Streamlining Geotechnical Slope Reconciliation for Open Pits: a Slope Optimization and Recommendation Approach at Brockman 2 Operations in the Pilbara Region, Australia

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Abstract

Geotechnical slope reconciliation is driven indirectly by legislative framework of most advanced jurisdictions to meet regulatory requirements, firstly on personnel safety and secondly mining production. This has also become organisational culture for some mining industries to promote and improve its own internal safety practices as well as ensuring economic recovery of out of design resources to limited data and conservative slope designs. Over the years, many iron ore mines in the Pilbara region of Western Australia have acquired enough primary geotechnical data through numerous site investigations for ground characterisation including; geology, rock mass, structures and groundwater conditions. Geotechnical information such as rock mass shear strength parameters of the Brockman Iron Formation (BIF) in Pilbara are known in different operations of generally having similar properties. However, capital expenditure for drilling for new data is increasing for new projects with similar geotechnical and geologic resembles to those mined over 50-year period. Mining companies today are reviewing the traditional ways of acquiring data for new projects by utilising bench progression mapping data for slope optimisation and geotechnical risk management to minimise capital cost through systems such as geotechnical slope reconciliation. Acquired bench face mapping combined with historic drilling data could be utilised for new projects without compromising on quality but has great potential for saving cost. This paper discusses the framework for geotechnical slope reconciliation for open pit practitioners adopted at Brockman 2 operations owned by Rio Tinto in Western Australia. The paper focuses on three areas and methodology used for two open pits in Brockman 2 operations namely the BS2 and Pit 7 pits. A successful reconciliation process for achieving additional ore recovery in Pit 7 and geotechnical risks management in BS2 are discussed.

Keywords: Geotechnical Reconciliation, Optimisation, Risk Management, Streamlining, Benefit, Process Model

1 Introduction

Brockman 2 is one of the mining operations owned by Rio Tinto. It is located in the Pilbara region of Western Australia, about 60 km northwest of Tom Price, some 1500 km from Perth. The operation commenced in 1992, that led to the mining of shallow high grade called the Brockman detritals ore deposits. Over the years the operation has advanced to mining of high-grade deposits in deep open pits in order of 200 m to 300 m deep and below ground water table.

The average production rate is approximately 55M tonnes per annum and as part of high-grade source for blending, the lower grades ore from other mines of the company. Over 45 automated and manned production fleets operate side by side in the pits for ore hauling. The mine consists of over thirteen (13) operating pits including BS2 and Pit 7 some of them having strike length ranging from 0.5 km to 5 km.

The introduction of comprehensive geotechnical pit wall mapping campaign and effective data collection for slope reconciliation purposes at the time in Brockman 2 operations led to a considerable input into the management of geotechnical risks and economic gains of the mine. Geotechnical slope reconciliation is a continuous process that involves the collection of data from excavated slope bench face and comparing to the designed input parameters in addition to the pit design models to identify opportunities for slope optimisation and/or improving geotechnical risk management in open pit.

In determining risk sectors in open pit, geotechnical domains are first defined using appropriate investigation results such as input rock properties and interpretation of engineering geological model. The domains must relate to site geological model and boundaries interpreted based upon existing pit wall conditions using engineering geological judgement. This approach is adopted in mine slope reconciliation where the pit walls are categorised into geotechnical domain of different risk sectors based on the performance of the slopes, interpretation of slope monitoring results and analysis of operable rock mass properties. The conformance between design and as-built in BS2 and Pit 7 was assessed from:

- Pit wall geometry
- Structural orientation data and
- Rock mass parameters

This paper highlights on the methodology involved in slope reconciliation adopted at the Brockman 2 operation that the author was involved to make informed decision when dealing with instabilities and for slope optimisation process.

2 Case Study

The case study discusses the framework for geotechnical reconciliation to adequately manage geotechnical risk and determine the most appropriate process of collecting geotechnical data as mining progress leading to suitable slope remediation in an event of slope failure.

2.1 Geological Setting

Brockman 2 is located within the regional Hamersley Province. The Hamersley Province is about 2500 m thick and comprise of sequence of marine sedimentary and volcanic rocks of Late Archean to Palaeoproterozoic age Hayman (2020). The Hamersley comprises of five iron banded stratigraphic sequence including Brockman Information (BIF) and Marra Mamba Iron Formation of the Brockman 2 area. The Brockman Iron Formation is approximately 500 m to 620 m thick and comprised of Yandicoojina and Whalebacks Shales, Jeffery and Dales Gorge Members, The Mt McRae and the Foot Wall Zone formations are other group of rock types that sit below the BIF in the Hamersley sequences of Brockman 2 area. The Dales Gorge (DG) Member comprises the following rock types, DG1, GD2, DG3 and different thin shale layers. Figure 1 shows the stratigraphic sequence of the Hamersley Province and Brockman Iron Formation (Wedge *et al.*, 2010).

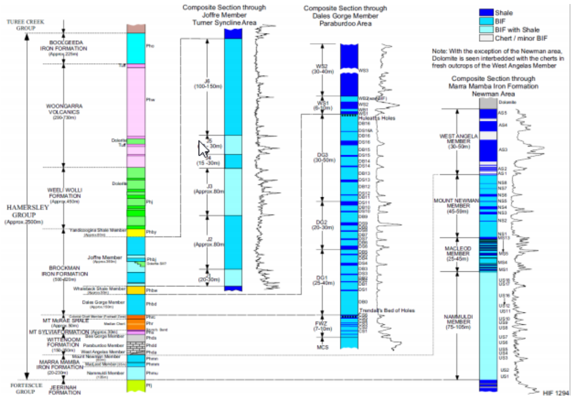

Figure 1 Stratigraphic Units, Subdivisions, and Gamma Responses for the Hamersley Group (Wedge *et al.*, 2019)

2.2 BS2 Pit

The Brockman Syncline 2 pit (BS2) was developed in a synform structure of north-south direction. The north wall of the pit was designed at an overall height of about 120 m high with multiple slope configuration of 55° to 50° batter face angle (BFA), 20 m to 10 m bench heights and 5 m to 12 m wide berm in places. The north wall consisted of a shallow to steep folding McRae Shale (MCS) and a Foot Wall Zone (FWZ) confined in the north limb of the syncline. The north walls encountered many stability challenges induced by blasting, mining and the interaction of weak geological contacts and pore water pressure.

The overall design height of the south wall was planned at 210 m deep with different slope design configurations. The first 50 m inter-ramp slope from 730 mRL to 680 mRL was designed as 10 m benches / 70° BFA and 5 m berms. The middle slopes were designed at 20 m benches with 65° and 70° BFA to 580 m RL. The last 40 m slope to 540 mRL was changed to 10 m single benches and 5 m wide berm to manage instability that emerged from over steepened of the top benches. The south wall was formed in hydrated hard to friable Dale Gorge Member (DG) units with shallow to moderate dipping structures.

The south wall experienced geotechnical stability issues as a result of undercutting of pervasive bedding planes, aggressive BFA and unknown deep-seated fault and tension crack at the back of the slope. The medium-term planning at the time decided to mine beyond the planned depth of 540 m RL to 520 m RL to contribute to ore balance. The geotechnical assessment conducted to back this decision increased potential slope failure risk from medium to high. In addition to the data collected from routine geotechnical mapping, arrays of slope monitoring instrument were implemented to manage the geotechnical risk associated with the design changes. Two slope stability radars (SSR) Groundprobe and Reutech were deployed, each monitoring the south and north walls in addition to using automated prisms monitoring systems for both walls. The groundwater condition in the pit walls was monitored using standpipe piezometers whiles lowering the water level by high head dewatering pump from the pit bottom.

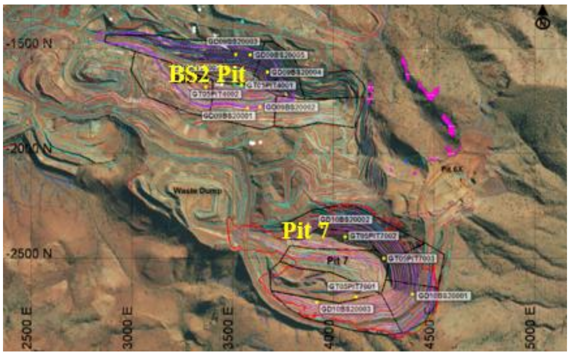

Figure 2 Location and Overview of BS2 and Pit 7 with Overlain Risk Sectors

2.3 Pit 7 Pit

The overall heights of the north and south walls of Pit 7 were designed at 140 m and 260 m deep respectively, within similar stratigraphy as the BS2 pit. A combination of single to double benches was recommended in the design. The 10 m benches around the pit started from the 920 m RL to 860 mRL and 20 m bench heights from 860 m RL to 780 m RL with varying berm sizes of 5 m, 8 m and 10 m wide leading to different inter-ramp slopes configurations. From 780 m RL to the final pit depth, the slopes were designed at 10 m high benches keeping slope angles and berm sizes as above. The BFA of each inter-ramp were designed at 65° for both single and double batters. Most of the slope was formed in Dales Gorge units, DG1, DG2 and DG3. The as-built pit geometry of Pit 7 performed to geotechnical requirements with little slope instability issues. The geotechnical performance was measured by the outcome of routine bench face mapping and implementation of slope risk management through automated prism monitoring systems. The potential steepening of the lower benches for optimal ore recovery was assessed using limit equilibrium (LE) and numerical analyses to study the mechanism of potential slope failure.

3 Methodology

3.1 Slope Sector Risk Domaining

At Brockman 2 mine, each sector of the pit walls is first categorised into various geotechnical domains, which are defined using appropriate rock input strength properties, interpretation of engineering geological/structural model and analysis of slope deformation results obtained from slope monitoring (e.g. radar and prisms) as well as hydrogeological conditions. Any identified geotechnical risk sector requiring geotechnical design review are required to undergo ‘geotechnical risk assessment’ using adequate mapping and drillhole (e.g. oriented Televiewer data). In general, the risk sectors are defined in the pit as areas that have similar geological and hydrogeological conditions or risk. In this paper, eight risk sectors were assessed for reconciliation. There were four risk sectors in BS2 Pit namely, GSRSBS201, GSRSBS202, GSRSBS205 and GSRSBS206 (Figure 3). The risk sectors assessed in Pit 7 are GSRSBS208, GSRSBS209, GSRSBS210 and GSRSBS211 (Figure 4).

In selecting these risk sectors, geotechnical bench face mapping was conducted. The data was combined with available orientation data from drilhole and Televiewer historically drilled through each sector to account for spatial variability of discontinuity orientation, persistence and spacing. Additional data include geological structural model, groundwater and pore pressure measurements from (vibrating wire piezometers) VWP bores. These measurable indicators aligned with slope model inputs, which can be used to reconcile any new found or measured slope model parameters. The outputs of reconciling the design and as-built were used to determine the degree of conformance and non-conformance using heatmap format. The slope risk sectors showing the distribution of drillholes versus areas mapped for the reconciliation campaign are presented in Figure 3 and 4.

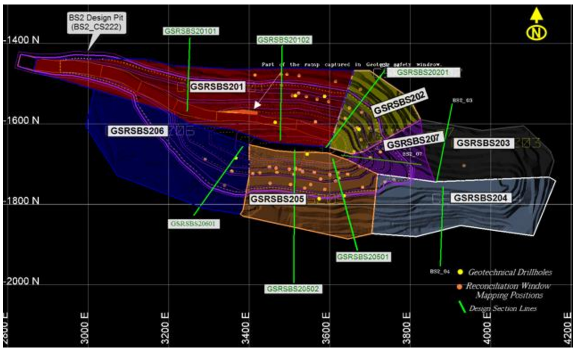

Figure 3 BS2 Risk Sectors Showing Face Mapping and Drill holes Information and Cross Section Lines

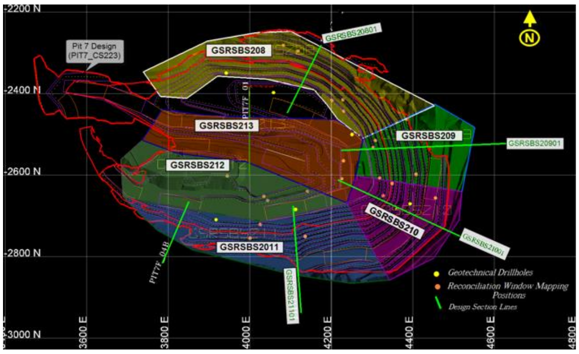

Figure 4 Pit 7 Risk Sectors Showing Face Mapping and Drillholes Information and Cross Section Lines

3.2 Bench Face Mapping and Analysis

The rock mass discontinuity data were obtained using the modified strip window mapping method. This technique samples a strip of window within the reach of the sampler where physical properties of discontinuities are measured. The maximum strip height of the mapping window is normally based on the height of sampler. The preferred length of the strip window is generally assumed to be the start to end of identified risk sector of every bench. The section of the window above the reach of the sampler is considered as an observation window where no physical joints data are measured. Discontinuities within the observation window could only be described, which can vary in a short space hence introducing biases to strip window samples. However, recent technologies like laser scanning and photogrammetry are sometimes used to obtain data from risk related and inaccessible areas such as areas above the sampler in strip window mapping. Figure 5 is an overview of the modified strip window mapping showing the strip and observational windows in bedded slope face in one of the Brockman 2 operations. Strip mapping techniques remove some of the challenges of conventional mapping methods in bedded geological deposits. One advantage is mapping a dip slope face where dozing techniques are commonly used leaving debris to cover potential discontinuities for mapping.

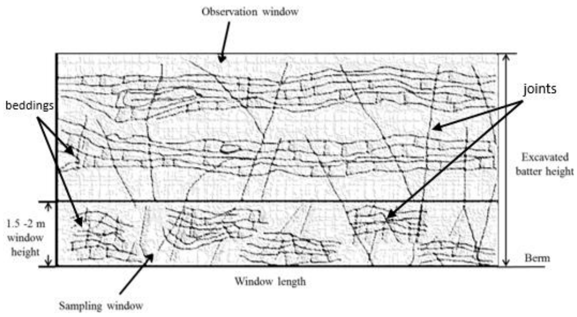

Figure 5 Modified Strip Window Method Used in Mapping BS2 and Pit 7 Anisotropic Rock Mass

The field structural orientation data of BS2 and Pit 7 pits were plotted on stereonets for the risk sectors or window mapped area. The discontinuity orientation data from dillholes used for designing the pit are stereographically analysed and compared with the pit wall mapping data. The average dip and dip directions of major discontinuity sets were determined. A conformance was evaluated using ±10° tolerance to measure dip and directions variation of the orientated data sets. Figure 6 shows an overview of stereographical projection of the bench face mapping and drillhole data.

Table 1 Summary of total measured discontinuities data mapped to verify design structural model in each risk sector of both pits.

RASS	Total design boreholes structural measurements		Total mapping (measured) structural measurements	
	Bedding (BG)	Joints (JN)	Bedding (BG)	Joints (JN)
GSRSBS201	178	79	212	210
GSRSBS202	70	57	150	128
GSRSBS205	330	121	432	101

GSRSBS206	41	37	127	9
GSRSBS208	334	102	78	45
GSRSBS209	190	67	89	60
GSRSBS210	263	89	76	55
GSRSBS211	298	69	28	57

Generally, Pit 7 main structural orientation sets dipicted good corelation with observed mapping oreitation data and those used in designing the pit. Th dip and direction of the BS2 structures indicated high varition than expected. The orientstion of the bedding sets of the mapping data had appeared steeper dipping than the design. The major set misaligned more than 10° on the south wall of BS2. The data sets of both pits also indicated different population densities on the stereonets which were not picked in either the design or the measured.

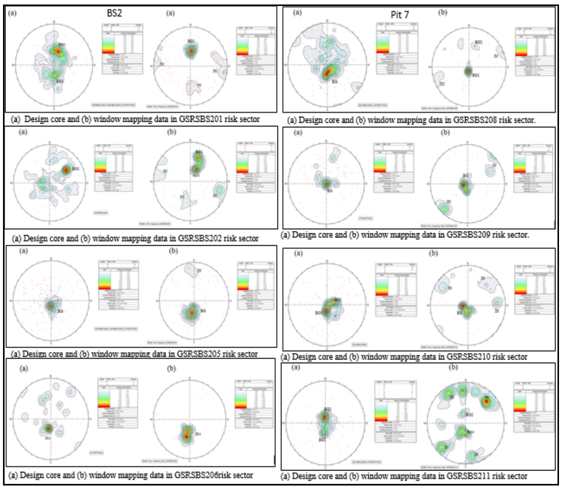

Figure 6 Stereographic Presentation of Measured Mapping and Design Drill hole Orientation Data of BS2 Pit and Pit 7. Design and Measured Data Denoted By (a) And (b) Respectively By the Risk Sectors

3.3 Pit Wall Geometrical Conformance Analysis

The degree of geometrical deviation between the survey as-built pit and design models are generally done in computer-aided applications such as Maptek Vulcan or I-site, Surpac, Datamine and many others. Some of these applications have advanced plug-in modules that can produce heat maps or thematic layers for highlighting areas of batter and berm losses of the pit slopes. In this paper, Excavation Compliance Indicator (ECI) application concept after Seery and Lapwood (2007) was used. The ECI is a tool for measuring batter-berm deviations and capable of providing statistical analysis and charts. The ECI tool requires two compactible *"dxf"* file formats of the design and as-built pit models. The generated output files are based on sets input tolerance values. Acceptable tolerance values for batter-berm conformance are generally site specific based on cumulative average performance. The selected range were in alignment with batter check standards agreed between site geotechnical team, mine planning and more or less corporate technical team to manage ore losses and geotechnical risks. One challenging factor of not meeting the site-specific tolerance values in any software application is the limitation of minimum value of each parameter to produce desirable heat map. Three conditions for setting geometrical tolerance values in order to produce an output heat map in ICE were:

- As-built batter angle steeper or shallower than the design BFA acceptable range.
- As-built berm width ahead or behind the design berm and too narrow to serve as catch capacity.
- As-built bench floor/height condition lower or higher than the design

Table 2 Tolerance range used for measuring geometrical conformance based on bench heights of the pits

Area	Tolerance	Deviation from Design	
BFA	+/-6^{o}	<6^{o}	> 6^{o}
Berm	+/-2.0 m	<2.0 m	>2.0 m
Crests	+/-1.0 m	<1.0 m	> 1.0 m
Toes	+/-1.0 m	<1.0 m	> 1.0 m
Batter Height	+/-1.0 m	<1.0	>1.0 m

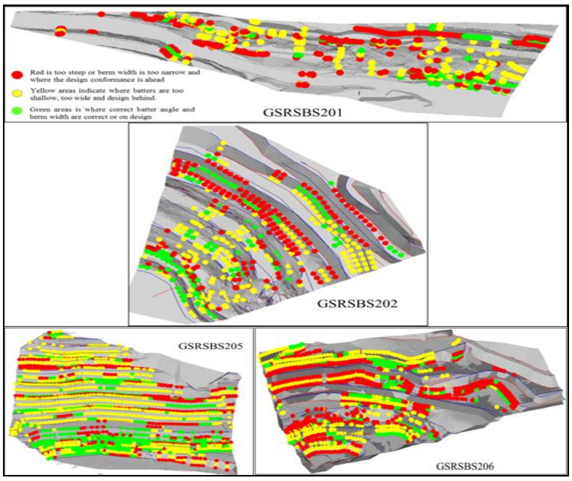

Figure 7 BS2 Pit ECI Heat Map Results by Risk Sectors

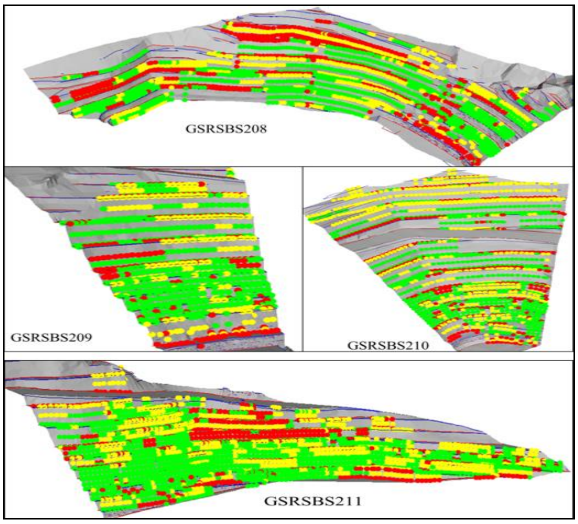

Figure 8 Pit 7 ECI Heat Map Results by Risk Sectors

Table Summary of BS2 and Pit 7 overall batter and berm geometrical conformance by risk sectors

Pit Name	Risk Sector	Design Mean BFA (°)	As-built Mean		Design Mean Width (m)	A-built Mean	
			BFA (°)	Std Dev		Width (m)	Std Dev
BS2	GSRSBS201	55	47	8.4	11	6	4.1
	GSRSBS202	55	48	5.8	9	7	3.2
	GSRSBS205	65	59	6.1	10	8	3.2
	GSRSBS206	65	53	8.9	19	14	10.3
Pit 7	GSRSBS208	65	59	6	9	7	2.4
	GSRSBS209	65	60	3.1	8	6.4	1.7
	GSRSBS210	65	59	4.3	7	6	2.6
	GSRSBS211	65	59	4.7	6	5	1.8

3.4 Rock Mass Conformance

The measured rock mass parameters and characteristic of the discontinuities from the bench excavation face are individually verified against inputs design properties. A simplified equation expressed in percentage was used to check variation in the data sets to generate a rock mass parameters heat map. The output of the as-found parameters being better, same or worse to the design may lead to a review of design input material proprieties to address conservative slope design, Owusu-Bempah (2014).

$$RMP\ Conformance = \frac{(Design) - (Measured)}{(Design)} x100$$

where RMP is rock mass parameter.

The measured rock mass parameters include, intact rock strength (IRS) UCS, geological strength index (GSI), rock quality designation (RQD) and rock mass rating (RMR_{89}).

Table 3 Tolerances values set for verifying rock mass parameters

Reconciliation Outcomes		Colour Code	Rock Mass Properties (IRS,RQD%,GSI,RMR_{89}) Range (%)
Better	Optimise	Blue	> +10%
Same	Continue Mining	Green	+/- 10%
Worse	Remediation	Red	< -10%

The interpretation of the rock mass parameters outcomes is explained below;

- Better results (Blue)
- Same results (Green)
- Worse results (Red)

Table 4 summarises the average difference of rock mass parameters of the geological units in BS2 and Pit 7 pits. The rock mass assessment was done for each risk sector using measured mapping and design drillhole data. The variations in the field mapping and design rock mass data are indication of potential slope design review for fact that new rock mass shear strengths parameters could be derived using bench face mapping data where the outcome becomes more favourable than expected. Potential new shear strength parameters could then be used to recalibrate the stability models to review the safety factors of the pit walls.

Table 4 Summary of mean measured and design rock mass parameters showing percentage deviation

Rock Mass Units (RMU)	Design Data (Core)				Window Mapping Data (As-built)				Difference (%)			
	UCS Est (MPa)	ROD%	GSI	RMR_{89}	UCS Est (MPa)	ROD%	GSI	RMR_{89}	UCS Est (MPa)	ROD%	GSI	RMR_{89}
J1	8	10	36	41	75	10	42	47	+837	0	+17	+15
WS1	23	15	45	50	3	28	38	43	-87	-87	-16	-14
DG3	41	35	46	51	23	11	47	52	-44	-69	+2	+2
DG2	18	12	37	42	51	51	49	55	+64	+75	+32	+31
DG1	30	25	43	48	19	19	40	45	-37	-24	-7	-6
FWZ	5	24	39	44	32	36	46	51	+86	+50	+18	+16
MCS	17	27	47	51	16	21	39	44	-6	-22	-17	-14

4 Results and Discussion

As observed from the assessment areas, by comparing measured/as-found and design data, the performance of the three areas in this paper warranted for the completed remedial actions for BS2 and slope optimization opportunity in Pit 7. Sections 4.1 and 4.2 discuss reconciliation benefits for optimisation in Pit 7 and remediation in BS2 pit.

4.1 Pit 7 Slope Optimization

The bench face structural orientations were observed to show consistent dip and directions with less bias. The measured mapping sets depicted distinctive position on stereographic projection as compared to the design drillhole or televiewer data. The rock mass parameters in Dale Gorge units had come more than expected or met the design expectations in most of the risk sectors as shown on the pit walls and in Table 4. Figure 9 represents as-built geometry of Pit 7. Also as indicated in Table the overall geometrical performance of the pit showed good conformance or better. Three risk sectors showed positive results of the four areas assessed, giving an opportunity to optimise the slope to recover high grade blocks. The last 30 m from 730 m RL to 700 m RL in the risk sectors GSRSBS209 and GSRSBS210 were optimised. The BFA of the two risk sectors were changed from 65° to 75° to increase the inter-ramp slope angle by 2°. This yielded an extra 63,000 tonnes of high-grade ore in the block model, with a price value approximately $7.5M. Figure 9 shows the overall slope performance of Pit 7 and optimised benches below the dashed yellow line.

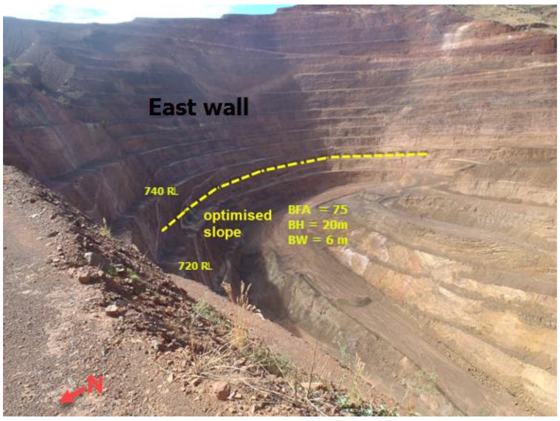

Figure 9 Pit 7 Slopes Performance and Optimised Last Benches in Dales Gorge Units

4.2 BS2 Slope Remediation

Series of slope remediation were undertaken in BS2 pit to manage the risk of both south and north pit walls. The geometrical conformance of pit as-built in risk sectors GSRSBS2001 and GSRSBS2006 under performed while GSRSBS2002 and GSRSBS2005 moderately performed against the design as shown in Table . The risk of the north wall was characterised by about 85% predominant unfavorable and delicate black and white McRae Shale (MCS). In addition, a weak contact of the MCS with Foot Wall Zone (FWZ) in the middle of the ramp. The result of the MCS was poor and lower than expected as shown in Table 4. The risks were mitigated by introduction of number of factors including;

- Routine geotechnical pit slope reconciliation mapping to understand the structures, rock mass and wall performance.
- Implementation of control blasting techniques such as un-stemmed buffer holes, easer holes, pre-shearing blasting, small hole diameter, adjustment of burden and spacing and post blast inspections for blast design reviews.
- A dip slope (30°) was introduced from 575 mRL to 520 mRL by mining the Foot Wall Zone and McRae shale contact to prevent potential undercutting below the ramp. As a result of the dip slope, a single lane was introduced along where the contact daylighted the ramp.
- Slope design modification on the south wall slope was reviewed from 540 mRL to 520 mRL by changing double batters proposed by mine planning to single benches and reducing the inter-ramp angle of the goodbye cut.

Figure 10 shows BS2 north and south walls pit floor level at 530 mRL at the time of this assessment. Mining was still progressing from 530 mRL to 520 mRL. A sump for managing elevated ground water level on the pit floor was established for pumping.

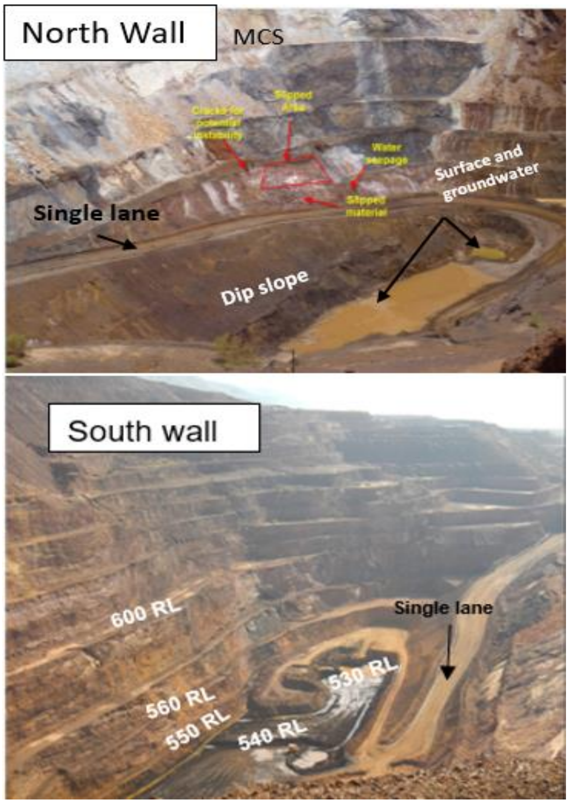

Figure 10 BS2 Pit North in McRae Shale (MCS) and South Wall Dales Gorge (DG) BIF Unit

4.3 Robust Slope Reconciliation Process Model

The outcome from the BS2 and Pit 7 reconciliation process facilitated three results in this paper based on interpretation of the bench face data, geological conditions, mining excavation and blasting. The three results include:

- Better results (Blue) – optimise by increasing design BFA.
- Same results (Green) – continue mining and adopt data for future references or attempt to optimize.
- Worse results (Red) – remedial action for geotechnical risk management.

A better result may indicate an opportunity for slope optimisation by steeping the pit walls. When there are no observed changes between the design assumption and measured data, then the design of slope is achieved as expected. In the case of the design becoming the same as the as-built, a safe and mining process can continue. This situation gives an opportunity to steepening the walls or attempt to optimise the slope. The worse than expected results derived from reconciliation process may indicate a design modification for possible geotechnical risk mitigation or remedial actions.

The three derived results from the reconciliation process bring the process into a close loop. Further investigation may be required to use in situ data for long-term design change in advance of mining.

The slope model inputs are initial processes for open pit slope designs before implementation stage. These input models can be recalibrated to reconcile any measured bench face data. The geotechnical slope reconciliation starts when the pit design is approved for site implementation. Figure 11 shows robust slope reconciliation process model that can be followed in open pit mining.

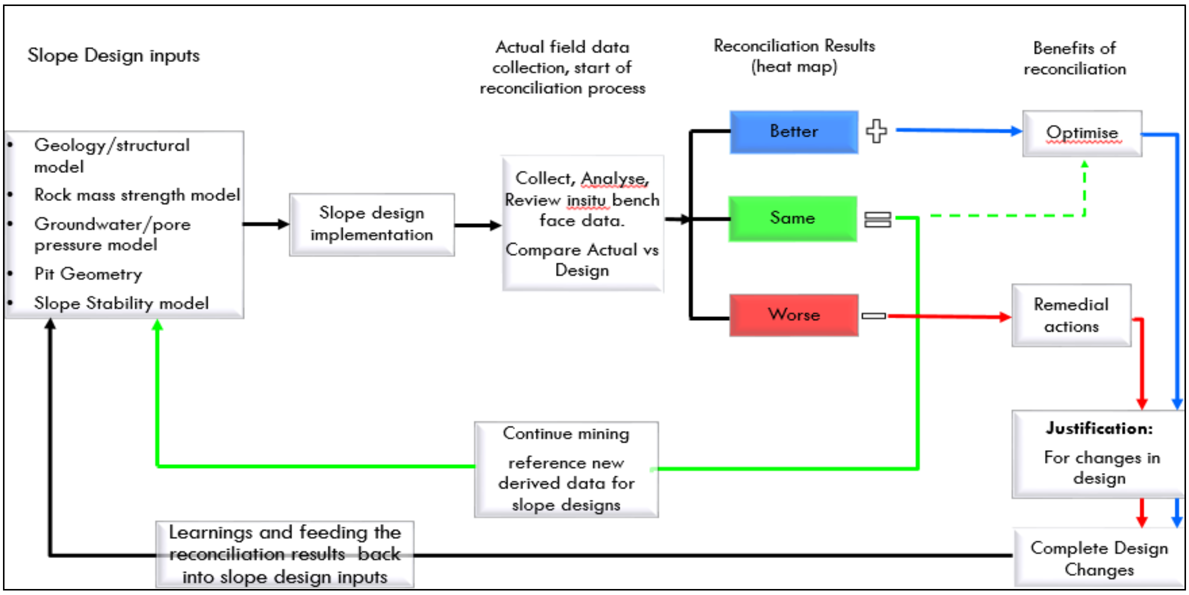

Figure 11 Robust Geotechnical Slope Reconciliation Process Model

5 Conclusions and Recommendations

As shown in the three assessment areas, geotechnical slope reconciliation is an approach to progressively evaluate the in-situ rock mass, geological structures and ground water conditions and excavated pit wall performance to manage geotechnical risks in open pit operations. Geotechnical reconciliation process aligns with "Section 13.8 of the Mine Safety and Inspection Act (1994), Mine Safety, and Regulation Act (1995)" of Western Australia.

The implementation of geotechnical slope reconciliation in open pit is value adding while aligning with regulatory requirement of some jurisdiction on geotechnical engineering. The results of slope reconciliation in this study have highlighted reliability of the measured orientation and rock mass data and must be used in slope design change process.

The benefits gained from slope reconciliation:

- Provided credible data that allowed engineers to effect required slope design changes.
- The measured structural orientation data shown in the interpretation depict distinctive structural model for accurate design making decisions thereby reducing conservative slope designs
- The reconciliation model in Figure 11 provides a framework for mine geotechnical engineers for value adding into short and medium term plans.

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