BHP Iron Ore Pty Ltd
Marillana Creek (Yandi) Closure Plan

Appendix R Volume 4 - NOT PUBLICLY AVAILABLE

Appendix R Technical Reports

The index of documents contained in this appendix is provided below. Each document is bookmarked in the navigation pane (refer to Section 1.6 of the MCP for instructions on how to use the navigation pane). Each document can also be accessed from the index by clicking on the document title (note the links will only work for documents contained within a particular volume).

Appendix R - Volume 1

R.1. Materials characterisation

R.1.1 Physical characterisation

Landloch. (2016). Yandi Waste Material Erosion Study

Soil Water Group. (2016). Email titled CID Lab Test Results.

R.1.2 Geochemical characterisation

Earth Systems. (2019a). Wall Rock Acidity Generation, Release, and Management in the Marillana Creek Diversion Project

Earth Systems. (2019b). Additional Test Work to Verify the AMD Risk Assessment of Marillana Creek Diversion Blasthole Samples GHD. (2014). Yandi Operations Preliminary Risk Assessment for Acid and Metalliferous Drainage

Golder. (2020d). Yandi Closure Identification Phase Study - Geochemical Risk Assessment

Mine Waste Management. (2020). Yandi IPS Acid and Metalliferous Drainage Assessment

Mine Waste Management. (2022a). Yandi IPS Phase 2 Environmental Geochemistry Source Assessment

WAIO. (2020a). Marillana Creek Diversion - AMD Hazard Assessment

R.2. Soil / growth media characterisation

Ecologia. (1998). Yandi Vegetation and Soil Survey

Golder. (2020a). Site Waste Material Characterisation and Quantification Assessment

Outback Ecology. (2005). Characterising Waste Materials for Rehabilitation

R.3. Seismicity, geotechnical stability & erosion assessments

R.3.1 Seismicity

Meynink Engineering Consultants. (2012). Probabilistic Seismic Hazard Assessment

R.3.2 Geotechnical stability

Advisian. (2020a). Yandi Closure IPS - Surface Water Engineering

Advisian. (2023f). Yandi Closure Landform. SPS Geotechnical Engineering Report

BHP. (2021c). C1 Landbridge Stability Assessment

BHP. (2023k). C1 Land Bridge Monitoring Report

BHP Billiton. (2015). Yandi Closure Geotechnical Study

Golder. (2020c). Yandi Closure Identification Phase Study - Stability Assessment

R.3.3 Erosion

Okane. (2023b). Yandi Closure Landform SPS Erosion Study Report

R.4. Flora and fauna

Astron. (2014). Coondewanna Flats Ecohydrological Study Ecological Water Requirements of Vegetation Report

Appendix R - Volume 2

Onshore Environmental. (2015). Marillana Creek Riparian Flora and Vegetation Survey

WRM. (2015). Yandi Aquatic Fauna Survey. Wet & Dry Season Sampling 2014

WRM. (2018). Yandi: Marillana Creek Aquatic Fauna Survey. Wet and Dry 2017 Sampling 2017

R.5. Completion criteria

Landloch. (2018). Acceptable Erosion Rates for Mine Waste Landform Rehabilitation Modelling in the Pilbara

Syrinx Environmental. (2019). WAIO Rehabilitation Completion Criteria

Syrinx Environmental. (2023). Revised Completion Criteria Operational and GNA Sites

R.6. Water

R.6.1 General

CSIRO. (2015a). Hydroclimate of the Pilbara: past, present and future

CSIRO. (2015b). Pilbara Water Resource Assessment: Upper Fortescue region

Golder. (2015b). Ecohydrological Conceptualisation of the Marillana Creek Region

Hydro Geochem Group. (2022). WAIO Water Quality Data Review, Marillana ("Yandi") Operations

MWH. (2015). Ecohydrological Conceptualisation of the Fortescue Marsh Region

R.6.2 Surface water & surface water infrastructure design

Advisian. (2017a). Creek Constrained Ore Project Hydraulic Design Report

Advisian. (2017b). Creek Constrained Ore Project. Geomorphology Report

Advisian. (2017c). Creek Constrained Ore Project Sediment Transport Modelling Report

Appendix R - Volume 3

Advisian. (2017d). Creek Constrained Ore Project Geotechnical and Civil Design Report

Advisian. (2017e). Creek Constrained Ore Project Engineering Design Report

Advisian. (2019). Yandi Mine- Spillway Design. Identification Phase Study

Advisian. (2020b). W1-SP0 Spillway Alternative Alignment

Advisian. (2022). Identification Phase Study. Yandi Closure Landform Spillway

Advisian. (2023a). Bunds versus Spillways Trade-off Study

Advisian. (2023b). Spillway Width Trade-off Study

Advisian. (2023c). Marillana Creek Baseline Hydrology Study

Appendix R - Volume 4

Advisian. (2023d). Trade-off study: Spillway Energy Dissipator

Advisian. (2023e). Trade-off Study: Asbestos Risk at W1-SP0 Flood Channel

Advisian. (2023g). Trade-off Study: Bund Slope and Rock Armour Size and Volume

Advisian. (2023h). Trade-off Study: Rock Armour for Bunds: Submerged Toe versus Launchable Toe

Advisian. (2023i). BHP Yandi Closure Landforms SPS. Trade-off study: Buttress Eastern Pits

Advisian. (2024a). Yandi Closure Landform. SPS Surface Water Engineering Design Report

Appendix R - Volume 5

AQ2. (2017). Creek Constrained Ore Project Shallow Aquifer Design Report

MWH. (2016a). Marillana Creek Flow Study

MWH. (2016b). Marillana Creek - Water Quality Monitoring Programme 2015-2016

Surface Water Consulting. (2023). Marillana Creek Sediment Monitoring Report 2021 - 2022

WAIO. (2020b). Yandi Inspect Creek Diversion and Flood Bund Post Wet Season

R.6.3 Water balance / backfill option evaluation

AQ2 & Equinox. (2016). Ecohydrological Assessment of Yandi Mine Voids (Closure)

AQ2. (2020a). Yandi Mine Closure Final Void Water Balance and Ecohydrology

AQ2. (2020b). Yandi Closure Plan Update Water Balance and Ecohydrology Overview

AQ2. (2022a). Yandi Closure IPS Phase 2: Revised Pit Closure Water Balance Modelling

AQ2. (2023a). Mungadoo / E7 Closure Water Balance

AQ2. (2024). Updated Pit Closure Water Balance Modelling

Golder. (2016). Peer Review of Yandi Closure Water Balance Model

R.6.4 Pit lake assessments

AQ2. (2022b). Review: MLC Report on Yandi Pit Lakes

McJannet, D., Hawdon, A., Boadle, D., Van Niel, T., Baker, B., & Trefry, M. (2016). Pit Lake Evaporation Study

Mine Lakes Consulting. (2022). Alternative Pit Lake Configuration Assessment

Mine Lakes Consulting. (2023). Conceptually Modelling Nitrogen Dynamics in Yandi Pit Lakes

Mine Waste Management. (2022b). Hydrogeochemical Pit Lake Model for Pits C4/5

Mine Waste Management. (2023a). Hydrogeochemical Pit Lake Models for Permanent Pit Lakes

Mine Waste Management. (2023b). Perspectives on the surface expression of salt in post-closure pits with seasonal water

Mine Waste Management. (2023c). Pit Lake Overtopping

SRK. (2022a). Review of MWM modelling inputs / approaches

SRK. (2022b). Yandi Closure Landforms Assessment: Third Party Review

SRK. (2023). Extract from Yandi Closure Landform SPS: SRK Review Tasks and Way Forward

Appendix R - Volume 6

R.6.5 Groundwater

AQ2. (2023b). Review of Groundwater Levels in Alluvium over Yandi Land Bridges

BHP. (2024a). Yandi Conceptual Hydrogeological Model

BHP. (2024b). Ministers North Aquifer Numerical Groundwater Modelling

BHP. (2024c). Yandi Modelling 2024 - Prediction Summary

Golder. (2015a). Update of Site Specific Trigger Values for Yandi

INTERA. (2024). BHP Yandi E8 Groundwater Model

WAIO. (2022d). GWL Operating Strategy for Yandi

R.7. Rehabilitation

R.7.1 Rehabilitation research

Restoration Seedbank Initiative. (2020a). Program 3. Seed Capability and Enhancement. Fact Sheet 7.3

Restoration Seedbank Initiative. (2020b). Program 3. Seed Capability and Enhancement. Fact Sheet 7

Restoration Seedbank Initiative. (2020c). Case Study 2. Influence of Moisture and Soil Substrate on Seedling Recruitment.

R.7.2 Revegetation strategy

Golder. (2020b). Yandi Closure Identification Phase Study. Rehabilitation and Revegetation Strategy

Okane. (2024b). Yandi Closure Landform SPS Rehabilitation and Revegetation Plan

R.7.3 Rehabilitation monitoring

Biota. (2016). Rehabilitation Development Monitoring - Yandi 2016

Spectrum Ecology. (2019). Yandi Rehabilitation Monitoring 2019

Spectrum Ecology. (2021). Yandi Rehabilitation Monitoring 2021

Spectrum Ecology. (2022). Yandi Rehabilitation Monitoring 2022

Spectrum Ecology. (2023). Yandi 2023 Rehabilitation Monitoring Summary

Woodman Environmental. (2015)

R.8. Infrastructure

GHD. (2022). Yandi Closure Phase 1 - Infrastructure. Hazardous Building Material Assessment Register

R.9. Backfill design

Okane. (2023c). Yandi Closure Landform Design SPS - Field Investigation

Okane. (2024a). Yandi Closure Landforms. SPS Pit Backfill and landform Engineering Design Report

R.10. Visual amenity

GHD & 360 Environmental. (2015). BHP Billiton Iron Ore’s Strategic Proposal - Landscape and Visual Impact Risk Assessment. Internal Report for BHP Billiton Iron Ore.

Advisian. (2023d). Trade-off study: Spillway Energy Dissipator

Advisian Pty Ltd (Worley Group)
Level 14, 240 St Georges Terrace
Perth, WA 6000
Tel: +61 8 9278 8111
Fax: +61 8 9278 8110
www.advisian.com

Cover Sheet

Project No: **311012-01707**

Project Title: **Yandi Closure Landforms SPS**

Customer: **BHP**

Document No: **311012-01707-CI-PRE-0002_C**

Document Title: **Trade-off Study: Spillway Energy Dissipator (Steps versus Slopes)**

Electronic File Location: I:\Projects\311012-01707 Yandi Closure Landforms SPS\9_Deliverables

Originator: **Saj Haque**

Document Status

REV	DATE	DESCRIPTION	CHKD	APPD
A	Friday, 23 June 2023	Issued for internal review	MR	LM
B	Monday, 24 July 2023	Issued for client review	MR	LM
C	Thursday, 31 August 2023	Issued for Study	MR	LM

BHP Yandi Closure Landforms SPS

Trade-off study: Spillway Energy Dissipator

311012-01707-CI-PRE-0002_C – Issued for Study

31 August, 2023

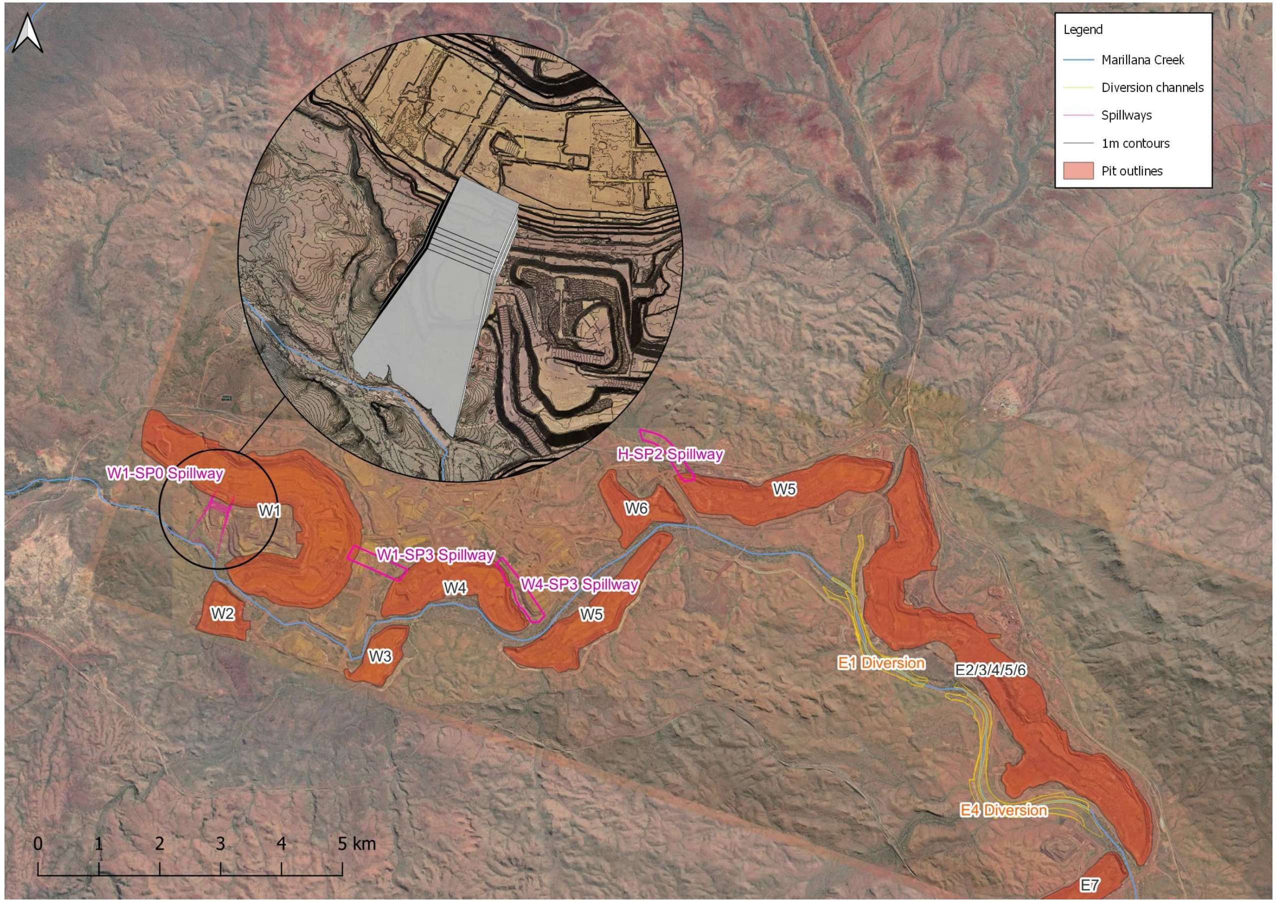
advisian.com

Outline of Presentation

1. Background
2. Objective
3. Energy Dissipation Design Options - Examples
4. Methodology
5. Hydraulic Modelling Results
6. Erodibility Assessment
7. Cost Comparison
8. Risks
9. Summary
10. Alternative Dissipator
11. Conclusion and Recommendations
12. Next Steps

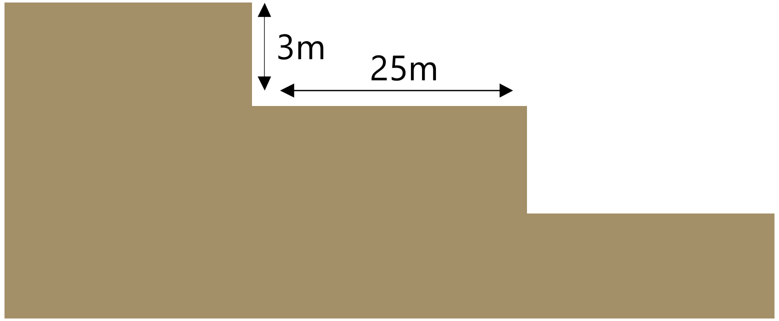
Background – Yandi Spillways

- There are currently four spillways based on the previous study phase (IPS):
  - W1-SP0 spillway to capture ~50% of 1:10,000 AEP flow from Marillana Creek
  - W1-SP3 to link W1 and W4 pits for additional storage
  - W4-SP3 outlet from W4 Pit
  - H-SP2 to reduce flow over the Herberts Creek land bridge
- The benefits of the spillways are:
  - Minimise the risk of creek capture at high-risk areas
  - Reduce flood bund fill and rock armour costs
  - Protect the performance of the E1 and E4 diversions
- Energy is dissipated as water flows over the spillways, which influences the rate of erosion of the spillway rock and downstream environment.
- Spillways can either be stepped or sloped, which influences the amount of energy dissipation and design of downstream structures.
- The IPS design for the W1-SP0 spillway energy dissipator is a series of 3 m vertical steps.
- The type of energy dissipation (stepped vs. sloped) to be adopted for the W1-SP0 spillway is the subject of this trade-off study.

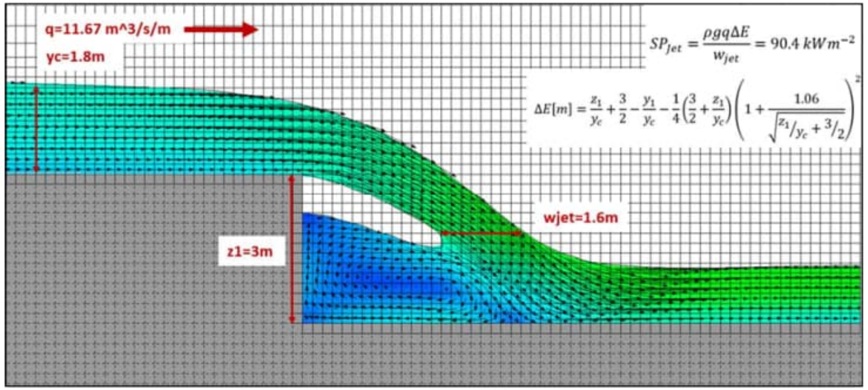


Background – W1-SP0 Energy Dissipator

- The W1-SP0 stepped spillway design was developed during a separate study prior to the Yandi Closure IPS
  - A range of spillway geometries was assessed, assuming a width of 300 m:
    - Single 16 m drop option;
    - 3 m stepped option; and
    - A uniform slope option.
  - Computational Fluid Dynamics (CFD) modelling and calculations were used to estimate the stream power acting on the rock for each option.
  - Analysis of the geology at the spillway location led to the understanding that erosion would likely be minimal if the stream power was kept below 90 kW/m^2 (when assessed using the Wibowo method).
  - The CFD modelling and analysis found that both the sloped and 3 m stepped options resulted in stream powers within the ~90 kW/m^2 limit.
  - The 3 m stepped option was selected as the preferred geometry, and the stepped energy dissipator was designed with step drop height of 3 m and step length of 25 m.
  - This design was adopted in the Yandi Closure IPS with no further analysis, as the design was already at IPS-level of engineering; however, safety risks associated with uncontrolled access to the spillway steps were identified.
- Full details in PREP-1220-C-12033.



IPS W1-SP0 spillway step geometry



Stream power calculated using CFD results

Objective

The objective of this trade-off study is to:

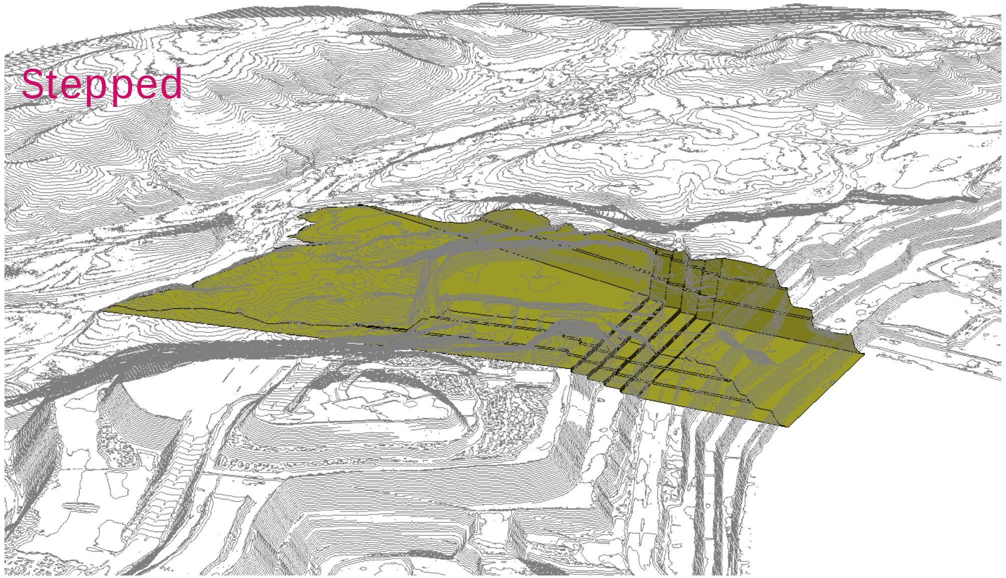
Identify the preferred energy dissipator geometry for the W1-SP0 spillway, either stepped or sloped, considering the estimated hydraulic performance of each option as well as cost and risk.

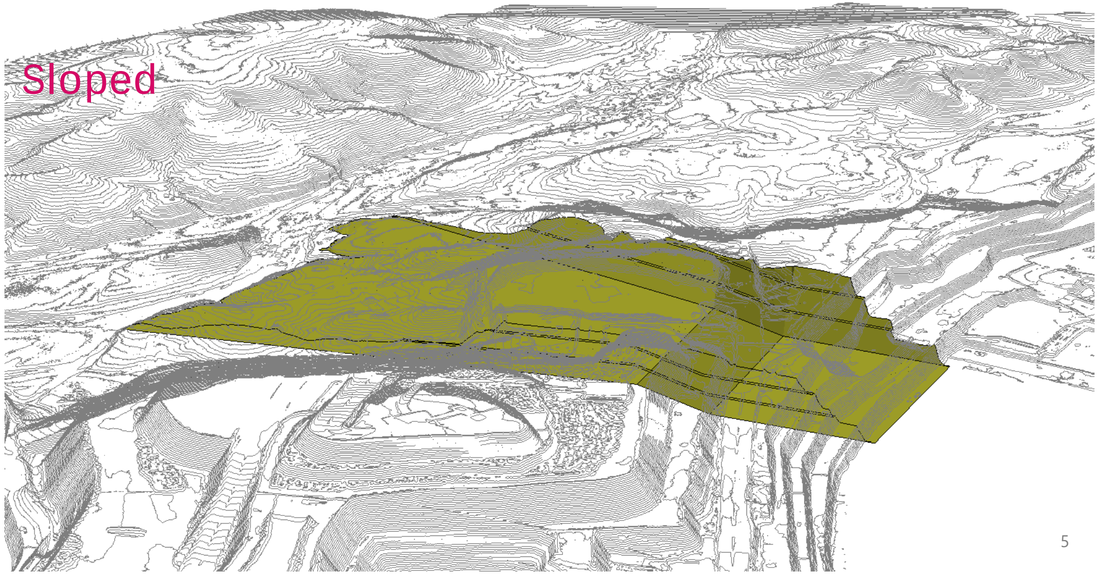
Stepped Spillway:

- Energy is dissipated as water cascades down series of steps.
- Flow regime can be nappe flow (free-falling jets) or skimming flow (flow skimming down virtual boundary layer formed by steps).

Sloped Spillway:

- Single sloping chute directing water into the W1 pit, energy dissipated through friction and hydraulic jump downstream of structure.
- Water is higher velocity / energy exiting the spillway than for a stepped dissipator.





Energy Dissipation Design Options - Examples

Stirling Dam spillway (near Harvey, WA)

- Stepped spillway with 2 x 15 m steps and one 7 m step.
- Detailed and careful blasting required to create profile – note that steps aren't perfectly smooth and level.

Energy Dissipation Design Options – Examples

Serpentine Dam Spillway (near Jarrahdale, WA)

- Sloping spillway with an initial grade of 1V:5H, sloping to 1V:14H.
- Note base and sidewalls aren’t perfectly smooth and planar.
- Significant issues during construction of benches due to sloping stress relief joints.

Methodology

The methodology for this trade-off study was:

- Undertake hydraulic analysis of stepped and sloped dissipator options using TUFLOW and CFD hydraulic modelling software. Design flood event is the 0.01% AEP event (1:10,000 AEP event). See note below.
  - Utilise existing modelling results from the Spillway Width Trade-off Study for a spillway with of 200 m for the stepped option, and a spillway width of 100 m for the sloped option.
  - Consider the timing of flows and pit tailwater conditions.
- Workshop to identify risks related to public access, construction, performance, etc.
- Utilise hydraulic modelling results to further evaluate risks identified.
- Estimate cost of each option.
- Recommend preferred option.

Note: This study relies upon the conclusions of the Spillway Width Trade-off Study (311012-01707-CI-PRE-0001), which recommends a spillway width of 200 m for the stepped option, and a spillway width of 100 m for the sloping option.

In this trade-off study, the hydraulic analyses from the Spillway Width Trade-off Study have been interrogated further, while also identifying the potential risks associated with the 200 m stepped and 100 m sloping spillway options. These risks were analysed in this trade-off study for the selection of the preferred dissipator type.

Hydraulic Modelling Results

For full results refer to 311012-01707-CI-PRE-0001

Stepped Spillway – 200 m wide

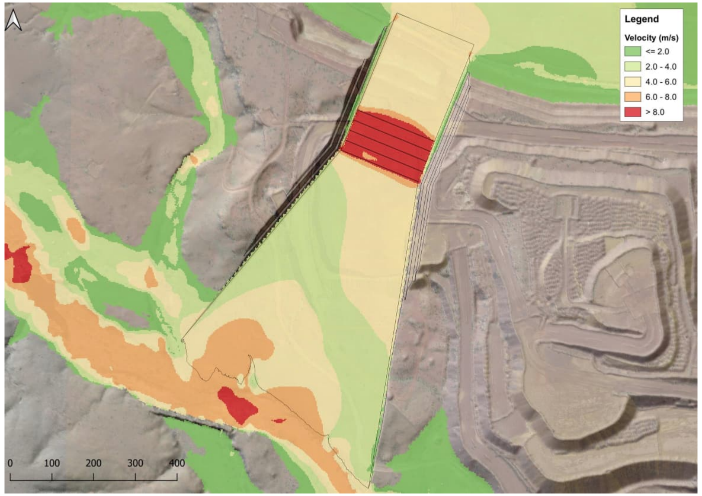
- The TUFLOW, CFD and analytical methods estimated stream power to be in the range of 20 – 35 kW/m^2.
- The TUFLOW model estimated the velocity exiting the spillway to be in the range of 4 to 6 m/s.

Sloped Spillway – 100 m wide

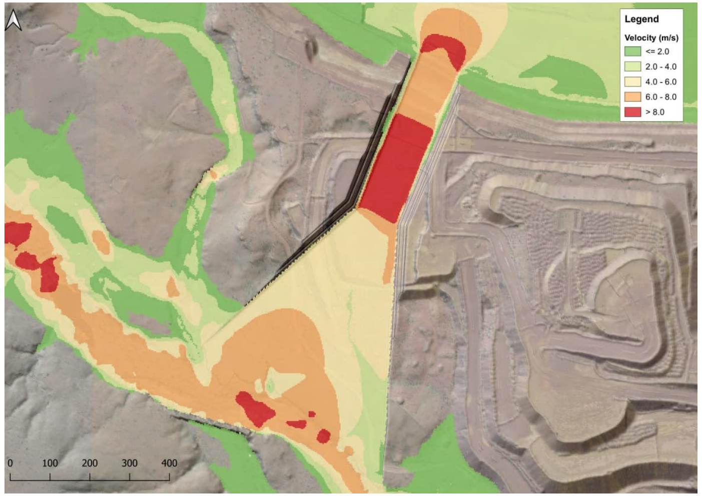
- The TUFLOW, CFD and analytical methods estimated stream power to be in the range of 10 – 25 kW/m^2.
- The TUFLOW and CFD models estimated the velocity exiting the spillway to be in the range of 11 to 16 m/s and up to 12 m/s as it reaches the opposite pit wall in W1 Pit.

Comparison

- Stepped spillway dissipates more energy than the sloped spillway.
- Consequently the velocity of water is higher as it leaves the spillway and enters W1 Pit for the sloped spillway.



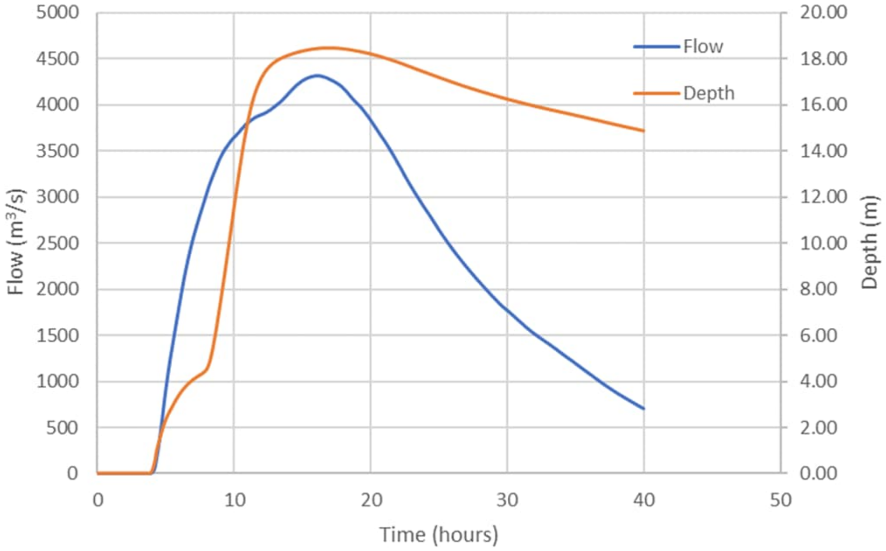
Stepped spillway TUFLOW peak velocity map



Sloped spillway TUFLOW peak velocity map

Hydraulic Modelling Results

- The chart to the right is for the stepped spillway option, but there is almost negligible difference compared with the sloped option.
- The hydrograph comparison to the right shows that the steps (or slope) are partially submerged as the peak flow comes through the spillway. This will have a "dampening" effect of the floodwater impact on the steps and W1 pit:
  - at ~6 hours the depth of water is 3 m at the dissipator and the bottom step would be submerged with the flow at ~1,500 m³/s
  - at ~10 hours all steps are submerged and the flow is at ~3,600 m³/s, still less than the peak discharge of ~4,600 m³/s.
- These results suggest that when the peak discharge occurs:
  - the spillway dissipator is likely to be fully submerged and therefore not experience the full force of the water on the in-situ rock
  - The pit backfill is likely to be submerged by more than 10 m (up to 18 m) of water.



Stepped spillway: depth and flow over time

Summary of Hydraulic Modelling Results

- The TUFLOW and CFD modelling results were also compared to an analytical solution of stream power provided by Pells (2016).
- The three different calculation methods allow us to determine a range of expected stream power values.
- High stream power is expected in the stepped dissipator option, with lower velocities downstream of the structure in the pit.
- Lower stream power is expected in the sloped dissipator option, with higher velocities downstream of the structure in the pit.
- The higher velocities downstream in the W1 pit in the sloped dissipator option are due to the relatively lower energy dissipation compared to the stepped option.

Geometry	Width (m)	Velocity (m/s)		Unit Stream Power Dissipation (kW/m^2)	
		LOW	HIGH	LOW	HIGH
Stepped	200	4	6	20	35
Sloped	100	11	16	10	25

Erodibility Assessment

- As unlined structures, the Yandi spillways will solely rely on the characteristics of the in-situ rock mass, i.e. the strength of the rock, but particularly the characteristics of the defects therein (orientation, spacing, infilling, shear strength, etc.), to withstand the hydraulic forces from flood events.
- Erodibility assessment methods of unlined spillways in rock are graphical, plotting unit stream power dissipation (**Π_{UD}**) against an assessment of the "quality" of the rock mass.
- The erodibility of the rock was assessed in 311012-01707-CI-PRE-0001 (refer for full discussion) using several methods to determine the preferred spillway width for each energy dissipator type. Advisian recommends that the Pells method is used for the project. It is the most recent method and was developed with a larger dataset than the two older methods.
- The Pells method predicts that there will be "Class II (Minor)" erosion for Stepped 200 m and Sloped 100 m wide geometries. "Class III (Moderate)" erosion possibly expected within poorer quality rockmass during flows characterised by higher end of anticipated stream power range.

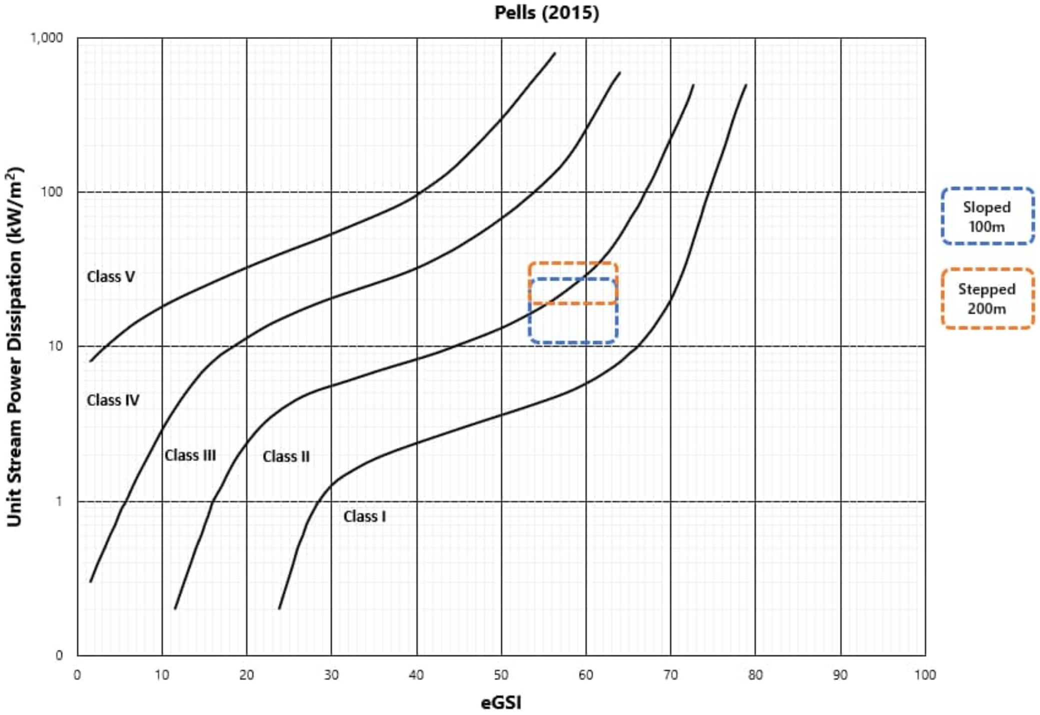
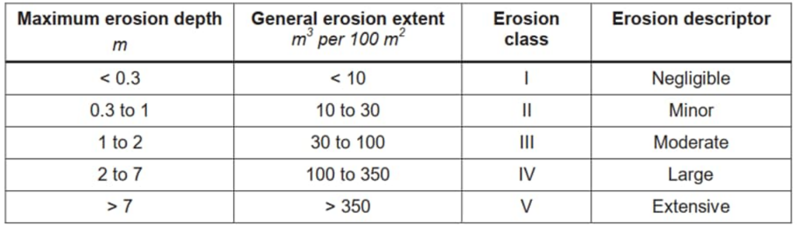


Table 1. Erosion classes, as adopted by Pells, 2015.



Maximum erosion depth *m*	General erosion extent *m³ per 100 m²*	Erosion class	Erosion descriptor
< 0.3	< 10	I	Negligible
0.3 to 1	10 to 30	II	Minor
1 to 2	30 to 100	III	Moderate
2 to 7	100 to 350	IV	Large
> 7	> 350	V	Extensive

Cost Comparison

- The Spillway Width Trade-off Study has identified the optimum width for both energy dissipator types:
  - A stepped spillway of 200 m width is estimated to require excavation of 6.4 Mm^3 at a direct cost of $49M.
  - A sloped spillway of 100 m width is estimated to require excavation of 4.5 Mm^3 at a direct cost of $35M.
- These volumes and costs assume the current overburden will be removed and that excavation will commence from the natural ground surface.

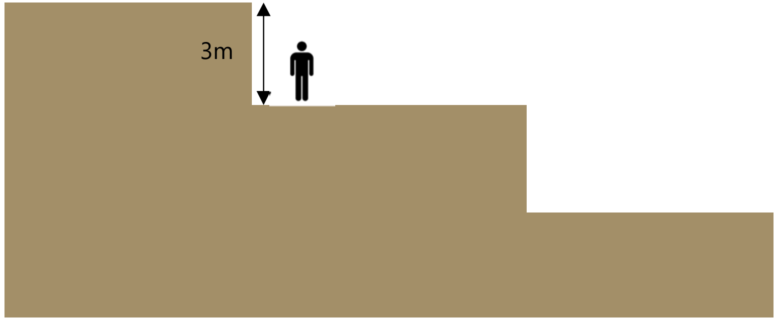
Geometry	W1-SP0 Spillway Width (m)	Excavation Volume (Mm^3)	Direct Cost of Drill and Blast & Load and Haul ($M)
Stepped	200	6.4	49
Sloped	100	4.5	35

Direct unit rates taken from 311012-00024-PM-EST-0001_D:
Drill and Blast Rock = $4.19 /BCM, Load and Haul < 2km = $3.49 /BCM

Risks – Stepped Spillway

Safety hazard for vehicles and pedestrians

- Although the spillway would not be intended to be accessed by members of the public, following closure there will be no means of preventing access and some may choose to hike or drive vehicles through the spillway.
- A drop height of 3 m is a safety hazard for vehicles and pedestrians, which can potentially lead to serious injury or fatalities. Consequences from any fall could be exacerbated by becoming trapped in the structure afterwards.
- Controls to manage this risk could include:
  - Signage near the spillway entrance can be used to warn the general public of a fall hazard
  - Steep or near-vertical ~1 m cut at entrance of spillway to prevent inadvertent access.



Risks – Stepped Spillway

Construction of Stepped Surface

- Construction of a stepped surface will require careful blasting – more so than sloped surface. Potential for higher costs.
- Dominant defect sets will play a significant role in the final geometry – nice squared edges of steps might not be achievable.

Risks – Sloped Spillway

Erosion of pit backfill material

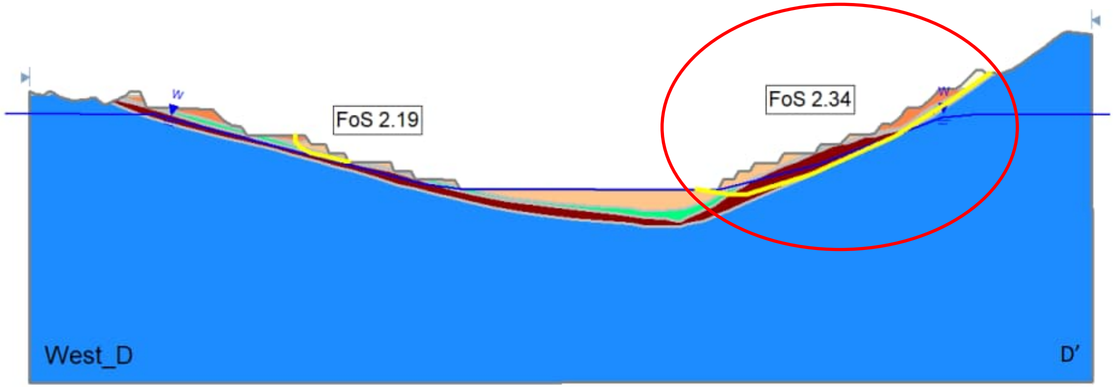
High energy flow at the spillway outlet will result in erosion of pit backfill material, which could have the following consequences:

- Development of deep scour holes in backfill material, possibly exposing the groundwater table and leading to localised increases in salinity from evapo-concentration.
- Deposition of eroded material elsewhere in W1 Pit.
- Erosion of the backfill material / scour holes could lead to dissatisfaction from stakeholders (regulators, Traditional Owners) due to poor aesthetics of the landscape and/or the impression that the design has not performed as intended (i.e. backfill in place for many years is subsequently significantly disturbed).
- Controls to manage this risk could include:
  - Placing large boulders near the outlet of the spillway to further dissipate energy
  - Include rock-armour protection in some sections of the backfill material to prevent scour holes
  - Consultation with stakeholders to ensure expectations are realistic
  - Shifting location of dissipator further upstream, at a greater distance from backfill material (increased excavation costs).

Risks – Sloped Spillway

High velocity water interacting with W1 Pit wall

- Modelling shows that the velocity at pit wall opposite the spillway outlet is in the order of 14-16 m/s for the 1:10,000 AEP event.
- Impact of high velocity flood water could potentially lead to pit wall failure. The consequence of such a failure would be limited to failure of the abandonment bund as any person potentially in the pit would have already been affected by the flood causing the pit wall failure.
- The pit wall is shallow in this area with a high factor of safety. Any failure is likely to be within the CID / Basal Clay zone (yellow line) and not within the host Weeli Wolli Formation.
- Controls to manage this risk could include:
  - Placing the abandonment bund slightly further from the pit crest (if not already).

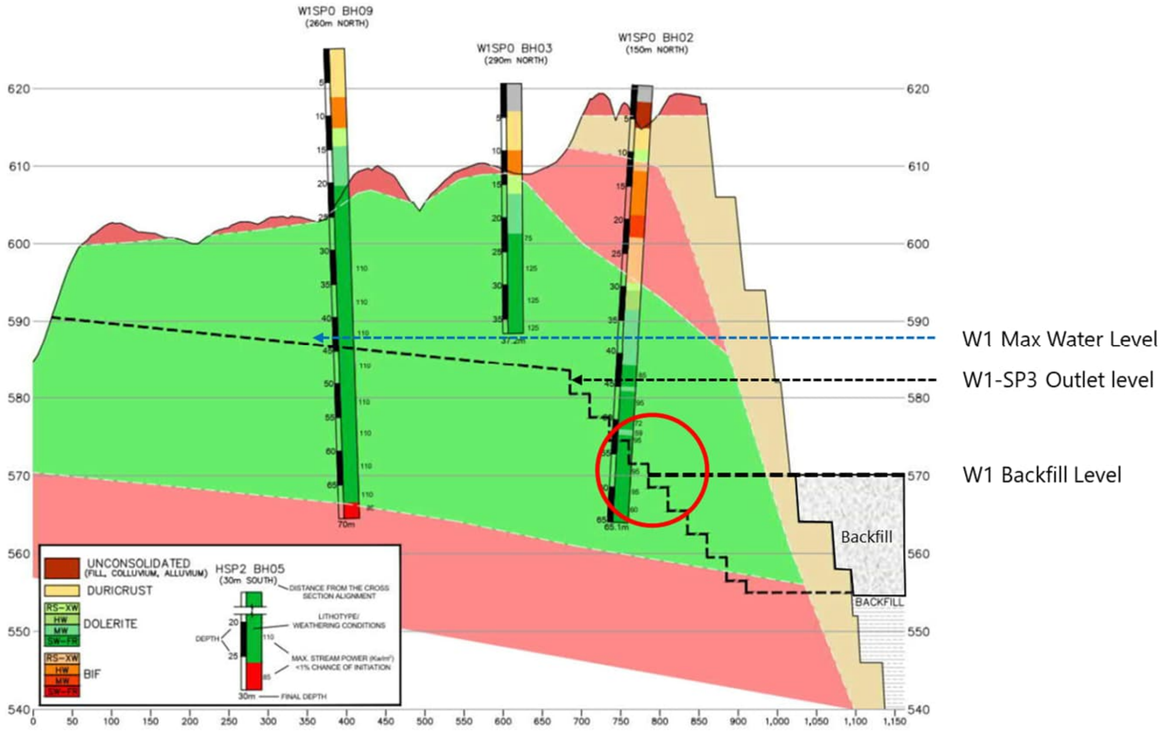


Stability modelling results of W1 pit (Golder, 2020)

Risks – Sloped Spillway

Undercutting of Spillway Outlet

- High energy flow at the spillway outlet where it enters W1 Pit could erode backfill and underlying weaker rock.
- Erosion of underlying weaker material can result in collapse of the stronger material under its own weight. This process can continue and lead to progression of the erosion upstream.
- This is expected to be an almost inconceivable event because:
  - current geological analyses suggests that the outlet will be located in SW-FR Dolerite
  - there is now expected to be ~10 m of backfill material above the weaker units, which is expected to be sufficient to prevent this process
  - there is a large distance between the spillway exit at W1 and the spillway entrance (~1000 m).
- Possible controls include post-construction monitoring following flow events to evaluate progressive erosion.



Summary

Geometry	Disadvantages	Advantages
Stepped	Drop height of 3 m is a safety risk for pedestrians and vehicles Construction more challenging – more detailed and careful blasting required to create steps – final geometry controlled by dominant defect sets Plucking during flow events will affect geometry and “smooth” out profile with time Jet impact causes localised areas of high stream power Higher cost (by $14M)	Reduced energy and velocity water leaving the spillway and entering W1 Pit
Sloped	Very high energy water at spillway outlet leading to erosion of backfill material High velocity impact of flood water on pit walls leading to possible failure of the walls High energy at spillway outlet leading to undercutting and eventual failure of structure	Lower cost (by $14 M) Easier construction Eliminated safety issues

Alternative Dissipator

Natural Analogue

- A third energy dissipator option was suggested by BHP, that of a design that mimics or resembles natural features reflective of the local area.
- This ‘Natural Analogue’ energy dissipator would be a nominal halfway point between the stepped and sloped dissipators (perhaps closer to the sloped) and would contain features similar to those seen at Flat Rocks:
  - Uneven ground
  - Bumps
  - Small drops
  - Irregularities
- The irregular features would result in more energy dissipation within the spillway compared with the sloped dissipator and therefore the width of the spillway would need to be nominally greater. A nominal width of 150 m is proposed.
- The advantages and disadvantages of this option would be very similar to the sloped spillway, with one key difference: the potential social benefit of creating a landform feature in keeping with the natural landscape and improving stakeholder views of the overall closure design.

Conclusion and Recommendations

- This trade-off study evaluated the hydraulic forces, rock erodibility indices and potential risks and uncertainties for sloped and stepped spillway options. It found a natural analogue of a sloped spillway to be the preferred option.
- Appropriate spillway widths for both dissipator types have been analysed in the Spillway Width Trade-off Study (311012-01707-CI-PRE-001):
  - Stepped spillway: 200 m width, with an excavation volume of 6.4 Mm^3 and $49M in cost
  - Sloped spillway: 100 m width, with an excavation volume of 4.5 Mm^3 and $35M in cost.
- The sloped spillway has high energy at the outlet, with several associated risks, however these risks are not deemed significant enough to outweigh the $14 M difference in direct cost and safety risks compared with the stepped dissipator.
- The natural analogue dissipator however may increase social value to the project without significantly increasing technical risk or cost.
- It is recommended that a natural analogue dissipator be adopted for the W1-SP0 spillway, generally resembling a sloped dissipator with adjustments.
- The erosion potential of the stepped spillway will be re-evaluated as new data becomes available and more detailed analysis is undertaken.

Next Steps

Following the conclusion of this trade-off study and the adoption of the recommended approach for the energy dissipator, the activities listed below will be undertaken:

- A trade-off study to investigate the need for the W1-SP3 spillway that links the W1 and W4 pit storages is underway. This study will consider the costs of each option as well as the benefits and risks associated with each.
- Following the completion of the drilling program, the logs and laboratory data will be analysed and used to estimate the erodibility indices presented in this study. The expanded dataset will cover the alignment of the spillway and provide a greater number of datapoints, thereby increasing confidence in the likely range of possible values.
- The information presented earlier in this study will be updated and the spillway widths previously recommended for each energy dissipator type will be revisited.
- In August a site visit is planned to inspect the locations where surface water engineered structures will be constructed, including the location of the W1-SP0 spillway
- After the drilling and analysis, site visit and all trade-off studies have been completed, the SPS design of the W1-SP0 spillway will be undertaken, utilising all of the data and knowledge gained from these precursor activities

References

- Pells, S. *Erosion of Rock in Spillways*. PhD thesis, UNSW, 17th June 2016.
- Pells, S., W.L. Peirson, and F. Al-Qassab, 2021. *Guidance on the calculation of stream power dissipation for rock scour assessments*, Proceedings, 10th International Conference on Scour and Erosion, Online, 21st October 2021.
- van Schalkwyk, A., J.M. Jordaan, and N. Dooge, 1994. *Die erodeerbaarheid van verskillende rotsformasies onder varierende vloeitoestande* (No. WNK Verslag No. 302/1/95). verslag aan die waternavorsingskommissie deur die Departement of Geologie, Universiteit van Pretoria, South Africa.
- Wibowo, J.L., D.E. Yule, and E. Villanueva, 2005. *Earth and Rock Surface Spillway Erosion Risk Assessment*, Proceedings, 40th U.S. Symposium on Rock Mechanics, Anchorage, Alaska, 2005.

Advisian. (2023e). Trade-off Study: Asbestos Risk at W1-SP0 Flood Chan

Advisian Pty Ltd (Worley Group)
Level 14, 240 St Georges Terrace
Perth, WA 6000
Tel: +61 8 9278 8111
Fax: +61 8 9278 8110
www.advisian.com

Cover Sheet

Project No: 311012-01707

Project Title: Yandi Closure Landforms SPS

Customer: BHP

Document No: 311012-01707-CI-PRE-0003_C

Document Title: **Trade-off Study: Asbestos Risk at W1-SP0 Spillway**

Electronic File Location: I:\Projects\311012-01707 Yandi Closure Landforms SPS\9_Deliverables

Originator: L. Miller

Document Status

REV	DATE	DESCRIPTION	CHKD	APPD
A	Wednesday, 30 August 2023	Issued for internal review		
B	Thursday, 31 August 2023	Issued for client review	MO	LM
C	Monday, 23 October 2023	Issued for Study	DH	JDP

BHP Yandi Closure Landforms SPS

Trade-off Study: Asbestos Risk at W1-SP0 Flood Channel

311012-01707-CI-PRE-0003_C – Issued for Study

23 October, 2023

Advisian
Worley Group

advisian.com

Outline of Presentation

1. Background
2. Objective of this trade-off study
3. Methodology
4. Summary of Field Results
5. Qualitative Risk Review
6. Key Risks
7. Conclusions
8. Next Steps
9. Recommendations and Forward Works

Background

- There are four flood channels in IPS design:
  - W1-SP0 to capture ~50% of 1:10,000 AEP flow from Marillana Creek
  - W1-SP3 to link W1 and W4 pits for additional storage and W4-SP3 outlet from W4 Pit (potentially replaced with W1-SP4 – SPS trade-off study underway- 311012-01707-CI-PRE-0013)
  - H-SP2 to reduce flow over the Herberts Creek land bridge (potentially removed during SPS)
- The benefits of the flood channels are:
  - Minimise the risk of creek capture at high-risk areas
  - Reduce flood bund fill and rock armour costs
  - Protect the performance of the E1 and E4 diversions
- The Yandi Spillway Report (PREP-1200-C-12033_B) provides the early literature review / case studies, rationale and optimisation for the IPS flood channel designs for closure.
- The Bunds vs Spillways Trade-Off Study (311012-01001-CI-PRE-0002_C, March 2023) concluded that including W1-SP0 in the closure design is preferable to excluding it
- The Spillway Width Trade-off Study (311012-01707-CI-PRE-0001_C, August 2023) assessed the extent to which W1-SP0 width could be reduced without increasing the risk of creek capture of Marillana Creek beyond appetite.

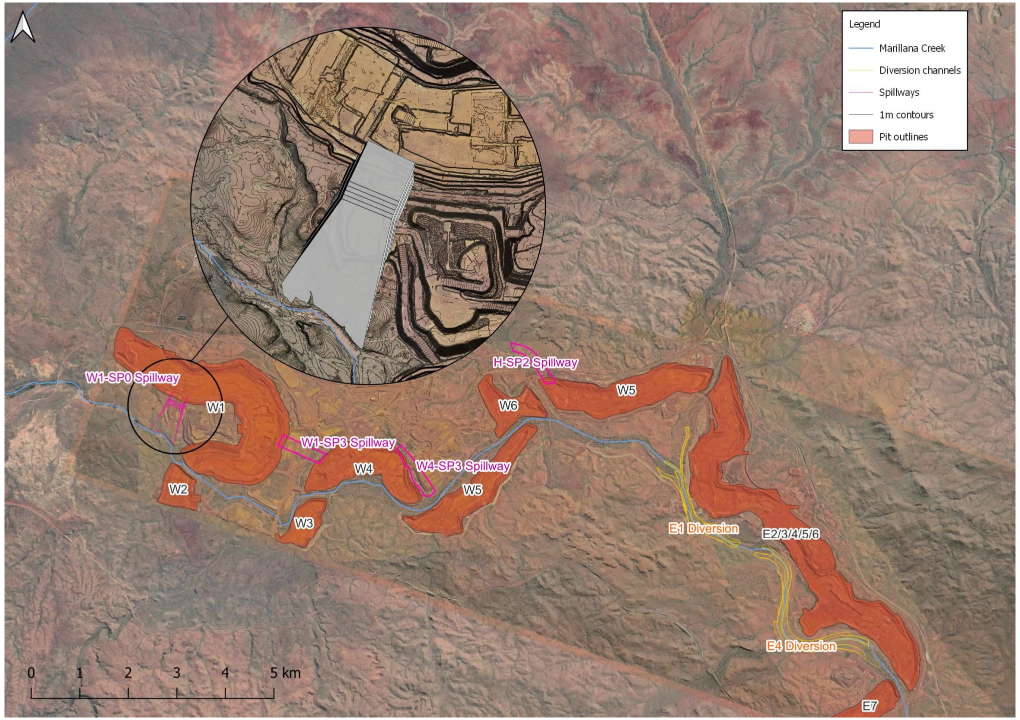


Figure 1. Overview of W1-SP0 location

Background

- W1-SP0 is designed to capture ~50% of 1:10,000 AEP flow from Marillana Creek. Drilling programs in 2019 (IPS) and 2023 (SPS) have characterised the geology in the area to inform the W1-SP0 design
- Figure 2 shows the W1-SP0 profile cut through a large section of dolerite with the weathering profile (slightly weathered to fresh) shown in the drill holes from 2019 (IPS)
- Naturally occurring fibrous materials have been previously recorded at Yandi within the dolerite during the 2017 Constrained Creek Ore W5 Quarry Geotechnical Site Investigation (PREP-610-G-00006) and at W1-SP0 during the 2019 Yandi Spillways Drilling Campaign (PREP-1210-C-12041)
- Risk assessments during the IPS identified the need to review the geological data and identify engineering controls that could be incorporated into the W1-SP0 design to reduce the risk of exposure to naturally occurring fibrous materials during, and after, construction of W1-SP0
- The 2023 SPS drilling campaign has also intersected naturally occurring fibrous materials within the dolerite at W1-SP0
- Naturally occurring fibrous materials washed downstream and deposited in alluvial beds are commonly observed at Marillana and Iowa Creeks (e.g., during an Iowa Creek field walkover 18 October, 2023 the random occurrence of several fibres and lumps estimated to be 50 mL (pebble-sized) was noted)

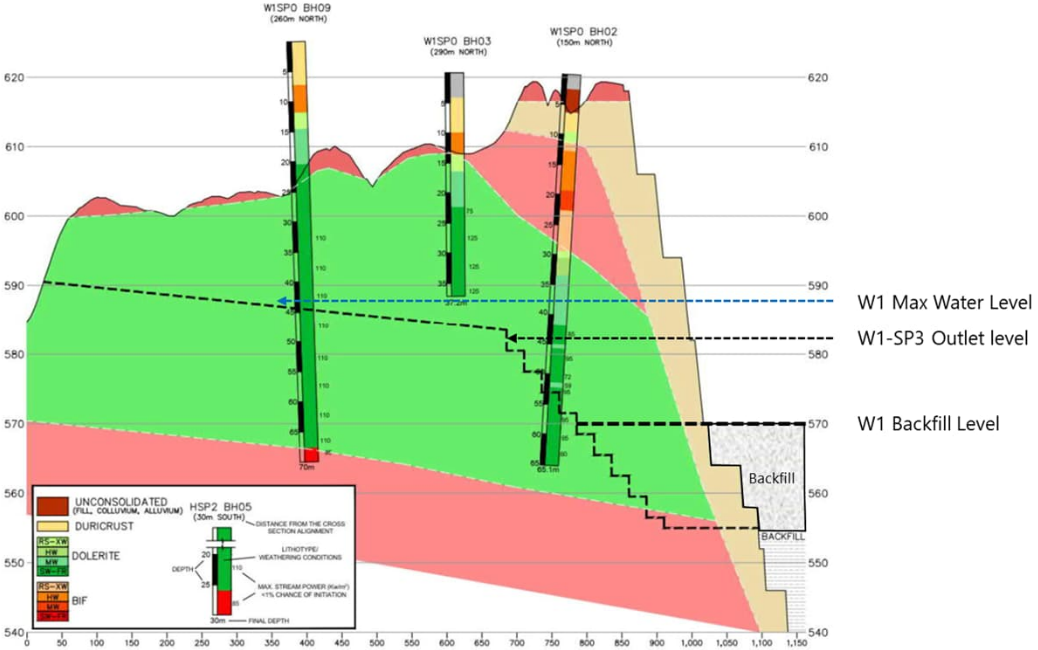


Figure 2. Geological profile and W1-SP0 profile

Objective

The objective of this trade-off study is to:

identify risks related to the IPS W1-SP0 design and alignment and, if required, recommend and communicate possible design and alignment changes that could mitigate asbestos risk

- The information relating to naturally occurring fibrous materials from the 2019 and 2023 drilling programs will inform:
  - design aspects or design and alignment risks
  - likelihood of naturally occurring fibrous materials risk during construction
  - likelihood of public exposure to naturally occurring fibrous materials post closure.

Methodology

The overall method undertaken for this trade-off study was:

- Review and summarise observations of naturally occurring fibrous materials from geotechnical drilling programs at W1-SP0
  - including 2019 IPS results and 2023 SPS results
- Conduct internal risk reviews (qualitative) to identify risks and potential controls
  - IPS W1-SP0 design and alignment
  - Early SPS designs to optimise width
- Recommend and communicate possible design and alignment changes that could mitigate risks.

Summary of Field Results:
IPS and SPS Geotechnical Drilling Program
Naturally occurring fibrous materials noted

Borehole	Depth (mbgs) / Description
W1/SP0-BH03	37.2m (discontinuous seam of potential fibrous materials up to ~ 100mm thick at base of run)
W1/SP0-BH18	50.7 to 51.5m (three potential fibrous seams between 1mm and 10mm thick)
W1/SP0-BH19	61.7 to 61.9m (80mm thick fibrous seam)
W1/SP0-BH21	41.4 to 43.9m (three potential fibrous seams up to 10mm thick)
W1/SP0-BH24	27.9 to 49.05m (numerous seams of fibrous material ranging from 1-50mm thick)
W1/SP0-BH26	29.90 to 30.15m (two 2mm thick fibrous material seams)

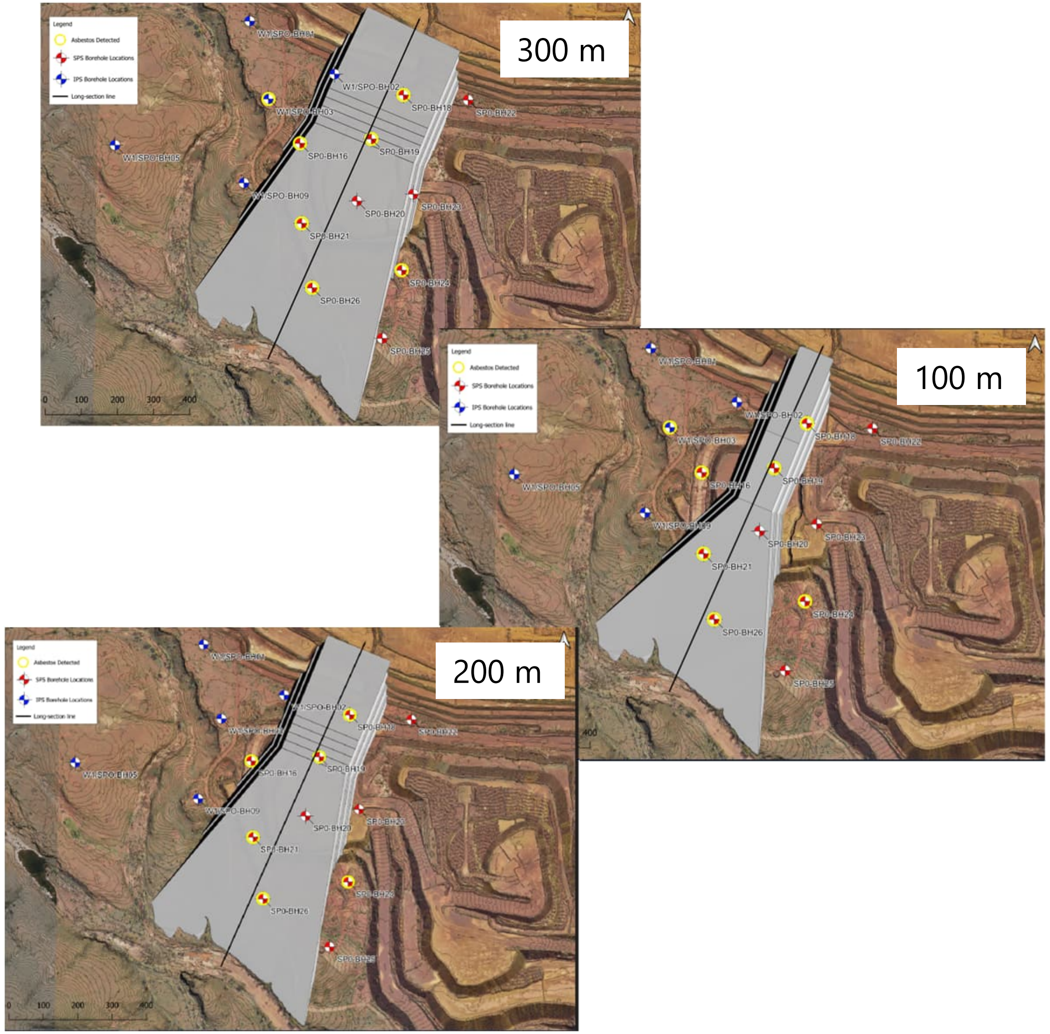


Figure 3. W1-SP0 designs with 300m, 200m, and 100m widths and boreholes where fibrous materials were noted

SPS Geotechnical Drilling Program

Occurrence of naturally occurring fibrous materials – W1-SP0

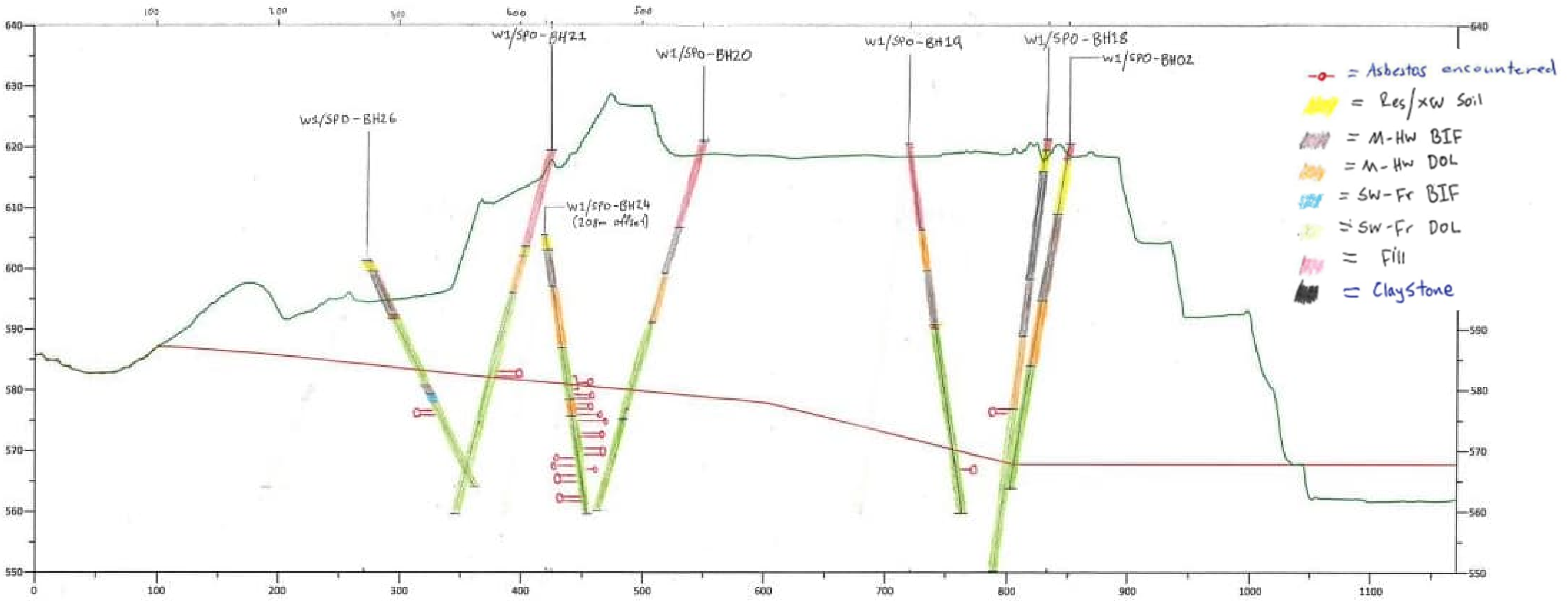


Figure 4. Cross section (5x vertical exaggeration) showing SPS boreholes at W1-SP0, geological interpretation, and depths at which fibrous materials were noted

W1-SP0 Naturally Occurring Fibrous Materials

- Draft borehole logs and photos show W1-SP0 will be cut into Fresh (occasionally slightly weathered to fresh) Dolerite – confirming IPS results.
- Majority of dolerite is fine- to medium-grained and dark grey, with lesser amounts of medium-grained grey dolerite encountered - typically present as layers up to ~1 m thick (grey dolerite is thought to be intruded into dark grey dolerite) – see Photo 1.
- Defects are typically widely spaced and Planar to Undulating, Slightly Rough to Rough and clean.
- Fibrous (asbestiform) materials observed locally between defects - all fibrous seams noted are within, or in immediate vicinity of, coarser grained grey dolerite – see Photo 2. Not all layers of medium-grained grey dolerite associated with fibrous material seams.
- Length / continuity of seams is unknown (random and unpredictable) – expected to be lenticular.
- Laboratory testing indicates that all fibrous materials tested to date comprise actinolite, a hazardous material (Safe Work Australia, 2021).

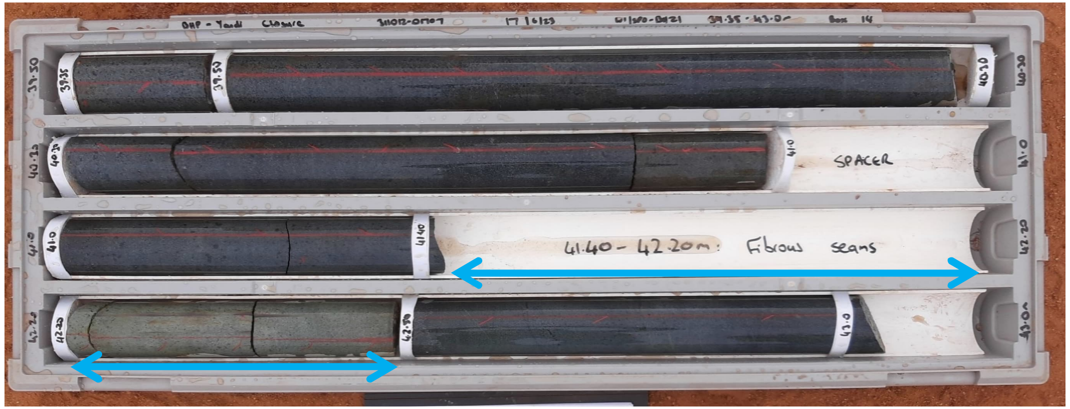


Photo 1. W1/SP0-BH21 showing ~1 m layer of medium-grained grey dolerite within fine- to medium-grained dark grey dolerite (section of medium-grained grey dolerite core removed from 41.4m to 42.2m where potential fibrous seams noted – see Photo 2)

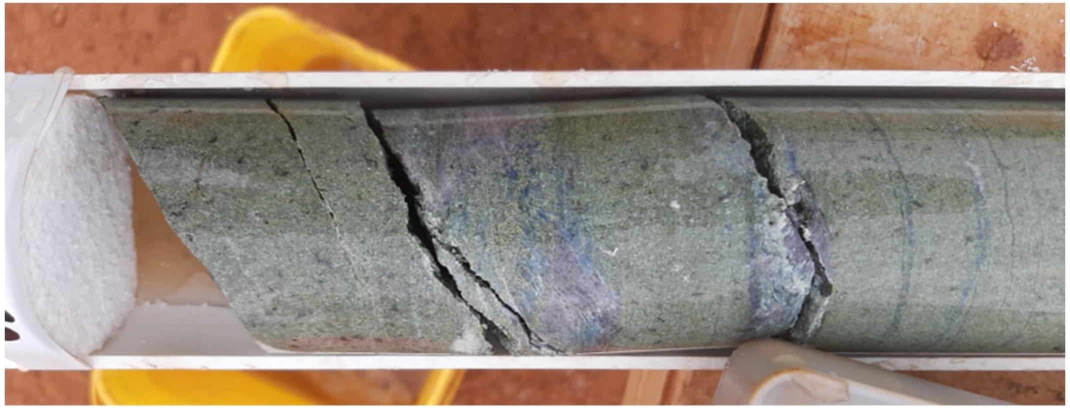


Photo 2. W1/SP0-BH21 41.4m to 42.2m – several potential fibrous seams up to 10mm thick between joints

W1-SP0 Naturally Occurring Fibrous Materials

- Total drilling at, or within immediate vicinity of, W1-SP0 during IPS and SPS = 959.9 m
- 74 individual seams of fibrous materials logged, ranging in thickness from 1 mm to 50 mm
- Total thickness of fibrous material seams = 0.648 m, i.e. 0.068% of core drilled at W1/SP0 during IPS and SPS drilling campaigns

Photo 5. W1/SP0-BH26 – 2 mm thick potential fibrous seam between joint at 29.9 m and 30.15 m

W1SP0-BH03_35.69-35.69.jpg

W1SP0-BH03_35.70-35.70.jpg

Photo 3. W1/SP0-BH03 – discontinuous seam of potential fibrous minerals up to ~100 mm thick at base of run at 37.2 m

Photo 4. W1/SP0-BH24 – example of potential fibrous seams, 1 mm to 50 mm thick encountered between 27.9 m and 49.05 m

Photo 6. W1/SP0-BH19 – potential fibrous seam between defect (61.7 m to 61.9 m)

Qualitative Risk Review

Following review of the geological logs, Advisian held internal qualitative risk reviews on 3 August and 15 August, 2023. The following key risks were identified:

1. Exposure during construction of W1-SP0 in current location using drill and blast methods
    - To construction personnel carrying out the drill and blast works
    - To personnel / public downwind (during construction)
2. Exposure to blasted rock potentially containing fibrous materials
    - To construction personnel carrying out the works hauling and placing the rock as rock armour, or disposing of it
    - To personnel / public exposed post-construction (monitoring / post-closure)
3. Exposure to fibrous materials seam outcropping on W1-SP0 excavation (or exposed following erosion in future)
    - To personnel / public exposed post-construction (monitoring / post-closure).

Key Risk: Construction of W1-SP0 in current location using drill and blast

Potential Control	Type	Comment
Remove W1-SP0 and rely on flood bund design	Elimination / Substitution	Not feasible as concluded by Bunds vs Spillways Trade-off Study (311012-01001-CI-PRE-0002_C)
Shift W1-SP0 location to avoid encountering naturally occurring fibrous materials	Engineering	Partially feasible: IPS design is 300 m wide and being optimised during SPS to ~100 m to 200 m wide. Figure 3 on Slide 6 shows that fibrous materials are still likely to be encountered even if a narrower W1-SP0 footprint is adopted and the alignment shifted east or west. While shifting W1-SP0 outside of dolerite will not meet design requirements for control of flows from Marillana Creek (location, erodibility; see Figures 1 and 2 on Slide 3), the design RL at the current W1-SP0 location can be adjusted to avoid known (through identification with geotechnical drilling program) intersections with fibrous materials. Note this will not guarantee avoidance of all naturally occurring fibrous materials
Evaluate options / procedures to minimise dust plumes during drilling and blasting	Engineering / Administrative	Feasible – for further review when it comes to construction methods and sizing of rock armour
Use earthworks contractors specialised in working with fibrous materials	Administrative	Industry experience exists (e.g., areas of known fibrous materials across Pilbara)
Fibrous materials management plan to reduce or eliminate exposure when drilling and blasting. Includes use of established / proven construction practices for control of exposure to emissions during blasting	Administrative / PPE	Industry experience exists as above. Includes LV controlling exclusion zone, positive air flow/pressurised cabs, special laydown areas, ensure blast sites are wetted down before and after blasting, restrict access after blasting until area has settled and been wetted, control of drill cuttings, etc. to reduce dust exposure prior to loading & hauling etc.
Evaluate potential dust plume and manage downwind activities at the time of blasting	Engineering / Administrative	Feasible – screening model recommended to estimate dust plume generated from blasting under a range of scenarios / seasonal conditions so that best practicable conditions (season / weather) prevail

Key Risk: Exposure to rock armour sourced from W1-SP0 potentially containing fibrous materials

Potential Control	Type	Comment
Avoid using blasted dolerite rock from the W1-SP0 area as rock armour – use rock armour sourced from Newman instead	Elimination / Substitution	To comply with industry standards dolerite is considered the most suitable rock type for rock armour. BIF is not a practical solution for rock armour due to the nature of its fragmentation during blasting, challenges in specification compliance with regard to particle size and particle shape, durability concerns and strength variabilities. Not practical due to cost and effort associated with importing quarried rock from Newman (note, imported local rock from Newman (Holcim) is characterised with fibrous materials) Would not negate the need to move rock out of the W1-SP0 area
Reduce exposure through placement of rock armour and / or disposal / burial of fragments	Engineering	Opportunity to preferentially orientate exposed faces with identified fibrous materials to minimise exposure (e.g., place exposed face down or flush against one another) Not feasible to check / dispose / bury each fragment of rock with fibrous materials that comes out of the W1-SP0 excavation Not feasible to prevent access to armoured bunds
Fibrous materials management plan to reduce or eliminate exposure when handling and placing material as rock armour Includes use of established / proven construction practices for control of exposure to emissions when moving rock	Administrative	Minimise handling and movement / appropriate handling (spray with water to wet) / avoid stockpiling or intermediate laydown / specialised laydown area & procedures for any stockpiling necessary. Industry experience exists as below. Includes LV controlling exclusion zone, positive air flow/pressurised cabs, etc.
Use earthworks contractors specialised in working with fibrous materials	Administrative	Industry experience exists (e.g., areas of known fibrous materials across Pilbara)
Access control: refer to controls for W1-SP0 access	Administrative	Limited opportunities to control access to bunds that have rock armour placed on them (especially post-closure)

Key Risk: Exposure to fibrous materials seam outcropping on W1-SP0 excavation

Potential Control	Type	Comment
Sterilisation	Elimination	There is no practical solution to avoid a potential fibrous materials seam from being exposed (occurrence is random and not able to be predicted)
Shotcrete barrier over exposed fibrous materials seams to reduce exposure (during monitoring and post-closure)	Engineering	Detailed mapping of exposed dolerite at W1-SP0 is recommended from erodibility point of view – provides opportunity to identify exposed fibrous material seams within the dolerite Barrier provides mitigation for ~50? years – not permanent solution Over time exposed face will erode naturally and disperse to floodplain – potentially both advantageous and disadvantageous May be an excessive solution for seams <100mm thick and of unknown length – shotcrete typically applied to larger areas (10s – 100s m^2)
Bituminous paint / sealant over seams to reduce exposure (during monitoring and post-closure)	Engineering	Opportunity to identify exposed fibrous material seams (as above) Requires identification of an appropriate product that would withstand environmental conditions (heat, UV) and can be applied to bare rock Likely to be effective for ~50? years – not permanent solution Could be completed during/immediately following mapping (painted on by hand with brush by hand) – or even during construction?
Access control: Construct concrete crest block at W1-SP0 entrance to control access post-construction (monitoring and post-closure)	Engineering	Not aesthetically pleasing and requires a lot of concrete – not a practical or sustainable closure design (see Photo 7, Slide 15). Hydraulically efficient if designed appropriately (e.g. ogee crest)
Access control: Include a ~1.5 m cut at the W1-SP0 entrance to control access	Engineering	Feasible, can be considered in the design, in addition to safety bunds Natural analogues exist in immediate area (see Photos 8, 9, Slide 15).
Access control: Fencing / signage to control inadvertent access to W1-SP0 post-construction (monitoring and post-closure)	Administrative	Fencing, signage not practical / effective post-closure (will not withstand flood events, vandalism, wear and tear)

Key Risk: Exposure to fibrous materials seam outcropping on W1-SP0 excavation

Photo 7. Example of a concrete crest block to deter W1-SP0 access

Photos 8, 9. Natural analogues of ~1.5 m cut in dolerite to deter W1-SP0 access

Conclusions

This trade off study concludes that it is not possible to eliminate the risks of exposure to naturally occurring fibrous materials associated with the W1-SP0 flood channel. Mitigating some of the risks for a period of time is possible, but some risks do not appear to be able to be mitigated. The study has identified the following key risks and possible controls:

Key risks:

1. Exposure during construction of W1-SP0 in current location using drill and blast methods
2. Exposure to rock armour (sourced from W1-SP0 excavation) potentially containing fibrous materials
3. Exposure to fibrous material seams outcropping in W1-SP0 excavation (including seams exposed in future following erosion during flooding).

Key Controls:

1. Construction management (including fibrous materials management plan) during blasting & excavation and placement of rock armour
2. Engineer a ~1.5 m deep cut in rock at W1-SP0 entrance to make access difficult
3. Post construction geological mapping to identify exposed seams which could be sealed / covered to provide medium term mitigation – conducted during or after mapping (or potentially during construction).

Next Steps: W1-SP0 Design

Following the conclusion of this trade-off study, the activities listed below will be undertaken during SPS:

- The W1-SP0 width and dissipator type trade-off studies will be finalised and an optimised width will be carried forward to the SPS design
- The Geotechnical Factual Report will be completed documenting the SPS Geotechnical Drilling Program results including borehole logs and laboratory testing results (including test results of naturally occurring fibrous materials) from W1-SP0
- The geotechnical logs and laboratory data will be analysed and used for geotechnical modelling, assessment of erodibility indices at W1-SP0, general stability of cuts, kinematic analysis of cuts, and design optimisation. The expanded dataset will cover the alignment of W1-SP0 and provide a greater number of datapoints, thereby increasing confidence in the likely range of possible values relative to IPS
- The SPS design of W1-SP0 will be completed, utilising all of the data and knowledge gained from previous field studies and the above precursor activities. The W1-SP0 design will be optimised during SPS with regard to width, dissipator, and to avoid wherever possible intersections with seams of naturally occurring fibrous materials. There is no guarantee, however, that intersections with seams of naturally occurring fibrous materials will be completely avoided during construction of the optimised design, due to their random and unpredictable occurrence within the dolerite layer
- Throughout the SPS design process, safety in design activities will continue to be completed including T5iDs, SiDOs, Hazard Reviews and hazards documented in the SPS Project Design Hazard Report.

During DPS, the W1-SP0 design will be further optimised, pending the outcome of further assessment, modelling, and a potential source-pathway-receptor risk assessment for naturally occurring fibrous materials within the dolerite (see Recommendations).

Recommendations / Forward Works

The asbestos trade-off study has confirmed that the Yandi Closure design will need to consider the presence of actinolite within the dolerite rock at W1-SP0, and that management of any residual risk will be required for Yandi Closure. Forward works that should be considered during DPS to further assess actinolite risk include the following:

- An internal review by BHP to determine how exposure to naturally occurring fibrous materials is currently being managed at Yandi (and regionally), whether similar approaches can be applied to W1-SP0 construction and post-construction, and impacts for closure. Consider the following sources of naturally occurring fibrous materials:
    - Materials washed downstream in Marillana Creek and Iowa Creek beds (can be identified through a site walkover with an experienced geologist)
    - Materials associated with dolerite that has been disturbed / blasted for the W5 quarry
    - Materials associated with rock imported to site from Newman (e.g., Holcim quarry)
    - On-site landfills where fibrous materials are buried.

Recommendations / Forward Works

- A quantitative human health risk assessment (HHRE) by a qualified expert in accordance with internationally recognised protocols to quantify the source-pathway-receptor linkages associated with exposure to actinolite in the W1-SP0 area at closure. The outcomes of the HHRA can then be assessed versus other site-specific closure risks (e.g., risk of creek capture at high-risk areas):
    - Source: small localised exposed actinolite in the W1-SP0 cut. Initially loose material will be present at surface, which will then erode through wind/rain/water action. Consider whether this material would then be similar to what occurs naturally in the dolerite at Flat Rocks and what is found in the alluvial beds in Marillana Creek and Iowa Creek. Consider also differences in source characteristics between asbestos mine tailings in the region, versus exposures of actinolite seams in dolerite at W1-SP0.
    - Pathway: Defined by the distance from source to receptor. A preliminary review suggests that mobilisation of exposed actinolite out of W1-SP0 is via wind or water (rainfall or W1-SP0 flow events). The HHRE should include modelling studies to predict such mobilisation events and quantify the concentration / condition of the transported material and the risk / likelihood of exposure / human health related impacts.
    - Receptor: Consider that the W1-SP0 design will be developed to prevent access, so direct exposure risk is eliminated. People will be able to walk up Marillana Creek, so they could get close to the W1-SP0 entrance but not into the flood channel itself. At the W1-SP0 entrance, they would also be standing in an area with exposed dolerite so would presumably already be in proximity to natural albeit weathered exposures of naturally occurring fibrous materials.
- If warranted considering the outcomes of the HHRE, further develop the W1-SP0 design, and develop a method for post construction geological mapping (may include imaging techniques) to identify exposed seams which could be sealed / covered to provide medium term mitigation – to be conducted during or after mapping (or potentially during construction).

References

- Department of Mines and Petroleum, 2015. Management of fibrous minerals in Western Australian mining operations – guideline (2nd edition): Resources Safety, Department of Mines and Petroleum, Western Australia, 47 pp.
- Department of Industry and Resources, 2001. Management of Asbestos in Mining Operations – Guideline: Mines Occupational Safety and Health Advisory Board, Department of Industry and Resources, Western Australia, 30 pp.
- Safe Work Australia, 2021. Hazardous chemicals information system (HCIS). 6 March, 2021. Accessed 13 October, 2023. https://hcis.safeworkaustralia.gov.au/HazardousChemical

Advisian. (2023g). Trade-off Study: Bund Slope and Rock Armour Size and Volume

Advisian Pty Ltd (Worley Group)
Level 14, 240 St Georges Terrace
Perth, WA 6000
Tel: +61 8 9278 8111
Fax: +61 8 9278 8110
www.advisian.com

Cover Sheet

Project No:	311012-01707
Project Title:	Yandi Closure Landforms SPS
Customer:	BHP
Document No:	311012-01707-CI-PRE-0009_C
Document Title:	SPS Trade-off Study Presentation: Bund Slope and Rock Armour Size and Volume
Electronic File Location:	I:\Projects\311012-01707 Yandi Closure Landforms SPS\9_Deliverables
Originator:	R. Perrigo

Document Status

REV	DATE	DESCRIPTION	CHKD	APPD
A	Sunday, 30 July 2023	Issued for internal review	-	-
B	Friday, 15 September 2023	Issued for client review	SA	LM
C	Friday, 20 October 2023	Issued for study	MR	LM

Yandi Closure Landforms SPS

311012-01707-CI-PRE-0009_C

Trade-off Study: Bund Slope and Rock Armour Size and Volume

20th October 2023

Advisian
Worley Group

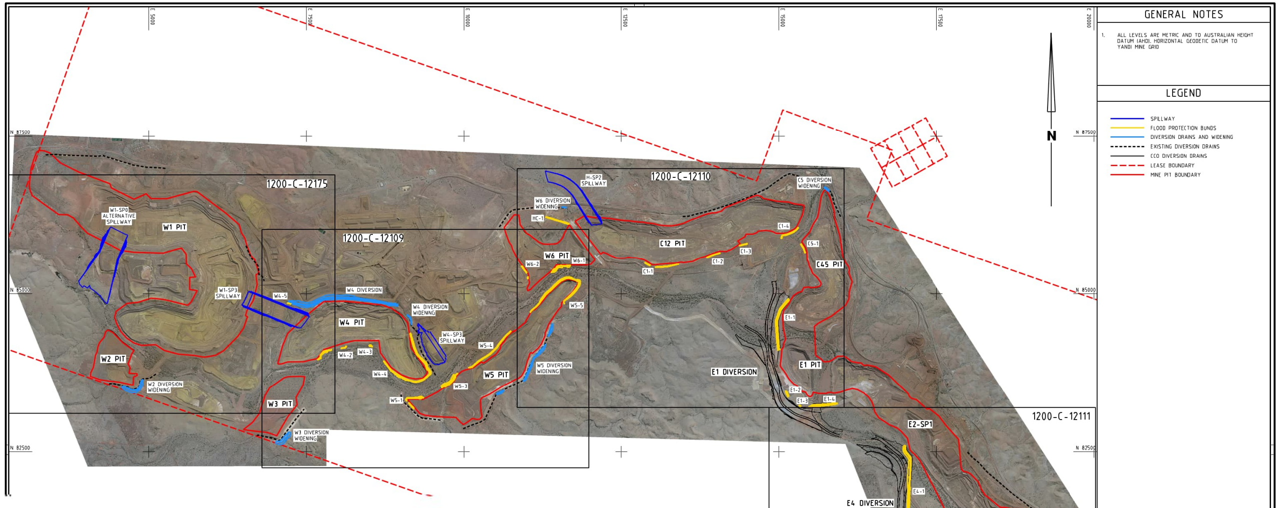
advisian.com

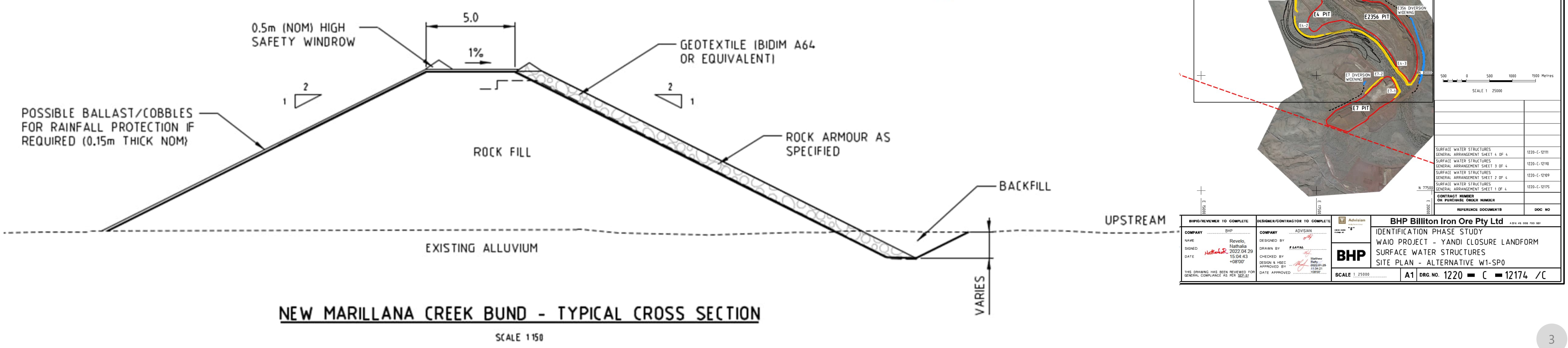
Outline of Presentation

1. Background
2. Objective of this trade-off study
3. Comparison of methods
4. Conclusions
5. Recommendations

Background – Flood Bund Rock Protection Design

- Rock protection on Flood Bunds:
  - 1:10,000 AEP event hydraulic modelling results adjacent to the flood bund locations have been used to design rock protection.
  - Rock armour protects bunds from scour and erosion, thereby protecting Marillana Creek from being captured by pits.
- The flood bund designs adopted at Yandi assume batter slopes of 1V:2H, as depicted below.
- The rock armour required for many of the bunds is large, up to 4 Tonne Class (d_{50} = 1.45 m), which could be challenging to procure and construct.





NEW MARILLANA CREEK BUND - TYPICAL CROSS SECTION

SCALE 1:150

SURFACE WATER STRUCTURES GENERAL ARRANGEMENT SHEET 4 OF 4 1220-C-12111
SURFACE WATER STRUCTURES GENERAL ARRANGEMENT SHEET 3 OF 4 1220-C-12110
SURFACE WATER STRUCTURES GENERAL ARRANGEMENT SHEET 2 OF 4 1220-C-12109
SURFACE WATER STRUCTURES GENERAL ARRANGEMENT SHEET 1 OF 4 1220-C-12175
CONTRACT NUMBER OR PURCHASE ORDER NUMBER
REFERENCE DOCUMENTS DOC NO

BHPIO/REVIEWER TO COMPLETE
COMPANY BHP
NAME Revelo, Nathalia
SIGNED NathaliaR 2022.04.29 15:04:43 +08'00'
DATE
THIS DRAWING HAS BEEN REVIEWED FOR GENERAL COMPLIANCE AS PER SEP-57

DESIGNER/CONTRACTOR TO COMPLETE
COMPANY ADVISIAN
DESIGNED BY
DRAWN BY S LAVAL
CHECKED BY
DESIGN & HSEC APPROVED BY Matthew Rafty 2022.01.25 11:34:21 +08'00'
DATE APPROVED

Advisian

BHP

BHP Billiton Iron Ore Pty Ltd ABN 46 008 700 981
IDENTIFICATION PHASE STUDY
WAIO PROJECT - YANDI CLOSURE LANDFORM
SURFACE WATER STRUCTURES
SITE PLAN - ALTERNATIVE W1-SP0
SCALE 1:25000 A1 DRG. NO. 1220 – C – 12174 /C

Objective of Trade Off Study

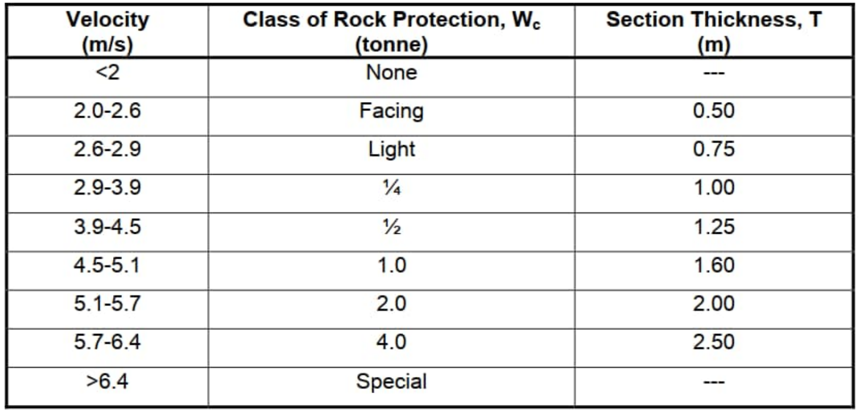
Determine if the current slope design for the flood protection bunds are reduced (flattened) that a different size armour rock could be used to provide the same level of erosion protection.

- Rock protection design is determined by the adopted method for sizing rock (selection of rock class).
- Several methods have been considered.

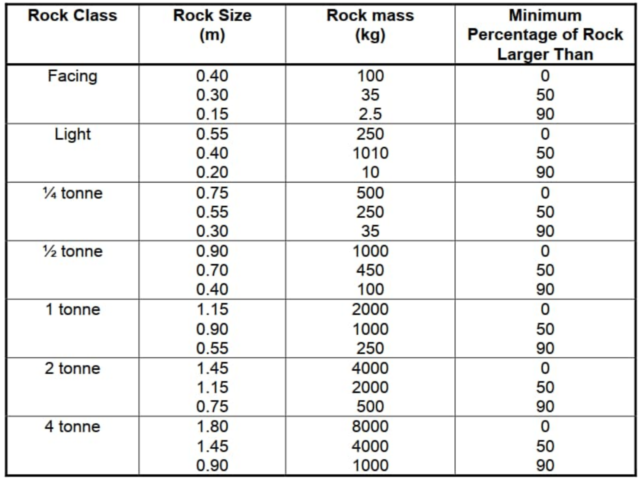
Austroads (2019)

Guide to Bridge Technology Part 8: Hydraulic Design of Waterway Structures (Austroads, 2019)

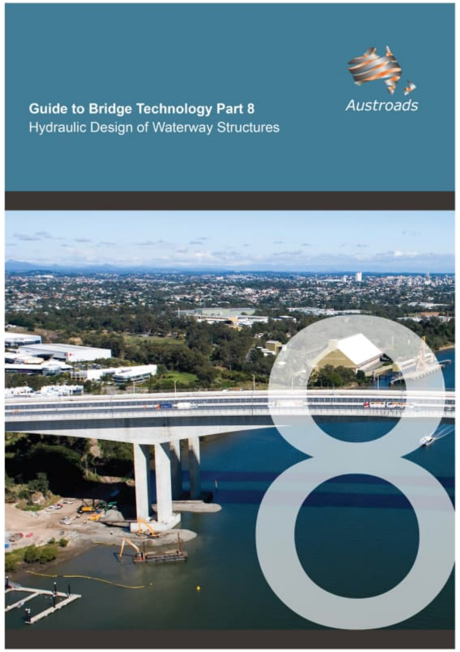
- Look-up tables presented for sizing and locating rock protection and hydraulic design of waterway structures in Western Australia.
- The Austroads Guide and rock sizing tables were first published by Austroads in 1994.
- The method used to develop the rock sizing tables, is based on the CALTRAN method by the California Department of Public Works, Division of Highways (1960).
- Maximum acceptable bund slope 1V:1.5H for application of the tables.
- Specific gravity = 2.65.
- Used widely in Pilbara region.
- Parallel (2/3) and impinging (4/3) factors are presented for design of guide banks which protrude into the watercourse. There is no justification (data or reference) for applying these factors to stream channels / flood bunds (USGS, 1986).



Velocity (m/s)	Class of Rock Protection, W_c (tonne)	Section Thickness, T (m)
<2	None	---
2.0-2.6	Facing	0.50
2.6-2.9	Light	0.75
2.9-3.9	¼	1.00
3.9-4.5	½	1.25
4.5-5.1	1.0	1.60
5.1-5.7	2.0	2.00
5.7-6.4	4.0	2.50
>6.4	Special	---



Rock Class	Rock Size (m)	Rock mass (kg)	Minimum Percentage of Rock Larger Than
Facing	0.40	100	0
	0.30	35	50
	0.15	2.5	90
Light	0.55	250	0
	0.40	1010	50
	0.20	10	90
¼ tonne	0.75	500	0
	0.55	250	50
	0.30	35	90
½ tonne	0.90	1000	0
	0.70	450	50
	0.40	100	90
1 tonne	1.15	2000	0
	0.90	1000	50
	0.55	250	90
2 tonne	1.45	4000	0
	1.15	2000	50
	0.75	500	90
4 tonne	1.80	8000	0
	1.45	4000	50
	0.90	1000	90

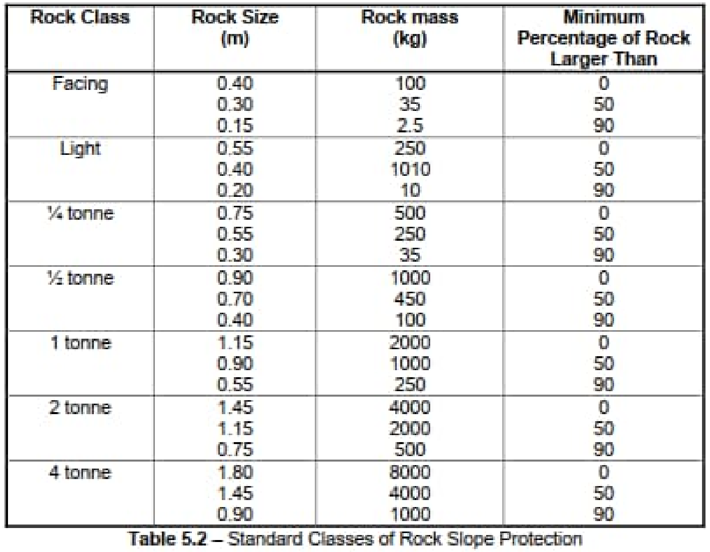


Guide to Bridge Technology Part 8
Hydraulic Design of Waterway Structures

Main Roads (2006)

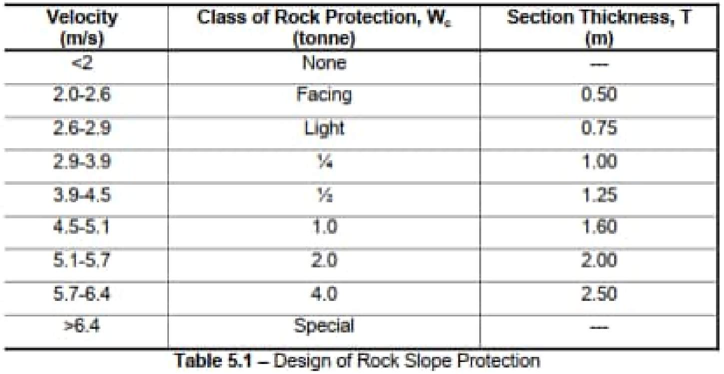
Floodway Design Guide (Main Roads WA, 2006)

- Adopts the same rock sizing tables as Austroads (1994 & 2019).
- Used widely in the Pilbara region.
- Applied to embankments regardless of slope.



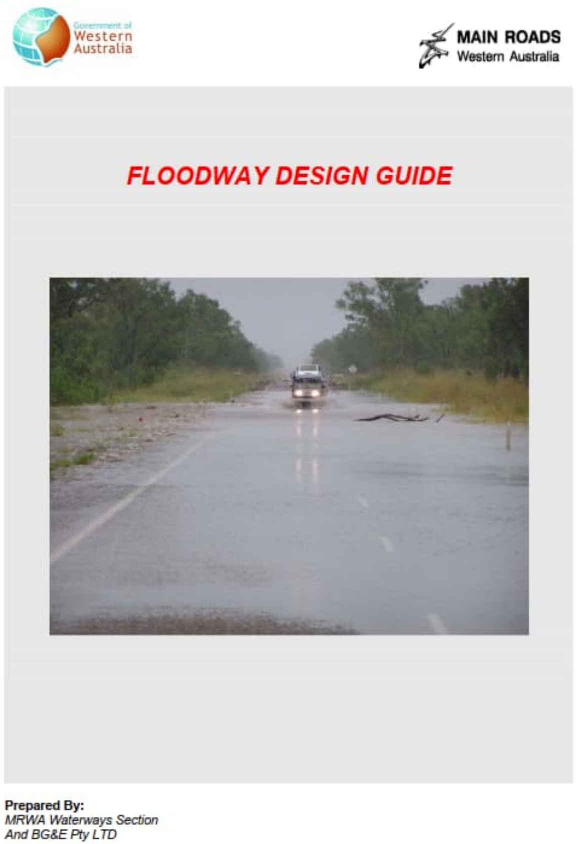
Rock Class	Rock Size (m)	Rock mass (kg)	Minimum Percentage of Rock Larger Than
Facing	0.40	100	0
	0.30	35	50
	0.15	2.5	90
Light	0.55	250	0
	0.40	1010	50
	0.20	10	90
¼ tonne	0.75	500	0
	0.55	250	50
	0.30	35	90
½ tonne	0.90	1000	0
	0.70	450	50
	0.40	100	90
1 tonne	1.15	2000	0
	0.90	1000	50
	0.55	250	90
2 tonne	1.45	4000	0
	1.15	2000	50
	0.75	500	90
4 tonne	1.80	8000	0
	1.45	4000	50
	0.90	1000	90

Table 5.2 – Standard Classes of Rock Slope Protection



Velocity (m/s)	Class of Rock Protection, W_c (tonne)	Section Thickness, T (m)
<2	None	—
2.0-2.6	Facing	0.50
2.6-2.9	Light	0.75
2.9-3.9	¼	1.00
3.9-4.5	½	1.25
4.5-5.1	1.0	1.60
5.1-5.7	2.0	2.00
5.7-6.4	4.0	2.50
>6.4	Special	—

Table 5.1 – Design of Rock Slope Protection



Government of Western Australia

MAIN ROADS Western Australia

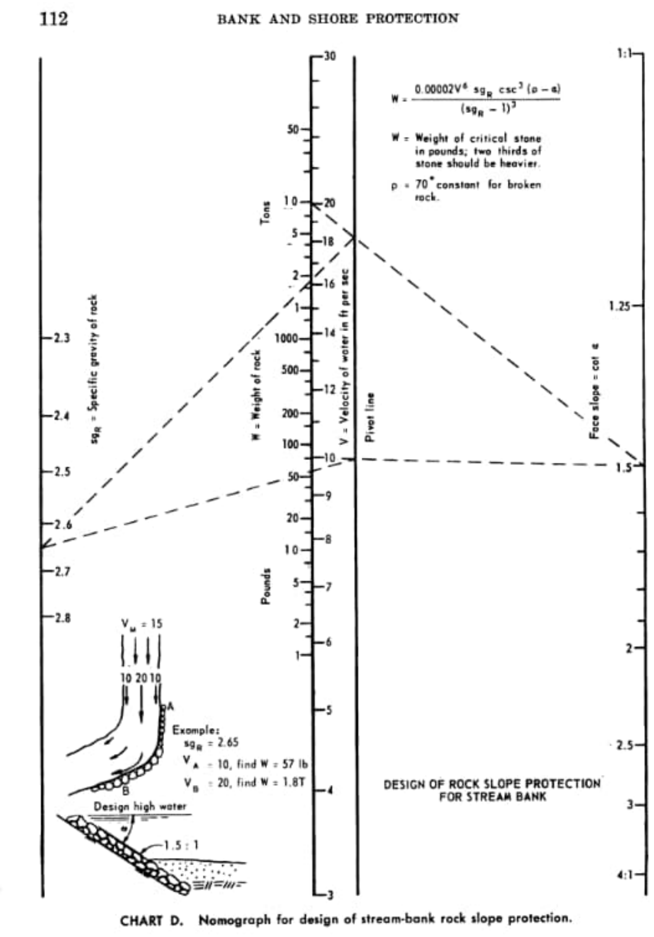
FLOODWAY DESIGN GUIDE

Prepared By:
MRWA Waterways Section
And BG&E Pty LTD

California Dept. of Public Works – Division of Highways (1960)

Bank and Shore Protection in California Highway Practice

- CALTRAN method (CDPW, 1960) presented.
- Rock size for stream-bank structures may be determined from either an equation or nomographic chart (nomogram).
- Allows for sizing of rock based on bund batter slope.
- Nomogram suggests flatter slopes could adopt lighter stones in a thinner section.
- CALTRAN has maximum slope to 1V:1.5H and suggests no restrictions to flatter slopes, other than the 1V:4H shown on the nomogram.
- Unable to relate the CALTRAN method back to the Austroads (2019) rock sizing tables.
- It is unclear how CALTRAN was used to develop the Austroads look-up table.
- Therefore, we are unable to derive a method to vary the Austorads (2019) rock sizing tables based on batter slope.
- CALTRAN assumes impinging and tangent velocities as 4/3 and 2/3 the average stream velocity respectively. However, there is no justification (data or reference) for applying these factors to stream channels / flood bunds (USGS, 1986).



112 BANK AND SHORE PROTECTION

$$W = \frac{0.00002V^6\ sg_R\ \csc^3(\rho - \alpha)}{(sg_R - 1)^3}$$

W = Weight of critical stone in pounds; two thirds of stone should be heavier.

ρ = 70° constant for broken rock.

Example:
sg_R = 2.65
V_A = 10, find W = 57 lb
V_B = 20, find W = 1.8T

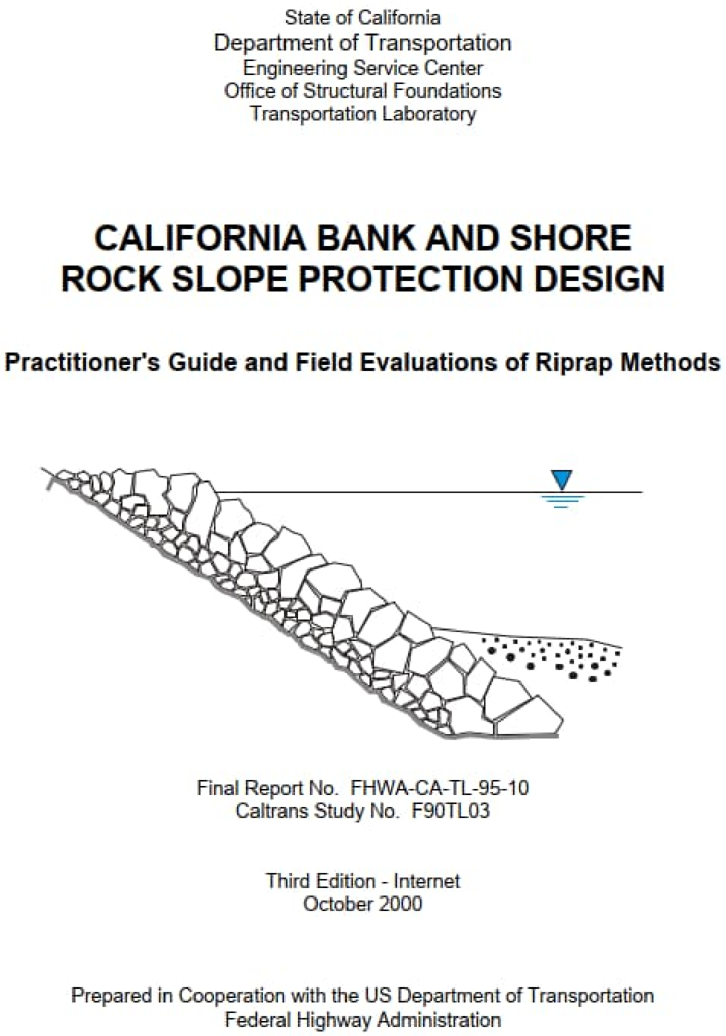
DESIGN OF ROCK SLOPE PROTECTION
FOR STREAM BANK

CHART D. Nomograph for design of stream-bank rock slope protection.

California Department of Transport (2000)

California Bank and Shore Rock Slope Protection Design

- A review of several theoretical studies that compared rock sizing methods.
- Study suggests that the CALTRAN method (CDPW, 1960) may produce oversized rock, however this “overdesign” is considered acceptable given the uncertainties in design and construction and risk.
- The CALTRAN method was recommended owing to the limited observed failures when adopted this method for design of stream-bank structures since 1960.
- CALTRAN method was used to develop Austroads (2019) rock sizing tables.



State of California
Department of Transportation
Engineering Service Center
Office of Structural Foundations
Transportation Laboratory

CALIFORNIA BANK AND SHORE ROCK SLOPE PROTECTION DESIGN

Practitioner's Guide and Field Evaluations of Riprap Methods

Final Report No. FHWA-CA-TL-95-10
Caltrans Study No. F90TL03

Third Edition - Internet
October 2000

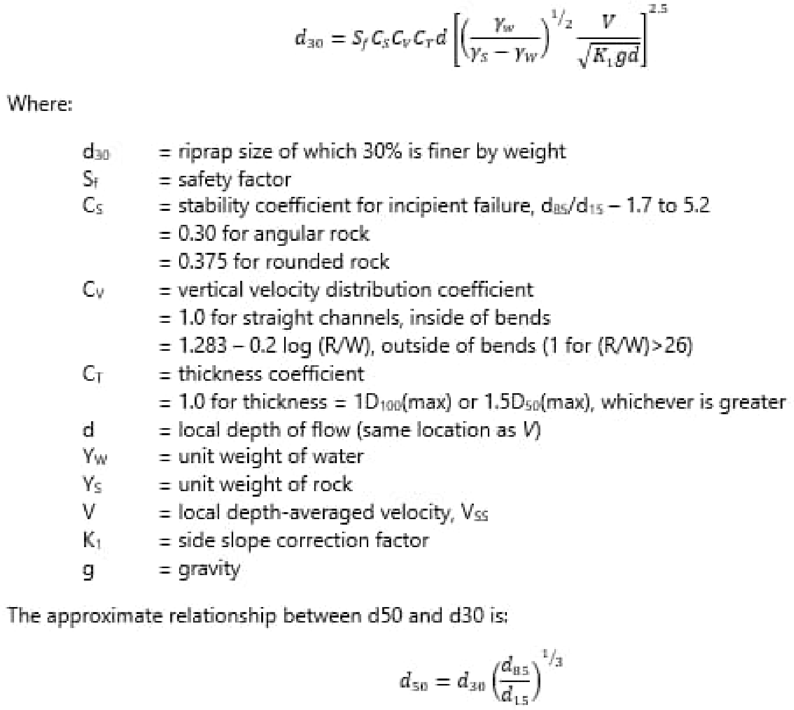
Prepared in Cooperation with the US Department of Transportation
Federal Highway Administration

National Cooperative Highway Research Program (2006)

Riprap Design Criteria, Recommended Specifications, and Quality Control

- There are numerous published methods for rock protection sizing:
- Using field and laboratory data, NCHRP (2006) compared 7 published rock protection sizing calculations and assessed their relative performance:
  - HEC-11 (Brown and Clyde, 1989)
  - Escarameia and May (1992)
  - Pilarczyk (1990)
  - US Army Corp of Engineers (USACE, 1994) - Maynord's equation
  - Isbash (1935, 1936)
  - CDPW (1960) - CALTRAN method
  - HDS6 (Richardson et al., 2001),
- The CALTRAN (CDPW, 1960) and the USACE (1994) methods were found to be the best performed.
- CALTRAN method was used to develop Austroads (2019) rock sizing tables.

USACE (1994)



$$d_{30} = S_f C_S C_V C_T d \left[\left(\frac{\gamma_w}{\gamma_S - \gamma_W} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5}$$

Where:

d_{30} = riprap size of which 30% is finer by weight
S_f = safety factor
C_S = stability coefficient for incipient failure, d_{85}/d_{15} – 1.7 to 5.2
= 0.30 for angular rock
= 0.375 for rounded rock
C_V = vertical velocity distribution coefficient
= 1.0 for straight channels, inside of bends
= 1.283 – 0.2 log (R/W), outside of bends (1 for (R/W)>26)
C_T = thickness coefficient
= 1.0 for thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater
d = local depth of flow (same location as *V*)
γ_W = unit weight of water
γ_S = unit weight of rock
V = local depth-averaged velocity, V_{SS}
K_1 = side slope correction factor
g = gravity

The approximate relationship between d50 and d30 is:

$$d_{50} = d_{30} \left(\frac{d_{85}}{d_{15}} \right)^{1/3}$$

Fischenich (2001)

Stability Thresholds for Stream Restoration Materials

- Presents tables with permissible (threshold) shear and velocity ranges for selection of lining materials.
- The threshold shear is calculated using equations developed by Shields (1936).
- Fischenich (2001) does not confirm the specific gravity associated with these tables however it is assumed that a typical specific gravity of 2.65 applies.
- The shear and velocity used to inform the rock sizing is extracted from a hydraulic model.
- No consideration of bund design batter slope.

Price (2021)

Advancing Australian Riprap Sizing Approaches

- The following 3 rock sizing methods should be considered for flood bund design:
  - *Velocity-based method* (CALTRAN method by CDPW, 1960)
  - *Shear-based method* (Australian guidance documents do not reference shear-based riprap sizing methods despite recommending the computation of shear stress for design purposes. There are numerous methods to chose from introducing uncertainty)
  - Maynord's equation (USACE, 1994).
- The methods produce different rock sizing.
- Safety factors also need to be considered.
- All methods require additional considerations for steep embankment slopes, sharp channel bends, rounded stones, low density, or other characteristics that deviate from assumed values and could reduce factors of safety.
- No recommendation were made over which method to adopt of the others. All three should be "considered".
- Slope not specifically discussed or investigated, just recommended that "slope is considered".

Yandi Creek Constrained Ore Project – DPS BoD (BHP, 2017)

Rock Sizing Methodology (developed with input from Krey Price)

- Krey Price (sub-consultant) was engaged to help Advisian develop a set of design criteria leveraging, much of which is presented in Price (2021).
- Published rock sizing methodologies can be broken into two categories:
  - Velocity-based approach. Based on Austroads (1994) - now superseded by Austroads (2019)
  - Force-based approach. Shields equation multiplied by a safety factor of 1.5, rounded up to the nearest rock class.
- The rock was sized based on the "worst-case" conditions that could reasonably be foreseen to eventuate over Closure timeframes. i.e., if the low flow channel could feasibly migrate to the toe of the bund, the rock will be sized based on the hydraulic conditions in the low flow channel.
- Hydraulic modelling results were extracted to size the rock.
- The velocity-based method (Austroads, 2019) consistently produced slightly larger rock than the force method.
- Austroads (2019) look up tables were adopted for detailed design.

Conclusions

- There are numerous published methods for rock protection sizing and papers comparing performance of methods. We have not presented them all here.
- Some methods produce larger / smaller rock size compared with others.
- Some methods consider the bund batter slope for sizing rock protection and others do not.
- All equations rely on either velocity and or shear for sizing rock, extracted from hydraulic models.
- The rock sizing tables published in Austroads (2019) have been used since 1994 for the hydraulic design of waterway structures in Western Australia. This method is tried and tested in the Pilbara Region of WA, and the fact that it has not changed in ~30 years suggests that it has been effective.
- The Austroads (2019) rock sizing tables were developed using the CALTRAN (1960) method which accounts for batter slope. However it is unclear how CALTRAN has been used in conjunction with practical experience and factors of safety, to develop the Austroads tables.
- Austroads recommends the use of the rock sizing tables for batter slopes no steeper than 1V:1.5H.
- In the absence of any other proven methods for rock sizing in Western Australia, which account for flatter batter slopes, Austroads (2019) is recommended.
  - While the CALTRAN method does relate flatter bunds to smaller rock armour, the uncertainty in how the method has been applied by Austroads and the fact that bund slope is not a factor across all rock sizing methods are the reasons that we recommend that the rock size is not reduced for flatter bund slopes.

Recommendations

- The results from this trade off study recommend the use of Austroads (2019) for rock sizing on flood bunds, regardless of flood bund batter slope.

References

- Austroads, 2019. Guide to Bridge Technology Part 8: Hydraulic Design of Waterway Structures.
- BHP, 2017. DEFINITION PHASE STUDY WAIO PROJECT – CREEK CONSTRAINED ORE PROJECT. DESB-1200-C-00002/F
- California Department of Transport, 2000. California Bank and Shore Rock Slope Protection Design.
- California Department of Public Works (CDPW), Division of Highways, 1960. Bank and Shore Protection in California Highway Practice.
- Fischenich, C., 2001. Stability Thresholds for Stream Restoration Materials. USAE Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Rd., Vicksburg MS 39180.
- Main Roads WA, 2006. Floodway Design Guide.
- National Cooperative Highway Research Program, 2006. Riprap Design Criteria, Recommended Specifications, and Quality Control.
- Shields, 1936. Anwendung der ahnlichkeits-mechanik und der turblenz-forschung auf die geschiebebewegung," Mitt. Preuss.Versuchsanst. Wasser. Schiffsbau, 26, 1-26 (in German).
- USGS, 1986. Rock Riprap Design for Protection of Stream Channels near Highway Structures.
- USGS, 1994. Hydraulic Design of Flood Control Channels, EM 1110-2-1601. Washington, DC.

Advisian. (2023h). Trade-off Study: Rock Armour for Bunds: Submerged Toe versus Launchable Toe

Advisian Pty Ltd (Worley Group)
Level 14, 240 St Georges Terrace
Perth, WA 6000
Tel: +61 8 9278 8111
Fax: +61 8 9278 8110
www.advisian.com

Cover Sheet

Project No: 311012-01707

Project Title: Yandi Closure Landforms SPS

Customer: BHP

Document No: 311012-01707-CI-PRE-0008_C

Document Title: SPS Trade-off Study Presentation: Rock Armour for Bunds: Submerged Toe versus Launchable Toe

Electronic File Location: I:\Projects\311012-01707 Yandi Closure Landforms SPS\9_Deliverables

Originator: S. Atkinson

Document Status

REV	DATE	DESCRIPTION	CHKD	APPD
A	Friday, 15 September 2023	Issued for internal review		
B	Tuesday, 19 September 2023	Issued for client review	MR	LM
C	Tuesday, 3 October 2023	Issued for study	MR	LM

Yandi Closure Landforms SPS

311012-01707-CI-PRE-0008_C

Trade-off Study: Rock Armour for Bunds: Submerged Toe versus Launchable Toe

3rd October 2023

Advisian
Worley Group

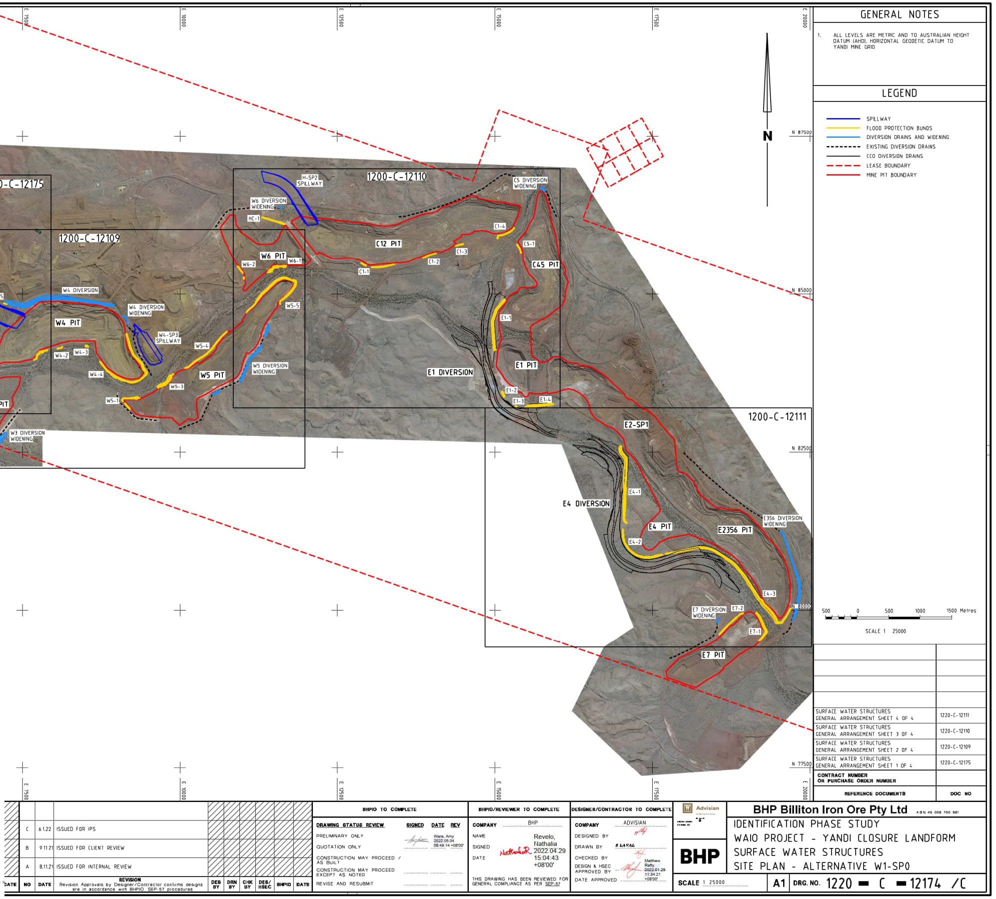
advisian.com

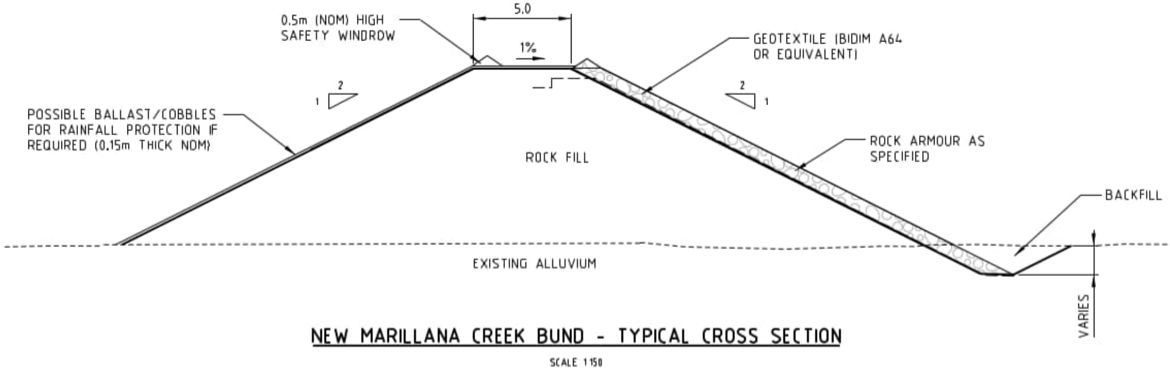
Outline of Presentation

1. Background
2. Objective of this trade-off study
3. Comparison of methods
4. E4-3 flood bund assessment
5. Conclusions
6. Recommendations

Background – Flood Bund Rock Protection Design

- Rock protection on Flood Bunds:
  - 1:10,000 AEP Hydraulic modelling results adjacent to the flood bund locations have been used to size and locate rock protection.
  - Rock armour protects bund structure from scour and erosion, resulting in a stable final landform design.
  - Stable flood bunds mitigate risk of pit capture of Marillana Creek.
- The flood bund designs adopted at Yandi assume batter slopes of 1V:2H, and rock protection extended below ground level to protect from lateral migration and undercutting of toe.
- The rock extended below depth of scour or to depth of competent rock (whichever governs).





NEW MARILLANA CREEK BUND - TYPICAL CROSS SECTION

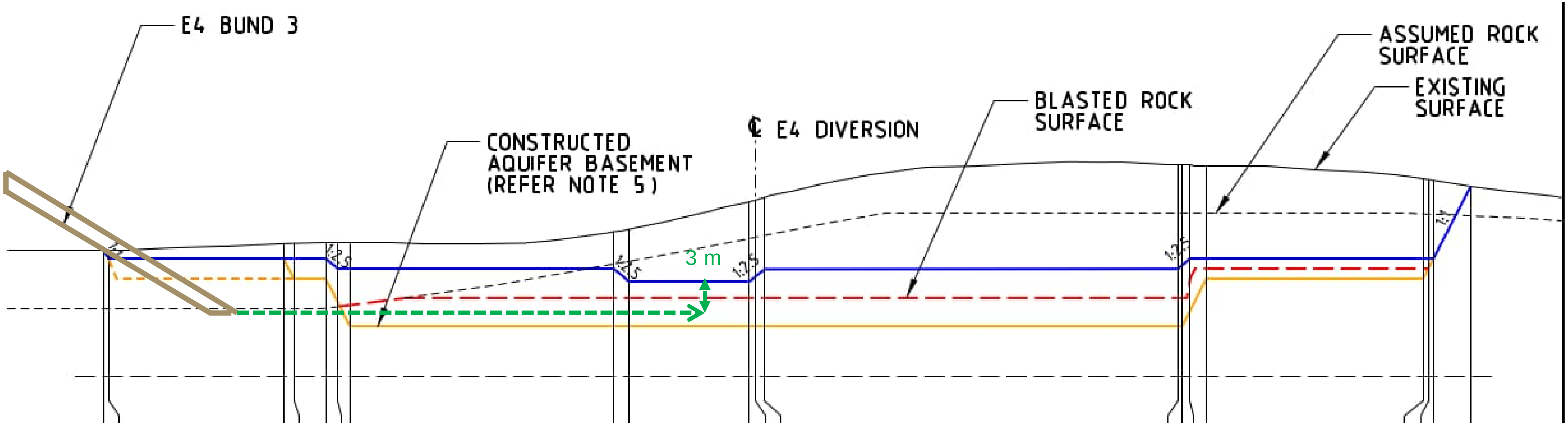
SCALE 1:150

Background – Flood Bund Rock Protection Design

- Marillana Creek has highly mobile, braided channels meaning the primary low flow channels can migrate over time. This migration of channels leads to scour, erosion and deposition, naturally.
- IPS Design of flood bunds assumes the rock is extended 3 metres below the base of the primary low flow channel (or until Rock is encountered) to protect the toe from scour/erosion and undercutting.
- It will require significant excavation in some areas, and may require dewatering of the superficial alluvial aquifer where present.
- It is also likely to require some disturbance of riparian vegetation to construct.
- Two flood bunds constructed at W5 Pit (designed for operations) include launchable toes for scour protection. These were designed to avoid removing trees in Marillana Creek due to clearing/approvals requirements.
- The flood bunds associated with the Creek Constrained Ore project for the E1 and E4 diversions included submerged toes in the DPS design. During execution, design changes were made by BHP and the Contractor to remove the submerged toe (instead extending the rock armour to a nominal 1 m below the finished surface). Factors contributing to that decision are speculated to include any of the following:
  - Additional cost of extending the rock
  - Additional cost / time for excavation and backfilling
  - Traffic management issues caused by volume of rock-laden trucks
  - Operational inspections can be used to identify potential scour/risks areas and initiate maintenance where required. There is already evidence of scour and undercutting of the E4-3 bund
  - Upgrades can be implemented at Closure.
- The high risk of scour in Marillana Creek requires protection of the toe of the flood bunds for mine closure. There are significant costs associated with the submerged toe rock armour design and there is an alternative launchable toe design option available. Therefore a trade-off study is required to evaluate the two toe protection options.

Undercutting of E4-3 Bund

Background – Flood Bund Rock Protection Design



Chainage 2800 Cross Section of E4 Diversion

- Ground level at bund is 541.2 mAHD
- Low flow channel is at 537.9 mAHD
- Base of scour estimated to be 534.9 mAHD
- Rock toe vertical depth is 6.3 m
- Excavation without benches would be at least 30 m wide with a 5 m working base at 1v:2h slopes

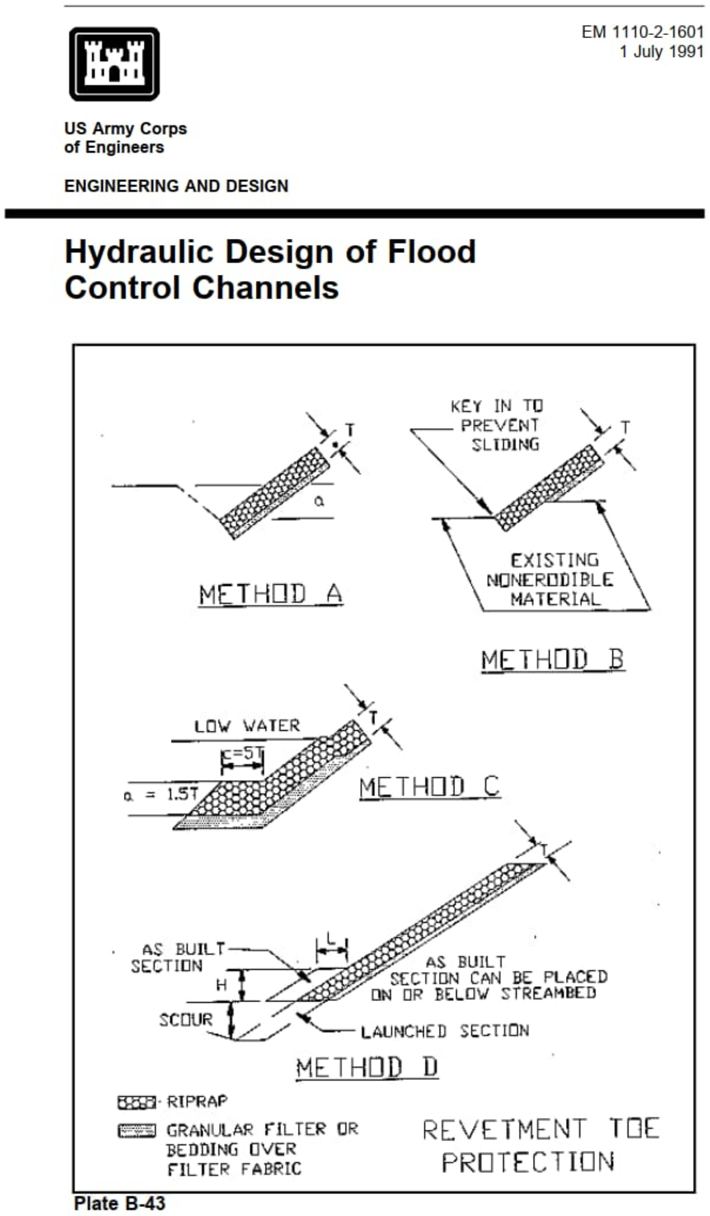
Objective of Trade Off Study

Compare the extended rock and launchable toe rock options, assess the pro's and con's as well as costs and select the preferred option for SPS design.

Flood Bund Toe Protection Options

- Toe protection may be provided by:
  a) Extend to maximum depth of scour to protect from lateral channel migration and scour, or
  b) Place launchable rock layer at toe. If toe is undermined by channel migration then the launchable toe rolls/slides down the slope formed by the undermining, which stops the erosion.
- Extending to maximum depth of scour:
  - Was adopted in the IPS.
  - Included a geofabric layer under the rock to prevent washing of fines from the bund formation (which can destabilise the flood bund).
  - Rocks are mechanically interlocked into place.
- Launchable toe:
  - Has been widely used on watercourses with sand beds, however for gravel beds the use of launchable rock is not as widely accepted as there have been “problems” associated with underestimation of scour depths in gravel beds, rock size and rock volumes.
  - Rocks slide/drop into place and are not mechanically interlocked.
  - There is no geofabric layer under the rock to prevent washing of fines from the bund formation.
- Available methods:

  There are several alternative methods for toe protection at Yandi depicted in the image right. Methods A and D are considered given the site conditions and ephemeral nature of watercourses.



EM 1110-2-1601
1 July 1991

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Hydraulic Design of Flood Control Channels

Plate B-43

Extending to maximum depth of scour (Method A)

- This method is applied when the toe excavation can be made in the dry (using dewatering if required).
- The rock protection layer is extended below the existing ground level to a depth greater than the maximum depth of scour estimated for the design AEP event (1:10,000 AEP).
- Marillana Creek is ephemeral and has a primary low flow channel that regularly migrates. To mitigate the risk of lateral channel migration, the rock is to be extended to at least the maximum depth of scour estimated in the low flow channel.
- Failure to extend the rock below the maximum depth of scour in the low flow channel can lead to undermining of the toe, when the low flow channel migrates, as seen recently at the E4-3 flood bund adjacent to E6 pit (August, 2023). Pictures below show erosion from what is likely to be no larger than a ~50% AEP event, well below the design event.

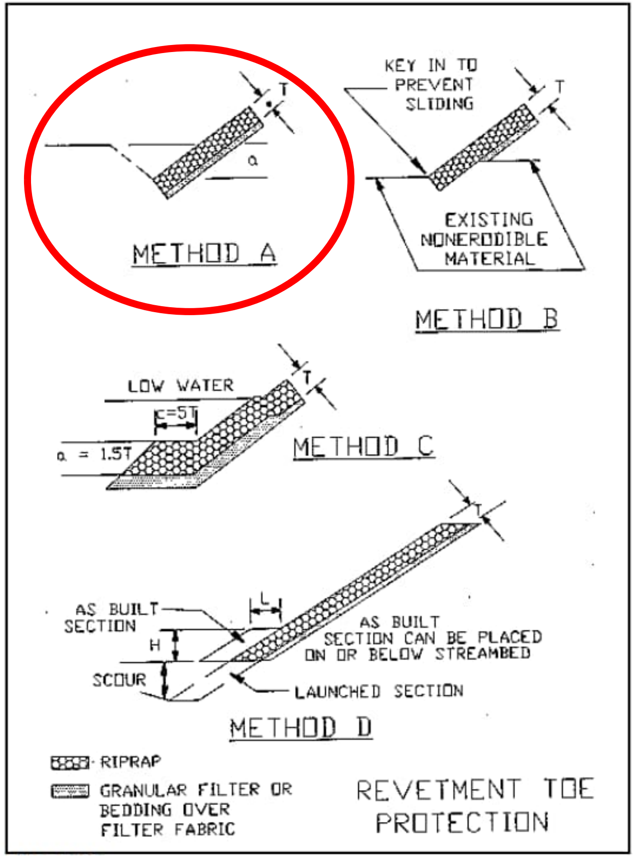


Plate B-43

Launchable toe (Method D)

- This method is often applied where Method A cannot be achieved, OR where it is cheaper than Method A.
- The method uses toe scour as a substitute for mechanical excavation.
- No mechanical interlocking of rock, no geofabric protection to prevent washing out of fines from the lower section of the flood bund / beneath the flood bund.
- Method has " *a built-in scour gauge, allowing easy monitoring of high-flow scour and the need for additional rock reinforcement by visual inspection of the remaining toe rock after the high flow subsides or by surveyed cross sections* " (USACE, 1994) - suggests operational maintenance is required.
- For rapid scour in impinged flow environments or in gravel bed streams (which is the case at Yandi / Marillana Creek) the rock section height before launching should be 2.5 to 3.0 T (where T = thickness of the rock protection on the bund).
- "*Providing an adequate volume of rock is critical. Rock is lost downstream in the launching process; and the larger the scour depth, the greater the percentage of rock lost in the launching process*" (USACE, 1994). - suggests operational maintenance is required.

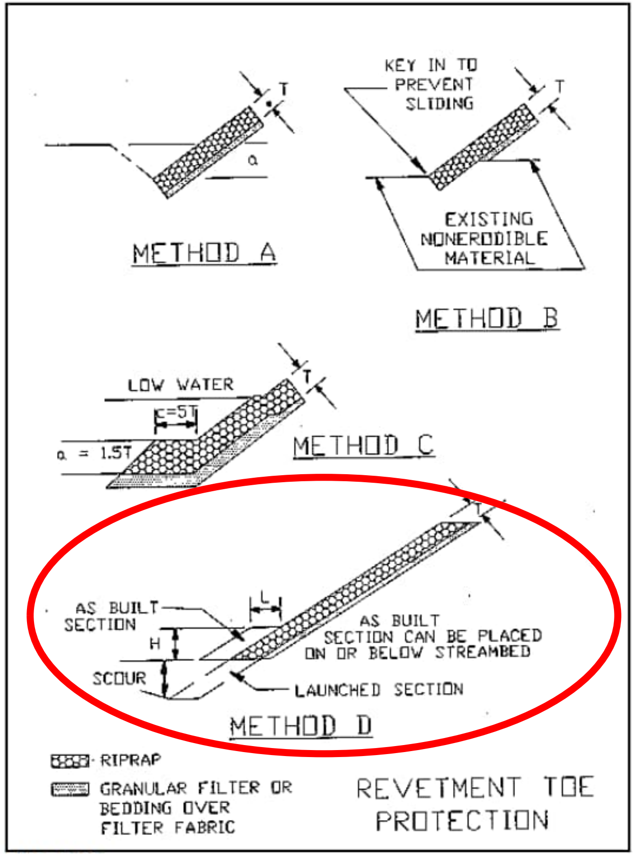
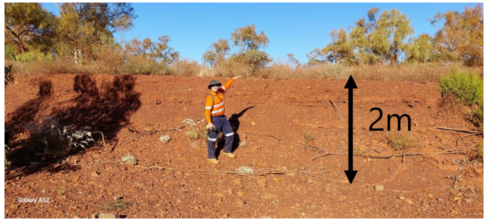


Plate B-43

Launchable toe (Method D)

- To calculate the required launchable rock volume for this method:
  1) Launch slope = 1V:2H
  2) Scour depth = existing ground elevation – maximum scour elevation in the main low flow channel in Marillana Creek (to account for channel migration)
  3) Thickness after launching = thickness of the bank revetment (T).
- To account for the rock lost during launching, the increases in rock (stone) volume listed in Table 3-2 are recommended.
- Add a safety factor if data to compute scour depth are unreliable or if monitoring and maintenance after construction cannot be guaranteed (USACE, 1994). No guidance on what factor to apply, other than to consider the consequence when selecting a factor.
- Widely graded rock riprap is recommended because of reduced rock voids that "*tend to*" prevent leaching of lower bank material through the launched riprap. Launchable rock should have D85/D15 ≥ 2.
- The estimated depth of scour in the low flow channel of Marillana Creek is 3 m. The low flow channel invert level is approximately 2 m lower than bund toe location on average.



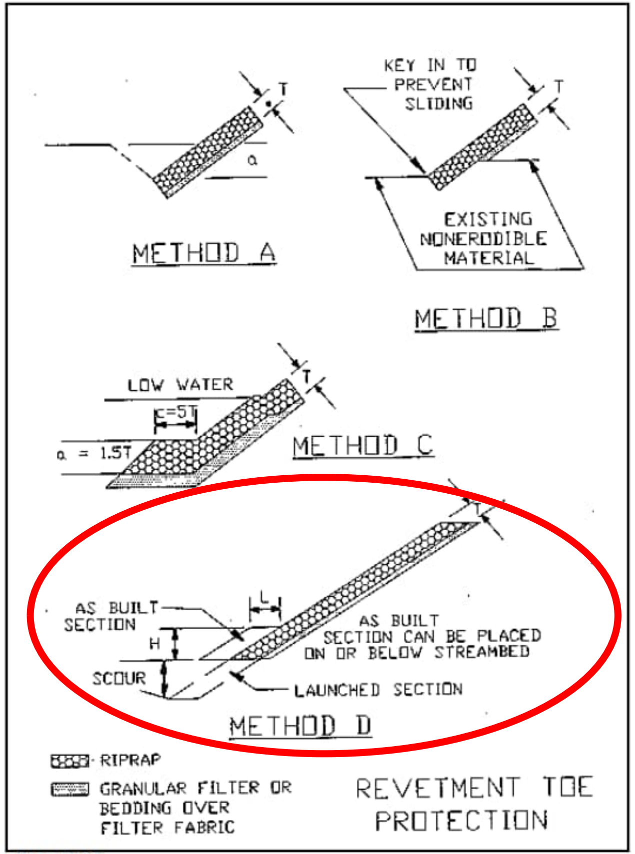


Plate B-43

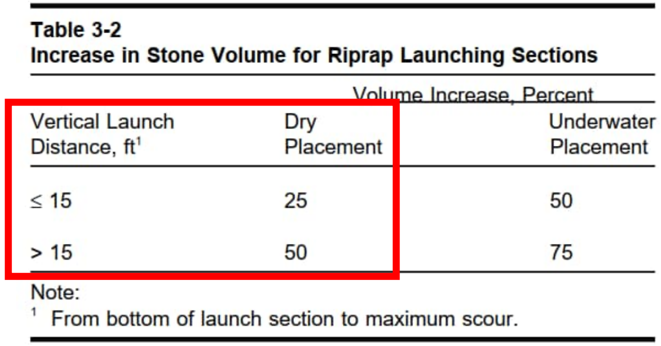


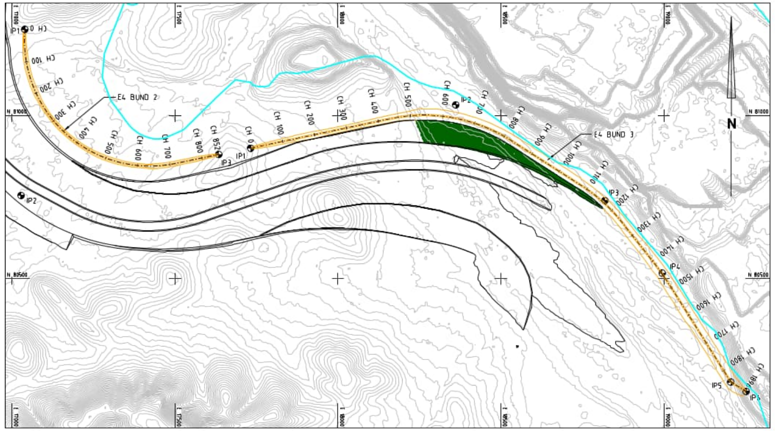
Table 3-2
Increase in Stone Volume for Riprap Launching Sections

Vertical Launch Distance, ft[1]	Volume Increase, Percent Dry Placement	Underwater Placement
≤ 15	25	50
> 15	50	75

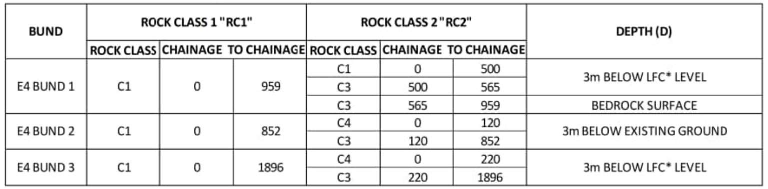
Note:
[1] From bottom of launch section to maximum scour.

E4-3 Flood Bund – Extended Rock Volume Estimates

- The E4-3 flood bund was selected as a case study to assess and compare the difference in rock volumes needed to implement Method A and D.
- For this assessment, we referred to the WAIO Creek Constrained Ore Project, Definition Phase Study, Engineering design Report (BHP, 2017) which states:
  - *"The armour rock design includes a submerged toe beneath the finished ground surface to prevent undercutting by the low flow channel, if the channel could plausibly migrate laterally adjacent to the bund over closure timeframes. The toe was designed to extend 3 m below the base of the low flow channel, along the alignment of each bund, to exceed the maximum estimated scour depth. Where the boundary between material classified as Common and Rock is shallower than the estimated scour depth, the depth of the armour rock toe was set to the level of the Rock."*
- A combination of ¼ tonne (C3 class) and ½ tonne (C4 class) was adopted for the E4-3 flood bund. We have assumed ½ tonne for volume estimation purposes along full length, and 1.25 m thickness.
- The low flow channel is assumed to be (on average) 2 m higher than the toe of the flood bund. Therefore the rock needs to extend ~5 m below ground. This equates to 11.18 m x 1.25 m of volume per metre of bund.
- Bund is approximately 1900 m long.
- Total volume of extended rock = 11.18 x 1.25 x 1900 = 26,553 m^3.



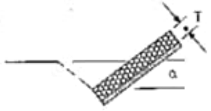
ROCK SIZING FOR FLOOD BUNDS



BUND	ROCK CLASS 1 "RC1"			ROCK CLASS 2 "RC2"			DEPTH (D)
	ROCK CLASS	CHAINAGE	TO CHAINAGE	ROCK CLASS	CHAINAGE	TO CHAINAGE	
E4 BUND 1	C1	0	959	C1	0	500	3m BELOW LFC* LEVEL
				C3	500	565	
				C3	565	959	BEDROCK SURFACE
E4 BUND 2	C1	0	852	C4	0	120	3m BELOW EXISTING GROUND
				C3	120	852	
E4 BUND 3	C1	0	1896	C4	0	220	3m BELOW LFC* LEVEL
				C3	220	1896	

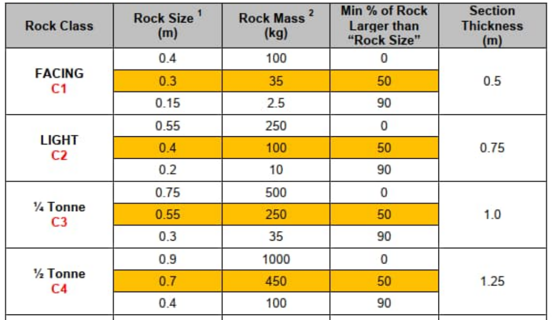
LFC = LOW FLOW CHANNEL

REFER TO SPEC-1200-C-00013 FOR ROCK CLASSIFICATIONS AND 1200-C-15089 FOR SECTION DETAILS



METHOD A

Table 5-1: Rock Armour Specification

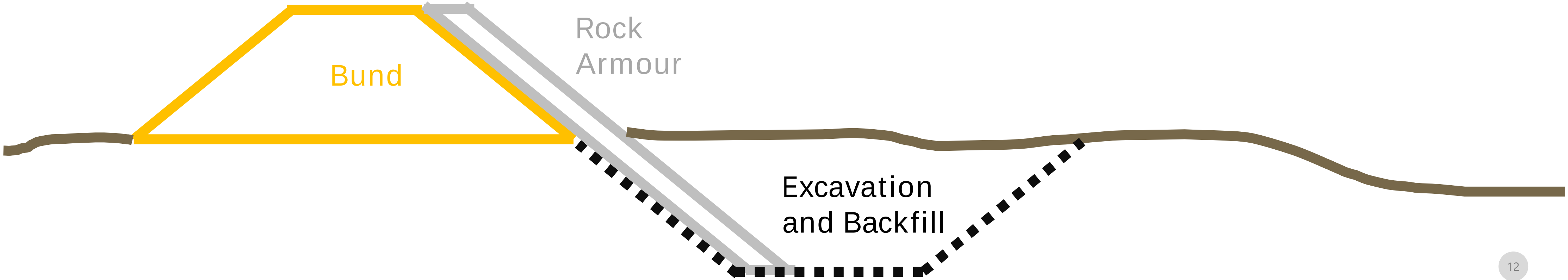


Rock Class	Rock Size [1] (m)	Rock Mass [2] (kg)	Min % of Rock Larger than "Rock Size"	Section Thickness (m)
FACING C1	0.4	100	0	0.5
	0.3	35	50	
	0.15	2.5	90	
LIGHT C2	0.55	250	0	0.75
	0.4	100	50	
	0.2	10	90	
¼ Tonne C3	0.75	500	0	1.0
	0.55	250	50	
	0.3	35	90	
½ Tonne C4	0.9	1000	0	1.25
	0.7	450	50	
	0.4	100	90	

E4-3 Flood Bund – Extended Rock Volume Estimates

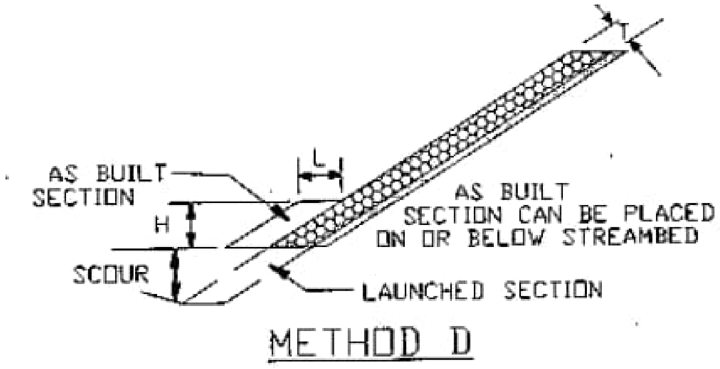
- Excavation of material is required to install the submerged toe
- Nominal design for cost comparison is 1V:2h slopes with 5 m base. This could be at least 25 m width required.
- Approximate direct cost of $10/m^3$ to excavate and backfill material
- Volume of excavation/backfill for E4-3 is ~142,500 m^3
- Examples of 25 m width shown at E4 and also W5 for comparison. Vegetation disturbance will be greater in some areas.

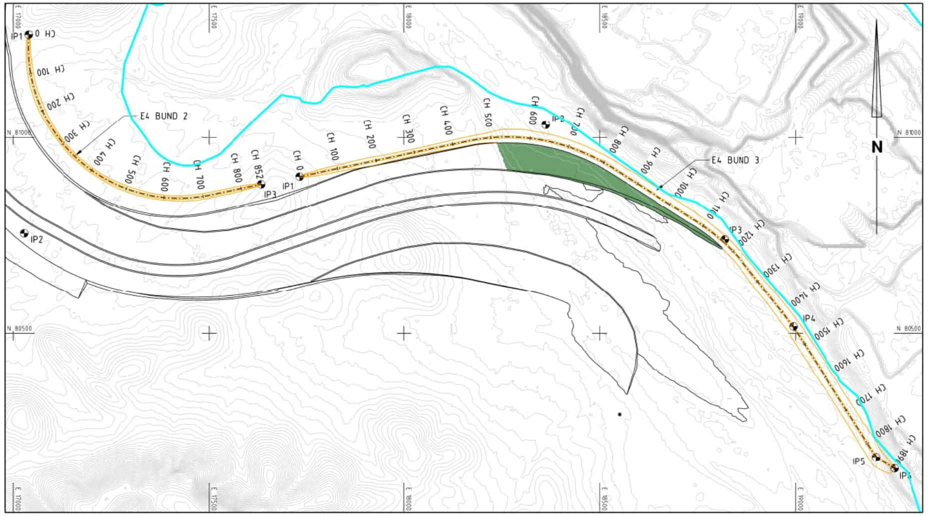
E4-3 bund and ~25 m disturbance from bund toe



E4-3 Flood Bund – Launchable Toe Volume Estimates

- Design parameters for launchable toe rock volume estimates:
  - ½ tonne rock
  - T = 1.25 m rock thickness
  - H = 3 x T = 3.75 m
  - Scour depth = bund toe level – ground level in low flow channel = ~5 m
  - Launch slope = 1V:2H
  - According to Table 3-2 (USACE, 1994):
    - 5 m > 15 ft, so adopt 50% increase in rock volume allowed for launchable toe
    - Launched section volume (per m of bund) = 11.18 x 1.25 = 14 m^3/m rock
    - 14 m^3 x 150% = 21 m^3/m
    - L = 21/H = 21/3.75 = 5.6 m
    - Length of E4-3 flood bund = ~1900 m
    - Total volume of rock = 21 x 1900 = 39,830 m^3





E4-3 Flood Bund – Trade Off Assessment

Option	Quantities	Cost ($)	Pro's	Con's
Extended Rock (Method A)	26,125 m^3 rock 142,500 m^3 excavation/backfill	$6.6M	Less rock, lower cost Rock is mechanically interlocked into place, lowering risk Geofabric installed to prevent washing out fines Greater certainty of outcome	Requires additional excavation for construction of extended toe Excavation may require dewatering Excavation may require clearing of vegetation
Launchable Toe (Method D)	40,000 m^3 rock	$8.0M	Easier to construct Could be used to avoid impact to trees No additional excavation to install No dewatering	Greater rock, higher cost Uncertainty with how the design will perform due to rocks being washed away and not falling into place and the rock not being mechanically interlocked. This is managed by increasing the volume of rock but the outcome is still uncertain. No geofabric so risk of washing out fines -> undercutting and potential failure of bund Lower certainty of outcome Literature suggests this option may require ongoing monitoring and maintenance

Assuming $200/$m^3$ for rock armour and $10/$m^3$ for excavation and backfilling material

Conclusions

- Extended rock (Method A) option for toe protection is preferred as it is cheaper and provides greater certainty in terms of protection from scour, erosion and undercutting of flood bund.
- Launchable toe (Method D) option could be considered to protect trees, however comes at greater risk and cost.

Recommendations

- Extended rock (Method A) option is recommended for the SPS flood bund design, which is the same design approach adopted for the IPS.
  - In some circumstances environmental, social, technical or other factors may require a launchable toe to be considered.
- If competent in-situ rock is encountered below the toe of the flood bund during excavation, then the extended rock protection should tie into the rock (stopping at the in-situ rock).

References

- BHP, 2017. WAIO Creek Constrained Ore Project, Definition Phase Study, Engineering Design Report. PREP-1200-G-12417/C.
- WL I Delft Hydraulics, 2006. Falling aprons, internal report.
- U.S. Army Corps of Engineers (USACE), 1994. Hydraulic Design of Flood Control Channels. EM 1110-2-1601. June 30th 1994.
- U.S. Army Corps of Engineers (USACE), 1995. Toe Scour and Bank Protection Using Launchable Stone. HL-95-11. September 1995.

Advisian. (2023i). BHP Yandi Closure Landforms SPS. Trade-off study: Buttress Eastern Pits

Advisian Pty Ltd (Worley Group)
Level 14, 240 St Georges Terrace
Perth, WA 6000
Tel: +61 8 9278 8111
Fax: +61 8 9278 8110
www.advisian.com

Cover Sheet

Project No: 311012-01707

Project Title: Yandi Closure Landforms SPS

Customer: BHP

Document No: 311012-01707-CI-PRE-0006_C

Document Title: Trade-off Study - Buttress Eastern Pits

Electronic File Location: I:\Projects\311012-01707 Yandi Closure Landform SPS\9_Deliverables\313 TRADE OFF STUDIES\31307 TRADE OFF STUDY BUTTRESS EASTERN PITS PRESENTATION

Originator: Andrew Rajapakse

Document Status

REV	DATE	DESCRIPTION	CHKD	APPD
A	Friday, 16 June 2023	Issued for internal review	SA	LM
B	Wednesday, 21 June 2023	Issued for client review	SA	LM
C	Tuesday, 25 July 2023	Issued for study	SA	LM

BHP Yandi Closure Landforms SPS

Trade-off study: Buttress Eastern Pits (GEN.10)

311012-01707-CI-PRE-0006_C – Issued for Study

25 July, 2023

advisian.com

Outline of Presentation

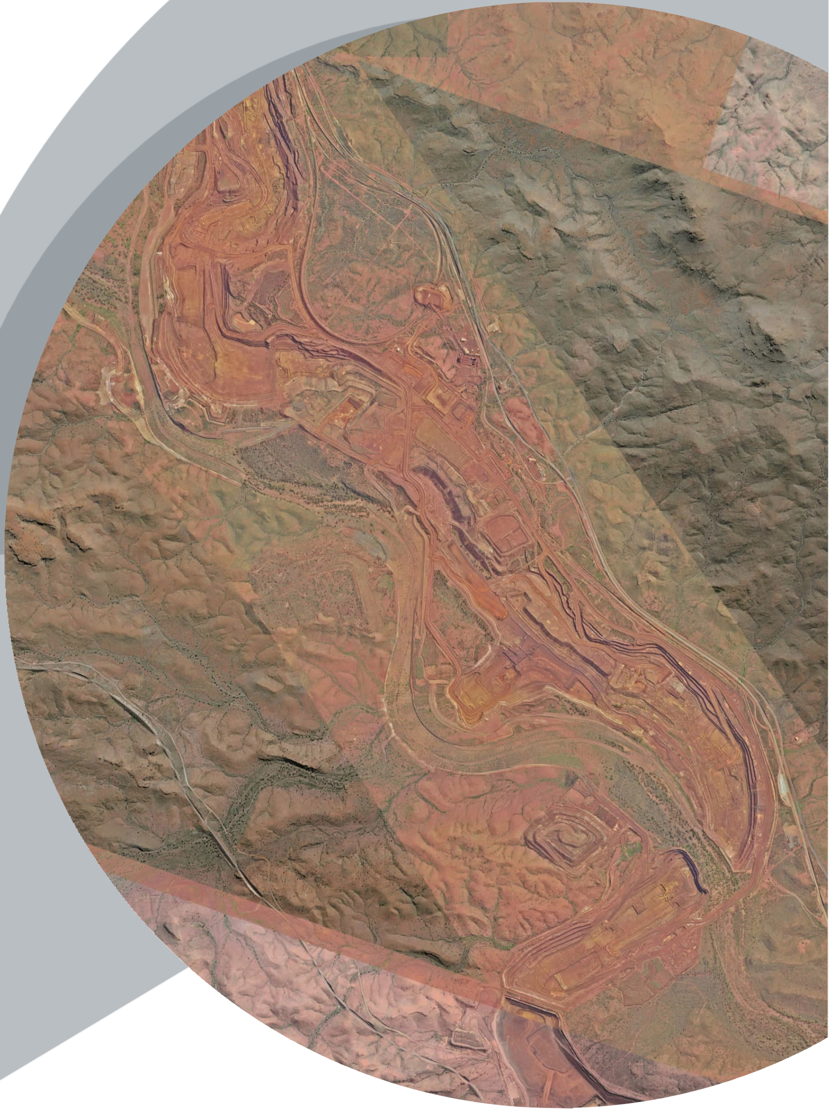
1. Background and Objectives
2. Methodology
3. Basis of Design
4. Setback calculations at E1, E4 & E7 flood bunds
5. Downstream flood bund raising toe location estimates:
    a) Locations where additional buttressing is required
    b) Buttress calculation (quantity and cost estimation)
6. Comparison of upstream v downstream flood bund raising:
    a) Cost of additional buttressing
    b) Pro's / Con's of each option
7. Recommendations
8. Next Steps

Background and Objectives

- The IPS assumed that existing E1, E4 & E7 flood bunds will be raised at closure (upstream raise, into the creek) and earthworks quantities were estimated.
- The toe of the flood bunds will extend into Marillana Creek, potentially impacting on flows & hydraulics. This would also mean removing the existing rock from levees and replacing with the same or larger rock depending on hydraulics.
- Objective of Trade-off Study is to assess alternative downstream raising option (towards the pits) at E1, E4 & E7 flood bunds and compare with upstream raising base case.

Methodology

- Estimate the extent of the downstream flood bund toes if assuming downstream raising of E1, E4 & E7 flood bunds
- Identify locations where downstream raising encroaches on pit setbacks, and at those locations assess additional pit wall buttressing required to maintain stability of final landform
- Calculate additional buttressing quantities and costs
- Compare upstream versus downstream flood bund raising options based on:
  - Additional costs for buttressing
  - Qualitative assessment of pro's and con's of each
- Recommend preferred option at E1, E4 & E7 flood bunds in consultation with BHP
- Document results



Basis of Design

Pit Design

- Ultimate pit shell/design has been adopted.

Design AEP Event

- 1:10,000 AEP flood event.

Pit Setback Calculation

- Pit setbacks defined at each flood bund location are based upon 2D sectional analysis, the intersection of HJ (Weeli Wolli Formation) with the pre-mining surfaces and the remaining MESA. A 10m buffer is applied to crest offsets where applicable.
- Pit setback calculations assume Scenario B backfill and groundwater conditions (the E2-6 pit is partially filled, whilst the E7 pit remains a pit lake).
- The risk of pit wall instabilities is higher under greater pore pressure conditions associated with high rainfall and flood events. Therefore, pit setback calculations assume high pore-pressure conditions.

Buttressing Analysis and Calculations

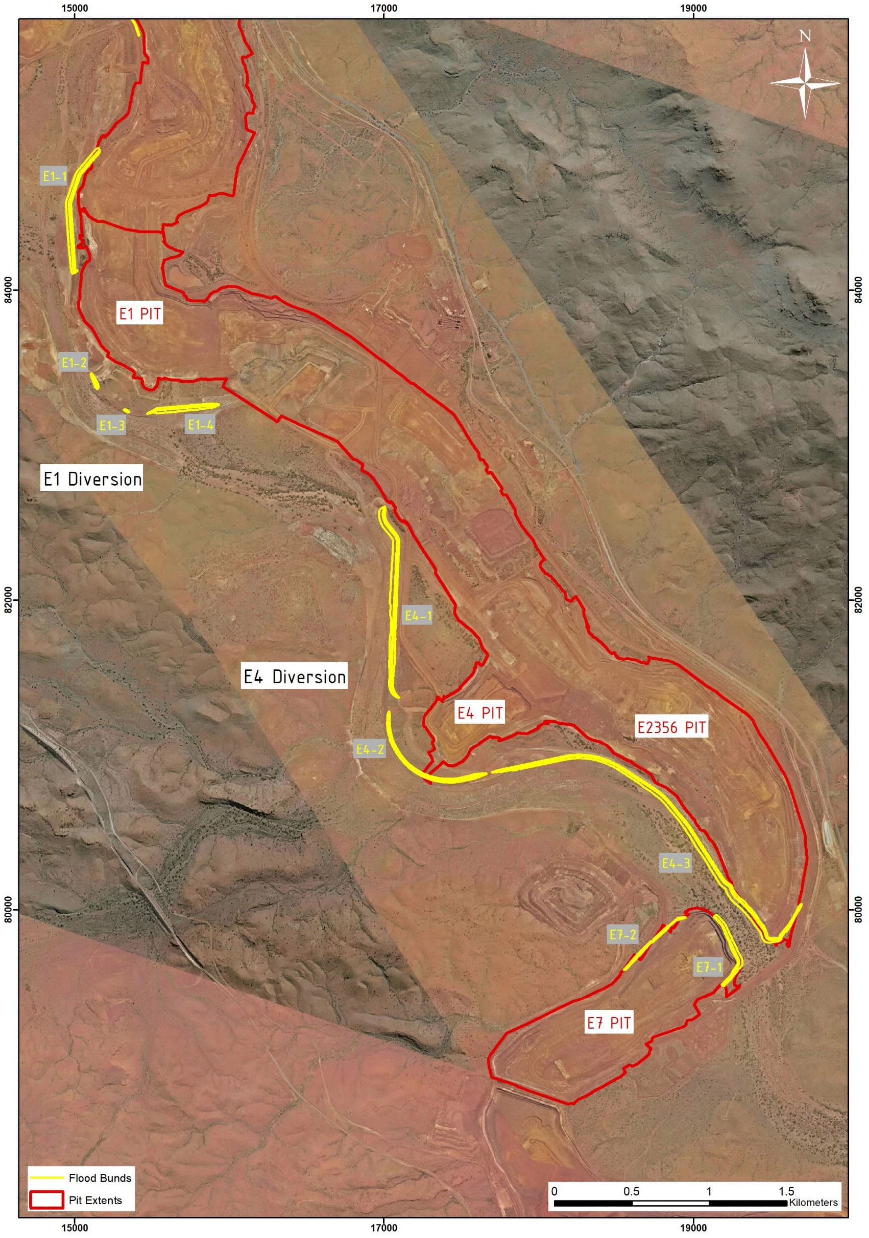
- Pit buttressing requirements and quantities estimated by:
  - As part of Slide2 sectional analysis, derive buttress assuming waste material rill angle and slope height.
  - Buttress areas are estimated and multiplied by the estimated length of the slope requiring support.
  - The resulting volume is adopted as a buttress volume for the trade-off study.

Earthworks Costs (approximate direct unit cost rates for comparative purposes only)

- Pit buttressing assumes end tipping of mine waste at $10/m^3
- Bund fill: $30/m^3
- Rock Protection: $200/m^3

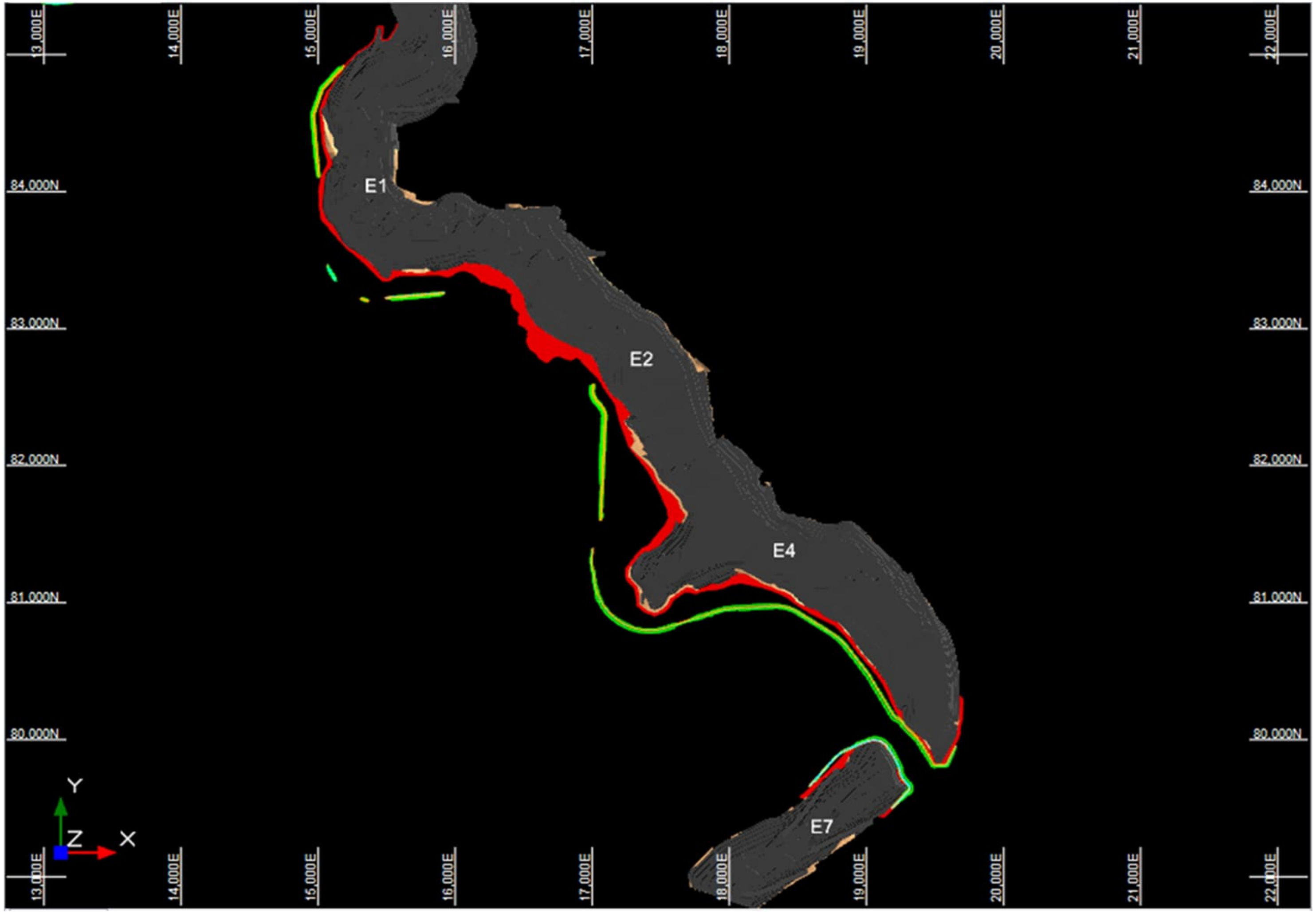
Flood bunds assessed

- E1-1
- E1-2
- E1-3
- E1-4
- E4-1
- E4-2
- E4-3
- E7-1
- E7-2



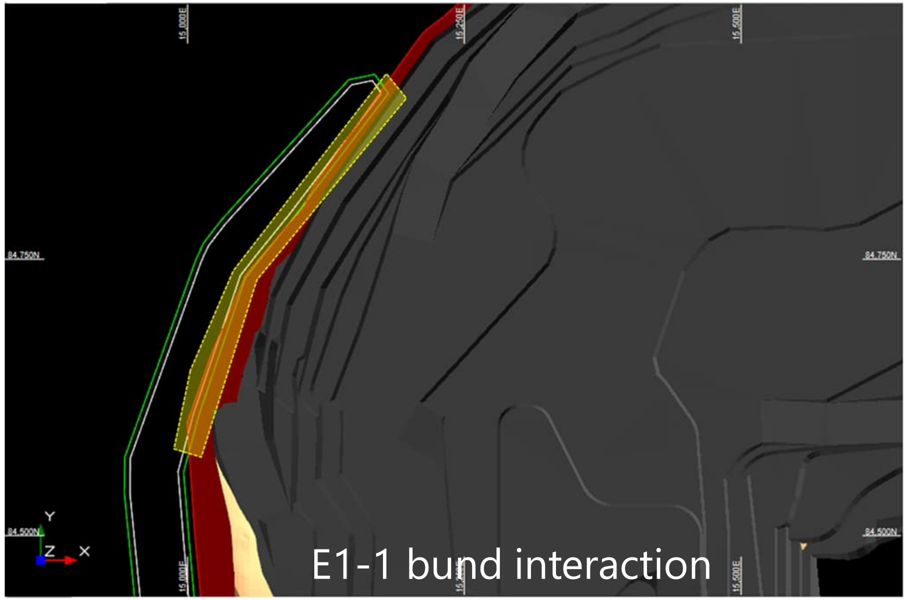
Pit wall setback

- Pit wall setback/exclusion shown in red.

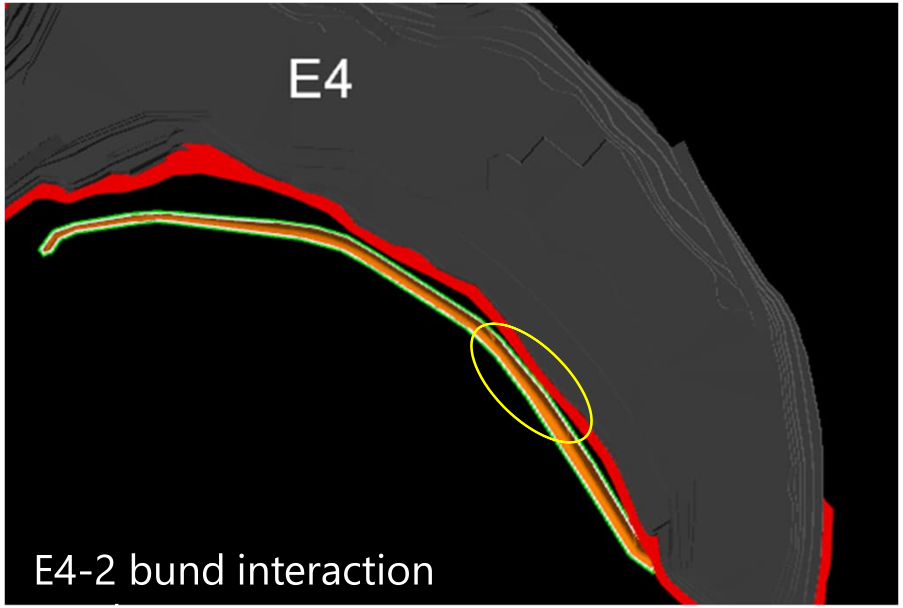


Flood bund interaction

- The toe of the existing flood bund was digitised from topography.
- The difference between the upstream design and the existing flood bund was measured and estimated to be 5 m.
- The downstream toe location was estimated by expanding the toe of the current flood bund outward by 5 m.
- Probable buttress locations (due to downstream raising encroaching on pit setbacks) have been identified using the interaction between the toe line and the exclusion zone.



E1-1 bund interaction



E4-2 bund interaction

Upstream Raise: Additional Buttressing and Flood Bund Quantity Estimates

Bund ID	Additional Flood Bund Quantities	Buttressing Quantities	Cost
E1-1	-	-	-
E4-3	-	-	-
E7-1	Bund Fill: 150 m^3/m Rock Protection: 25 m^3/m Bund Length: ~325 m Bund Fill Volume: ~50,000 m^3 Rock Protection Volume: ~10,000 m^3	-	Bund Fill Cost: $1.5M Rock Protection Volume: $2.0M Total: ~$3.5M

Downstream Raise: Additional Buttressing and Flood Bund Quantity Estimate

Bund ID	Additional Flood Bund Quantities	Buttressing Quantities	Cost
E1-1	-	250,000 m^3	Bund: \$0 Buttressing: \$2.5M Total: ~\$2.5M
E4-3	-	39,000 m^3	Bund: \$0 Buttressing: \$390,000 Total: ~\$390,000
E7-1	Bund Fill: 20 m^3/m Rock Protection: ~3 m^3/m Bund Length: ~325 m Bund Fill Volume: ~ 6,500 m^3 Rock Protection Volume: ~1,000 m^3	694,000 m^3 (excludes buttressing which is required for pit wall stability regardless)	Bund Fill: \$200,000 Rock Protection: \$200,000 Buttressing: \$7.0M Total: ~\$7.4M

Results

Flood Bunds E1-2, E1-3, E1-4, E4-1, E4-2

- Downstream Raise recommended:
  - Can retain existing rock protection (subject to confirmation: BHP specification SPEC-610-G-00000/1 provides the rock sizes for the flood bunds; however hydraulic and flood assessment during the design phase are required to confirm current rock sizes are suitable for closure)
  - Does not encroach on Marillana Creek, therefore not impacting the hydraulics
  - Does not encroach on the pit setback and therefore not expected to present additional long term stability risk
  - Reduces risk of flood events impacting construction activities.

Flood Bund E7-2

- E7-2 has not been constructed and therefore can be constructed as per the closure design:
  - Does not encroach on Marillana Creek, therefore not impacting on the hydraulics
  - Does not encroach on the pit setback and therefore not expected to present additional long term stability risk
  - Construction unlikely to be impacted by flood events.

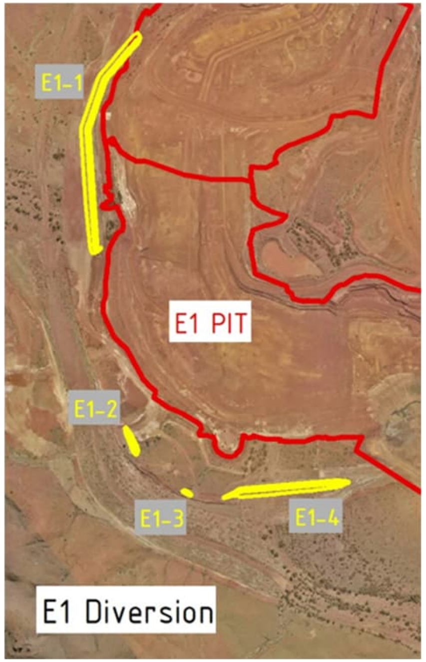
Flood Bunds E1-1, E4-3 & E7-1

Trade-off required to compare upstream versus downstream raising.

Upstream and Downstream Raising Trade-off Assessment

E1-1

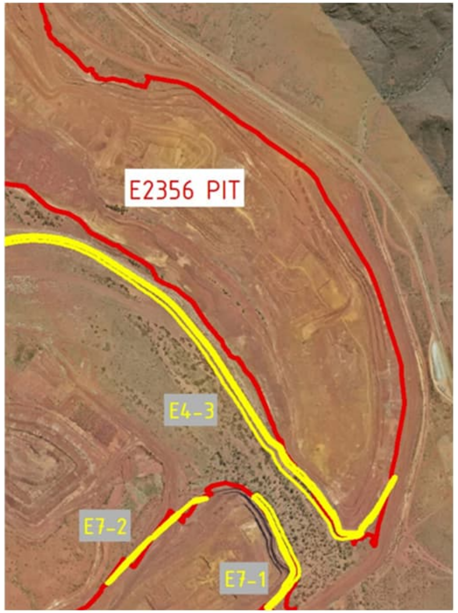
Option	Additional Cost ($)	Pro's	Con's
Upstream	-	Simpler construction method due to ease of access No large trees present, so no disturbance to vegetation	Construction impacted by flood events Need to remove existing rock and replace
Downstream	$2.5M	Construction not impacted by flood events Potential to retain existing rock armour	Potentially more complex flood bund construction due to proximity to pit crest (at or within minimum of 10 m) Very narrow operating width between design pit crest and flood bund, presents construction safety risks



Upstream and Downstream Raising Trade-off Assessment

E4-3

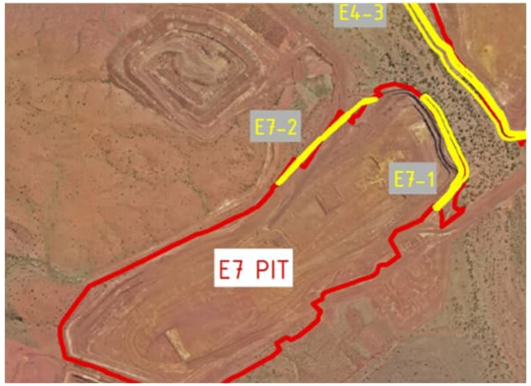
Option	Additional Cost ($)	Pro's	Con's
Upstream	-	Simpler construction method due to ease of access	Construction impacted by flood events Encroaches on creek and impacts/removal of large trees Increasing hydraulics & potentially rock size Need to remove existing rock and replace
Downstream	$390,000	Construction not impacted by flood events Does not encroach on creek or impact on hydraulics Potential to retain existing rock armour Potential to retain existing material at pit wall, and avoid need for buttressing	Potentially more complex flood bund construction due to proximity to pit crest (construction of flood bund on or along the land bridge's residual MESA). Assumes 5 m offsets to provide a working width through the land bridge. The very narrow operating width between the design pit crest and flood bund presents construction safety risks.



Upstream and Downstream Raising Trade-off Assessment

E7-1

Option	Additional Cost ($)	Pro's	Con's
Upstream	$3.5M	Simpler construction method due to ease of access	Construction impacted by flood events Encroaches on creek and significant impacts/removal of large trees Increasing hydraulics & rock size required (the rock sizes can be designed based on hydraulic and flood assessment)
Downstream	$7.4M	Construction not impacted by flood events Does not encroach on creek or impact on hydraulics	More complex pit buttressing and flood bund construction due to proximity to pit crest and narrow width of existing pit crest. Assumes 5 m offsets to provide a working width. Potential settlement risks of constructing flood bund across CID and buttress/backfill Could be managed through staged construction to allow for settlement prior to flood bund construction



Recommendations

Flood Bunds E1-2, E1-3, E1-4, E4-1, E4-2

- Downstream bund raise recommended

Flood Bund E7-2

- E7-2 has not been constructed and therefore can be constructed as per the closure design.

Flood Bunds E1-1, E4-3 & E7-1

Trade-off assessment concludes:

- E1-1:
  - Upstream raising is recommended for northern section of E1-1, as it avoids cost of additional buttressing.
  - Downstream raising of the southern section of E1-1 flood bund as it does not impact on the creek and does not require buttressing.
- E4-3:
  - Downstream raise recommended as the cost of buttressing is relatively low compared to the negatives of the upstream option.
  - Opportunity: if you can retain existing material at pit crest (i.e. don’t mine to full extent of pit shell design provided), then you may avoid cost of additional buttressing. Where agreed options require a buttress, the relevant information will be documented in the SPS Pit Wall Stability Report (PREP-1200-C-12137).
- E7-1:
  - Downstream raise recommended as it does not impact on the creek. There are some construction complexities to navigate.
  - Risks associated with encroaching on creek outweigh the additional cost of buttressing due to downstream raise.

Next steps

Following the conclusion of this trade-off study and the adoption of the recommended approach for each flood protection bund, the activities listed below will be undertaken:

- A trade-off study is underway looking at the costs and benefits of backfilling sections of W5 and E6 pits to surface in order to increase the width of the floodplain and consequently the flood bund and rock armour costs. The outcome of this trade-off study is relevant to the E7-1 and E7-2 flood bunds.
- A trade-off study will be undertaken to assess whether rock armour on existing flood bunds will be left in place or removed and stockpiled for re-use or disposal.
- A trade-off study will be undertaken to determine the benefits of flattening the flood bund slope to reduce rock armour size required.
- A trade-off study will be undertaken to determine the preferred approach to protecting the flood bunds from undercutting during a flood event: either a buried rock armour toe or a ‘launchable’ toe.
- Following the completion of the drilling and test pit program, the logs and laboratory data will be analysed and used to assess the foundation conditions that the flood bunds will be constructed upon, which will inform the design.
- In August a site visit is planned to inspect the locations where surface water engineered structures will be constructed, including the locations of the flood protection bunds throughout the site. This ground-truthing exercise will be essential to identify constraints and inform the design of each flood bund.
- SPS design of the flood protection bunds will be undertaken, utilising all of the data and knowledge gained from the relevant trade-off studies, site visits and field data collection. The design process will include stability modelling, consideration of the offsets and the outcomes of this trade-off study.
- The rock armour size will be determined based on the hydraulic and the flood assessment during the flood protection bund design stage of SPS.

Advisian. (2024a). Yandi Closure Landform. SPS Surface Water Engineering Design Report