

# Waste rock characterisation and stability assessments for feasibility level studies

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## Abstract

*Regulatory approval frameworks, such as that of the Department of Mines, Industry, Regulation and Safety (DMIRS) in Western Australia Mining Proposal approval process, require detailed design reports for waste rock dumps for mining projects.*

*Determination of waste rock shear strength parameters for waste rock dump design at a feasibility project level is often challenging as a result of factors such as spatial variation, lack of representative data and limited knowledge of waste rock movement schedules. Trial open pits or blasted representative material are rarely available.*

*A practical approach to derive design material parameters using the Barton–Kjaernsli criterion (Barton & Kjaernsli 1981; Barton 2008) is provided, based on available site-specific feasibility level geotechnical data for a case study site in the Pilbara region of Western Australia. Stability assessments for various scenarios including for possible unfavourable conditions such as earthquake and storm events expected in the long-term are required to demonstrate that safe operational conditions and effective mine closure designs can be facilitated.*

**Keywords:** *material classification, waste rock dumps, slope stability analysis*

## 1 Introduction

As discussed within the *Guidelines for Mine Waste Dump and Stockpile Design* (Hawley & Cunning 2017), the physical properties of the various material types and their relative distributions within waste rock dumps will influence, or potentially control, overall stability.

As part of the Department of Mines, Industry, Regulation and Safety (DMIRS) Mining Proposal Approval Framework, a detailed design report for waste rock dumps (WRD) is required. Geotechnical parameters must be defined, and stability analysis outcomes presented, for both operating and closure scenarios, the closure scenarios being an input into the mine closure plan (MCP). It is the expectation of the assessing body that adequate studies have been completed to provide confidence that there is limited risk through operations and into closure as a result of poor waste rock dump performance.

At the approval phase of a project, feasibility level data, at best, is all that is available presenting a significant challenge in demonstrating waste rock dump performance. This data may include field mapping of exposures, geotechnical logging data from feasibility studies for the open pits, and in some cases trial open pits. Representative blasted material is rarely available; however, in the case study presented, blasted material from a trial pit was available to validate outcomes of the empirical assessment to some extent.

Operational requirements are typically governed by maximum allowable tipping height determined on an operational safety-based criterion. Closure requirements are governed by closure criteria set out in the site MCP encompassing safety, environmental (including erosional stability) and end land use. Slope profiles to achieve erosional stability typically result in low overall slopes and hence becomes the key design criteria as opposed to overall stability.

This paper outlines an approach adopted for a case study site to derive geotechnical shear strength models for waste rock dump design assessment, and the slope stability scenarios and sensitivity assessments to demonstrate geotechnical stability for operational and closure conditions.

## 2 Iron Bridge Magnetite Project

### 2.1 Location and resource

The Iron Bridge Magnetite Project is located 145 km south of Port Hedland in the Pilbara Region of Western Australia. The project holds Australia's largest magnetite resource prepared in accordance with the Joint Ore Reserves Committee (JORC) code resulting in a significant mine life. The project is anticipated to produce 22 million tonne per annum (Mtpa) of high-grade 67% Fe magnetite concentrate product, with first ore on ship scheduled from mid-2022.

The Iron Bridge site currently includes a site access road, camp, trial open pit of shallow depth, small temporary ore stockpiles, waste rock dump, pilot plant and tailings storage facility. Further development of the project will consist of several deposits that will be mined over the life-of-mine over a north–south strike length exceeding 12 km, these deposits are named North Star, Eastern Limb and Glacier Valley. The Eastern Limb deposit is sub-divided into Eastern Limb North, Eastern Limb Central and Eastern Limb South mine areas, this was based on the geological and geotechnical differences between the three zones of this deposit.

### 2.2 Geological setting

The details of the Iron Bridge geological setting and deposit have previously been published by Simpson (2017). The deposit host geology is a steeply dipping banded iron formation (BIF) of the Pincunah Member (Gore Creek Group) containing iron-rich deposits that deformed and metamorphosed over geological time. The Kangaroo Caves Formation (Sulphur Springs Group) and Corboy Formation (Gore Creek Group) form the western and eastern bounds of mineralisation respectively. The weathering profile is typically 40–60 m from the surface, forming an oxidised (weaker strength) caprock (Figure 1). The transition between oxide and fresh material is clearly distinguishable in diamond core.

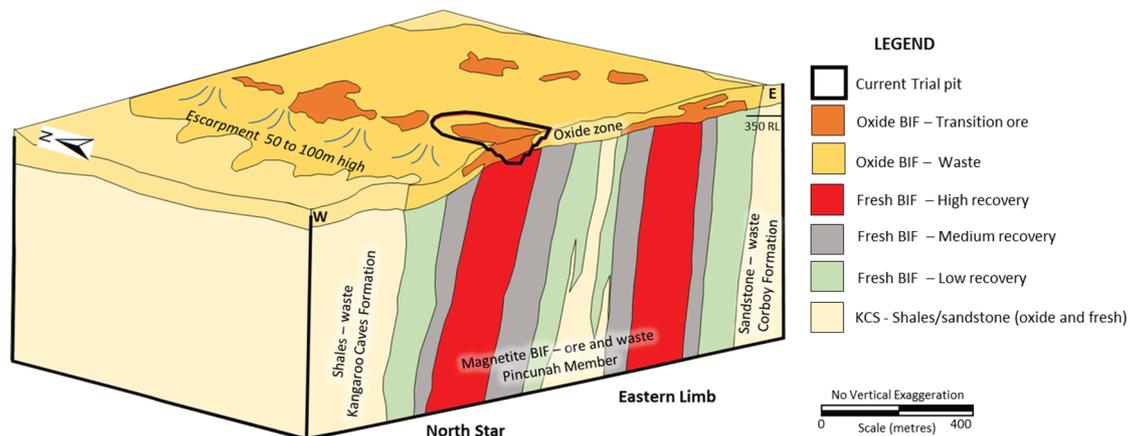


Figure 1 Block diagram of the Iron Bridge deposits (Simpson 2017); BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

The Kangaroo Caves Formation (KCF) consists of massive to pillow-brecciated andesitic volcanic rocks, with variable amounts of cherts and shales increasing towards the top of the sequence that is conformably overlain by the Pincunah Member. The Pincunah Member is dominated by cherty silicate BIF with minor (locally dominant) siltstone and trace sandstone. Five periods of structural deformation are recognised with the larger faults through the deposits thought to have occurred during the D3 deformation event (c. 2,940 M Ma). Although identical host stratigraphy, dislocated by several faults, each deposit has been variably deformed and altered resulting in unique material differences (Simpson 2017).

### 3 Material characterisation

Determination of the shear strength of waste rock is considered difficult due to several factors such as spatial variations and limitations in obtaining representative data, material placement methods and associated segregation, particle crushing under loading and time-dependent consolidation. At a project feasibility stage, there is typically no practical method to derive shear strength of an in situ sample and hence empirical strength models, based on site-specific data as available, have been adopted. In this case, the Barton–Kjaernsli criterion (Barton & Kjaernsli 1981; Barton 2008) has been adopted to develop non-linear shear strength parameters of the waste rock materials. The relationship and input parameters are outlined:

$$\tau = \sigma_n \tan(R \log \frac{S}{\sigma_n} + \text{Phi}_r) \quad (1)$$

where:

- $\sigma_n$  = Effective normal stress.
- R = Equivalent roughness, which is a function of the particle roundness and the porosity (n) of the dumped waste.
- S = Size-dependent equivalent strength of the blasted particles, based on the unconfined compressive strength (UCS) and the typical rock waste particle size at 50% passing ( $D_{50}$ ).
- $\text{Phi}_r$  = Residual friction angle on the sawn surface of rock.

Application of Barton–Kjaernsli criterion will require a number of waste rock characteristic parameters to be derived. Representative data for a blasted waste material are limited and hence the characterisations are based on the blasted oxide waste rock material from the trial pit, the diamond core logging data from the pit slope geotechnical feasibility study, and the data collected for foundation and construction material assessments for the detailed design of the tailings storage facilities and access road cut.

In addition to the parameters required for the Barton–Kjaernsli criterion, other parameters relevant to the geotechnical assessment of the waste rock dump such as durability and permeability were also assessed and defined. Material characterisations were performed for most representative waste rock materials based on lithology and weathering.

#### 3.1 Particle size distribution

The particle size distribution (PSD) of a waste rock material will be naturally variable due to spatial variation in the material properties and drill and blast practices. The challenge at a feasibility level study stage is that there is typically no blasted waste rock available and hence PSD testing on actual materials is not possible. In these scenarios, blasting fragmentation empirical assessments and site benchmarking are required to be adopted. The PSD for design purposes should be adopted with an appreciation of the data collection method, prediction techniques and associated limitations. During data collection, a representative number of samples are required to be collected and assessed to account for material variability. The reliability of the data source should be reflected in the values. Several data sources are typically considered to assess a representative  $D_{50}$  value; the adopted order of priority for the data source is presented here:

1. Large-scale bulk sampling and laboratory PSD (i.e. sample size > 1 t).
2. Spilt desktop analysis of waste rock dump, fill embankment and existing stockpile material if available.
3. Small-scale laboratory sampling with an estimate of oversize during sampling.
4. Blasting fragmentation empirical assessment based on known site-specific material properties and a typical blast design pattern.
5. Benchmark against a similar site.

The data sources available for this study included Split desktop fragmentation analyses on materials collected from a starter pit and access road cut and a small-scale PSD assessment of waste rock samples.

The Split desktop process derives an estimated PSD from a digital image of a waste rock dump or muck pile. A reasonable output estimate of the PSD can be obtained using a good representative image, good judgement of the percentage of fines content in the sample and a combination of the use of the automatic and manual editing functions of the software. A typical output of Split desktop analyses is shown in Figure 2.

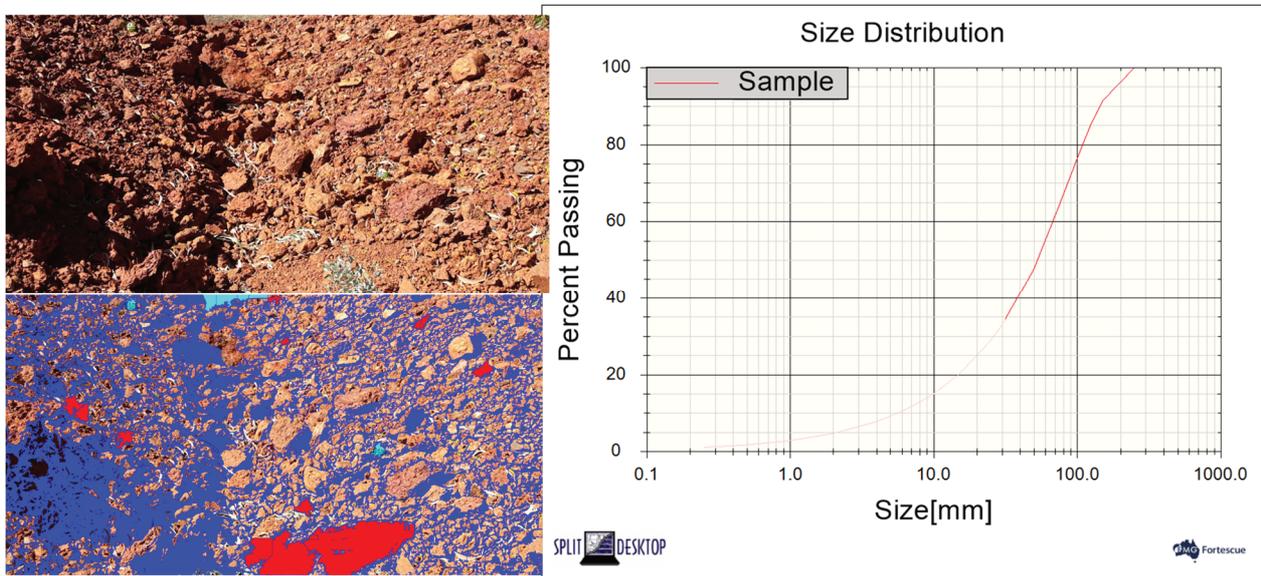


Figure 2 Typical Split desktop processing and output

The PSD data assessed from these sources were plotted along with the PSD results of fragmentation blasting studies that produced a minimum and mean blasting target (Figure 3). To understand the influence of variability, appropriate design and sensitivity PSD scenarios were adopted in the assessments. The selected ranges of PSDs and  $D_{50}$  values are presented in Table 1.

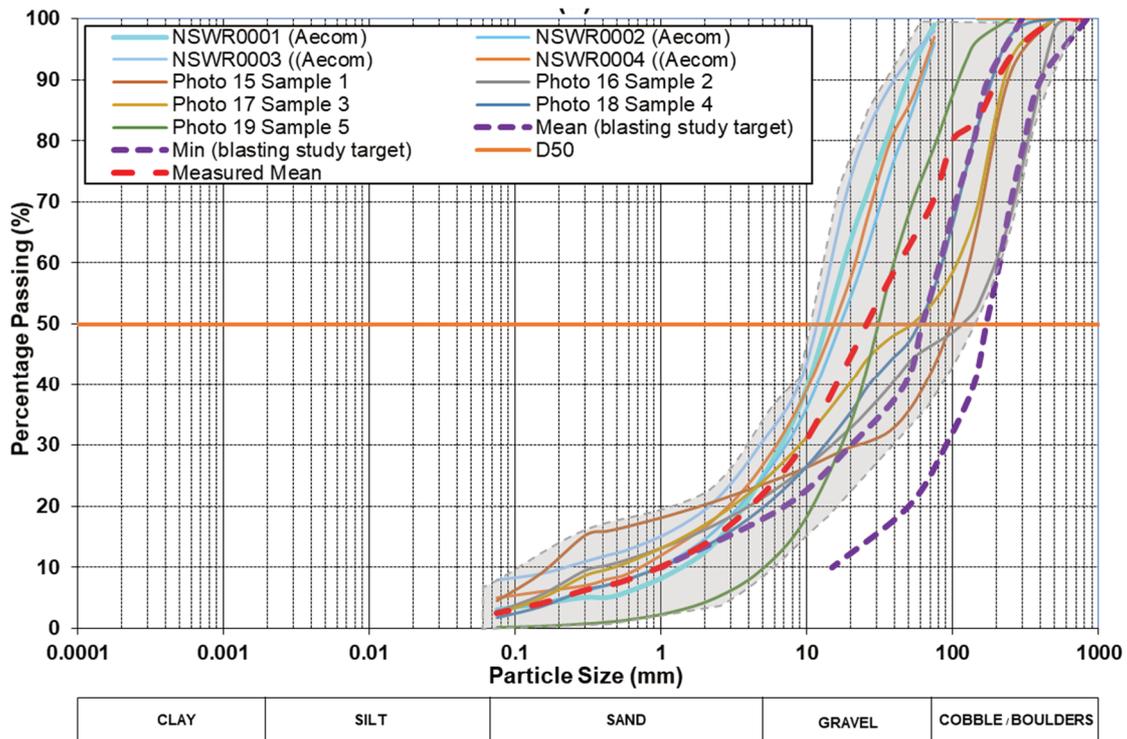


Figure 3 Particle size distribution curves for oxide banded iron formation

Table 1 Expected particle size distribution (PSD) range of waste rock units

Rock unit	PSD range		
	Lower	Upper	D <sub>50</sub> range
Oxide BIF	Measured mean PSD	Mean blasting study PSD	25–170 mm
Oxide	Measured mean PSD	Mean blasting study PSD	25–170 mm
Fresh BIF	Minimum blasting study PSD	Mean blasting study PSD	60–170 mm
Fresh KCS	Minimum blasting study PSD	Mean blasting study PSD	60–170 mm

BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

### 3.2 Intact rock strength

The intact strength for each rock type has been primarily defined based on UCS laboratory test results from extensive programs that form the Open Pit Geotechnical Feasibility Study (Figure 4) (AMC 2019). For oxide KCS, the intact strength has been derived based on core logging field estimated strength (FES) due to the absence of laboratory data.

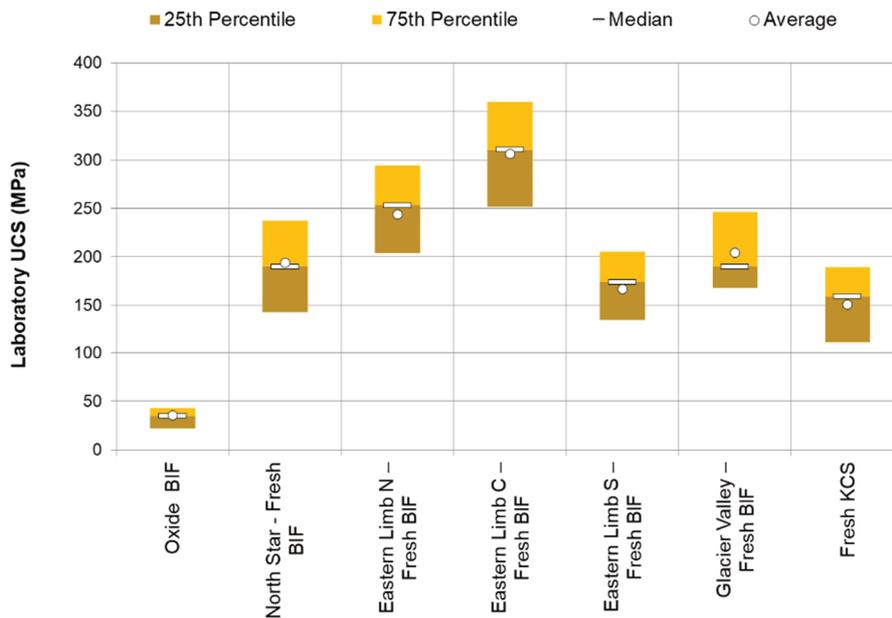


Figure 4 Intact rock strength; BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

### 3.3 Residual friction angle

The residual friction angle ( $\phi_r$ ) was evaluated using the results of direct shear testing conducted on a limited number of sawcut diamond core samples from the Geotechnical Feasibility Study (AMC 2019). The influence of  $\phi_r$  on the shear strength of waste materials is considered significant. The results were plotted in terms of normal and shear stresses and the envelopes for interpreted residual angles were defined (Figure 5 shows an example for oxide BIF). Based on the interpretation appropriate design and lower bound  $\phi_r$  values were selected for the assessment (Table 2).

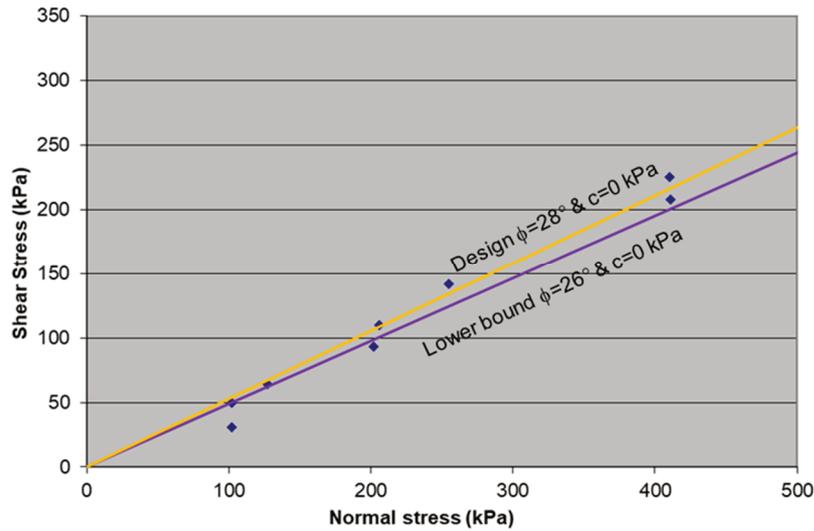


Figure 5 Sawcut test results for oxide banded iron formation

Table 2 Summary of residual friction angles

Rock unit	Residual friction angle (°)	
	Design	Lower bound
Oxide BIF	28	26
Fresh BIF	26	–
Fresh KCS	23	22

BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

### 3.4 Equivalent roughness

Equivalent roughness is a function of the particle roundness and surface roughness of waste rock and the ‘as-dumped’ porosity and is derived from an empirical assessment.

#### 3.4.1 Porosity and dump density

The waste rock volume will expand during blasting and excavation, and with a large range in particle size, this is typically represented as a percentage increase from the undisturbed in situ volume. Segregation is also typical on dump faces during construction and material consolidation within increased loading conditions will increase density and decrease the void ratio. These factors result in difficulty in the determination of void ratio, with limited benchmark data available.

In situ assessment of the dump density for this case study was not practical. A porosity value of 25% was assumed based on the experience gained from past studies (SRK Consulting 2014). Figure 6 illustrates the on-site measurement of dump density using the weight of waste rock dumped by truck and survey reconciliation of the rock pile for volume assessment. The dumped density was estimated using rock fragment densities derived from laboratory testing of relevant pit geotechnical studies and the dump porosity adopted. The resulting dump densities are summarised in Table 3. It is suggested that both porosity and dump density values be refined during the mining stage as part of the validation and reconciliation process by in situ measurements.



Figure 6 Reconciliation of weight and volume of dumped waste rock

Table 3 Rock type dump density

Unit	Rock fragment density (kN/m <sup>3</sup> )	Porosity	Dump density (kN/m <sup>3</sup> )
Oxide BIF	31	0.25	23
Oxide KCS	31	0.25	23
North Star – fresh BIF	33	0.25	25
Eastern Limb N – fresh BIF	32	0.25	24
Eastern Limb C – fresh BIF	34	0.25	26
Eastern Limb S – fresh BIF	32	0.25	24
Glacier Valley – fresh BIF	34	0.25	26
Fresh KCS	28	0.25	21

BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale.

### 3.4.2 Particle shape

The angularity of the blasted waste rock will influence in situ density, void ratio and shear strength of the material. The angularity will be strongly influenced by blasting and excavation processes, followed by secondary processes due to the influence of loading and changed stress conditions. Weathering and geochemical processes can also influence block shape in the long-term. An assessment of the existing waste material and stockpile (Figure 7) indicates that particles are partly angular or angular with a planar smooth surface.



Figure 7 Representative oxide banded iron formation materials

Considering the rock particle conservatively as partly angular with smooth surface and the waste porosity of 25%, the empirical scheme developed by Barton & Kjaernsli (1981) provided likely equivalent roughness (R) values in the range between 6.0 and 7.0. Design R values 6.5 and 6.0 were adopted for fresh BIF/KCF and oxide material respectively as presented in Figure 8.

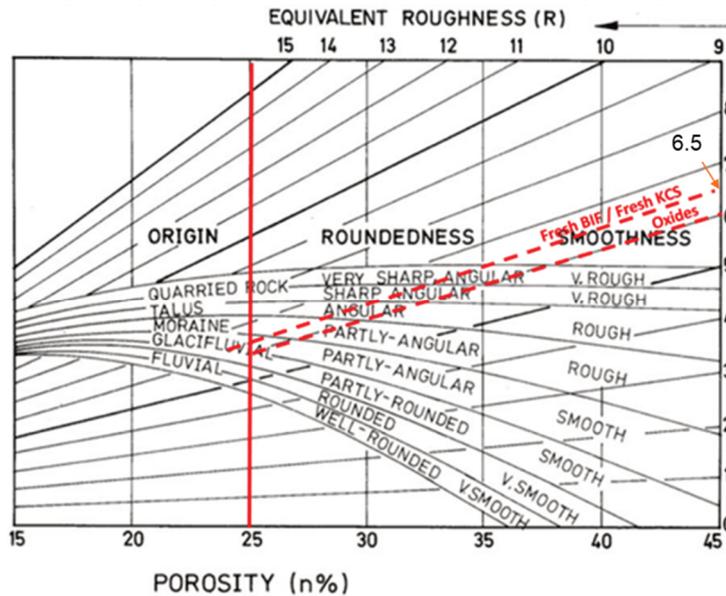


Figure 8 Empirical assessment of equivalent roughness parameters (modified after Barton & Kjaernsli 1981)

### 3.5 Equivalent strength

The size-dependent equivalent strength is based on the waste rock UCS values and the  $D_{50}$ . For rock surface strength, mean laboratory UCS values have been adopted for design, and half the mean value was conservatively adopted for the sensitivity assessment in each case to account for long-term closure conditions (weathering and degradation). The S values were assessed based on the strength assessment scheme proposed by Barton & Kjaernsli (1981) (Figure 9) which shows an S interpretation for a  $D_{50}$  of 100 mm as an example). The selected design and lower bound  $D_{50}$  and UCS values are shown in Table 5 with estimated S values.

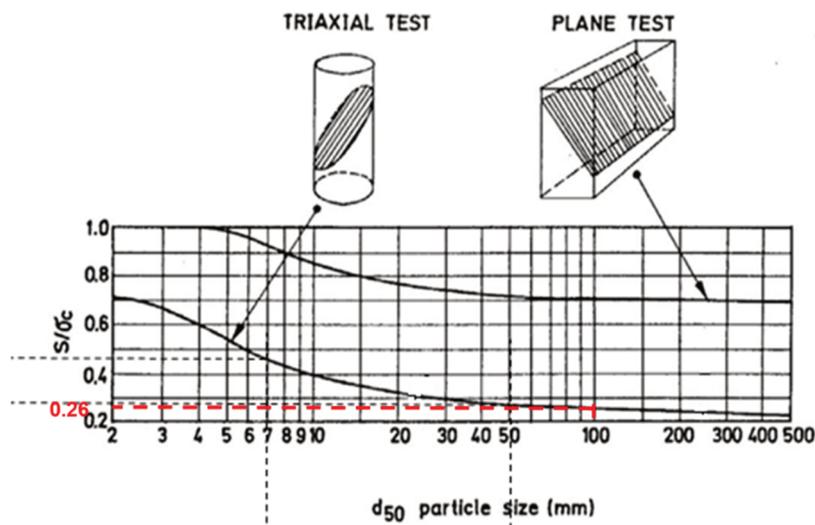


Figure 9 Equivalent strength (S) for a  $D_{50}$  of 100 mm (modified after Barton & Kjaernsli 1981)

### 3.6 Durability

Slake durability laboratory testing was undertaken on selected representative samples to evaluate resistance to deterioration under weathering conditions. The slake durability index (DI) provides a quantitative measure of durability. Based on slake durability index classification (Franklin & Chandra 1972), oxide and Pincunah fresh BIF had a very high to extremely high durability, whereas KCS has a high to very high durability. This indicates that long-term degradation for closure consideration is minimal.

### 3.7 Permeability

Permeability of waste rock materials will generally be influenced by many factors such as blasting practices, PSDs, the proportion of fines, porosity (degree of densification or consolidation) and fluid viscosity), which will, in turn, affect seepage and runoff rates. Permeability values considering the finer and coarser limits of the PSDs were assessed for saturated conditions using various empirical methods. However, the Kozeny-Carmen method was considered for the final interpretations. The summary of the lower and upper bound permeabilities using the Kozeny-Carmen method are in Table 4.

Table 4 Estimated estimated order of magnitude permeabilities

Rock unit	Permeability (m/s)	
	Lower	Upper
Oxide BIF	$\sim 1 \times 10^{-2}$	
Oxide KCS	$\sim 1 \times 10^{-3}$	1–4
Fresh BIF	$\sim 2 \times 10^{-2}$	

BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

## 4 Strength models

Derived input parameters for the non-linear shear strength models are shown in Table 5. Lower bound (LB) strength envelopes are defined using lower bound  $\phi_c$  and S values with the design R values.

Table 5 Input for the non-linear shear strength estimate

Rock unit	Dump density (kN/m <sup>3</sup> )	Waste porosity (%)	Equivalent roughness (R)	Design UCS (MPa)		D <sub>50</sub> (mm)		Equivalent strength (S) (MPa)		Residual friction, φ <sub>r</sub> (°)	
				Design	Sensitivity	Design	LB (upper)	Design	LB	Design	LB
Oxide BIF	23	25	6	36	18	65	170	10.1	4.3	28	26
Oxide KCS	23	25	6	11	6	65	170	3.1	1.3	23*	22*
North Star – fresh BIF	25	25	6.5	194	97	100	170	50.4	23.2	26	26**
Eastern Limb N – fresh BIF	24	25	6.5	244	122	100	170	63.4	29.2	26	26**
Eastern Limb C – fresh BIF	26	25	6.5	306	153	100	170	79.6	36.8	26	26**
Eastern Limb S – fresh BIF	24	25	6.5	167	83	100	170	43.4	20.0	26	26**
Glacier Valley – fresh BIF	26	25	6.5	204	102	100	170	52.9	24.4	26	26**
fresh KCS	21	25	6.5	151	76	100**	170**	39.4	18.2	23	22

Left to right, top to bottom: UCS – unconfined compressive strength; LB – Lower Bound; BIF – banded iron formation; KCS – Kangaroo Caves Formation Shale

The design and lower bound envelopes are presented in Figures 10 and 11, respectively. For comparison purposes, linear strength envelopes of 30°, 37° and 40° friction angles, the lower limit envelope for rockfill material proposed by Indraratna et al. (1993), and the envelope for high strength rockfill defined by Leps (1970), are included for reference. Oxide KCS presents significantly lower shear strength (lower than the envelope for friction angle of 30°), followed by fresh KCS and oxide BIF which are close to the minimum Indraratna envelope. The shear strength envelopes of all fresh BIF units show relatively stronger materials falling midway between the minimum Indraratna and maximum Leps empirical reference envelopes. ‘Eastern Limb S - fresh BIF’ presents the weakest strength envelope of all the fresh BIF units.

The existing temporary WRD has a measured angle of repose of approximately 36° representing a lower bound friction angle.

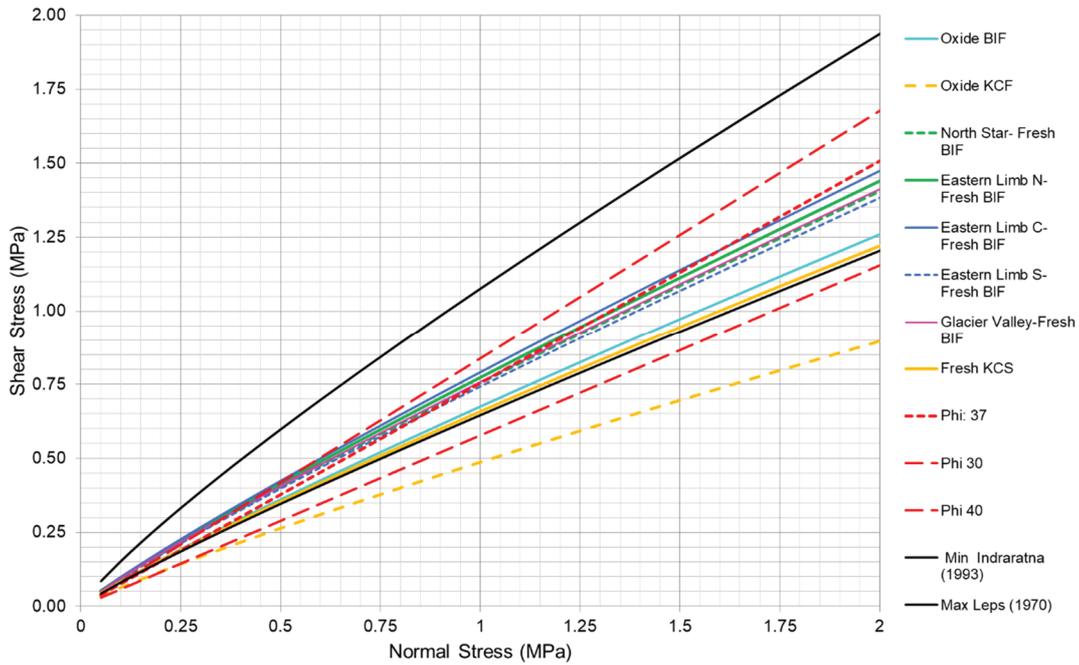


Figure 10 Design non-linear shear strength envelopes

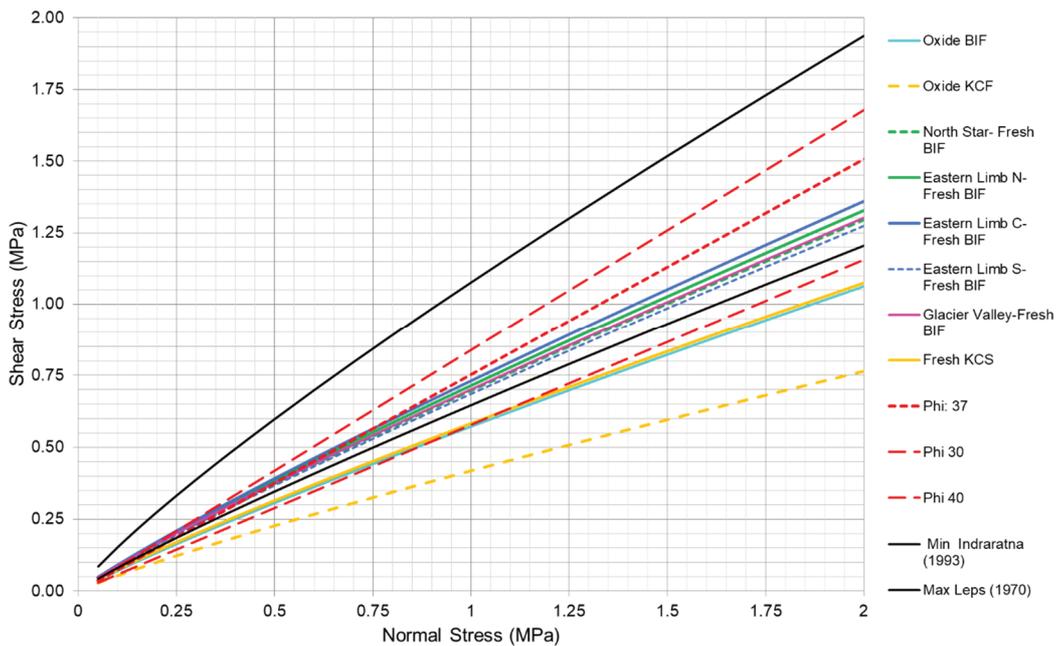


Figure 11 Lower bound non-linear shear strength envelopes

## 5 Slope stability analyses

Slope stability assessments using limit equilibrium (LE) methods were undertaken for both operational tip head dumping as well as the closure design. Field mapping during the site reconnaissance study and data from the pit slope feasibility study was used to characterise the foundation strength. The site consists of gently undulating terrain with small channels, predominately underlain by the Corboy Formation. This is relatively competent with insignificant loose cover and foundation angles not posing any stability concerns.

The stability assessments were performed for various scenarios such as for static and pseudo-static loading, and a range of storm events. Designs are required to meet different design acceptance criteria based on the site's management process for operations, industry guidelines (Read & Stacey 2009; Hawley & Cuning 2017), and regulatory feedback from previous design assessments. For this project, the design acceptance criteria (Table 6) were adopted based on the consequence of failure and data confidence.

For closure design, storm events of 1:500-year 24 hr and probable maximum precipitation (PMP) 72 hr precipitation were considered for the design and sensitivity assessments respectively. Relatively lower Factor of Safety (FoS) requirements were accepted during operations as there are adequate management and monitoring processes with competent geotechnical personnel present to reconcile the design assumptions.

**Table 6 Fortescue acceptable design criteria**

WRD slope	Loading	Pore pressure (PP)	Minimum FoS requirement
Operational profile (short-term)	Static	Dry	1.1
		1:500-year PP	≥1.5
Closure profile (long-term)	Static	PMP PP	1.1
		Dry	≥1.5
		Fully saturated	1.1
	Pseudo-static (design event)	Dry	1.15
	Pseudo-static (MCE)	Dry	>1.0

Left to right, top to bottom: WRD – waste rock dump; FoS – Factor of Safety; PMP – probable maximum precipitation; MCE – maximum credible earthquake

### 5.1 Operational assessment

During operation, the WRD is constructed by loose dumping in successive lifts, and optimum lift heights are defined ensuring safe mining operations while not impeding the ability to achieve final closure profile requirements. The toe position of each successive lift is stepped in an optimal bench design distance that will provide the required overall landform slope at closure. Truckloading is applied based on the largest site fleet to ensure an acceptable FoS for the exposure of the truck. The design chart generated by stability analyses (dry conditions) for assisting in the selection of operational optimum lift height is presented in Figure 12.

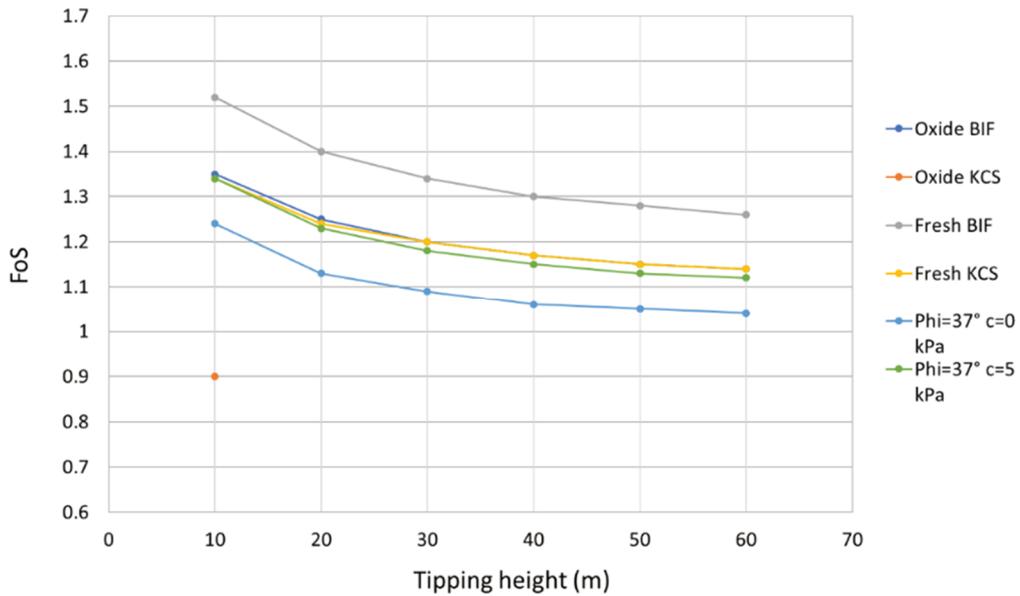


Figure 12 Results of tipping height for truck 5 m from edge of dump

### 5.2 Closure scenario

Waste rock dumps for closure are designed to ensure that they are physically safe to humans and animals, non-polluting and geotechnically stable. The objective of the stability assessment for closure is to demonstrate long-term geotechnical stability under possible unfavourable conditions (e.g. earthquakes and storm events) that the site can experience in the long-term. Typical stability analysis results are presented in Figure 13 for a static scenario under dry conditions. FoS achieved for the closure design was significantly higher than design acceptance criteria, and therefore the need for rigorous assessment of long-term rock degradation was not deemed necessary.

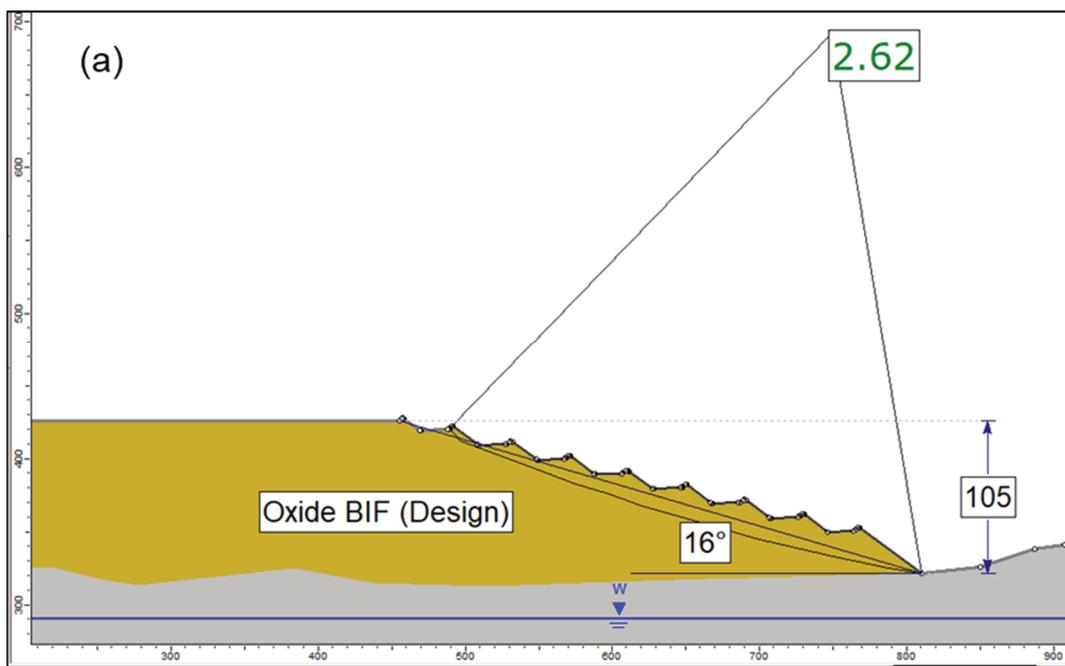


Figure 13 Stability assessment

Instabilities associated with WRD foundations interactions were also assessed for waste rock dump designs. In all cases, the design and sensitivity parameters were applied. The waste dump final profile was designed

such that all weak material such as the oxide KCF is not within the final structural zone of the WRD, thus it is paddock dumped within the middle of the dump.

The final WRD was classified using the industry guidance for mine waste dump and stockpile (Hawley & Cuning 2017) scheme. Low to Moderate Hazard level which is considered acceptable by Fortescue was identified for the WRD using regional and foundation condition data, material characterisation data, stability assessment results, expected rate of dump development and estimated performance based on stability assessment and WRD performance at other sites.

## 6 Verification

A number of assumptions were made in the process of developing the non-linear shear strength envelopes of various waste rock materials. Barton–Kjaernsli is typically applicable for general waste rock materials, and potential limitations in terms of particle shapes of blasted anisotropic rock masses in this case exist. This criterion was adopted due to practical reasons pending validation during construction. It is therefore essential that the design parameters of waste rock materials and the stability requirements be reviewed and updated during operations, as necessary. Performance of waste materials in the actual WRD during operations will be used for verifying the study outcomes.

## 7 Conclusion

This paper outlines an approach to deriving WRD material input parameters to be adopted in the analysis of waste rock dumps for operational and closure scenarios using representative and conservative (lower bound) material strength parameters. The assessments using lower bound strength provided increased confidence in the outcomes of the study, particular for closure scenarios. Reconciliation of actual performance using a good monitoring system and site-specific testing, and if possible large-scale testing, is essential to verify assumptions and to validate the model during operations, thereby increasing the design confidence level.

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