to use cable bolts (4.5 and 6.0 m) routinely, whilst it appears cable bolts are additional at ADM. The use of Osro straps appears to be common across all 3 regions.

The largest difference was in the surface support used:

- In Canada and Australia there seems to be a preference for shotcrete (FRS) – mesh–FRS sandwich approach.
- In South Africa, mesh appears to be the dominant surface support with shotcrete applied to protect the mesh.
- TSL are used in kimberlites with high smectite content.

For the Jwaneng underground mine, a decision has been made to consider both the Canadian and South African approaches during the pre-feasibility study and the cost of both options. Both approaches have been successfully applied, and it is likely that elements of both will be incorporated into the feasibility ground support patterns. Ultimately, underground trials will determine what is most appropriate for the Jwaneng underground mine ground conditions and practical constraints, and will allow for calibration of the design methods.

6 Conclusions

Kimberlites are a challenging rock mass to deal with in SLC and BC mining and the associated stress changes. They have variable strength and can have low strength. The presence of swelling clays in various proportions means they degrade or weather easily and have significant volume changes when exposed to water resulting in squeeing behaviour. They are difficult to sample and characterise and rock mass classification is challenging. These challenges result in difficulties in ground support design as well as implementation challenges.

A multifaceted design approach has been adopted that is based on benchmarking. Empirical methods and numerical modelling have been used to assess the proposed ground support patterns. The initial outcomes from numerical modelling are encouraging. A limitation of these methods is their inability to adequately account for the swelling clay behaviour.

Kimberlite behaviour is somewhat unique in comparison to a typical fractured rock mass and a ground support design based on benchmarking based on similar conditions is probably the most reliable, and can be optimised once the performance can be calibrated underground.

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