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Optimisation of slope design using three-dimensional limit equilibrium: case studies from the Pilbara

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Abstract

Slope design assessments for rock mass failure modes are typically undertaken utilising two-dimensional limit equilibrium (LE) software packages. What happens in scenarios where the design has adopted the recommended slope configuration and still the inter-ramp and overall slope do not meet the design acceptance criteria? This paper presents two case studies within the Pilbara where a three-dimensional LE approach was implemented to further assess slopes that fail to meet the adopted design acceptance criteria, providing an optimal final slope design for implementation.

Keywords: *geotechnical, slope stability analysis*

1 Introduction

Slope stability assessment is always undertaken for slope designs using the geological, structural, rock mass, and hydrogeological models that inform the geotechnical model to assess if a slope meets the adopted design acceptance criteria (DAC). This assessment is typically undertaken after basic slope design configuration checks to verify that mine planning have applied the correct slope design parameters. The adopted DAC should consider the consequences of failure, reliability of model input parameters, operational conditions, and implementation controls in addition to other factors such as slope height, geology, and design life.

Until recently, all geotechnical slope stability assessments for Fortescue Metals Group operations were undertaken using two-dimensional (2D) geotechnical packages. In the last few years, Fortescue Metals Group has employed the use of Plaxis three-dimensional (3D) limit equilibrium (LE) (Bentley 2021) package in the evaluation of pit slopes which are deemed critical or have marginal 2D Factor of Safety (FoS) in terms of the DAC. This paper presents two case studies where a 3D LE assessment was used to increase design confidence because the 2D slope stability assessment was less than the recommended DAC.

2 Case study location and geology

The Solomon mining area is located approximately 60 km north of Mt Tom Price in the Hamersley Ranges and is adjacent to the north-west boundary of Karijini National Park. Figure 1 shows the location of Solomon Hub with respect to the other Fortescue Metals Group's mining areas.

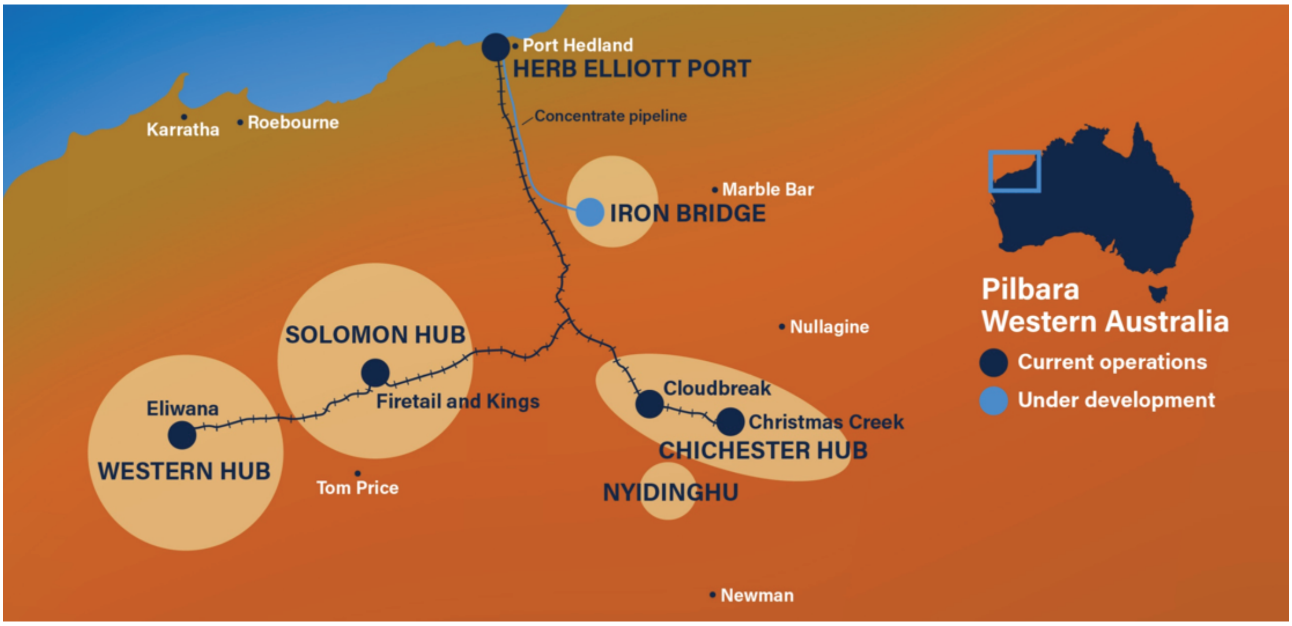


Figure 1 **Showing location of the Solomon Hub and other Fortescue Hub**

The Solomon Hub is located within the deeply incised terrain of the Hamersley Ranges. The Solomon iron resource comprises both tertiary aged detrital materials in valleys, and the proterozoic banded iron formation from which they are derived.

The case studies are from the Firetail and Frederick mining deposits within the hub. Both are bedded iron deposits hosted by the Brockman iron formation. The Dales Gorge, Whaleback Shale, and Joffre Members of the Brockman formation are variably mineralised and preserved along the limbs of a regional fold.

The Joffre Member is generally a more competent unit that forms a mesa cap. The underlying Whaleback Shale unit is weaker and, together with the Dales Gorge Member, forms gentle slopes below the Joffre Member.

3 Case study 1: Frederick

This case study involved the assessment of the Life-of-Mine pit design for the deposit within the bounds of the deposit's feasibility study. The assessment was undertaken using the derived shear strength parameters for both the bedding and rock mass derived from specific geotechnical drilling and laboratory programs.

The recommended slope configuration design parameters from the feasibility geotechnical study of the mining area to achieve the required DAC for the various geological units to be encountered in the deposit are shown in Table 1.

Table 1 **Recommended design configuration**

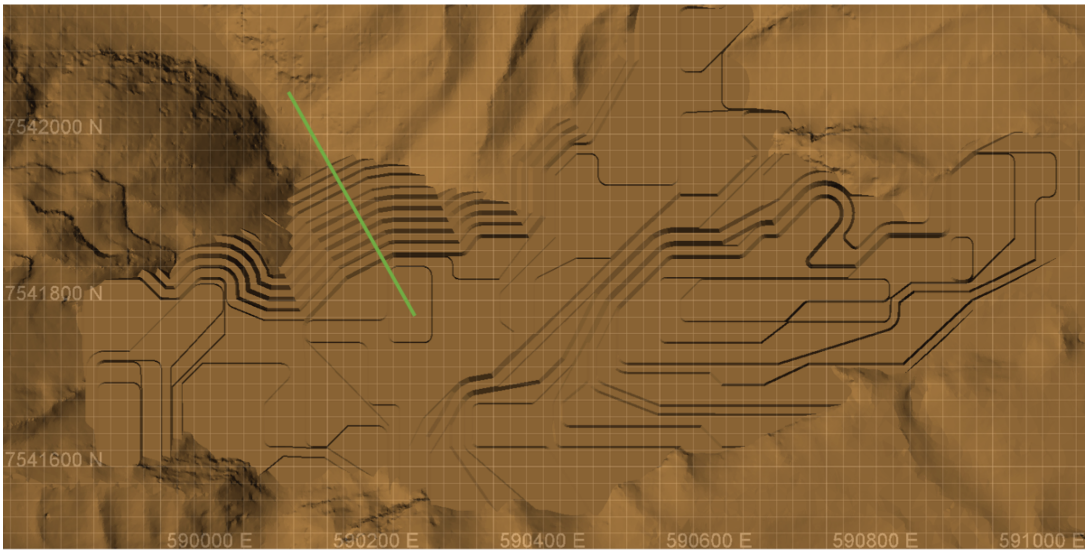
Geologic unit	Batter height, m	Batter face angle	Berm width m, min	Maximum stack height, m	Decoupling berm width, m
Joffre	12	75	8	90	20
Whaleback shale, BW	12	65	8	60	20
Dale Gorge, BW	24	75	10	60	20

For this pit, a 'moderate consequence' of failure was adopted. A DAC, in accordance with the *Guidelines for Open Pit Slope Design* (Read & Stacey 2009) were adopted for the deterministic slope stability assessment based on the confidence in the input parameters such as geotechnical, geology and hydrogeology and the consequence of failure of the slope. A summary of the adopted DAC is shown in Table 2.

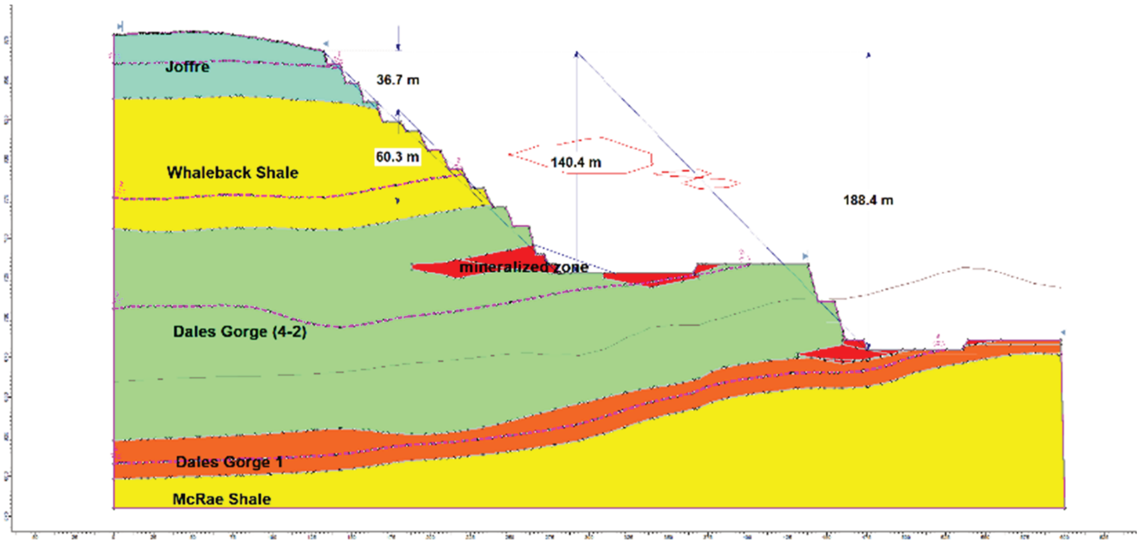
Table 2 Summary of design acceptance criteria

Slope scale	Factor of Safety (static)
Single batter	1.1
Inter-ramp slope	1.2
Overall slope	1.3

The critical section of the pit has a total height of approximately 188 m of which about 37 m is within Joffre (BJ), 60 m in Whaleback Shale (BW), and the remainder in Dales Gorge (BD). Based on the mine planning pit design optimisation, some mineralisation will be left within the highwall due to the high strip ratio. The main mineralised zone which was been left behind was between RL746 and 728 m. Figure 2 shows the plan view and a 2D geotechnical cross-section of the slope through that highwall showing the various geological units and the mineralised zone within the wall.



(a)



(b)

Figure 2 (a) Plan of the Frederick pit; (b) Critical cross-section of the Frederick pit

The 2D stability assessment was undertaken using the Snowden modified anisotropic linear strength function (Snowden 2011) in the form of shear normal function for the various geological units as applicable in Slide 2 (Roscience 2019). A summary of the 2D static assessment results is summarised in Table 3. The results from the 2D assessment were slightly below the DAC for the pit wall.

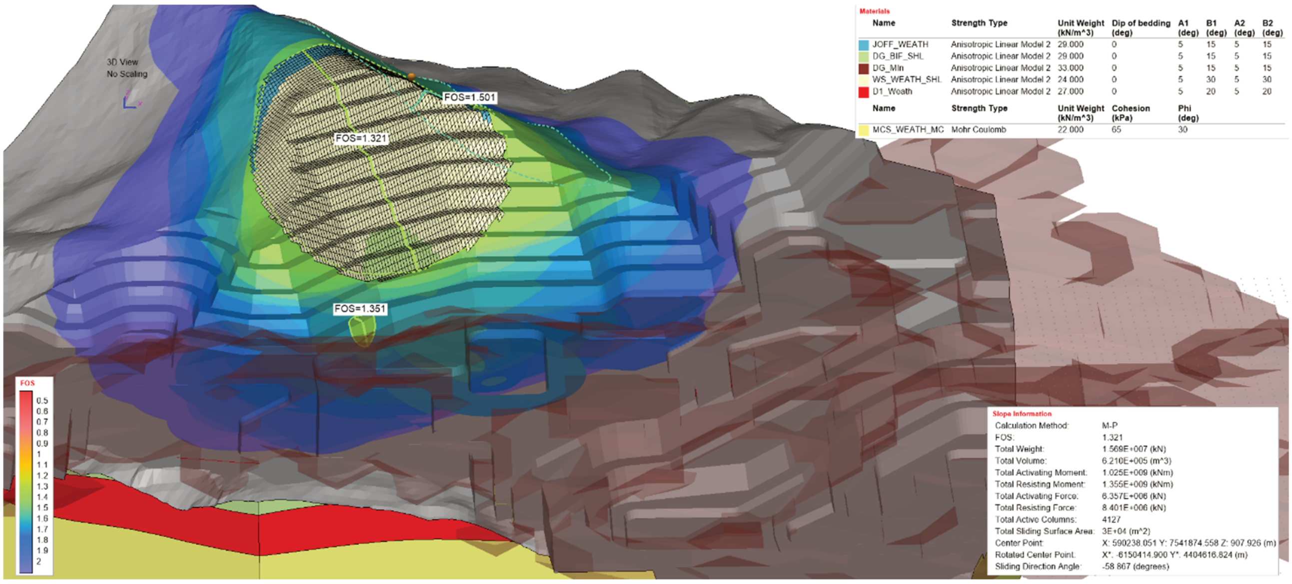
Table 3 Summary of two-dimensional static stability results

Slope scale	Acceptance design criteria, Factor of Safety	Achieved Factor of Safety
Inter-ramp	1.2	1.17
Overall	1.3	1.2

To modify the slope to achieve the minimum DAC, the following options were explored by the geotechnical and mine planning teams:

1. Introduce an additional decoupling berm within the slope.
2. Leave a buttress between RL746 and 728 m. This would have been constructed from ore.
3. Undertake further assessment of the slope to evaluate risk and implement controls to manage the risk.

The first two options would result in ore loss. This was not the optimal solution, hence further assessment using Plaxis 3D LE package (previously called Soilvision) (Bentley 2019) was used to evaluate the 3D slope stability of the pit to assess the design risk. The result of the 3D LE assessment is presented in Figure 3. The assessment returned a FoS of 1.32 at the critical section which is about 11% higher than the original 2D overall slope.



Materials

	Name	Strength Type	Unit Weight (kN/m^3)	Dip of bedding (deg)	A1 (deg)	B1 (deg)	A2 (deg)	B2 (deg)
🟦	JOFF_WEATH	Anisotropic Linear Model 2	29.000	0	5	15	5	15
🟩	DG_BIF_SHL	Anisotropic Linear Model 2	29.000	0	5	15	5	15
🟫	DG_Mln	Anisotropic Linear Model 2	33.000	0	5	15	5	15
⬜	WS_WEATH_SHL	Anisotropic Linear Model 2	24.000	0	5	30	5	30
🟥	D1_Weath	Anisotropic Linear Model 2	27.000	0	5	20	5	20

	Name	Strength Type	Unit Weight (kN/m^3)	Cohesion (kPa)	Phi (deg)
🟨	MCS_WEATH_MC	Mohr Coulomb	22.000	65	30

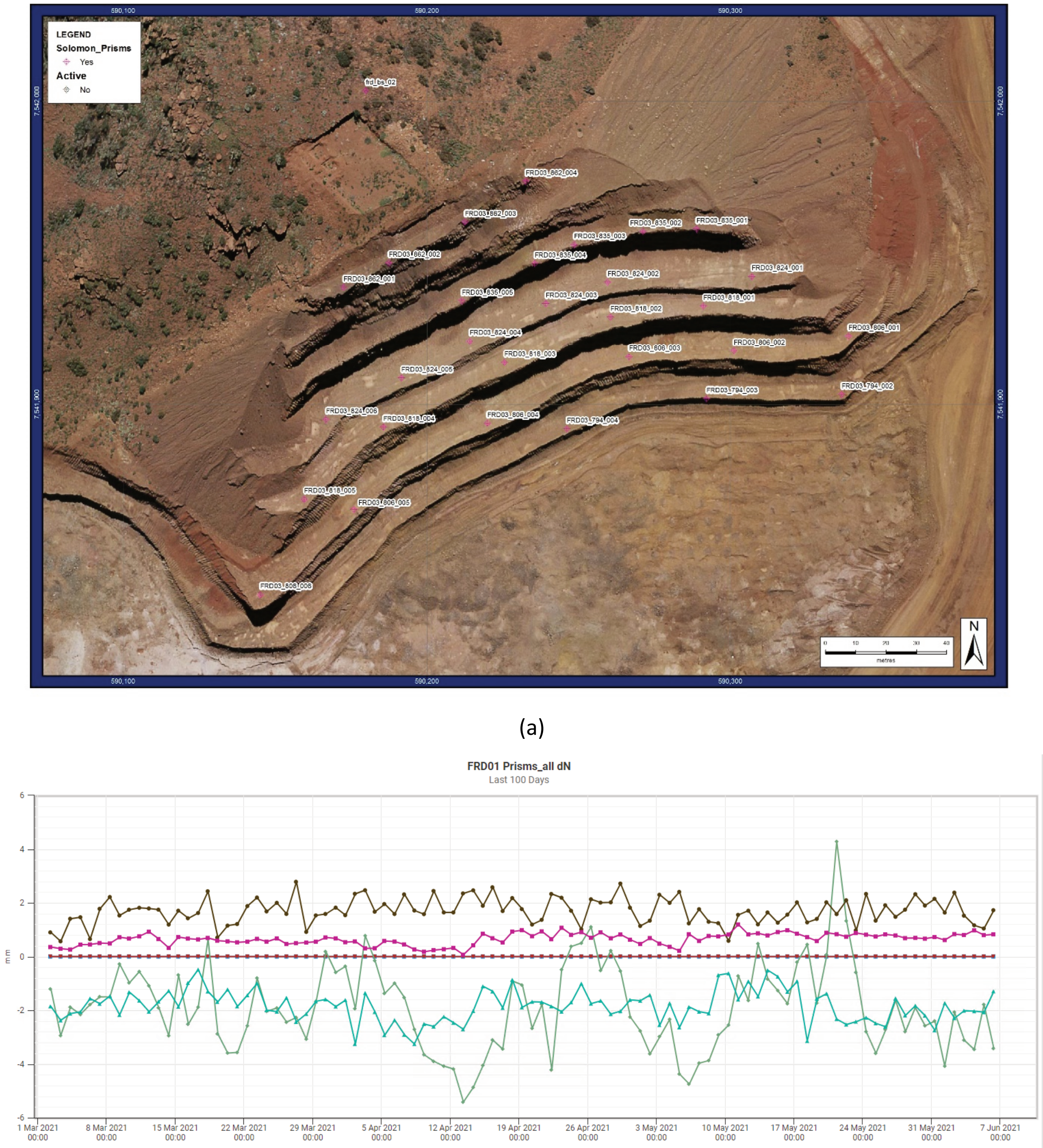
Slope Information

Calculation Method: M-P
FOS: 1.321
Total Weight: 1.569E+007 (kN)
Total Volume: 6.210E+005 (m^3)
Total Activating Moment: 1.025E+009 (kNm)
Total Resisting Moment: 1.355E+009 (kNm)
Total Activating Force: 6.357E+006 (kN)
Total Resisting Force: 8.401E+006 (kN)
Total Active Columns: 4127
Total Sliding Surface Area: 3E+04 (m^2)
Center Point: X: 590238.051 Y: 7541874.558 Z: 907.926 (m)
Rotated Center Point: X*: -6150414.900 Y*: 4404616.824 (m)
Sliding Direction Angle: -58.867 (degrees)

Figure 3 Plaxis limit equilibrium three-dimensional assessment results

3.1 Slope performance monitoring

Prisms are located on catch berms and are monitored by an automated reading and alarm system. Slope movement monitoring is supplemented by regulated inspections. This monitoring has not shown any significant overall movements to date. The highly fractured rock mass is not showing any sensitivity to rainfall (Figure 4b). Figure 4a is the prism monitoring layout within the pit. The rock mass is of low permeability.



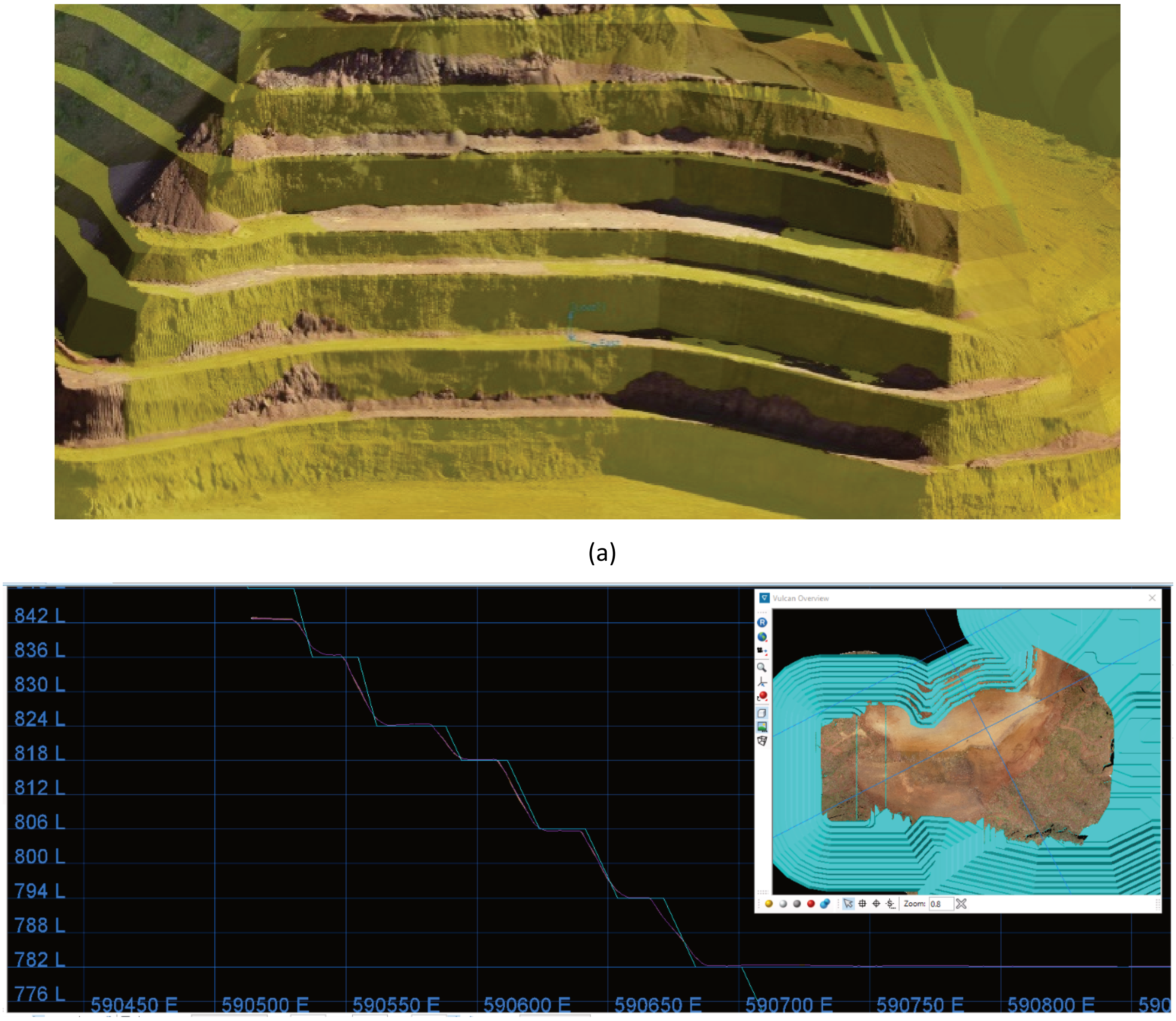
(a)

(b)

Figure 4 (a) Fredrick pit: monitoring layout; (b) Longitudinal displacements: no noticeable trend, high noise

Except for minimal crest loss in the upper benches due to blast damage, the current mined out section of the pit has performed well with no significant deformation. However, the real challenge at Fredrick's pits has been achieving the bench and berm configuration that allows the fair to good rock mass quality to be exploited with steep inter-ramp slopes, without compromising safety.

Figure 5 below shows an aerial map of the mined out pit and the crest loss at the upper benches.



(a)

(b)

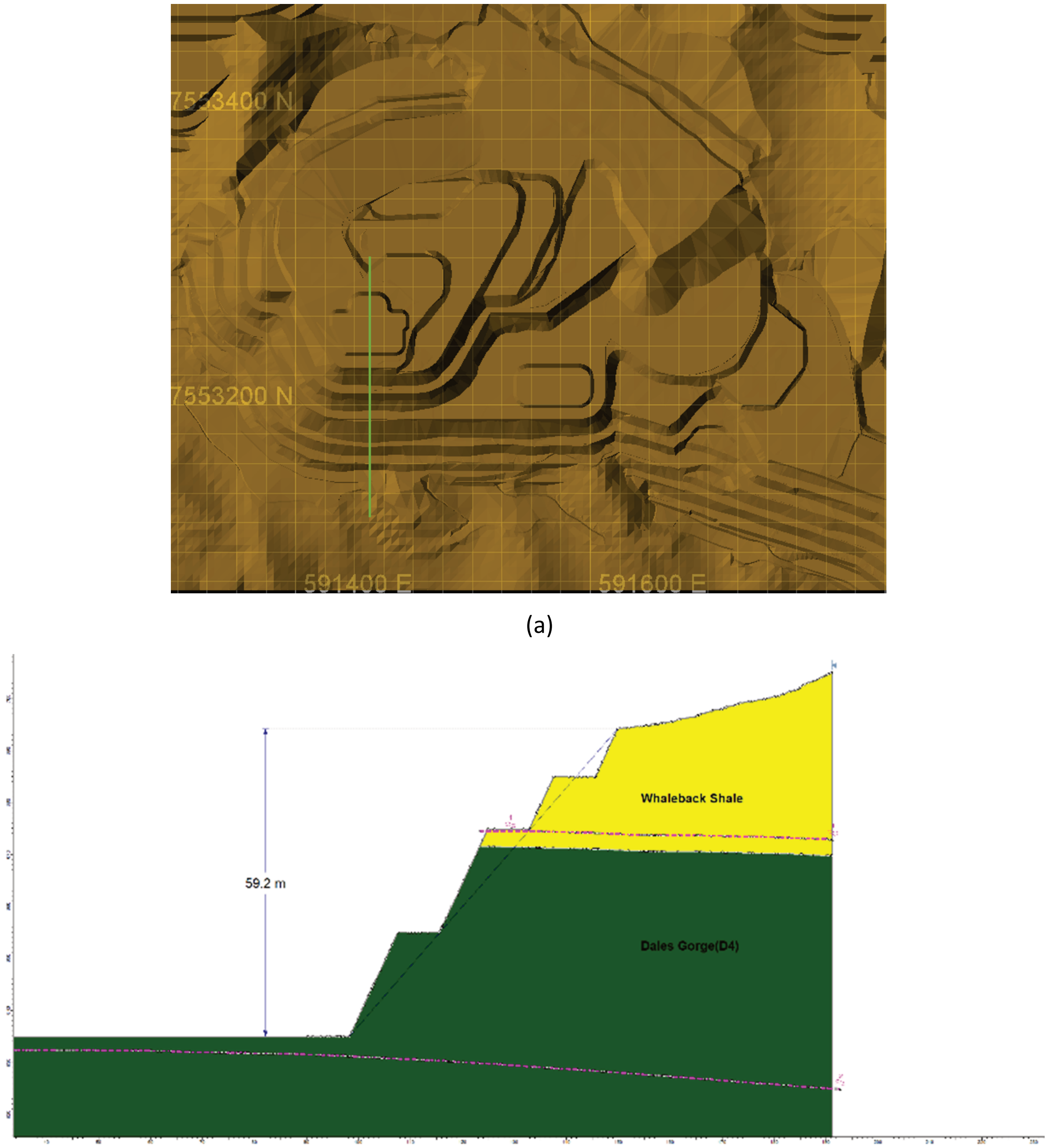
Figure 5 (a) Current mined out: as-built and design slope; (b) Cross-section comparing as-built (aerial) with design (blue)

The geology, geotechnical conditions and structure are the same for this wall. The results are mainly influenced by blasting and frequency of catch berms.

4 Case study 2: Firetail south pit design

This case study involves the assessment of an existing pit that was deepened to recover additional ore beneath the existing design pit floor. The existing pit had been assessed and approved to be mined to the 635 m RL. Geology mapping and an update of the site's ore blending requirements for the pit indicated there was an additional 20 m of ore below the existing final pit floor, hence the final base of pit was revised to 610 m RL from 635 m RL to retrieve the ore.

The section of the pit was originally designed to be about 60 m deep and consists of about 20 m of Whaleback Shale and 40 m of Dales Gorge. The base of pit within that section during the design stage was 635 m RL. Figures 6a and 6b are the plan view and a 2D geotechnical cross-section of the slope through that highwall showing the various geological units at the design stage.



(a)

(b)

Figure 6 (a) Plan view of the pit; (b) Cross-section through the pit

The pit slope design parameters and as-built configuration are shown in Table 4.

Table 4 The as-built and design configuration

	Design			As-built	
Geologic unit	Batter height, m	Batter face angle	Berm width m, min	Min as-built batter face angle	Min as-built berm width m, min
Whaleback shale, BW*	10	65	8	57	3
Dale Gorge, BD*	20	65	8	53	5.5

*The maximum stack height is 60 m. A 20 m decouple berm is required afterwards.

Based on risk assessment, a 'low consequence' of slope failure was adopted for this pit design. DAC in accordance with the *Guidelines for Open Pit Slope Design* (Read & Stacey 2009) (Table 5) was adopted for the deterministic slope stability assessment.

Table 5 Summary of design acceptance criteria

Slope scale	Factor of Safety (static)
Single batter	1.1
Inter-ramp slope	1.15–1.2
Overall slope	1.2

The assessment of the design was undertaken using the anisotropic linear strength model (Snowden 2007) as applicable in Slide 2 (Roscience Inc. 2019). The design returned a Factor of Safety of 1.2. Further assessment of the stability assessment of the as-built slope (to 635 m RL) was assessed to be about 1.23. This was mainly due to a slight reduction in the overall slope angle during the construction of the pit. A summary of the results is presented in Table 6.

Table 6 Design and as-built slope Factor of Safety

Overall slope	Factor of Safety (static)
Design	1.20
As-built slope	1.23

To recover the additional ore, the pit depth must extend an additional 20 m. Based on the geotechnical slope configuration parameters for the mining area, a decoupling berm of 20 m is required after 60 m stack height. As the area requiring the extra mining was not very extensive a decoupling berm will limit the optimisation of ore retrieve from the pit below 635 m RL.

To optimise the ore recovery, an initial pit design without a decoupling berm was generated for assessment. The as-built design was assessed for potential rockfall risk as the catchment berm had been reduced during the mining of the upper slopes (Table 4). The rockfall risk is not presented here. The results of the 2D static assessment for the proposed design to 610 m RL is summarised in Table 7. Both the inter-ramp and overall FoS were marginally below the minimum required DAC for the slope.

Table 7 Summary of two-dimensional static stability results

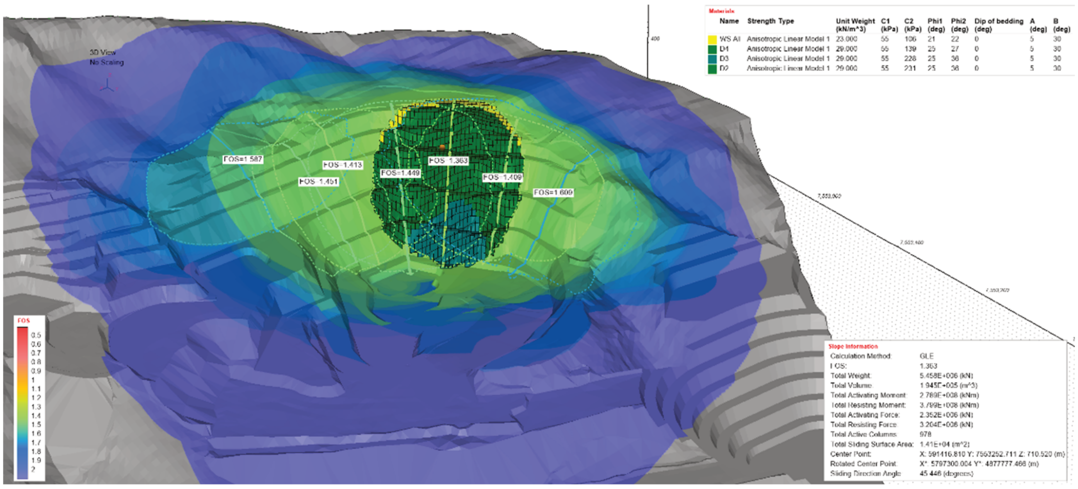
Slope scale	Acceptance design criteria, Factor of Safety (FoS)	Achieved FoS
Inter-ramp	1.15–1.2	1.14
Overall	1.2	1.18

To ensure the design meets the minimum DAC, one of the following had to be undertaken:

1. Detail 3D LE assessment of the slope using Plaxis 3D LE software (Bentley 2021) to evaluate the influence of the slope confinement in the slope stability assessment.
2. Redesign the slope with a decoupling berm at 635 m RL or leave a buttress.

As the 2D assessment was marginally below the recommended DAC, the first approach was to evaluate the 3D LE assessment of the pit as this will ensure maximum ore retrieval if DAC are met. The results from the 3D assessment would also support stakeholder engagement, informing on the risk of mining deeper without a decoupling berm.

The result of the 3D LE assessment is presented in Figure 7. The result indicates minimum FoS of 1.36 (overall) which is about 15% greater than the 2D assessment FoS.



Materials

	Name	Strength Type	Unit Weight (kN/m^3)	C1 (kPa)	C2 (kPa)	Phi1 (deg)	Phi2 (deg)	Dip of bedding (deg)	A (deg)	B (deg)
🟨	WS All	Anisotropic Linear Model 1	23.000	55	106	21	22	0	5	30
🟩	D1	Anisotropic Linear Model 1	29.000	55	139	25	27	0	5	30
🟩	D3	Anisotropic Linear Model 1	29.000	55	228	25	36	0	5	30
🟩	D2	Anisotropic Linear Model 1	29.000	55	231	25	36	0	5	30

Slope Information

Calculation Method:	GLE
FOS:	1.363
Total Weight:	5.458E+006 (kN)
Total Volume:	1.945E+005 (m^3)
Total Activating Moment:	2.789E+008 (kNm)
Total Resisting Moment:	3.799E+008 (kNm)
Total Activating Force:	2.352E+006 (kN)
Total Resisting Force:	3.204E+006 (kN)
Total Active Columns:	978
Total Sliding Surface Area:	1.41E+04 (m^2)
Center Point:	X: 591416.810 Y: 7563252.711 Z: 710.520 (m)
Rotated Center Point:	X*: 5797300.004 Y*: 4877777.466 (m)
Sliding Direction Angle:	45.446 (degrees)

Figure 7 Plaxis three-dimensional limit equilibrium assessment results

The 3D LE assessment outcome provided the additional confidence to all stakeholders to proceed to mine the 20 m ore beneath the current base of pit via a risk assessment, with monitoring.

5 Discussion and conclusion

The two case studies provide examples where targeted application of 3D LE geotechnical assessment provided increased confidence in the design outcome for situations where a 2D assessment is marginally below DAC. It is important to note that confidence in the results from any 3D LE assessment is dependent on the reliability and confidence in the input data and models and, if applicable, slope reconciliation data from site. Ongoing monitoring and model reconciliation is always vital to help evaluate the effectiveness and robustness of the slope design assessment.

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