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Structural data bias assessment at Jwaneng Mine

K Gabanakgosi *Debswana Diamond Company, Botswana*

O Mogorosi *Debswana Diamond Company, Botswana*

K Rametlae *Debswana Diamond Company, Botswana*

B Boitshepo *Debswana Diamond Company, Botswana*

OM Barei *Debswana Diamond Company, Botswana*

Abstract

Successful delivery of a life-of-mine plan largely depends on the reliability and performance of the geotechnical models. Assessments of the reliability of the geotechnical model have therefore become a key focus in managing mining operations. A major risk to the reliability of the geotechnical model is data confidence, and the focus for every mine site is on the key aspects affecting the design and stability of mine excavations. Stability of the mining excavation is controlled in large by geology and structures. In this regard, the confidence in data used to confirm the geology is critical. Pertinent for mines affected by geological structures is an assessment of data bias as structures not appropriately defined could be detrimental to the mine's stability. Jwaneng Mine's open pit stability is controlled by steeply dipping bedding daylighting into the pit on the eastern slopes and dipping into the walls on the western slopes. Data confidence in relation to the data collection method has been carried out. This includes spatial resolution, accuracy and precision of the chosen data collection method, as well as bias.

Extensive geotechnical data collection through drilling and pit face mapping has been undertaken throughout the life-of-mine. Data collection methodologies have been discussed which informed the data source selection from respective data collection methodologies. Low quality datasets were excluded and assessment was made as to whether significant data gap (spatial) will arise due to exclusion of these datasets. This was, however, not realised as Jwaneng Mine has extensive data coverage, but it presented an opportunity for retrospective assessment of potential data bias. Bias assessment undertaken from the data covered a review of existing drillhole core orientations and mapped discontinuity orientations. Stereonet plots, and 3D plotting of the drillholes, together with discontinuity from geophysical televiewer logs were used for the bias assessment. Evident from the assessment is bias that results from unfavourable drillhole orientation with respect to certain geological structures. The methodology provided a means of proactively realising the gaps and adequately addressing them. This has proven to be valuable knowledge that can be shared with the industry such that mine design studies, as well as operation design reviews, should include it in order to ensure the mine design objectives are successfully delivered.

Keywords*: slope design, slope stability, model reliability, data confidence, data bias*

1 Introduction

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 and is currently mining Cut 7 on the west and Cut 8 on the east, as shown in Figure 2. The mine is the largest contributor to the national economy of Botswana and is the world's richest diamond mine by value (Gabanakgosi et al. 2018). The importance of this mine to Botswana cannot be over-emphasised and has significantly contributed to the growth and development of Botswana. Jwaneng Mine is currently undergoing a critical transition in its life with the current Cut 8 mining which is expected to take the pit from the current depth of about 444 m below surface (726 m above mean sea level (AMSL)) down to a depth of about 624 metres below ground level (MBGL) (546 m AMSL) by 2029. It is estimated that the proposed Cut 9 pushback will sustain production until about 2036. However, the first ore from a post Cut 8 mining project is expected around 2034. A significant part of the resource that is envisaged to be mined from the post Cut 9 mining project is expected to be derived from 850–1,000 MBGL. 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).

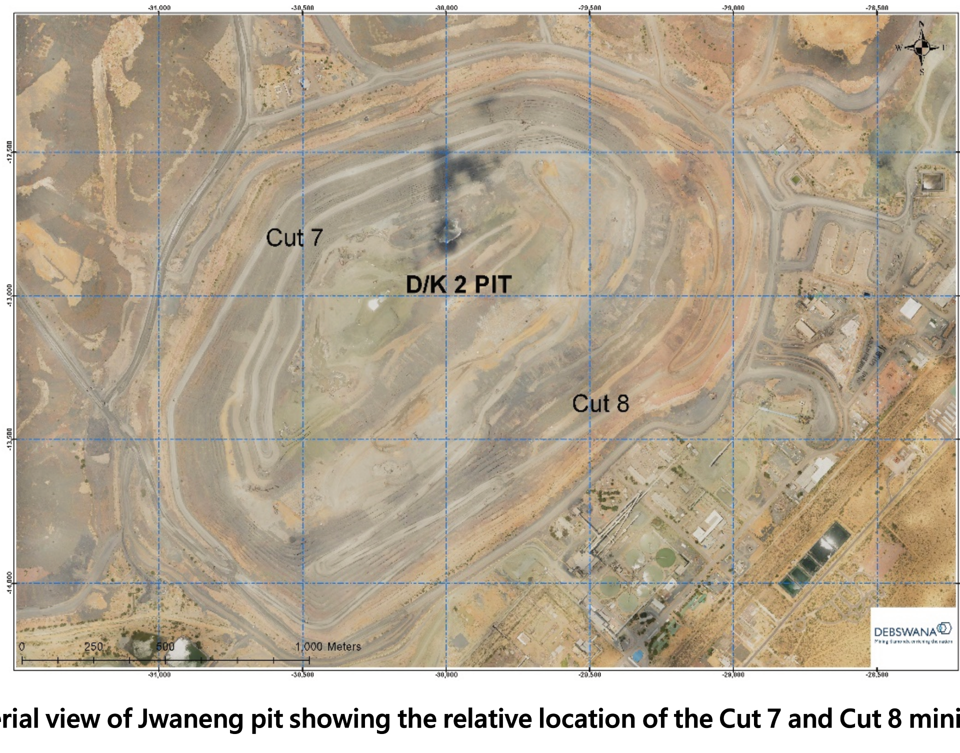


Figure 2 Aerial view of Jwaneng pit showing the relative location of the Cut 7 and Cut 8 mining pushbacks

2 Jwaneng Mine stratigraphy and structural geology

The Jwaneng Mine 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).

Creus et al. (2017) suggest that the Jwaneng Mine country rock has been subjected to at least three deformational events. The first deformation (D1) is northwest–southeast directed compression which resulted in northeast trending open folds (F1) and low-angle thrust faults that tend to dissipate into bedding. Creus et al. (2017) further suggests that the second deformation (D2) involved the rotation of principal stress to north–south that resulted in north–south shortening leading to sinistral, oblique shearing along the pre-existing radial cleavage developed around the F1 folds coupled with development northwest trending open folds (F2). The third deformational event (D3) is a northeast–southwest extensional deformation leading to development of normal faulting along pre-existing F1 cleavage creating a series of wedge-shaped, fault-bounded blocks. The normal faulting was coupled with rotation of blocks towards the north resulting in a high dip value on the eastern slopes daylighting into Jwaneng Mine open pit (Creus et al. 2017). The structural geology at Jwaneng Mine is clearly dominated by these northeast–southwest striking faults with a strong normal dip slip shear sense component (Barnett 2009). Figure 3 shows the complex structural geology of Jwaneng Mine.

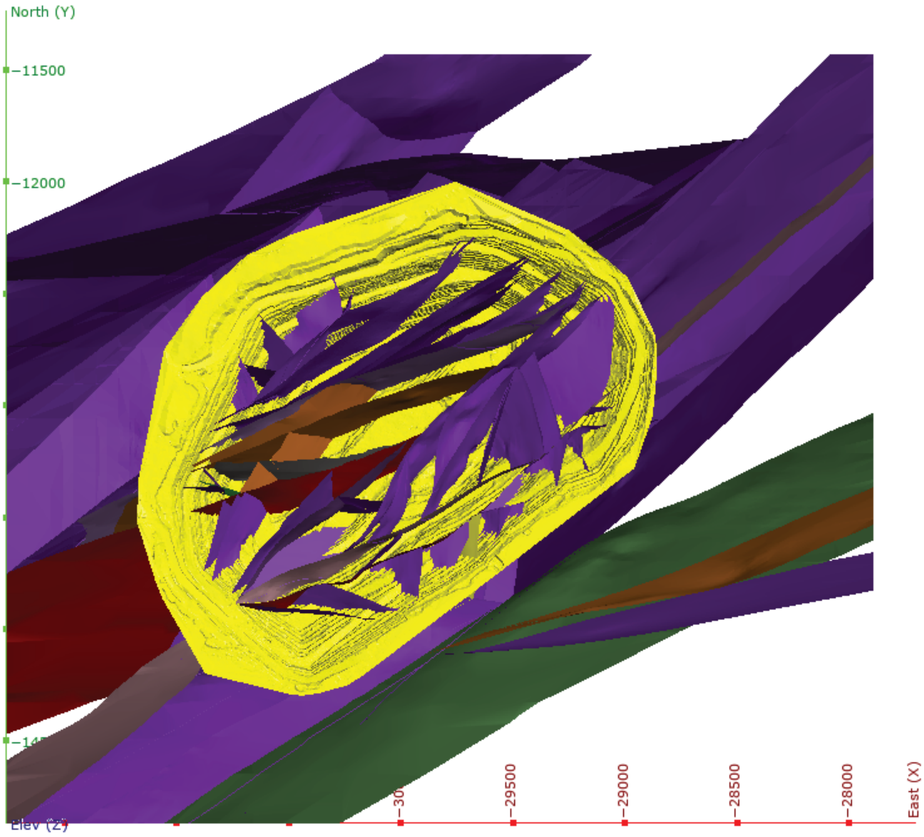


Figure 3 Plan view of modelled structures around Jwaneng Mine

3 Jwaneng Mine pit slope stability

Structural geology defects inherently negatively affect the mechanical and hydrogeological properties of the rock mass, thereby affecting design and maintenance of an open pit mine (Verma et al. 2011). Stead & Wolter (2015) emphased the importance of a detailed understanding of structural geology concepts and principles in geotechnical studies. Jwaneng Mine pit slope stability for the eastern slopes is controlled by the steeply dipping bedding planes that are parallel to the strike of slope discussed in the structural geology section of the document. Single to multiple bench instabilities have, over the years, been experienced for the eastern side of the pit as a result. Figure 4 shows a failure of the slopes affecting three benches that occurred on the eastern side of the pit.

Figure 4 Three-bench failure in the eastern side of the pit

4 Data confidence/model reliability

Steffen et al. (2006) attributed the attainment of mine planning targets on the performance of ore resource and geotechnical models as predicted, and achievement of productivity and cost budgets, as well as adequate resourcing in the form of skills in management, leadership, and human resources. A geotechnical model comprising of geological, structural, rock mass, and hydrogeological models is the key building block of slope designs (Read & Stacey 2009). It is, therefore, paramount that the geotechnical models are reliable, and in that regard assessment of this reliability is undertaken throughout life-of-mine. Assessments of the reliability of the geotechnical model has therefore become a key focus in managing mining operations. A major issue related to the reliability of the geotechnical model is data confidence, and focus for every mine site is based on this key aspect affecting the design and stability of the excavation. Specific to Jwaneng Mine's eastern slopes is confidence related to the bedding. As a result, data confidence specific to the bedding has been assessed considering spatial resolution, accuracy of the data collection technique, and bias with respect to the geological structures. Understanding that model reliability is influenced by data used, this paper undertakes to assess reliability of the structural model through assessment of data bias.

4.1 Accuracy and precision of the data collection method

Geotechnical data collection in Jwaneng Mine covers conventional mapping (pit face and scan line mapping), digital techniques, and borehole drilling (percussion and core drilling). Figure 5 presents a plot of all the data points for Jwaneng Mine from all the data collection methodologies.

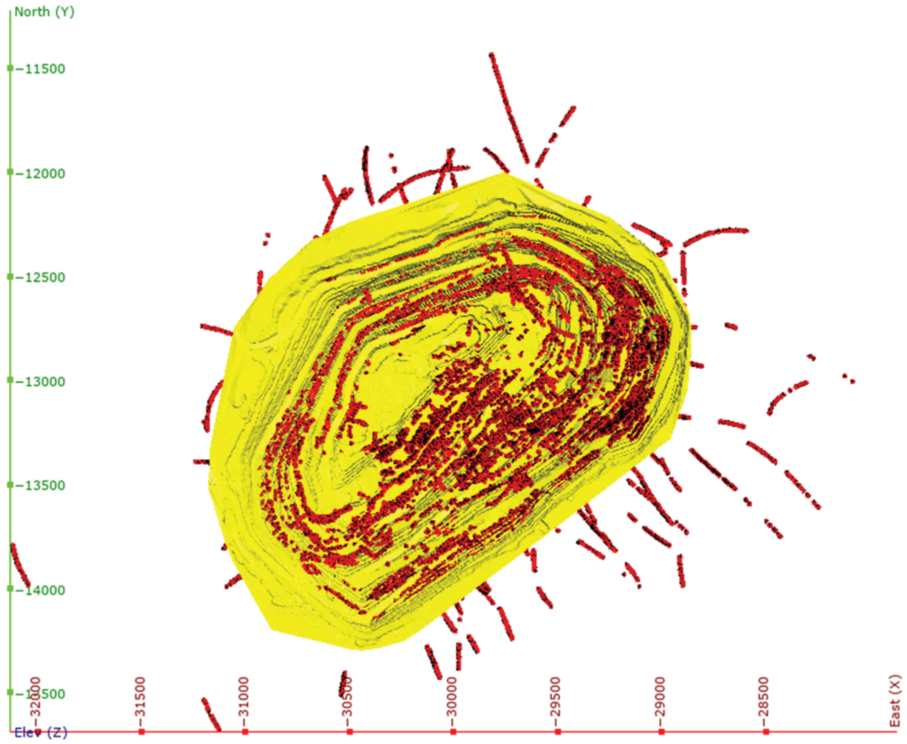


Figure 5 Jwaneng Mine pit showing data points (mapping and drilling)

4.1.1 Mapping

Mapping in Jwaneng Mine is done using different techniques; one being conventional mapping with a compass, and high resolution laser scanning. Each mapping technique has its own inherent limitations in as far as data confidence is concerned. Though structure orientation, information for scanline mapping is generally correct; the structure position accuracy is compromised because structures are not individually surveyed. The position is deduced from start point of the scanline using the distance at which the structure occurs from the start point. Laser scanning provides point cloud data which are dense enough to generate high resolution three-dimensional (3D) surfaces from which orientation of various structures can be accurately picked. Both position and orientation of structures picked from laser scan mapping are of high confidence. Figure 6 shows a pit face with point cloud on the mapped structures derived from laser scanning.

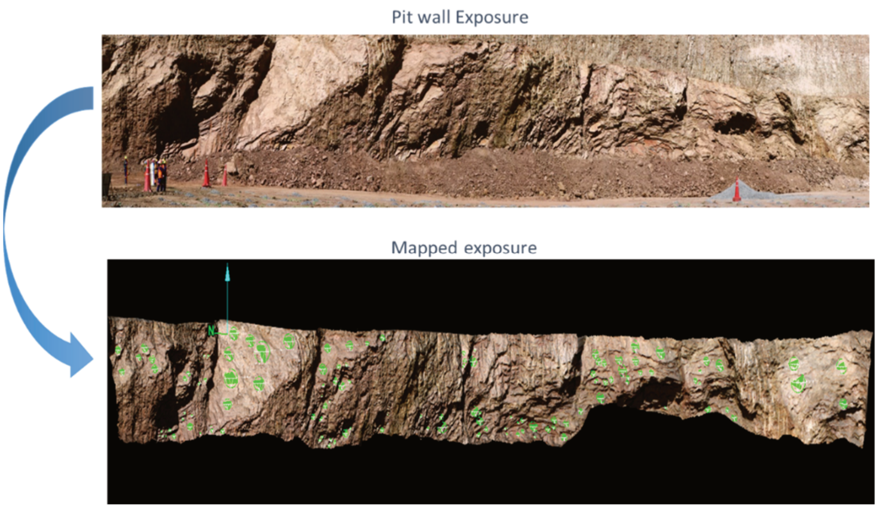


Figure 6 Pit face with point cloud on the mapped structures derived from laser scanning (Mogorosi et al. 2017)

4.1.2 Drilling

Structure picks from drillholes are measured in two ways: using orientation line from oriented core or employing geophysics (televiewer). Deriving structure orientation from oriented core involves logging of drillhole core essential to attain alpha and beta readings which are later translated to dip and dip direction of the geological structure. Figure 7 shows a core stub and its alpha angle with reference to the joint surface and the core axis. Orientation accuracy of the geological structures is therefore greatly dependent on the accuracy of the orientation line which in many cases lacks consistency down the hole resulting in a compromised structure orientation accuracy.

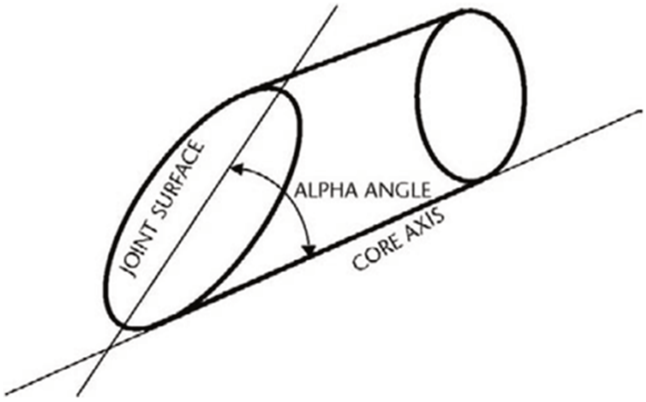
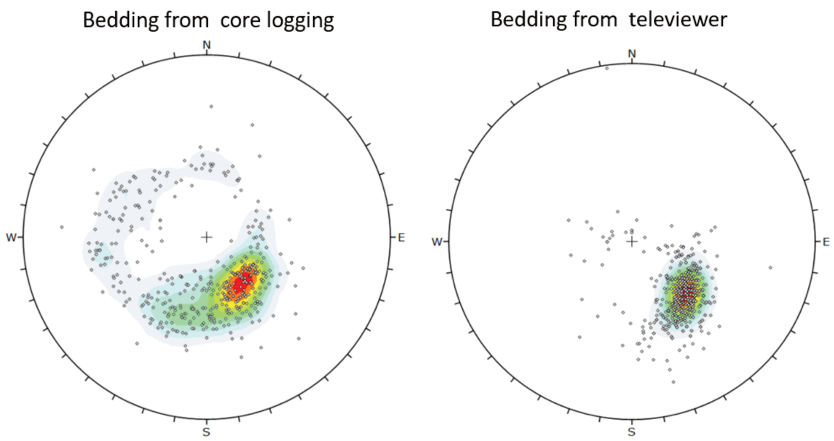


Figure 7 Illustration showing a core stub and its alpha angle with reference to the joint surface and the core axis (Read & Stacey 2009)

Borehole televiewer data, on the other hand, is more accurate as it is based on imaging of the borehole wall from which structures can be resolved using the borehole orientation. Televiewer data, both optical and acoustic, is becoming more frequently recorded along with geophysical downhole surveys, and provides a reliable and accurate method of recording structural data. Televiewer tools work best in cleaned boreholes. Diamond coring tends to produce the smoothest drillhole wall, and reverse circulation drilling tends to result in a less uniform hole, with greater potential for disturbance of soft or broken zones. Figure 8 shows structure picks from two holes drilled in the same area where structures from oriented core are compared to those picked using a televiewer. Worth noting is the inconsistency in the orientation of structures from oriented core hole. Figure 8 presents stereonet plots of the respective drillholes; the inconsistencies are evident with the televiewer data showing bedding clustered around the known orientation whereas the manual logs show a wider scatter.



(a) (b)

Figure 8 (a) Stereonet showing structural picks from oriented core; (b) Stereonet showing structural picks from televiewer

4.2 Data spatial coverage

Based on the quality of data collection methodologies discussed, high-confidence data from the televiewer and laser scanner data were used in spatial coverage assessment. Figure 9 presents a plot of the televiewer and laser scanner data points with the conventional mapping points excluded, demonstrating that a sufficient number of data points still exists. It is worth noting that extensive work has been carried out on the structural geology of Jwaneng Mine and the key to assessing spatial coverage adequacy is determining the data point spacing tolerance that allows for sufficient determination of the structural environment. This was done through interpreting fold axial trends for bedding dip and azimuth, as shown by Figure 10. Bedding dip orientation within the Jwaneng Mine pit is generally towards the northwest, meaning that bedding daylights on the southeastern slopes, hence requiring the evaluation of bedding orientation variation on the southeastern slopes.

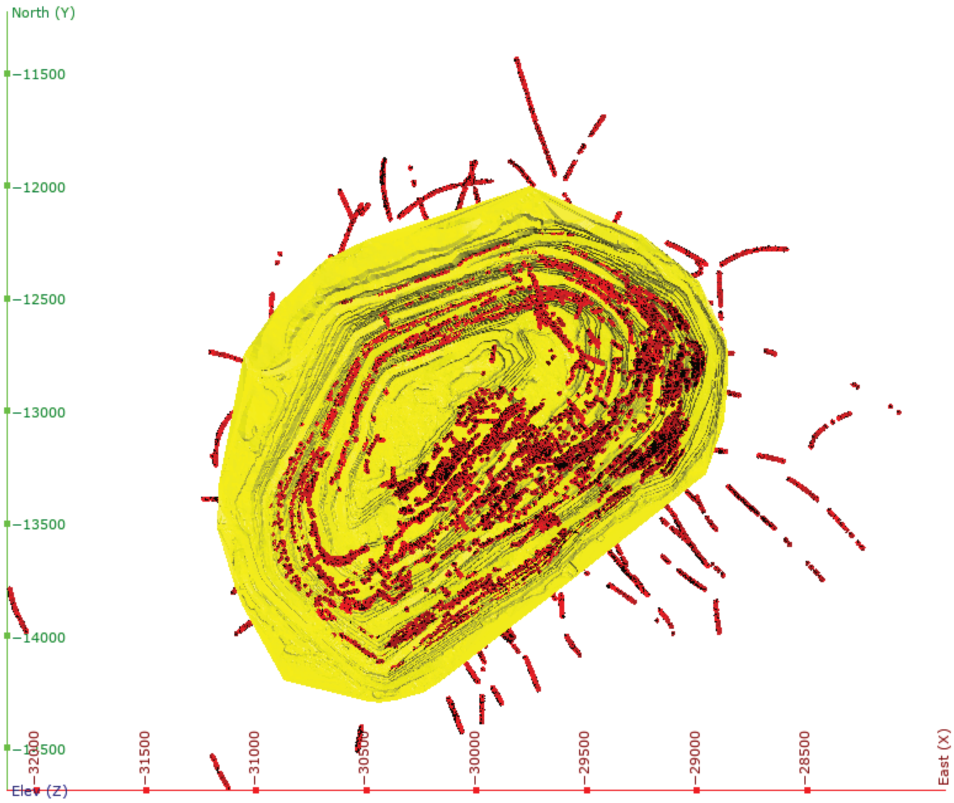


Figure 9 Jwaneng Mine pit showing data points (laser scanner mapping and televiewer)

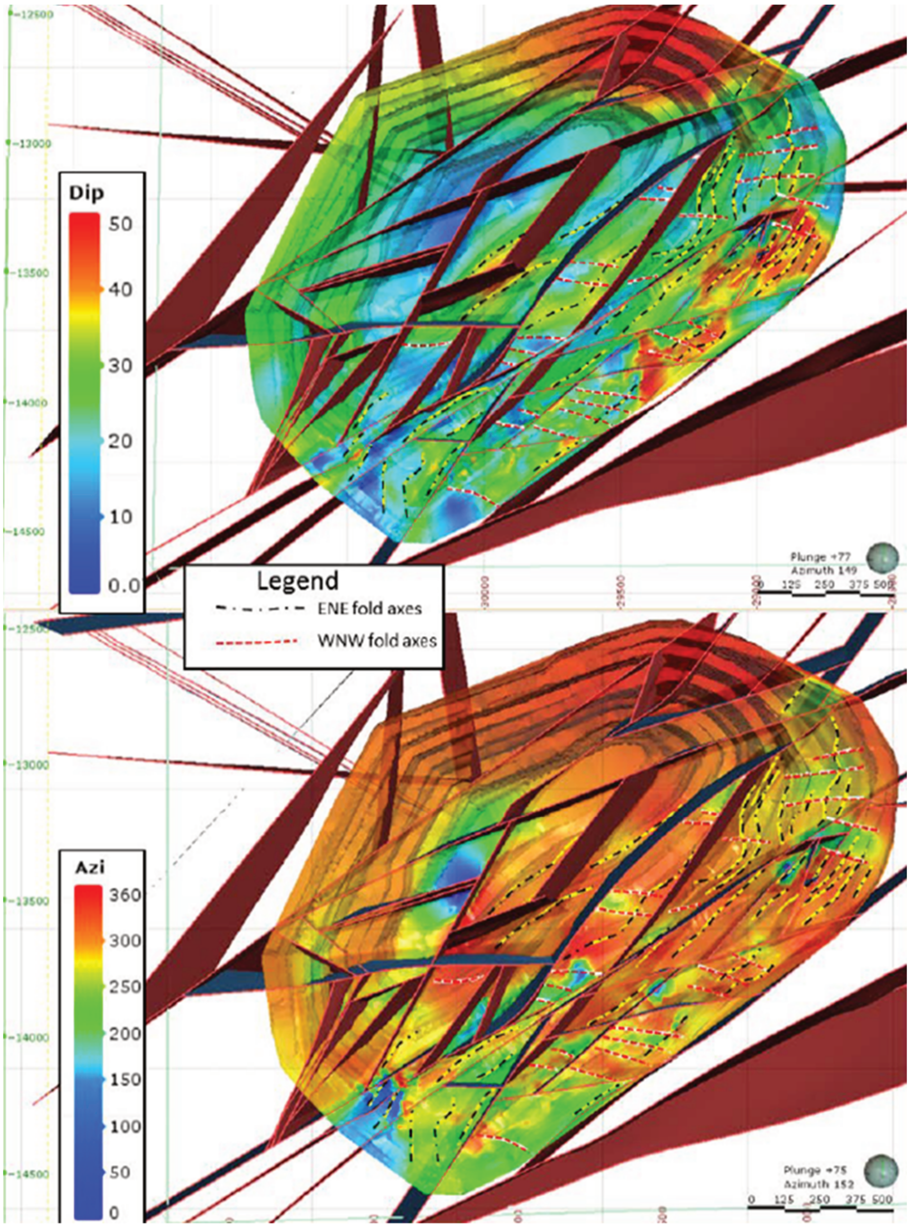


Figure 10 Bedding dip and azimuth plots with interpreted fold axial trends (Barnett 2016)

Resulting from this work is a realisation that the fold wavelength down-dip is shorter at a minimum of about 100 m. This then provides guidance for variation of bedding fabric orientation due to folding to be sufficiently captured. Data should have been collected on both limbs of the folds, i.e. data points' distance should be less than 50 m. Based on this understanding of the bedding, data was evaluated against the Jwaneng Cut 8 design to find a portion of the design where there are no bedding data points constraining bedding fabric model within a 50 m radius from the design. The result of this data spatial coverage analysis shown in Figure 11 enabled detection of areas where bedding data is greater than 50 m from the design, i.e. hot colours. This means that the bedding fabric model in that area is poorly constrained, hence posing a risk to the accuracy of design assumptions. A data collection program through mapping and drilling (laser scanning and televiewer data) was carried out between 2016 and 2018 to reduce data spacing to 50 m or less (cool colours) on the pit design. Data confidence based on this minimum sampling distance carried out on the pit design shows progressive improvement on data coverage from 2016 where the gaps were ranging from 100–150 m to 2018 where the gaps are predominantly within the 0–50 m range.

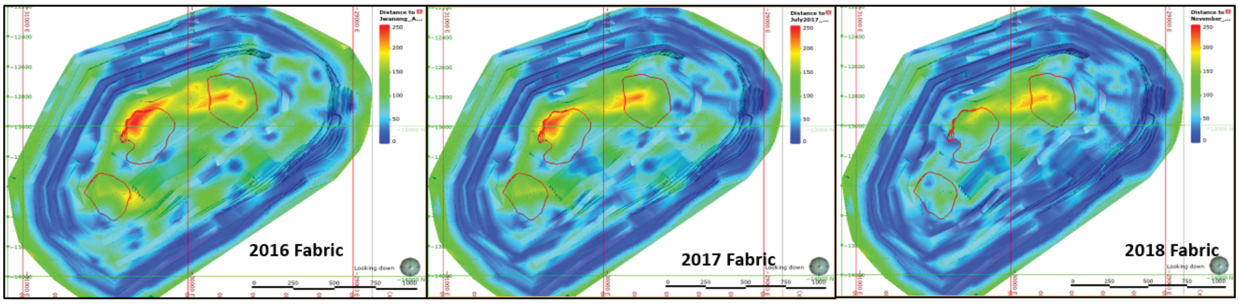


Figure 11 Progressive bedding data confidence map based on distance between data points from 2016–2018

4.3 Data bias

Data bias assessment with respect to the high-confidence data assessment discussed earlier was carried out on downhole televiewer and laser scanner mapping datasets. This section will cover data bias of the borehole televiewer data. Televiewer data, which is digital imaging of a borehole wall and is collected downhole, suffers from one-dimensional (1D) sampling bias (Terzaghi 1965). Figure 12 presents this concept which leads to underestimating frequency of certain geological structures as they would not intersect the sampling line the same number of times regardless of the fact that in the example their occurrence is the same.

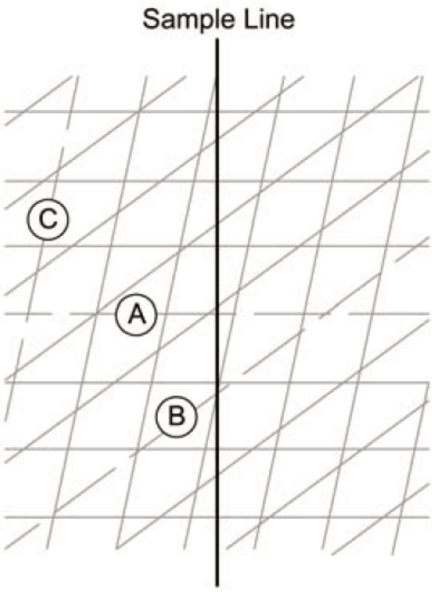


Figure 12 Sampling bias which under-represents occurrence of structures due to their intersection with the sampling line (Terzaghi 1965)

Televiewer data are subject to some forms of bias, and recognition of these biases and errors is important in characterising the distribution of discontinuities in the rock mass as the foundation for sound engineering (Fowler 2013). Figure 13 represents a borehole scenario with a simplified stereograph where the blind zone (where tool data may either be sparse or not recorded at all) is approximated by a light-grey shape. Based on Figure 13, the interpreter should bear in mind the following scenarios:

a) Blind zone on the east arising from a single drillhole drilled towards the west (1D array).

b) Northern and southern blind zones arising from drillholes drilled west and east (2D array).

c) No blind zone after drillholes are oriented to cover the entire 3D spectrum.

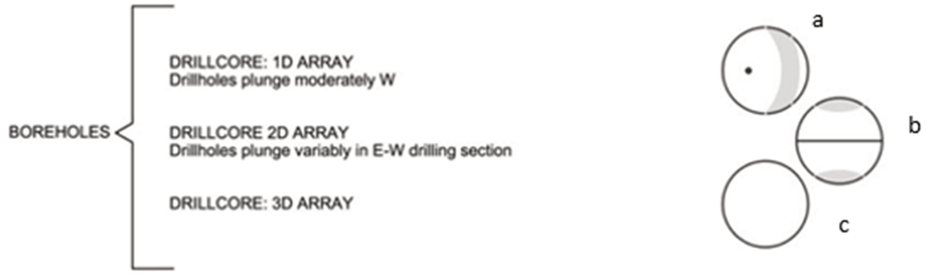


Figure 13 Blind zones for conventional borehole and mapping (after Laing 2005 in Fowler 2013)

Considering a planar feature (such as a fracture) intersecting a borehole, it will appear as a sinusoid on the 2D acoustic image. The amplitude of this sinusoid increases as the angle between the feature and the borehole decreases. For example, the upper fracture in Figure 14 intersects the borehole axis at ~7°and has a high amplitude sinusoid, whereas the lower fracture intersects the borehole axis at an angle of ~19° and has a lower sinusoid amplitude (Massiot et al. 2012). Fractures subparallel to the borehole will either not be intersected or will be systematically under-sampled as they are less likely to be intersected by the well (Barton & Zoback 1992 after Massiot et al. 2012). In addition, spalling from the borehole wall may occur due to the weakness of the rock at the low-angle intersection between the fracture and the borehole wall, preventing the detection of the fracture (Massiot et al. 2012).

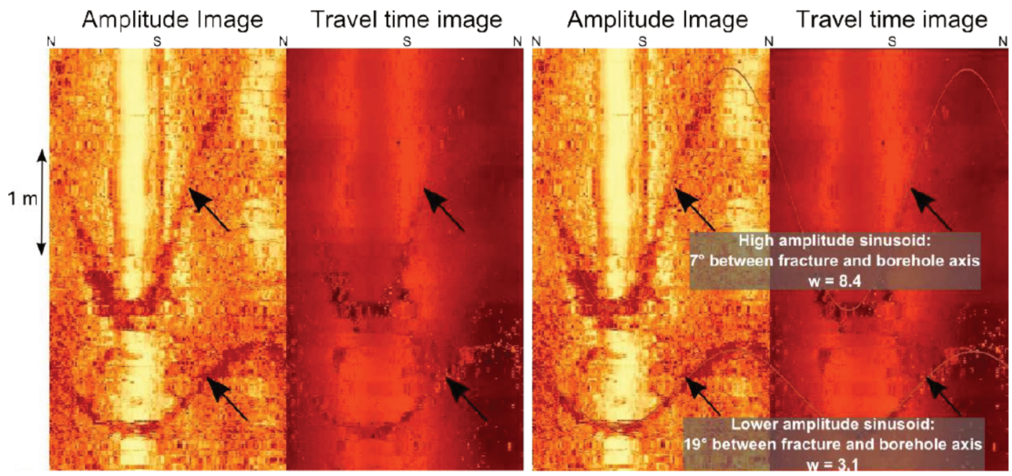


Figure 14 Acoustic images of fractures with various angles to the borehole axis images on the right display interpreted sinusoids (after Massiot et al. 2012)

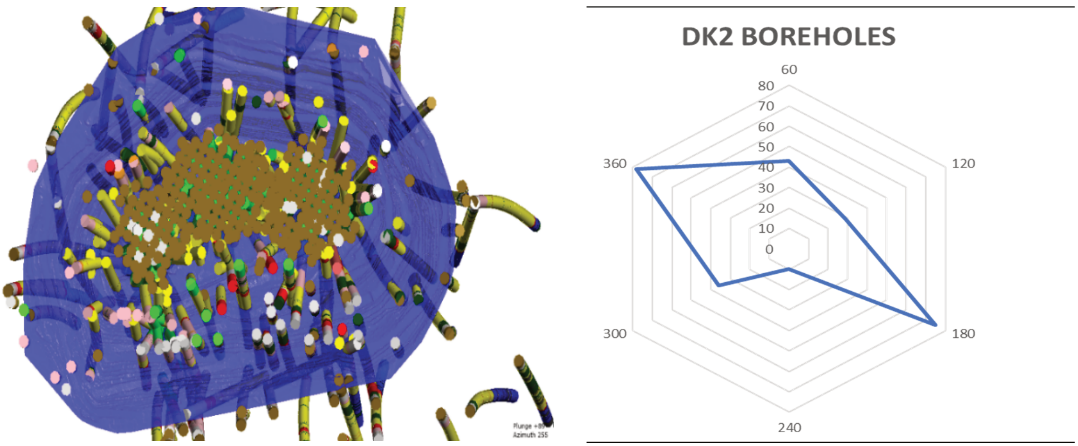
Interpreting televiewer data collected may result in the following:

- Under-representation of discontinuities parallel to the axis of the borehole.
- Blind spot caused by 1D sampling which will be normal to the drillhole direction, as shown by Figure 15a.
- Bearing in mind that mapping of discontinuities involves assigning a sine wave to the unwrapped borehole image, structures normal to the borehole axis are under-represented as the resulting defect is flat and sometimes difficult to assign a sinusoidal wave, as shown by Figures 15b and 15c.

(a) (b) (c)

Figure 15 (a) Blind spot indicated by light-grey crescent resulting from 1D sampling; (b) Sinusoidal waves showing that flat sine waves are more often missed during mapping; (c) An additional blind spot perpendicular to core axis resulting from structure normal to the core axis (Fowler 2013)

In order to properly assess the data bias from the boreholes, borehole orientation was divided into 60° bins and a stereo plot from each bin produced to assess if a data gap arising from the orientation of holes in relation to structures existed. The theory behind how this data gap comes about is detailed in the geophysics illustrations in Figure 13. Figures 16a and 16b show a Jwaneng Mine pit plan with drillholes and spider graph of the drillhole orientations respectively. Drilling has covered all directions, however, with relatively fewer holes in the 240° direction as can be seen in Figure 16b.

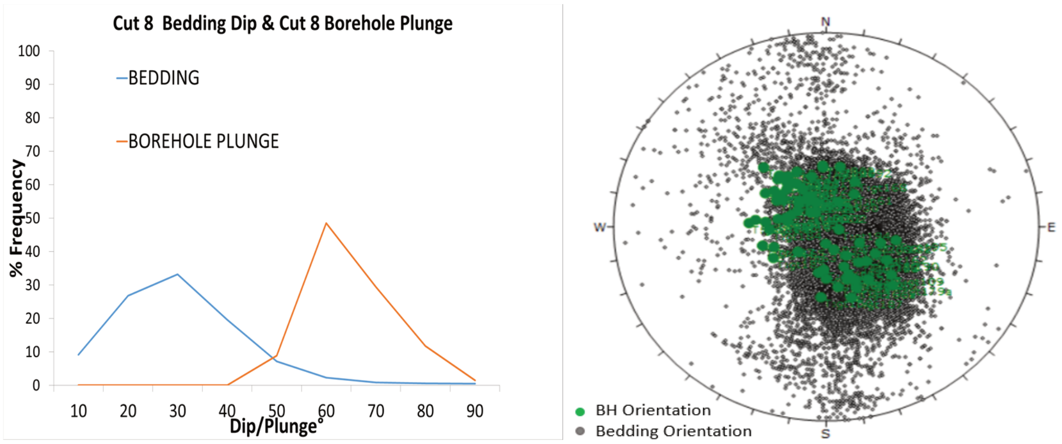


(a) (b)

Figure 16 (a) Jwaneng Mine pit with drillholes; (b) Spider graph showing number of holes per 60° orientation bin

4.3.1 Data bias assessment results

The eastern slopes (Cut 8) are characterised by daylighting bedding planes. These are the main structures' drive stability for the eastern walls. Any borehole steeper than bedding planes should be able to sample bedding irrespective of borehole direction in relation to bedding. Cut 8 holes are generally steeper than bedding; therefore. no directional sampling bias is expected (Figure 17). Possible bias can occur as a result of folding where only one limb has been sampled. This has been addressed in Section 4.2 where determination of the fold wavelength has been established and used to optimise sampling space to ensure that bias sampling is eliminated.



(a) (b)

Figure 17 (a) Histogram showing bedding dip and hole plunge for eastern walls; (b) Respective stereonet plot for bedding poles and drillholes plunge for eastern walls

The western walls (Cut 9) are characterised by shallow west-dipping bedding planes and east-dipping and high-angle faults which are non-daylighting. Despite the non-daylighting nature of the known modelled structures, any encounter of unfavourable faults and persistent joints during mining can result in a catastrophic failure if not detected proactively. It is therefore prudent that an assessment of directional bias on televiewer data is analysed in order to address the risk of encountering undetected unfavourable structures during mining. All televiewer discontinuity data from Cut 9 side holes was plotted in a stereonet in order to check if there will be any sampling bias detected. Directional sampling bias analysis for this holistic Cut 9 holes does not show any clear gaps on data as shown on the stereonet (Figure 18).

Considering the data coverage described, there is confidence that the design can be achieved with minimal risk associated with structural data. However, learnings from the performance of Cut 8 slopes necessitated the adoption of a dynamic mine design approach. The approach primarily looks at collection and reconciliation mine design inputs during implementation of the design at the micro (i.e. bench) scale. This ensures that risks and opportunities that could materialise due to changes on the inputs at the micro scale, potentially affecting the design, are proactively identified with the optimal solution identified. Assessment of micro-scale data gaps/bias that are to be addressed by design requires taking into account the position of the holes, in that holes drilled in a particular direction may be concentrated in one corner of the pit and their absence elsewhere will create a sampling bias with respect to that direction.

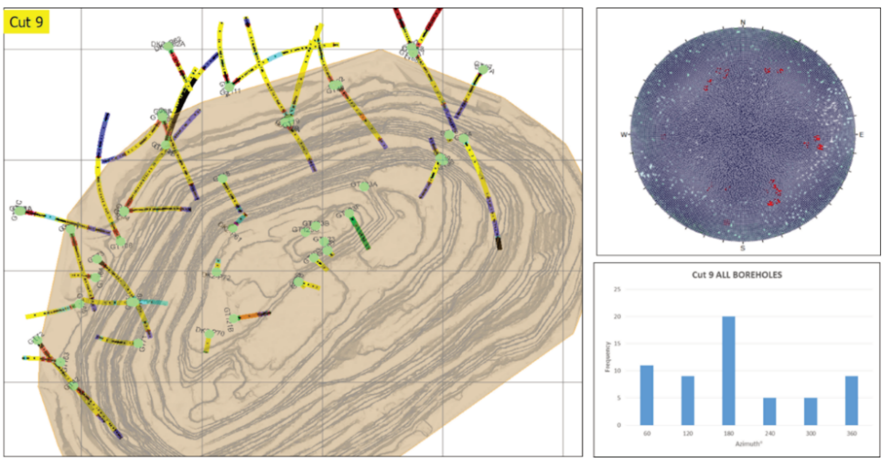


Figure 18 Overall stereonet plot for the Cut 9 drillholes and respective structural picks. There is no obvious bias detected from the stereonet plot

As mentioned previously, failure to take into account the position of the holes in relation to the pit shell may cloud directional sampling bias analysis. In order to address this, the Cut 9 design shell was subdivided into areas based on face orientation. Six areas were identified and data gap analysis performed per area. Figure 19 shows an example of directional sampling bias analysis carried out in Area 4 where all televiewer data in that area is plotted on the stereonet to check for any directional sampling bias. The stereonet plot shows a clear data gap for east-dipping structures arising from the fact that boreholes in this area were drilled towards the east. This then means new holes planned targeting the data gap on specific benches will be drilled towards the west.

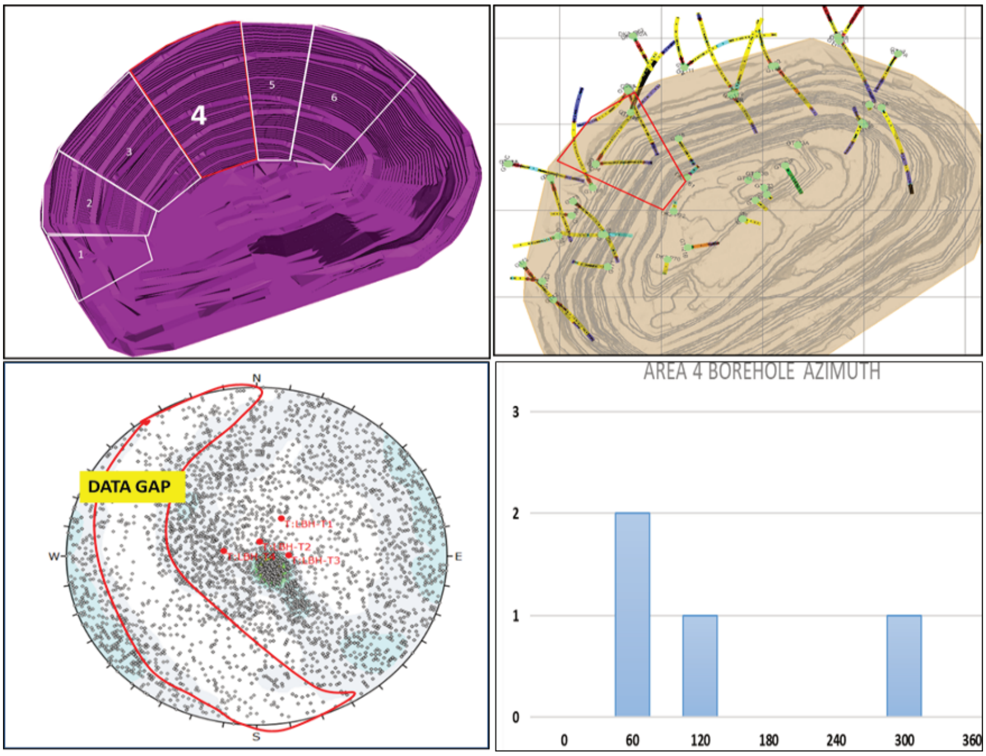


Figure 19 Cut 9 data gap analysis at Area 4 showing under-representation of structures dipping towards the east

As a way of assessing the impact of data gap picked per area on pit stability, each area's data gap was evaluated against the three failure mechanisms being planar sliding, toppling, and wedge failure. This gives an indication of which failure mechanism will not be detected due to that data gap. Taking Area 4 as an example, the possibility of planar sliding will be underestimated as the missing data (data gap) plots within the area are amenable for planar sliding (Figure 20).

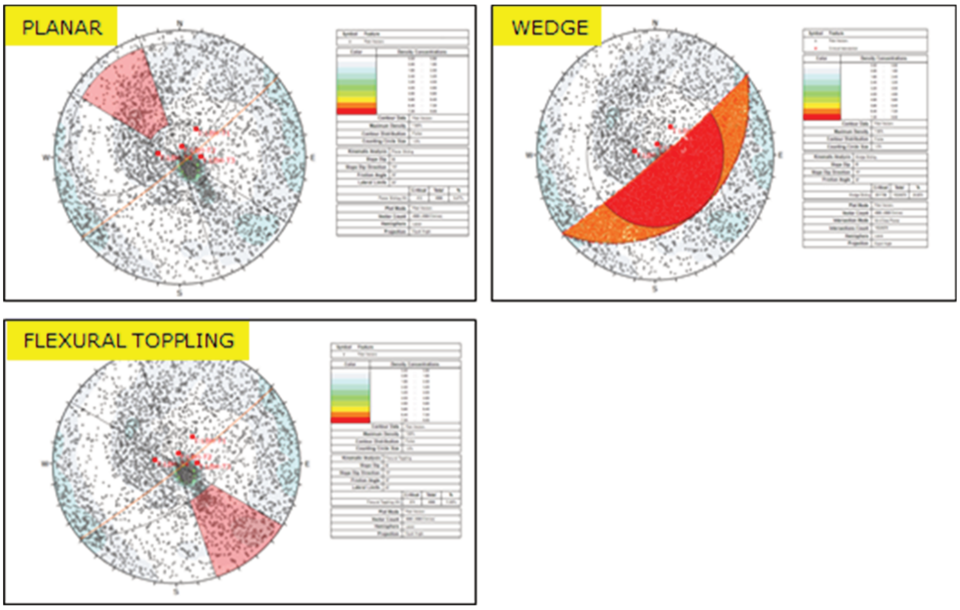


Figure 20 Kinematic analysis of Area 4 to identify the possible failure mechanisms

In line with the aforementioned data gap analysis performed on Area 4, the same approach was adopted across the remaining areas including evaluation of the failure mechanism impacted by under-represented structures. This exercise has allowed detection of under-sampled structures for each area, thereby enabling proactive intervention through planning holes targeting identified data gaps from this exercise. Figure 21 shows the drillholes planned to close the directional gaps on the Cut 9 slopes from all six areas. It is important to highlight that these holes will be drilled in phases as the design is excavated in line with the dynamic design process (i.e. drilled at different elevation with the data used to reconcile mine design inputs and proactively assess risks and opportunities).

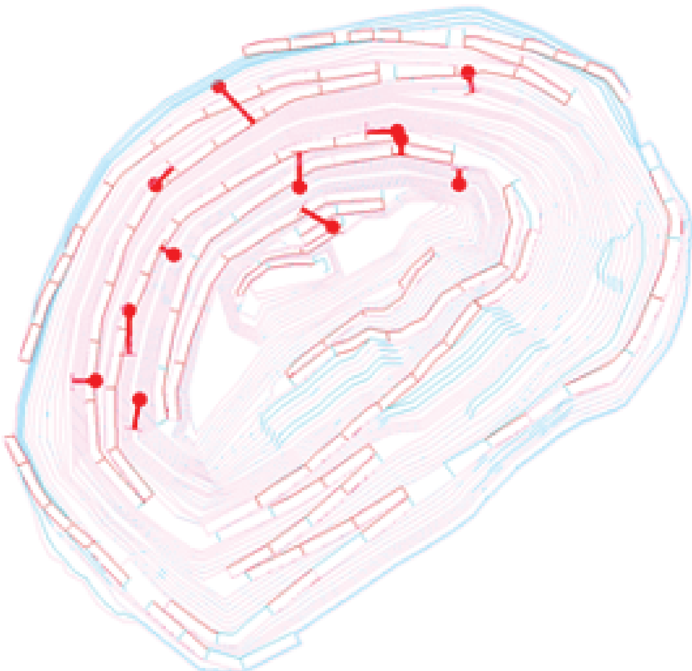


Figure 21 Boreholes planned to address the identified directional sampling data gaps on the western slopes

5 Conclusion

The reliability of the geotechnical model is critical to ensuring the life-of-mine objectives are attained. There is inherent bias in all methods of collecting geoscience information, and advancement in technology such as digital mapping and borehole imaging can assist in mitigating these issues. A combination of all available data collection techniques and datasets is recommended as this allows augmentation of data to address any gaps that might arise. Assessment of data confidence should be undertaken at all stages of the life-of-mine and with increased knowledge, such assessments should be refined. Assessment of data bias has enabled identification of existing gaps which informed targeted data collection programs aimed at closing the aforementioned gaps, and subsequently improve the confidence of the current geostructural models for the Cut 8 and Cut 9 slopes. The approach undertaken at Jwaneng Mine has afforded the operation to assess the requirements for construction of the geotechnical model and provides a mine design of high confidence that will ensure the life-of-mine plan is attained.

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