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Key outcomes of functional benchmarking for waste rock landform closure at a Western Australian iron ore mine

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Abstract

The initial closure design for a waste rock landform (WRL) at an iron ore mine in the Mid West region of Western Australia (WA) was based on a traditional linear slope design, but this changed to a concave slope design when new studies demonstrated that this would provide better long-term stability and protection against erosion. As the use of concave slopes in WRL closure is still relatively new in WA, and tall concave slopes are not common in the Mid West region, a benchmarking study was conducted to increase stakeholder confidence in the revised closure design.

The benchmarking study examined key lessons from six mines in WA where tall concave slopes had been implemented or were proposed as part of WRL closure, and six mines where linear slopes had been implemented or were proposed. The latter sites were included to provide information on WRL closure in the Mid West and adjacent Pilbara regions.

As a result of this study, it was found that a high standard of WRL closure implementation occurs when waste rock and topsoil characterisation, closure risk assessments, surface drainage studies, erosion modelling and other investigations are conducted as part of closure planning. Further, it was found that the likelihood of achieving acceptable WRL closure outcomes increased significantly when well-qualified and experienced operators along with an appropriate fleet were utilised for the closure earthworks, and careful attention was paid to construction controls and tolerances.

The outcomes of the study were used to refine the closure risk assessment and risk management measures proposed for WRL closure at the iron ore mine for which the benchmarking was conducted. Subsequently, the revised WRL closure design and an updated Mine Closure Plan were approved by the WA mining regulator. In issuing this approval, the regulator stated that the exercise was "particularly useful and should be encouraged throughout industry' and was a 'potentially powerful agent for use in mine closure [planning]".

This paper summarises the benchmarking methodology and discusses the key findings of the benchmarking study, including the main success factors and key challenges associated with the use of concave slope designs in closing WRLs. The way in which the study outcomes were used to refine the WRL closure design and closure risk assessment for this iron ore mine is also discussed.

Keywords: *waste rock landform closure, functional benchmarking, iron ore mine closure*

1 Introduction

The original closure design for a waste rock landform (WRL) at an iron ore mine in the Mid West region of Western Australia (WA) was based on a traditional linear (bench/berm) design. However, as a result of additional mine closure planning studies including waste material characterisation, it became apparent that a concave slope design would provide better long-term stability and protection against erosion. Consequently, it was proposed that the WRL closure design be revised so that the final landform would comprise a series of concave slopes, the tallest of which would be 80 m in height. It was proposed that the upper 50% of the slope height would be at 20° and the lower 50% of the slope height at 15°. These would be trimmed to form a smooth concave slope with no sharp hinge points and an overall slope angle of 17.5°. Surface water management features comprising storage areas on the top surfaces of the WRL were included in this landform's closure design. These features were designed to contain at least one in 500-year Annual Recurrence Interval (ARI) events with appropriate spillover points. Drains were also designed to at least a one in 500-year ARI.

The revised WRL closure design was presented to the then WA Department of Mines and Petroleum (DMP) (now known as the Department of Mines, Industry Regulation and Safety [DMIRS]) in June 2015. The DMP was generally accepting of the revised design but was uncertain about some aspects because the use of tall concave slopes in WRL closure is not common in the Mid West region or elsewhere in WA. Consequently, the DMP sought further information from the mining company (i.e. the proponent) on whether the design could be implemented successfully to increase its confidence that the proposed environmental outcomes could be achieved.

When uncertainty in mine closure planning is due to incomplete knowledge, it is recommended that a structured approach be adopted to obtain the additional information (Sánchez et al. 2014). This often includes field trials, but significant movement of different waste material types was needed to allow formation of any of the proposed concave slopes, which meant that, in effect, most of the landform would need to be reworked to create representative areas suitable for field trials. It was therefore proposed that a benchmarking study be undertaken instead of field trials to identify key success factors and challenges at those mines where tall concave slopes has been implemented, or were proposed, as part of WRL closure. Additional sites were included to provide information on WRL closure in the Mid West and adjacent Pilbara regions.

This paper summarises the benchmarking methodology, presents the key findings of the benchmarking study and discusses the way in which the study outcomes were used to refine the WRL closure design and the mine's closure risk assessment. It follows on from a paper on the benchmarking methodology presented at the 12th International Conference on Mine Closure (Finucane & Robinson 2018).

2 Methodology

The study described in this paper is a form of 'functional benchmarking' in which data on agreed parameters are collected and then compared to identify potential strengths and weaknesses, and to identify areas of improvement (Bhutta & Huq 1999; Ajelabi & Tang 2010; Charles & Wilson 2012). The study was conducted between July 2015 and December 2016.

As discussed in Finucane & Robinson (2018), the methodology used for this benchmarking study comprised five steps:

1. Determine what to benchmark.
2. Form the benchmarking team.
3. Identify benchmarking partners/sites.
4. Collect and analyse benchmarking information.
5. Take action by adapting, improving and implementing findings.

The first, and possibly most important, step in planning a benchmarking exercise is agreeing on the objectives of the study. For this study, the mining company, the DMP and Bioscope Environmental collectively determined that the objective would be to evaluate the use, or proposed use, of tall concave slopes designs for WRL closure at other sites in WA to identify key success factors and challenges. Further, it was agreed by these parties that a series of questions would be asked during the benchmarking exercise. These are defined by Finucane & Robinson (2018) as follows:

- What are the key factors that have contributed to the success or otherwise of rehabilitation and closure of tall concave slope WRLs?
- What are the key challenges experienced in rehabilitation and closure of tall concave slope WRLs?

- What are the lessons learned from the above that are relevant to the WRL at the subject mine site and could be used to improve its closure design?

The study team comprised representatives from the proponent and Bioscope Environmental. Once formed, the team designated the roles and responsibilities of each team member, determined the study milestones and defined a realistic completion date.

Step 3 comprised selection of potential benchmarking study sites. Following review of publicly available literature and discussions with the DMP, it was agreed that the benchmarking study would draw information from the following sites:

- Iron ore mines (existing or proposed) in the Mid West region.
- Iron ore mines (existing or proposed) in the Pilbara region.
- Mines exploiting different commodities in different regions of WA, but implementing concave WRL slopes.

Twelve mine sites were selected. Of these, six sites had implemented, trialled or proposed WRL concave slopes (Table 1). The remaining six sites had proposed to implement, or had implemented, linear closure designs. These sites were included in the study as they were able to provide useful information on WRL closure in similar environmental conditions and for the same or similar rock types (Finucane & Robinson 2018). It was considered by both the proponent and the DMP that this diversity of sites would provide sufficient information for the purposes of this study (Finucane & Robinson 2018).

Table 1 Study sites

Site	Region	Commodity	Concave slope implemented
Karara iron ore project	Mid West	Iron ore	No
Mungada East/Blue Hills extension	Mid West	Iron ore	No
Extension Hill hematite operation	Mid West	Iron ore	No
Mine A	Mid West	Iron ore	No
Mine B	Pilbara	Iron ore	No
Mine C	Pilbara	Iron ore	No
Mine D	Pilbara	Iron ore	Implemented
Mine E	Pilbara	Iron ore	Implemented
Telfer gold mine	Pilbara	Gold	Trialled
Coobina chromite mine	Pilbara	Chromite	Proposed
Sunrise Dam gold mine	Goldfields	Gold	Implemented
Wattle Dam gold mine	Goldfields	Gold	Implemented

Step 4 of a benchmarking study is 'perhaps the heart of the benchmarking process' (Butta & Huq 1999) as the process is devalued if the wrong information is collected. For the study described in this paper, it was determined that information would be collected on slope and drainage design parameters, erosion control mechanisms, revegetation strategies, completion criteria and rehabilitation performance (where known) for each of the study sites. These factors were selected as it was considered that the main controls for post-closure performance of the WRL for which this study was conducted were likely to be waste material type, rainfall patterns and revegetation.

The reason that the study was conducted is that the use of concave slopes is relatively new to WA and few sites have issued publicly available information on this technique. This means that literature that is directly relevant to this study is unfortunately, but unavoidably, limited. Information on the selected factors was sourced through a review of 19 publicly-available literature (AngloGold Ashanti 2009; Eco Logical Australia Pty Ltd 2016; Golos 2013; Howard et al. 2010; Hoy 2014; Jacobs Group (Australia) Pty Limited 2014; Karara Mining Limited 2015; Landloch 2011, 2012; Mount Gibson Mining Limited 2015, 2016; Newcrest Mining Limited 2013, 2015a, 2015b; Nie 2011; Process Minerals International Pty Ltd 2016; Sinosteel Midwest Corporation Limited 2016; SRK Consulting (Australia) Pty Ltd 2015; Tiemann & Wealleans 2015). Information on WRL closure at mines B-E collected during site visits by the proponent.

The literature cited above and notes from the proponent's site visits were reviewed to identify key success factors and limitations for WRL closure at the study sites. Key findings from the review were used to refine the concave slope closure design and implementation process proposed for the subject WRL. The outcomes of the benchmarking were also used as part of the closure risk assessment for the mine.

3 Results

The findings for each of the sites reviewed during this benchmarking study are summarised in Table 2. In summary, it was found that those sites where concave slopes designs for WRL closure had been implemented successfully had:

- Conducted risk assessments during planning phases.
- Conducted thorough modelling and testing of waste rock and soil materials to guide WRL closure design.
- Included a top surface water storage in the WRL closure design to reduce water flow down slope.
- Used rock armour to reduce the likelihood of erosion.
- Included topsoil in design of surface cover along with ameliorates such as fertiliser or gypsum to enhance vegetation establishment.
- Used qualified and experienced operators in the field.
- Ensured that construction controls and tolerances were observed.

Table 2 Key findings of the functional benchmarking study

Site	Region	Commodity	Concave slope implemented	Summary of key findings
Mine E	Pilbara	Iron ore	Yes	• Tall concave batter design (70 m) for WRL closure. • WRL rehabilitation in partnership with Traditional Owners. • Development of specialised bat habitat as part of WRL closure works.
Telfer gold mine	Pilbara	Gold	Trial concave slopes constructed between 2007 and 2013	• Concave slopes used for all WRLs (25–60 m tall). • Slope angles are 12–37°. • Topsoil and rock armour were delivered to the tipping edge using a side tipper and applied to WRL slopes using a push-through approach with a D9. • Substantial published research onsite-slope trials (Tiemann & Wealleans 2015). • Rilling and sheet erosion occurring on two WRLs as a result of equipment tracks affecting surface drainage patterns on the constructed landform. Tunnelling has also been reported (Tiemann & Wealleans 2015). • Revegetation research found that there was a relationship between soil depth, germination success and seedling survivorship (Golos 2013).
Coobina chromite mine	Pilbara	Chromite	Proposed	• Concave slopes proposed for WRL closure (Process Minerals International 2016). • WRL tops to be inward sloping to shed water away from the outer WRL crest and have internal cross-bunds to reduce volume of water ponding in any one place (Process Minerals International 2016). • Bunds to be installed along each WRL crest to prevent surface water spilling down landform batter (Process Minerals International 2016).

Site	Region	Commodity	Concave slope implemented	Summary of key findings
Sunrise Dam gold mine	Goldfields	Gold	Concave slopes implemented, with 85% of rehabilitation activities completed prior to 2014	• Concave slope design used for part of WRL closure design as prior bench/berm design was not performing. WRL batters were unstable. Rilling and large gullies occurred as a result of overland flows concentrating on berms, overtopping at low points or gullying out of constructed rock drains (Jacobs Group (Australia) Pty Limited 2014). • Average height of waste dump where concave slopes were used was 42 m. Rock armour placed at 400 mm on surface with 100 mm of topsoil (AngloGold Ashanti 2009; Jacobs Group (Australia) Pty Limited 2014).
Wattle Dam gold mine	Goldfields	Gold	Concave slopes implemented, with works onsite commencing in 2009 and almost complete in 2014	• Initial proposal was for a linear (bench/berm) WRL closure design, but this was changed to a concave design to help control erosion of the slope (Howard et al. 2010). • Short concave slope design proposed for WRL closure (20 m high, maximum angle 18°) and considered by the company to be implemented successfully (Howard et al. 2010). • 50% tree trash included in topsoil to achieve an annual erosion rate of less than five tonnes per hectare of WRL (Howard et al. 2010).
Karara Iron Ore Project	Midwest	Iron ore	No	• Short (40 m tall) linear slope design proposed as modelling showed that a linear batter of 20° would be more stable than a concave slope (Landloch 2011). • Top surface of the WRL has been designed to be water-holding. • Measures to minimise concentration of flow on batter slopes include prevention of off-contour ripping and irregular batter slope shapes (Landloch 2011).
Mungada East/Blue Hills Extension	Midwest	Iron ore	No	• Linear slope closure design proposed (10 m bench and 10 m berm) (Sinosteel Midwest Corporation Limited 2016). • Commitment made to return of 70% of flora species diversity through WRL rehabilitation (Sinosteel Midwest Corporation Limited 2016).

Site	Region	Commodity	Concave slope implemented	Summary of key findings
Extension Hill Hematite Operation	Midwest	Iron ore	No	• Linear slope closure design proposed (10 m berm, WRL maximum height 35 m). • WRL slopes to be sheeted with a 2:1 mix of rock and soil. Crest and cross bunding installed (Mount Gibson Mining Limited 2015). • WRL contoured to be water shedding (Mount Gibson Mining Limited 2015).
Mine A	Midwest	Iron ore	No	• Linear slope design implemented for WRLs, which are 60 m high. • WRL closure design comprises slopes battered to 15–20° and back-sloped berms angled towards drainage points. • Most of site is in post-closure monitoring phase and the mine owner has advised that completion criteria have been fulfilled.
Mine B	Pilbara	Iron ore	No	• Example of ‘lab to construction’ approach to minimise risk of erosion and instability. • Differences observed between WRL areas that were topsoiled and fertilised, and those that were not topsoiled and fertilised.
Mine C	Pilbara	Iron ore	No	• WRL rehabilitation conducted in partnership with Traditional Owners. • Progressive rehabilitation of WRLs undertaken. • Limited topsoil available for use in rehabilitation so a fertiliser blend was used in growth media development.
Mine D	Pilbara	Iron ore	No	• Concave and linear WRL closure design. • Successful WRL rehabilitation attributed to operator training and use of a dedicated rehabilitation crew, along with placement of large rocks to minimise erosion. • Germination trials conducted in various waste rock materials. • High costs incurred in material handling to fill voids within WRL batters to meet completion criteria.

4 Discussion

The four key factors affecting the success of concave WRL slopes were found to be surface drainage design, physical waste characterisation, revegetation strategies and execution methodologies.

4.1 Surface drainage design

All the benchmarking sites are located in semi-arid regions of WA where annual rainfall ranges between 200 mm and 400 mm (Bureau of Meteorology [BoM] 2019a), and is unpredictable spatially and temporally. Indeed, annual and intra-annual rainfalls tend to be skewed towards both lower totals and smaller individual events. There are usually lengthy dry periods and occasional very large rainfalls (Morton et al. 2010) which strongly influence erosion rates and slope stability. Examples of modelled rainfall rates for a 72-hour 100-year average recurrence interval include 2.4 to 4.08 mm/h (Jacobs Group (Australia) Pty Limited 2014; BoM 2019b). Consequently, adequate drainage design is critical to success WRL closure.

A number of WRLs reviewed during this study utilised linear slopes that were designed to be water shedding (such as the WRL at the Extension Hill Hematite Operation). However, all the sites reviewed during this benchmarking study at which a concave slope design has been applied used a water-holding design for the top surface of the WRL. These included Coobina and Wattle Dam, which used WRL designs that included standard water-holding features such as crest bunds and bunded cells on the top surface of the WRL (Table 2). In both cases, the design allowed for bunds along the dump crest of about 0.75 m high and approximately 2.0 m in width, with internal bunds used to create cells to reduce the volume of water ponding in any one location of the landform's upper surface. Most of these designs were based on a modelled 500-year ARI rainfall event. This approach was adopted as it limited the exposure of a WRL slope to erosional processes resulting from water flowing from the top surface to the base of the structure.

At Telfer, hummock dumping (approximately 50 cm high) of different materials was used to create a number of micro-catchments to increase vegetation growth and to dispose of water (Table 2). Tiemann & Wealleans (2015) report that the hummocks functioned successfully in the first year of the trial even after a higher than average rainfall 650 mm over a three-month period.

At those sites where it was expected that surface water could come in contact with the base of the WRL, diversion drains were installed in the catchment above the toe of the WRL. These were designed to withstand a 1 in 100 peak-flow event and a 500-year ARI to prevent clean water from contacting the WRL. At some sites, sediment traps were installed downstream of the WRL though there were concerns that these would become ineffective in the longer term as they filled with silt and sediment.

4.2 Characteristics of waste rock and soils

Testing and modelling of waste rock and soil properties, and use of the resulting data to guide WRL closure design, were found to be a key success factor during this benchmarking study.

Most of the benchmarking sites, and all of those that used or proposed tall concave slopes for WRL closure, tested and modelled their site-specific waste rock and soil properties using industry-accepted methods and ensured that their proposed WRL closure designs considered these characteristics. In all cases, suitability qualified personnel selected representative waste rock and soil samples to test for erodibility (using techniques such as simulated rainfall erosion testing). Subsequent modelling using methodology such as the Water Erosion Prediction Project (Flanagan & Nearing 1995) and SIBERIA (Willgoose et al. 1989, 1991a, 1991b) included rainfall and surface water flow simulations of the materials (waste rock types, growth medium and proposed mixtures). The results from these simulations were then analysed to determine the performance of various materials and slopes.

A number of sites (e.g. Telfer and Wattle Dam) conducted field trials to test the results of the model. These sites found a strong correlation between the outcomes predicted by the model(s) and the data obtained through field trials, suggesting that is it possible to reliably predict performance of the slope using models.

In WA, it was generally considered acceptable for sediment loss from a WRL to be approximately 10 tonnes per hectare per year in the absence of known sensitive receptors. However, for most of the benchmarking sites it was considered important to achieve erosion levels lower than this. Where this was not achievable, non-standard solutions were modelled, and these have been used successfully. For example, at Wattle Dam gold mine it was found that a single concave slope alone would not be sufficient to ensure that erosion would be within the required parameters. Consequently, other solutions were investigated and the revised universal soil loss equation (RUSLE) (Renard et al. 1993) was used to determine that a 50% vegetation debris cover would be sufficient to reduce erosion to an acceptable level (Howard et al. 2010).

In general, those benchmarking study sites that experienced slope failures due to erosion had not undertaken modelling using site-specific data to determine how the WRL was likely to perform post-closure. For example, a linear (bench and berm) closure design was applied at the Wattle Dam WRL without testing the characteristics of the soil and waste rock, and erosion occurred (Howard et al. 2010).

4.3 Revegetation strategies

All sites included in this benchmarking study committed to establishing at least some vegetation on the slopes of the WRLs. A number of sites aimed to establish at least some degree of functioning ecosystem, with the Mungada East WRL being required to re-establish flora and vegetation with not less than 70% of known original species diversity to comply with the project's government-issued environmental approvals (Sinosteel Midwest Corporation Limited 2016). However, not all revegetation programs aimed to develop a functioning ecosystem. For example, for the Blue Hills North and Terapod components of the Karara Iron Ore Project, revegetation on the single slope was intended only to be aesthetically pleasing. Indeed, it was considered that the vegetation that would establish under the low annual rainfall conditions (annual average ranging from 286 to 335 mm in the local area) in the area that the vegetation was unlikely to change the stability and erosion characteristics of the slope (Landloch 2011).

All sites reviewed during this benchmarking study committed to using topsoil in the surface cover of WRL slope design and all planned to utilise ameliorates such as fertiliser or gypsum to increase the potential for vegetation establishment. However, there was a difference between the sites as to whether armouring material would be added to the topsoil. The impact of rock armour incorporated into slopes was investigated by Golos (2013) as part of research undertaken at Telfer. His work found that although the addition of rocks to topsoil impeded seedling emergence, the increase in water-holding capacity of the soil profile that resulted from rock armouring resulted in lower seedling mortality and increased seedling size.

4.4 Execution methodologies

None of the information reviewed during this benchmarking study suggested that post-closure rework of concave slopes had been necessary or had been conducted. This suggests that the implementation of concave slope designs at the six concave slope study sites has been undertaken to a high standard and that the rehabilitated WRL slopes are performing as expected. From the literature and other information reviewed, it appears that closure execution achieved a high standard where risk assessments were conducted before undertaking activities; well-qualified and experienced operators that engaged with the rehabilitation concept were employed to conduct rehabilitation earthworks (Golos 2013); and an appropriate earthmoving fleet was utilised.

The importance of adhering to the proposed construction methods and use of experienced operators is exemplified by experiences at the Telfer WRL. At this site, erosion occurred during field trials where equipment tracks created low points on the WRL and tunnelling occurred from a track in the inside of the top surface from the track towards the batter (Tiemann & Wealleans 2015). Further, it was found through vegetation trials that inconsistent mixing of topsoil and waste rock down the slope had occurred where the process to spread these materials had varied to that proposed (Golos 2013). This meant that fines in the material dropped out at the top of the slope, so better performing vegetation developed at the top of the slope than further down the slope (Golos 2013).

5 Conclusion

As a result of the benchmarking study, it was found that a high standard of WRL closure occurs when risk assessments, waste rock and topsoil characterisation, surface drainage and erosion studies, and other investigations are conducted before closure earthworks are undertaken. Indeed, use of risk assessment is now a regulatory requirement for mine closure planning of WA mines (Department of Mines, Industry Regulation and Safety 2018). All these activities assist in reducing uncertainty in the areas of incomplete knowledge and variability or unpredictability (Sánchez et al. 2014).

It was also found that the use of well-qualified and experienced operators along with an appropriate fleet, and careful attention to construction controls and tolerances, improved the likelihood of achieving acceptable WRL closure outcomes, and that small changes to the design executed on the ground had the potential to change the performance of the WRL.

The outcomes of the benchmarking study were used to refine the risk assessment of the closure design proposed by the mining company for which this study was conducted. This revised design and a report on the benchmarking study were included in the mine closure plan (MCP) for this mine and subsequently approved by the DMP. Following its review of the MCP, the DMP took the opportunity to 'recognise areas of the MCP that had been done well or are likely to result in improved outcomes', commenting that the benchmarking review was 'particularly useful and should be encouraged throughout industry… and is potentially a powerful agent for use in mine closure'.

The primary driver behind any benchmarking study is improvement. This paper demonstrates the importance of risk assessment and that the use of systematic and reasoned planning is likely to enable the use of a concave slope design for WRL closure can obtain desired environmental outcomes (where site materials types and rainfall allow).

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