Developing a geotechnical model for the Jwaneng underground project

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Abstract

The Debswana Diamond Company (DDC) Jwaneng mine in Botswana, is a large open pit diamond mine extracting three kimberlite pipes. Open pit operations will cease in the early 2030s; studies are currently underway to transition to an underground operation at the cessation of open pit mining. It is anticipated that underground mining will be undertaken using a combination of sublevel caving (SLC) and other caving methods; mining will extend to a depth of ~1,000 m below surface. The Jwaneng open pit has been in full production since 1982 and has a mature high-quality geotechnical model that has been progressively developed and improved over many years. Debswana makes use of a geotechnical review board to guide the development of the geotechnical model.

The comprehensive geotechnical model is the foundation for all the open pit and underground designs at Jwaneng. The geotechnical model comprises of several components: lithology model, major structures model, rock mass model, fabric model and hydrogeology model. For the underground studies the geotechnical model has been extended in both depth and lateral extents. In 2018 the geotechnical logging procedure was changed to incorporate parameters and rock mass indices appropriate for underground mining. The Jwaneng mine is structurally complex with many large geological structures and a variable rock mass with strengths ranging from weak kimberlites (25 MPa) to very competent dolomites (>250 MPa).

The various components of the geotechnical model are regularly updated; generally, this is planned to coincide with the study stage, the intent being to meet the confidence level required for each stage. This paper considers all components of the geotechnical model but focuses on rock mass and fabric models for the underground studies. This included developing systems and workflows to allow for comparison of the pre and post 2018 geotechnical data before combining the data. Length weighted histograms and descriptive statistics for various parameters (RQD, Q', RMR_{89}, RMR_{2000}, GSI, etc.) were determined for different lithologies and structural blocks to assist with defining geotechnical domains.

Keywords: *geotechnical model, rock mass, characterisation, geotechnical domains*

1   Introduction

The Debswana Diamond Company (DDC) Jwaneng mine in Botswana, is a large open pit diamond mine extracting three kimberlite pipes. Open pit operations will cease in the early 2030s; studies are currently underway to transition to an underground mining operation by the time open pit mining ceases. It is anticipated that underground mining will be undertaken using a combination of sublevel caving (SLC) and other caving methods. Mining will extend to a depth of ~1,000 m below surface and will included excavations within very competent country rock and weak kimberlite rock. The geotechnical model and its various components are the foundation on which geotechnical design is based in both the open pit and underground environments. The Jwaneng mine has a long history of ongoing development of a high-quality geotechnical model to support open pit slope designs. This model has been updated and enhanced to support the underground studies.

2 Jwaneng mine setting

2.1 Location

Jwaneng mine is situated approximately 160 km southwest of the capital city of 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 and became fully operational in August of the same year. Figure 1 shows the geographical location of Jwaneng mine in southern Botswana (Gabanakgosi et al. 2018).

Figure 1   Location of Jwaneng mine in southern Botswana

The mine operates a split shell pushback approach; Cut 7 and Cut 8 are currently being mined and stripping for Cut 9 has commenced. Jwaneng mine is currently undergoing a critical transition in its life with the current Cut 8 mining expected to take the pit from the current depth of about 444 m below surface (726 m above mean sea level (AMSL)) followed by Cut 9 down to a depth of about 624 m below surface (546 m AMSL). The major axis of the pit has a general north-northeast–south-southwest orientation, with the waste dumps located to the west of the pit and the process plant to the east (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 upper-most stratigraphic units are the aeolian Kalahari Sands, as well as pedogenic calcretes. These units are underlain by the Timeball Hill Formation, which comprises a complex assemblage or mixture of laminated shales, quartzitic shales, and siltstones combined into one laminated shale unit. A consistent carbonaceous shale layer marks the base of the Timeball Hill Formation (Barnett 2009). The Timeball Hill Formation is underlain by the Rooihoogte Formation which consists of medium-grained, poorly sorted, and argillaceous quartzites, which could in general be classified as greywackes to sub-greywackes, and silty mudstone. Below the Rooihoogte Formation are carbonates (dolomites) of the Malmani Subgroup which are stratigraphical correlatives of the Campbellrand Subgroup in Griqualand West (Beukes 2006). The simplified stratigraphy is shown in Table 1. Various dolerite (DOLR) sills and dykes are also present.

The Jwaneng mine exploits a diamond-bearing kimberlite complex of three main pipes; these pipes have been named south (S), centre (C) and north (N) pipes. All three pipes are associated with steep (~80°) and relatively smooth sides. The contacts with the country rock (which is locally fractured adjacent to the kimberlite) is typically very sharp. Before the onset of mining, 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 (with bedded pyroclastic and volcaniclastic units preserved in the north pipe); there are also a range of breccias (Figure 2).

Table 1   Jwaneng country rock stratigraphy

Stratigraphic name	Rock type	Code
Kalahari Sequence	Sand	SAND
	Calcrete	CALC
Timeball Hill Formation	Laminated shale	LS
Lower Timeball Hill Formation	Carbonaceous shale	CS
Rooihoogte Formation	Quarzitic shale	QS
	Chert Pebble Conglomerate – Bevets	BVT
	Quarzitic shale	QS
Lower Rooihoogte Formation	Carbonaceous shale	CS2
Malmani Subgroup	Dolomite	DM
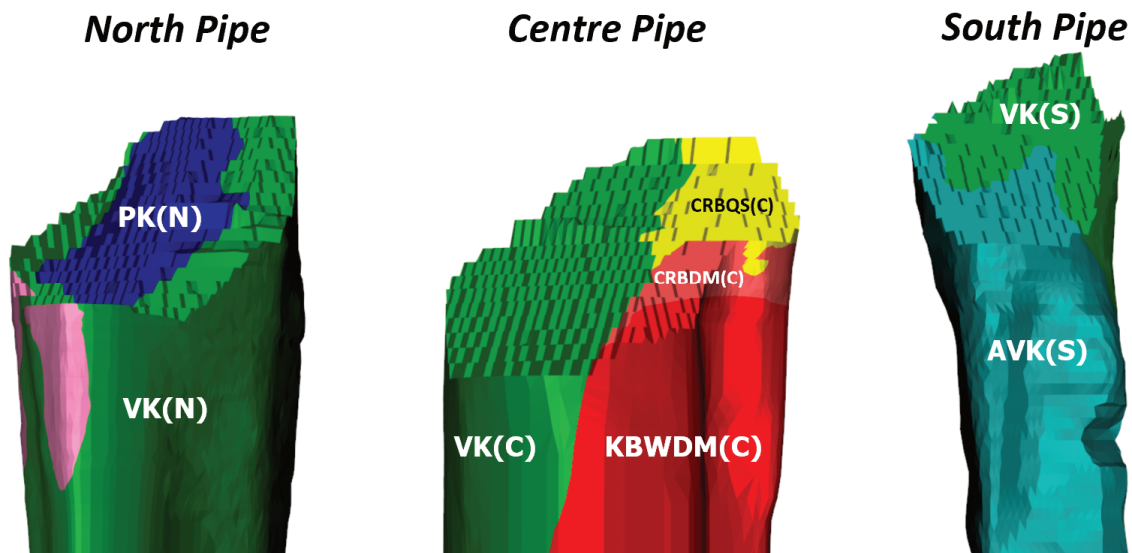
Figure 2   Main kimberlite facies within the underground horizon clipped against the Cut 9 open pit design

The main north pipe facies within the underground mining horizon are the volcaniclastic kimberlite and the pyroclastic kimberlite facies, VK(N) and PK(N). The south pipe consists of a volcaniclastic kimberlite and an autolithic volcaniclastic kimberlite, VK(S) and AVK(S). The centre pipe comprises of the volcaniclastic kimberlite, VK(C), and three breccia units which represent zones of relatively little kimberlitic material. The CRBQS(C) and CRBDM(C) are country rock breccia units dominated by QS and DM respectively. Kimberlitic material content in these units is generally less than 5%. The KBWDM(C) unit comprises of DM clasts in relatively more kimberlitic material than the other breccias (5–50%). A key challenge with these breccia units is how best to characterise their geomechanical properties due to the sharp contrast in strength between the very strong country rock units (QS and DM) and the relatively weak VK material.

2.3   Structural setting

The structural setting at Jwaneng mine is complex and the structural model is regularly updated as new mapping and drillhole information becomes available. The structural geology at 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, 2020).

3   Data available

The current Jwaneng mine geotechnical borehole database (as of 1 August 2021) consists of approximately 417 diamond drilled boreholes with geotechnical data, from various drilling campaigns spanning a period of more than 10 years (Figure 3). These boreholes represent a cumulative length of ~185,000 m of geotechnically logged core. Approximately 60% of this data is for the QS and DM units; the units that the underground mine development is predominantly located in. The boreholes have been drilled in different orientations to reduce directional bias. In addition to the comprehensive geotechnical logging database, a significant amount of laboratory work has been undertaken at Jwaneng covering a range of geomechanical laboratory tests. The borehole database is supplemented by geophysical methods (downhole and surface) and face mapping.
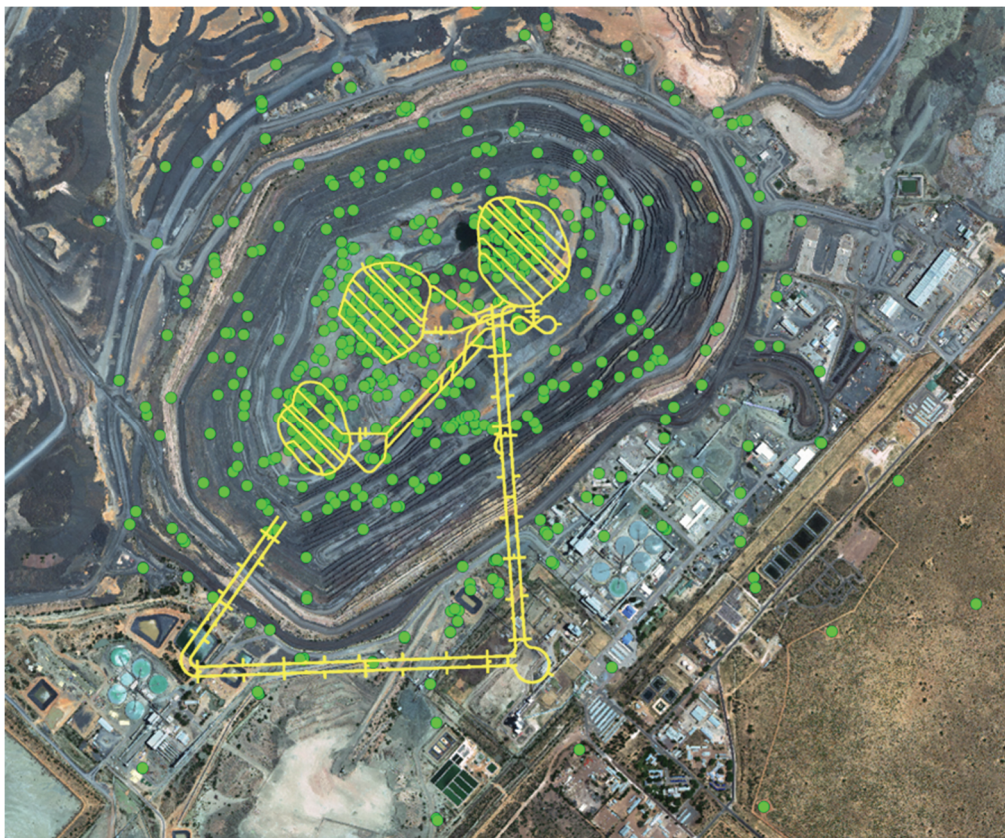
Figure 3   Spatial coverage of Jwaneng mine geotechnically logged boreholes superimposed on Exploration Access pre-feasibility design

4   Geotechnical model

The geotechnical model at Jwaneng comprises of five separate models; the geology, structural, hydrogeological, rock mass, and stress field models. This geotechnical model is continuously being reviewed and updated as new data becomes available and the understanding of the geotechnical environment evolves. Some of the investigations are carried out as part of the ongoing open pit operations while others are conducted specifically for the underground mining studies. Ultimately all learnings, regardless of where the investigations are conducted from, are consolidated into the official geotechnical model. As the stress field is an important consideration in underground mine design, it has been included into the geotechnical model development. This paper summarises the current understanding of the Jwaneng geotechnical model as derived from all previous studies and investigations, with a special focus on the rock mass model.

4.1 Geology model

The lithology model for the country rock and the kimberlites pipes is regularly updated as new drilling information becomes available; updates are typically planned to coincide with the study stages allowing for an increasing confidence level. With the changing focus to underground studies, the extent of the country rock model has been increased to take into account the location of underground infrastructure, sited to the east of the open pit; this necessitated additional drilling away from the open pit. The country rock model has recently been updated. A dedicated drilling program is underway to update the kimberlite models as part of the ongoing underground studies.

4.2 Structural model

The structural model consists of two components; i.e. major structures (large faults) and fabric (bedding and joints). The major structural model is regularly updated as is generally done when the country rock model is updated. The fabric model is updated when the rock mass model is updated. The structural model extents have been extended to capture the underground mine access infrastructure (surface and underground). The major structural model has also recently been updated.

4.3 Hydrogeology model

The watertable in the region of Jwaneng mine is below the Kalahari sequence and hence the Kalahari Sand and Calcrete units are hydrogeologically insignificant (Itasca 2015). The shale units (LS, CS and the thicker QS) are variably fractured and transmit water, though the porosity is low. Generally, the groundwater flow in the region of Jwaneng mine is structurally controlled. The natural recharge from precipitation is limited in this semi-desert area. There is a network of piezometers across the site and an ongoing process of collecting hydrogeological data. This data is fed into a three-dimensional hydrogeological numerical model which is regularly updated in sync with the study stages.

4.4 Rock mass model

A comprehensive rock mass was developed for the open pit; this model has been extended and enhanced to support the underground mining studies. A significant update of this model was undertaken in 2021 (Chiwaye 2021) and is the subject of this paper.

4.5 In situ stress field

Understanding the in situ stress regime is an important input into mine design and has a significant impact on designs analyses especially for numerical modelling. The magnitudes, ratios and directions of the principal stresses influence the choice of mining method, excavation stability, stand-off distances, etc. Debswana has undertaken a range of stress field assessments using three different techniques and extensive independent review and interpretation. The development of the in situ stress field model is covered in Dunn et al. (2022) and work is ongoing. Given the various uncertainties, two possible stress fields (Table 2) have been identified and these are used for sensitivity analysis in numerical modelling.

Table 2   Stress field options for Jwaneng mine

Stress field	σ_H	σ_h	σ_V	σ_H azimuth
Option 1	$1.1 * \sigma_V$	$0.5 * \sigma_V$	$\sigma_V \sim$ depth (m) * 0.027(MN/m^3)	340 (northwest–southwest)
Option 2	$0.9 * \sigma_V$	$0.5 * \sigma_V$	$\sigma_V \sim$ depth (m) * 0.027(MN/m^3)	215 (northeast–southwest)

5   Development of the rock mass model

There is a considerable amount of data available for the rock mass model; this data is as kept within a LogChief database. This data can be visualised in three dimensions using a range of platforms. Data analysis has been undertaken using length weighed data to account for variable logging intervals; descriptive statistics, box and whisker plots, histograms and cumulative curves are then generated. This allows for easy comparisons between different rock types, different geotechnical domains, etc. This approach also allows for an improved understanding in the data variability and how this may have an impact on data and model confidence.

A range of Excel spreadsheets have been developed to allow for analysis of laboratory testing and logging data. For assessment of logging data, it is possible to do analysis for specific rock mass indices as well as the various parameters (e.g. RQD, fracture frequency, joint properties, etc.) making up the indices.

5.1   Intact rock

Jwaneng mine has a comprehensive database of intact rock strength tests covering many different test types (uniaxial compressive strength – UCS; triaxial - TCS, Youngs Modulus – E; Poisons Ratio – v; indirect tensile strength (Brazilian) – UTB; direct tensile strength – DTS; base friction angle – BFA). Table 3 is a summary of test numbers; some units have low test numbers, and these will be addressed in future drilling programs. All test results are maintained in a LogChief database and are analysed and validated by the geotechnical engineers to identify valid tests (failure modes, length to diameter ratio, etc.) and outliers.

Table 3   Summary of all Jwaneng laboratory testing

Rock type	UCS	TCS	E/v	UTB	DTS	BFA	Slake durability	Free swell
CALC	25	28	48	25	0	5	–	–
LS	112	80	117	55	1	228	–	–
CS	110	113	140	102	4	39	–	–
QS	308	396	554	253	32	205	–	–
DM	391	563	817	392	50	198	–	–
DOLR	98	125	178	115	10	26	–	–
PK(N)	435	207	636	385	6	36	59	56
VK(N)	109	51	160	93	2	2	8	5
VK(C)	692	159	845	535	2	32	67	37
VK(S)	262	131	392	240	12	43	37	31
AVK(S)	72	69	141	119	27	7	70	39
CRBQS(C)	0	0	0	0	0	0	–	–
CRBDM(C)	4	12	16	6	0	2	–	–
KBWDM(C)	23	53	76	32	4	5	–	–

Summary statistics and histograms of these tests have been developed for the each of the main rock types. Only the UCS analysis is included in this paper as an example. A summary of the UCS for the major lithological units at Jwaneng mine is given below (Table 4 and Figure 4). From Figure 4 it can be interpreted that the CALC, LS and CS units have a moderate strength whilst the QS, CS2, DM and DOLR units have a high strength

and the volcaniclastic units have low strength. Examples of UCS histograms and cumulative curves are shown in Figure 5.

Table 4   Descriptive statistics for UCS (valid tests; outliers excluded)

Stats	CALC	LS	CS	QS	CS2	DM	DOLR	VK(C)	VK(N)	VK(S)	PK(N)	AVK(S)
Count	24	61	93	93	17	190	21	75	17	42	52	19
Mean	64	53	113	242	318	255	338	25	32	22	64	26
SD	50	30	60	44	72	63	98	10	13	8	24	9
Min	12	7	13	115	193	81	189	7	11	11	24	8
Max	190	117	272	359	458	397	501	49	56	53	105	49
COV	78%	58%	53%	18%	23%	25%	29%	40%	41%	34%	38%	36%
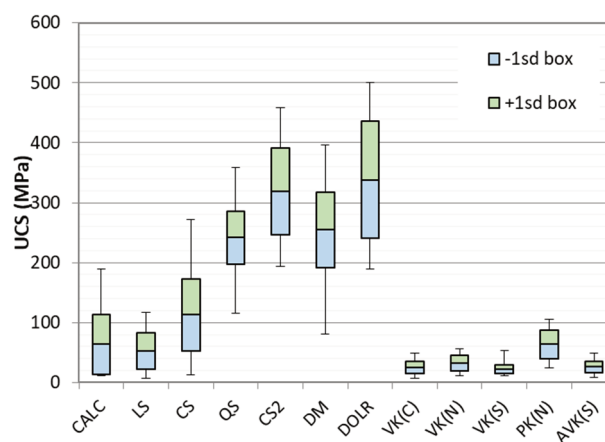
Figure 4   Box and whisker summary of UCS results
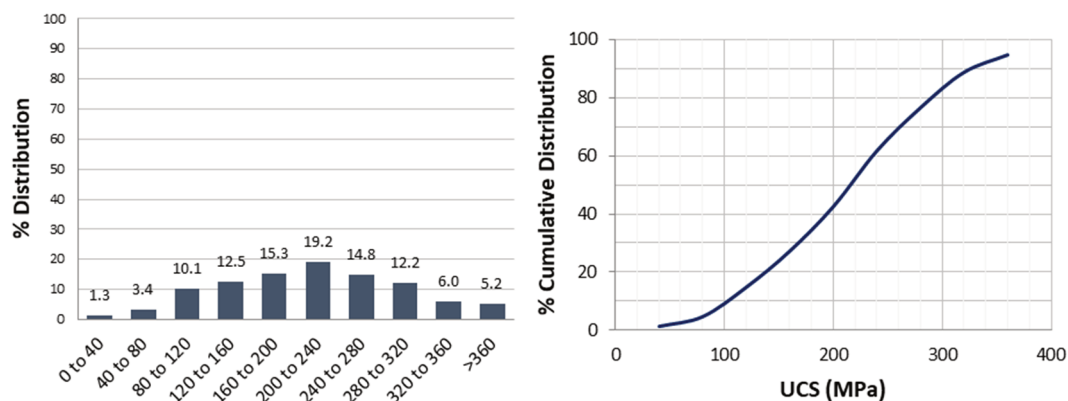
Figure 5   Example of UCS histogram and cumulative curve for DM rock type

5.2   Rock mass characterisation

5.2.1   Logging system

Historically the Laubscher (1990) rock mass rating classification (RMR_{90}) has been used at Jwaneng mine to address open pit slope designs requirements. For underground designs, several empirical methods are based on the Q-system (Norwegian Geotechnical Institute (NGI) 2015) for open stope designs, ground support design, etc.; for caveability assessments the Laubscher & Jakubec (2000) system (RMR_{2000}) is more appropriate. Both RMR_{90} and RMR_{2000} can be converted to MRMR values for caveability assessments, through

the application of the appropriate adjustments for weathering, orientation, induced stress, water and blasting; this is not covered in this paper. To address underground data needs, the logging system was modified in 2018 to cater for the Q (NGI 2015), RMR_{2000} and Bieniawski RMR_{89} systems, in addition to the RMR_{90} system.

The revised logging system meant that the data logged prior to the changes had some differences to the data logged after the changes, mainly relating to the specific indices. The calculation of the various rock mass indices was initially developed using an Excel spreadsheet but was subsequently included in the LogChief database. Debswana has well developed data assurances processes that take place at various levels to ensure the integrity of the data and data analysis; this includes an independent geotechnical review board (GRB) at the highest level.
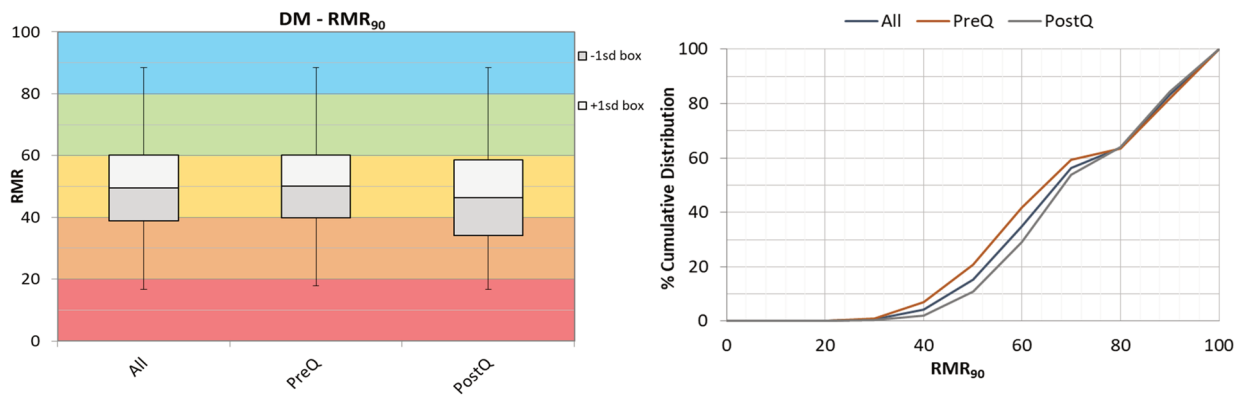
5.2.2 PreQ versus PostQ

The data collected prior to the revision of the logging protocol is referred to as the PreQ dataset, while the data collected after the transition to the new system is termed the PostQ dataset. Summary statistics for design take into account the consolidated dataset i.e. includes both PreQ and PostQ data. A cumulative total of more than 185,000 m of geotechnically logged core is available in the Jwaneng mine database. About 70% of this data relates to country rock units and 30% is for the kimberlite facies (orebody). A breakdown of the available logging data per rock type, and PreQ and PostQ datasets, is shown in Table 5.

Table 5   Comparison of PreQ and PostQ geotechnical logging per rock unit

Rock unit	PreQ (m)	PostQ (m)	Total (m)
CALC	3,357	2,113	5,470
LS	3,492	2,908	6,400
CS	3,578	2,553	6,131
QS	45,010	24,372	69,382
CS2	567	690	1,257
DM	11,608	14,742	26,350
DOLR	5,085	4,113	9,197
VK(C)	11,687	1,357	13,044
VK(N)	4,753	43	4,795
VK(S)	8,281	949	9,230
PK(N)	10,792	557	11,349
AVK(S)	465	387	852

A range of checks were undertaken to ensure that the two data sets were comparable and could be combined. These checks focused on the joint properties where the most significant logging changes had been made. Comparisons were made using box and whisker plots, histograms, and cumulative curves (Figure 6) and these checks confirmed that any differences were negligible and that the two data sets could be combined. It is possible to extract either dataset from the database if required.

Whilst the amount of PreQ data currently exceeds the PostQ data; this will change as more data is collected. The PostQ dataset will become dominant and is focused on the underground portion of the resource. The amount of kimberlite facies data for PostQ is significantly lower than the PreQ and this is being addressed with current and planned drilling programs.

Figure 6 Example of comparisons of RMR_{90} for DM – PreQ versus PostQ versus all (combined)

5.2.3 Rock mass indices and classification

The Jwaneng logging system is designed to capture data that allows for calculation of a range of commonly used rock mass indices or classification systems. A summary of all the rock mass classification indices is given in Table 6. Two different approaches were used to calculate the GSI from logging data: a method developed by SRK Consulting (GSI_{SRK}) and the method proposed by Hoek et al. (2013) (GSI_{Hoek}); GSI_{SRK} has shown better correlation with GSI values estimated from pit exposures using the standard GSI chart. Figure 7 shows box and whisker plots for RMR_{90}, RMR_{89}, GSI_{SRK} and GSI_{Hoek}; this is a useful way to summarise data and make comparisons.

Table 6 Summary rock mass classification indices for Jwaneng lithologies

Rock type	Cumulative length (m)	RMR_{90}	RMR_{89}	RMR_{2000}	GSI_{SRK}	GSI_{Hoek}	Q'	Rock mass class
CALC	5,470	70	75	69	79	73	42.0	Good
LS	6,400	45	61	46	47	58	2.6	Poor-fair
CS	6,131	49	67	50	51	66	3.5	Poor-fair
QS	69,382	55	72	57	57	70	4.8	Fair
CS2	1,257	66	80	69	69	80	17.3	Good
DM	26,350	71	83	73	71	81	20.7	Good
DOLR	9,197	56	74	57	53	71	7.8	Fair
VK (C)	13,044	66	72	58	75	70	7.1	Fair-good
VK (N)	4,795	65	68	53	76	63	4.0	Fair-good
VK (S)	9,230	66	72	58	76	70	6.1	Fair-good
PK (N)	11,349	67	73	61	76	71	7.5	Fair-good
AVK (S)	852	66	74	63	75	75	14.4	Good
CRBDM (C)	482	71	77	66	81	76	25.7	Good
CRBQS (C)	747	67	63	56	78	54	15.5	Good
KBWDM (C)	465	72	78	66	81	75	21.4	Good
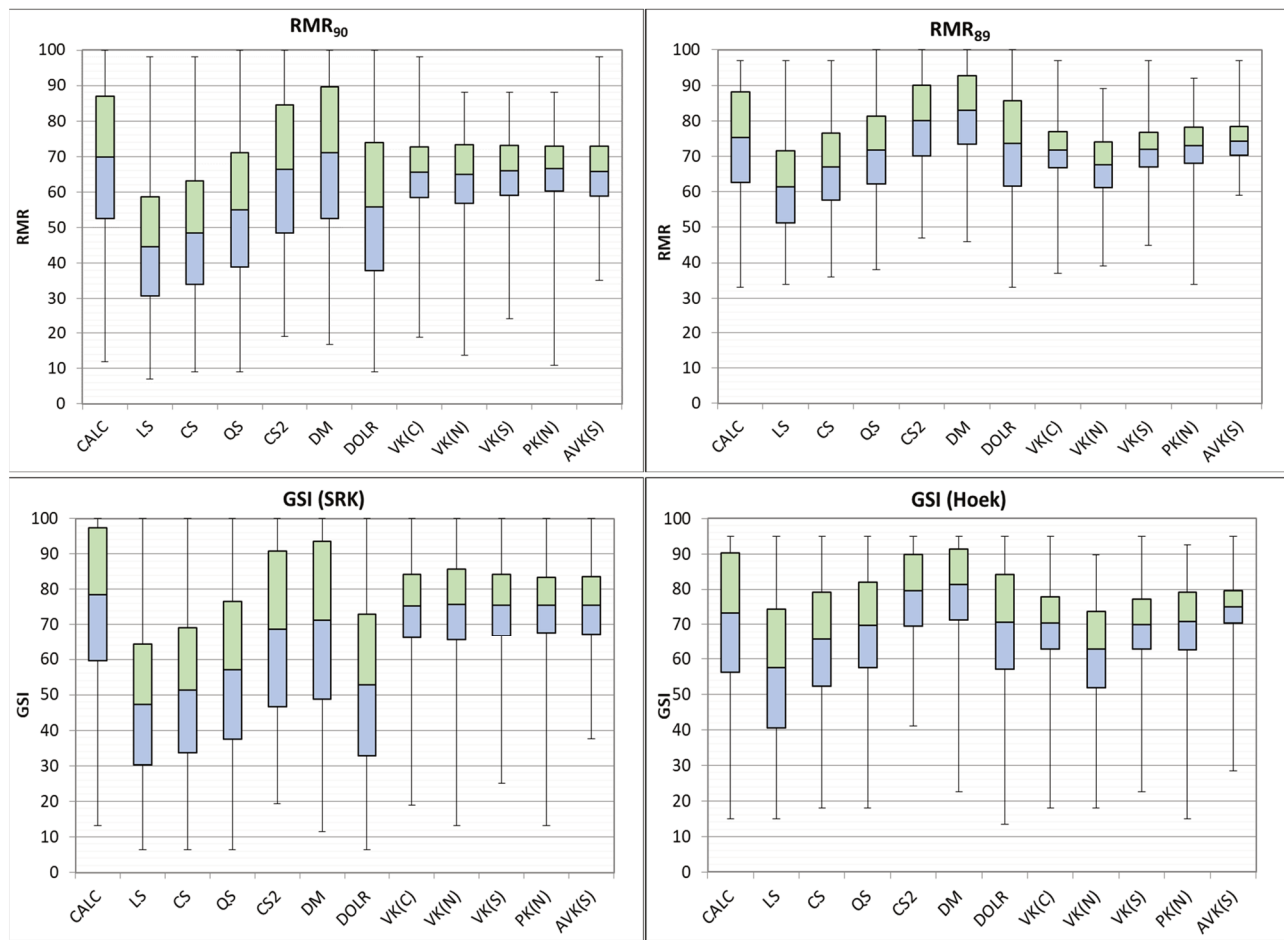
Figure 7   Summary rock mass statistics for main rock types at Jwaneng mine

5.2.4   Specific analyses

By spatially filtering data and using the Excel spreadsheet to generate descriptive statistics, box and whisker plots, histograms, and cumulative curves, a range of investigations have been undertaken; these have included:

- Assessment and characterisation of kimberlite pipe and country rock contacts.

- Analysis of different size halos (10, 20, 30 and 40m) around the kimberlite pipes to assess possible variations in rock mass quality.

- Assessment and characterisation of the neck (neck areas) in between the pipe.

- Comparisons between cherty and graphitic dolomite.

5.3   Durability and swelling

Some of the kimberlite facies at Jwaneng have a high content of swelling clays content and are therefore susceptible to slaking and swelling. X-ray diffraction (XRD) testing is used to determine the mineralogy of the kimberlite facies, including the smectites. The results show that the south pipe seems to have the highest levels of clay content followed by the centre pipe. The north pipe has the lowest clay content, with the PK(N) showing the lowest values as expected. Experiences from various drilling campaigns also shows that the south pipe presents the greatest drilling challenges due to the higher clay content.

Slake durability index (SDI) and Duncan Free Swell laboratory tests have been undertaken to characterise the different kimberlite facies. To confirm the laboratory testing, field testing of the durability of the kimberlites

was carried out by the site geotechnical team. The objective of the field testing was to assess whether the relatively short testing cycles in the laboratory were resulting in an overestimation of the durability. Field testing involved wetting cycles of 24 hours, followed by a drying cycle of 24 hours in air (or 12 hours in a warming oven on the lowest temperature setting).

A summary compassion between the laboratory and field testing is shown in Table 7. Core observations indicate that not all kimberlite facies show low durability and high susceptibility to weathering and these can be quite variable. Work has commenced to understand the spatial variability; however more data is needed, and this is currently being collected.

Table 7   Comparison of durability classification for laboratory tests and field tests

Kimberlite facies	Laboratory	Field	Smectite content
PK(N)	Medium-high	High	3%
VK (N)	Medium	Low	12%
VK (C)	Low	Low	44%
VK (S)	Very low-low	–	43%
AVK (S)	Very low-low	Very low	–
KBWDM (C)	High	High	–

5.4   Rock mass fabric

The rock mass fabric model consists of two components; the first is an analysis of orientation of the various discontinuity sets and second is an assessment of the shear strength.

5.4.1   Discontinuity sets

Previously Rock fabric analyses for Jwaneng mine have mainly been focused on the bedding planes within the shale units (LS, CS, and QS) since they influence the stability of the eastern slopes. Characterisation of the joint sets at Jwaneng has received less attention over the years since they have had little influence slope stability, with the focus being on bedding planes. With the planned transition to underground mining at Jwaneng mine, a detailed understanding of the joint sets becomes important to provide input into support design, stope design, caveability/fragmentation assessments, etc.

The rock fabric data was derived from three datasets: oriented core, televiewer, and face mapping. A total of 122 boreholes with televiewer data were analysed, representing approximately 121,000 data points. Eight of these 122 boreholes were drilled in kimberlite, while the rest are in the country rock. Due to challenges with maintaining boreholes long enough to allow for downhole geophysics, there are only 2,700 televiewer datapoints across all the different kimberlite facies. There are 209 boreholes with oriented core data representing over 145,000 data points; this data is almost exclusively in the country rock. Approximately 19,000 face mapping data points from the open pit are also available (Chiwaye 2022).

The analysis of the stereonets in the country rock units showed a general similarity in the rock fabric patterns. When analysing this data, different structural blocks or domains where considered. The illustrations of stereonets in Figure 8 depicts the orientations of the three sets identified as J1, J2, and J3; a brief description of these sets follows:

- J1 is a joint set trending east-northeast–west-southwest, i.e. parallel to the major fault system at Jwaneng mine (Figure 8). The set is steeply dipping with average dip between 80°–90°. Due to the steep nature of the set, it almost always wraps around the stereonet to the other side. This joint set is well developed in every structural domain that was analysed.

- J2 is a joint set that is almost orthogonal to the J1 set and has a north-northwest–south-southeast trend and is steeply dipping; the dip averages between 70–80°. The J2 set is poorly developed in some structural domains. The J2 set is parallel to the minor fault system at Jwaneng mine (Figure 8).

- J3 is the bedding set trending northeast–southwest with shallow dips typically between 10–30°. The bedding set is always well developed and is the dominant set on stereonets in terms of discontinuity count. For all lithologies, there are also joints that are parallel to this J3 orientation.

- J4 is an occasional shallow dipping set that appears in a few structural domains. This set is most likely due to localised folding of bedding planes and not necessarily an independent joint set.

The trend of these sets exhibits some slight variations between structural blocks, but the general pattern is consistent within the domains. The Jwaneng rock mass fabric system is characterised by two sets of steeply dipping orthogonal joint sets and a shallow dipping set (bedding or bedding parallel joints). Occasionally, some stereonets will show additional sets that are not represented by the three main sets above. This usually occurs when data for all domains is analysed in one stereonet; when the data is analysed for individual structural blocks, inevitably the sets reduce to the three sets or fewer in some instances. This analysis has been done for all structural blocks and main rock types within these blocks.

(a)   (b)
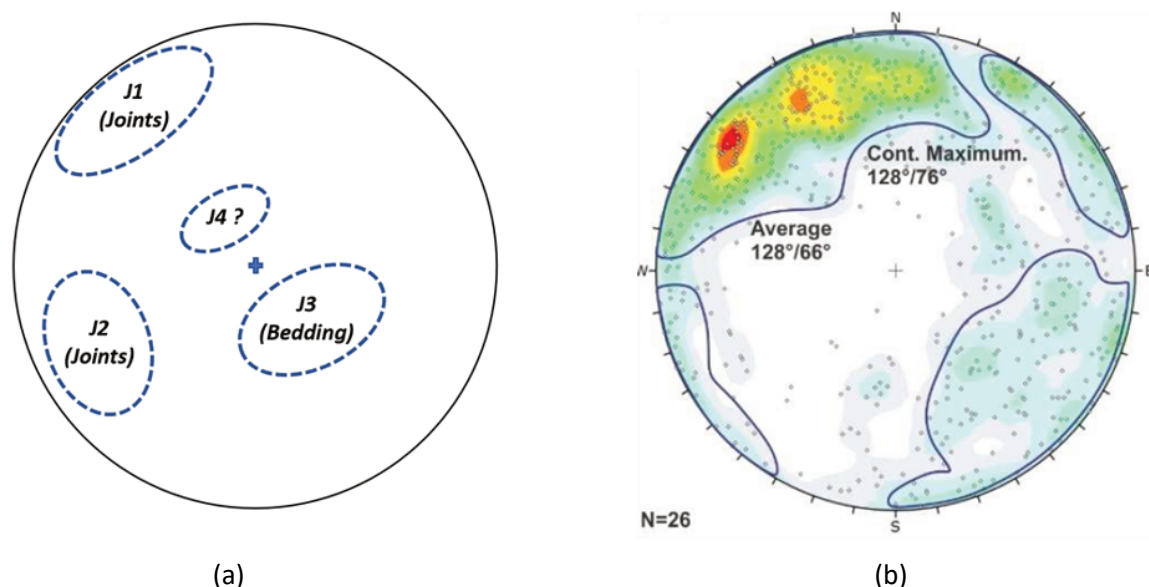
Figure 8   Stereonet illustrations showing the general orientation of discontinuity sets in QS and DM (a), and stereonet of normal faults measured at Jwaneng mine (after Creus et al. 2017) (b)

The is much less orientation data within the kimberlite facies and further work is required to better define discontinuity patters within these units. An analysis has also been undertaken to assess the spacing of various discontinuity sets.

5.4.2   Discontinuity shear strengths

Discontinuity shear strengths are derived using laboratory shear testing data and logging data. The methodology uses the residual friction angle from shear tests on natural joints, the joint roughness coefficient (JRC) estimated from micro roughness rating of the core logs, and the joint compressive strength (JCS) from laboratory UVS tests. The JRC and JCS values representative of field conditions are estimated by applying the scale factor corrections (Barton & Bandis 1982). Ideally, direct use of the non-linear Barton–Bandis shear strength criterion is preferred but some applications require Mohr–Coulomb parameters, and these are calculated from the Barton–Bandis parameters.

6 Geotechnical domains

Geotechnical domains have been based on the major rock types, structural blocks and the rock mass quality. When defining the domains, precedence was given to major rock type (lithology) with the most logging data (mainly QS and DM) as well as spatial proximity between blocks. Domains were derived by comparing the characterisation between structural blocks using the descriptive statistics and histograms.

Six geotechnical domains have been identified within the country rock as shown in Figure 9. Generally, the differences in rock mass quality between domains are in the order of 10–15 points for RMR_{90} and GSI with both falling within the same class. Most of the long-term access and underground infrastructure will be sited in Domains 1 and 2, within either QS or DM. Figure 10 is a summary of GSI and Q' for each rock unit within each geotechnical domain.
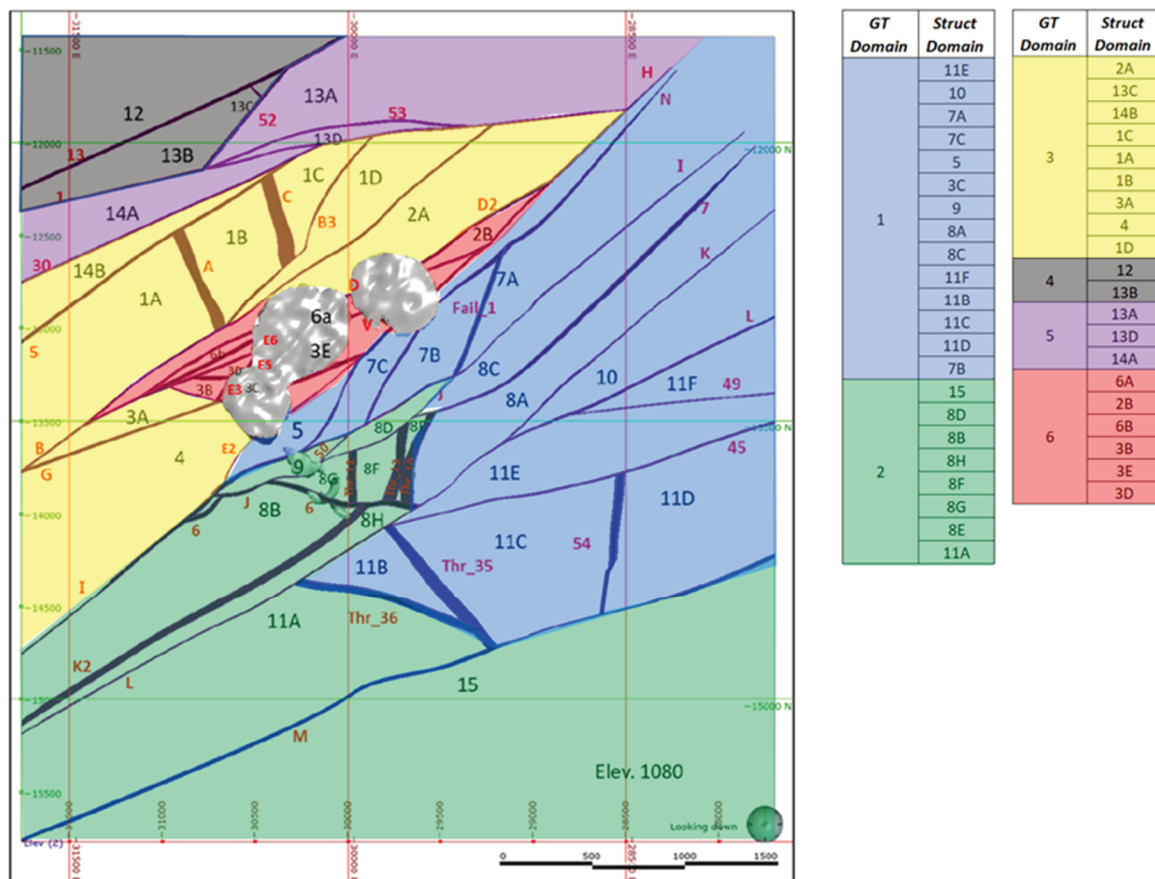

Figure 9 Country rock geotechnical domains and listing of structural domains within each domain
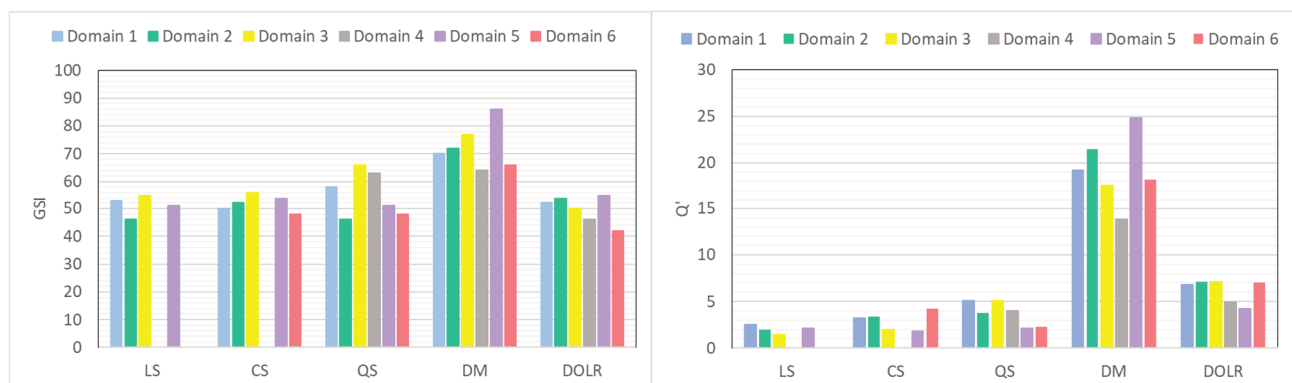

Figure 10 GSI and Q' average value summary for main rock types within geotechnical domains

7 Conclusion

The geotechnical model is the foundation of any geotechnical design. The Jwaneng open pit has a long history of good data collection and the development geotechnical models to support slope designs. These models have been updated and extended to cater for the underground expansion studies. Within Debswana there is a process to update all aspects of the geotechnical model on a regular basis; for studies this is generally aligned with the different study stages.

This paper focuses on the ongoing development of the rock mass component of the geotechnical model. There is a significant volume of laboratory testing and geotechnical logging available at Jwaneng collected over many years. In 2018 the logging system was modified to better cater for the collection and processing of data needed for underground design. This resulted in two data sets that were evaluated to assess whether they were comparable before being combined.

Several parameters are logged, and these allow for characterisation of the rock mass as well as classification using a range of rock mass indices. Length weighted descriptive statistics, box and whisker plots, histograms and cumulative curves have been used to summarise and analyse data. These methods allow for comparison between different data sets and sub-sets and are an extremely useful and powerful tool for domain analysis. Systems and processes have been developed that allow for models to relatively easily be updated and analysed; these can be used in conjunction with any software that allows for the spatial definition and filtering of data sets.

The current models and available tools allow for inputs in design analysis including numerical modelling to be derived. Understanding the variability allows for a more informed choices in design inputs. The current model is being used in the current study stage but data collection continues; geotechnical model components will be updated to support the next study and this is associated with an increasing model confidence.

Acknowledgement

Debswana staff who collect and process critical geological, hydrogeological and geotechnical data; without this contribution there can be no geotechnical model.

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