“Three-dimensional geotechnical analysis on strongly altered sedimentary domain at Bozshakol copper mine”

KAZ MINERALS

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Slope Stability in Mining

ACG AUSTRALIAN CENTRE FOR GEOMECHANICS

CSIRO | The University of Western Australia | Joint Venture

Outline

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Introduction

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Current Pit depth:
- Approximately 200 m

Dimensions:
- Length: 4.5 km (Northeast to Southwest)
- Width: 1.8 km (Northwest to Southeast)

Future Pit Slope Heights:
- Expected to reach 430 m

Bozshakol deposit :

Location:
- Ekibastuz, Pavlodar region, Republic of Kazakhstan

Type :
- Large-scale porphyry copper open pit mine

Distance from capital, Astana:
- 250 km (east)

Travel Time:
- Approximately 2.5 hours by road, 4.5 hours by train

Copper Grade:
- Average of 0.33%

Processing Facilities:
- On-site facilities with 30 million tonnes annual ore processing

Life of mine :
- 40 years, commencing with the first production in 2016.

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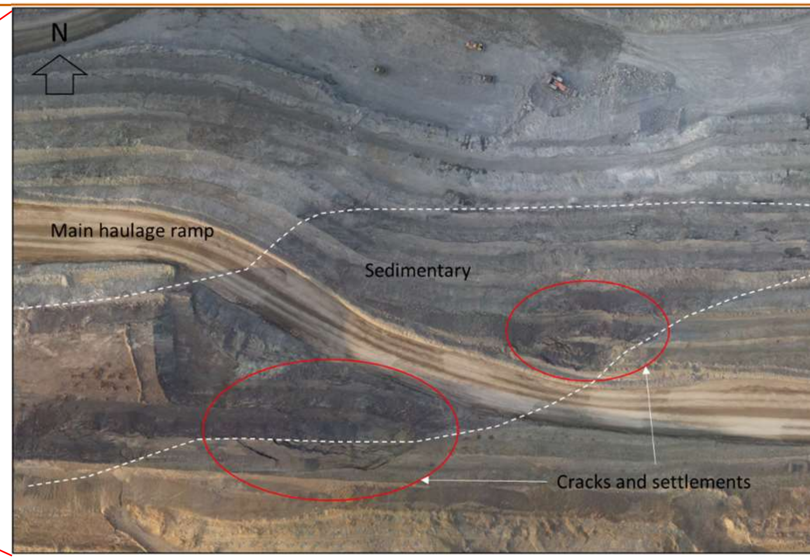
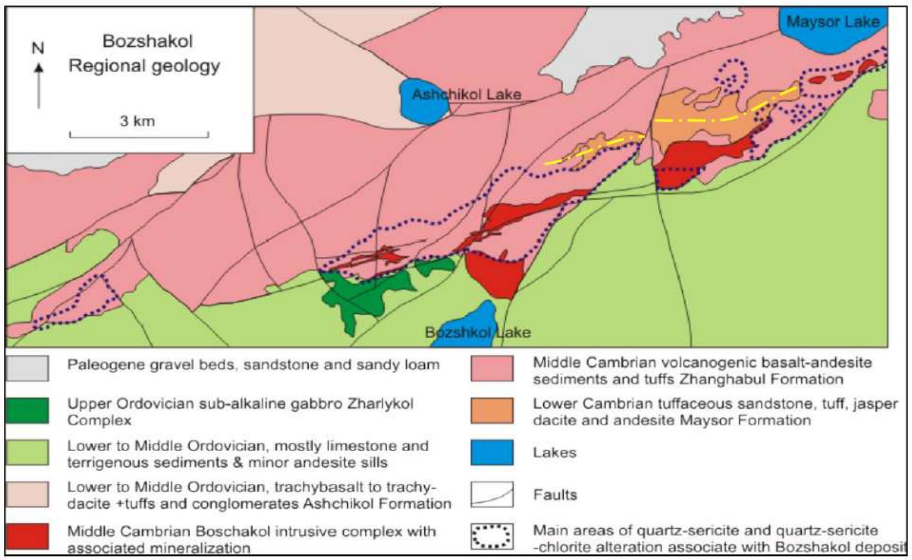
Introduction



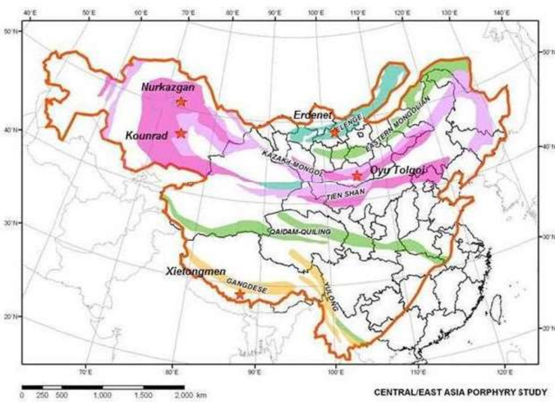
- Several instabilities were identified within the sedimentary domain on the south wall
- Failure mechanisms were considered complex and involved the combination of rock mass-controlled or step-path failures which were typically influenced by intense alteration on narrowly bedded sediments
- Series of cracks and ductile displacements propagated toward the pit direction
- The instabilities above and below the main haulage ramp have been effectively controlled using a combination of prism and radar monitoring

Engineering geological setting

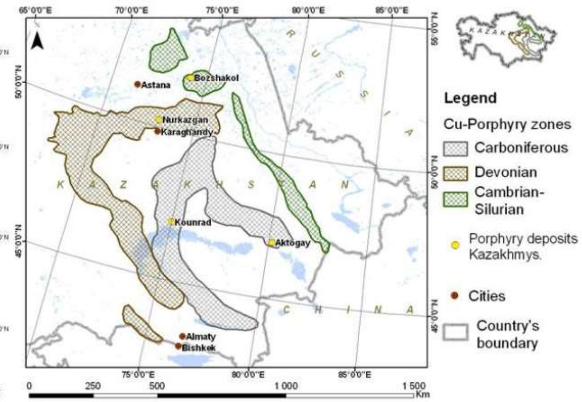


Geology Setting :

- Located on the western part of Central Asian Orogenic Belt (CAOB)
- Comprises a Cambrian-Ordovician, high-level intrusive complex emplaced into the east-northeast-trending Bozshakol anticline



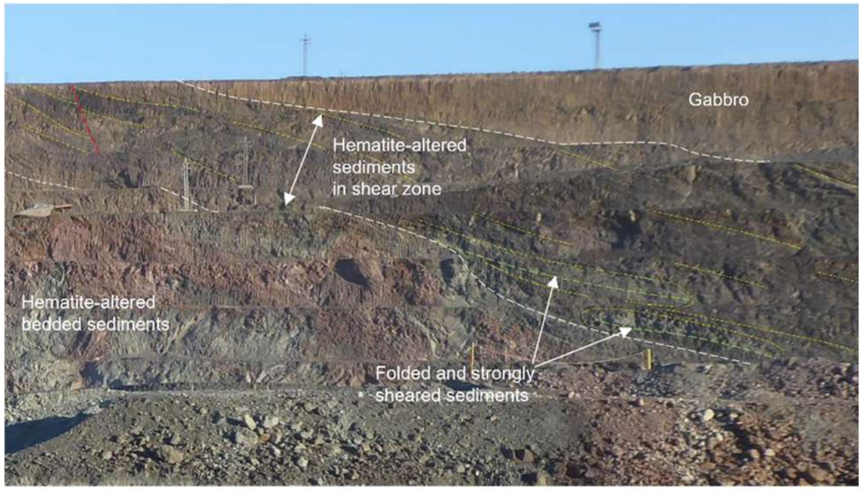
Porphyry belts of the CAOB
Source: Kaz Minerals



Porphyry belts of Eastern Kazakhstan
Source: Kaz Minerals

- Major geological units : Lower-Middle Cambrian sandstones and intermediate-mafic volcanic rocks (lavas and tuffs)
- Intruded by granodiorite to tonalite porphyry and porphyritic dykes; spatially associated with mineralisation
- A major shear zone cuts sedimentary succession on the south wall, the bedded sediments are variably deformed and strongly hematite-altered

Engineering geological setting



Geology setting :

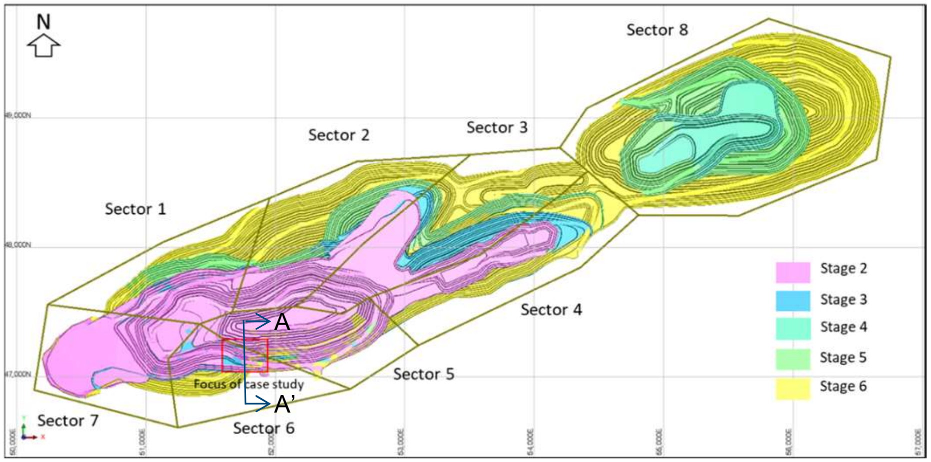
Significant features within the sedimentary domain on the south wall :

- Red-brown stained, intensely hematite-altered rocks
- Bedded sediments moderately to intensely deformed
- Strongly sheared beds and layers
- Tight folds along margins on a 10cm to several meters scale
- Clastic sediments affected by brittle-ductile deformation
- Shallow shear zone: Subsequently faulted, folded, and locally rotated

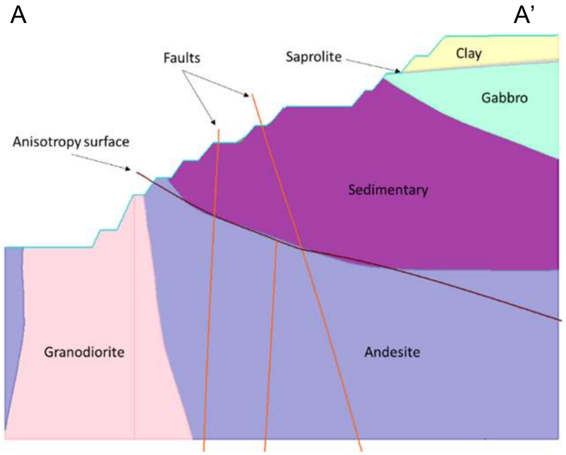
Engineering geological setting

Geotechnical considerations :

- Geotechnical domains primarily based on lithology and pit slope sectors; 8 (eight) different design sectors, cover 6 (six) planned pit development stages
- Subdivided on the basis of similarities of geotechnical characteristics and strength properties
- Major structures appear frequently and interpreted to be interlinked
- Faults modelled as discrete surfaces



Pit design sectors and development stages



Typical section of geotechnical domains at the south wall

Engineering geological setting

Geotechnical considerations :

- Bedding orientation dipping into the wall and a potential for toppling, however field observations point to a composite mechanism with rotational failure surface, potentially shearing through the highly altered sediments.
- Sedimentary rock mass strength gradually decreases in the southwest direction while the alteration intensity increases.
- Ductile ground behaviour observed in the highly altered sediments; considered a significant concern for the long-term stability of haulage ramps.
- Sedimentary domain has high-intensity hematite alteration within Sector 6 and reduced strength compared to the sedimentary domain in another sector.
- Divided into two classes :
  - Sedimentary-class 1: high-intensity hematite alteration sedimentary material located at Sector 6. Low-strength anisotropic rock which behaves like soil in some instances. Rotational failure mechanisms observed
  - Sedimentary-class 2: anisotropic sedimentary material located at Sector 5. Less altered, however, found within a major shear zone within bedded sediments

(a) (b)

Weaker sedimentary domain with high intensity hematite alteration at (a) sector 6 compared to (b) sector 5

Engineering geological setting

Geotechnical considerations :

Summary of adopted geotechnical shear strength parameters :

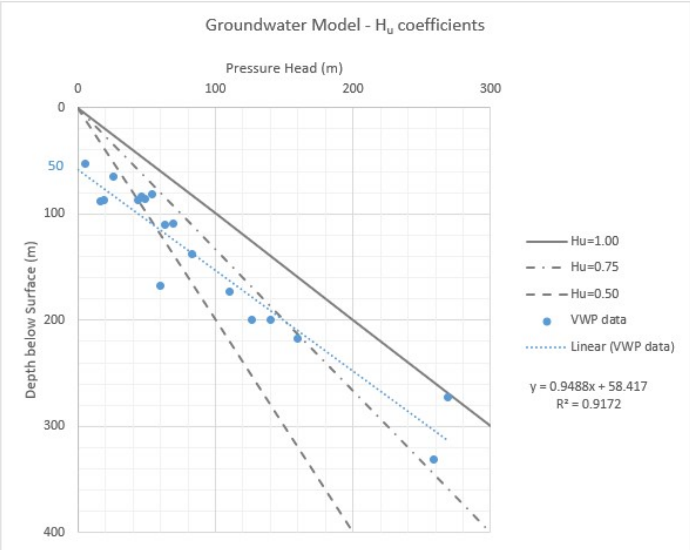
Domain		Class	Sector	c'	ϕ'	UCS	GSI	mi	D	E_i	ν	ϕ	σ_i
				KPa	⁰	MPa				GPa			MPa
Clay			6	22	33								
Saprolite			6	22	39								
Andesite			6			48	60	25	0	41	0.25	0.4	9
Gabbro			6			14	45	15	0	14	0.24	0.5	4
Granodiorite			6			50	65	29	0	26	0.28	0.4	5
Sedimentary	Rock mass	1	6	25	34								
	Bedding	1	6	5	16								
Sedimentary	Rock mass	2	5			48	30	22	0	20	0.26	0.5	6
	Bedding	2	5	5	16								
Faults			All	1	22								

- Disturbed samples in sedimentary-class 1 were also collected and sent to a laboratory for direct shear testing to estimate shear strength parameters, cohesion (c’) and the friction angle (φ’)
- Isotropic Hoek–Brown failure criterion material properties derived for rock domains
- Mohr–Coulomb material strengths for clays and saprolites
- Anisotropic material strength properties are assigned to sedimentary
- Wall control blasting has been rigorously applied with consideration of a negligible blast disturbance factor (D = 0)
- The geological faults have been (conservatively) assumed as being slickenslided or polished planar surface

Engineering geological setting

Groundwater model:

- H_u coefficients that are used to correlate real pore pressures (from VWP data) to the model with an assigned phreatic surface
- H_u coefficients provides flexibility for assessing groundwater sensitivities
- Obtained via 19 vibrating wire piezometers (VWPs) located around the pit in various inclined boreholes



Engineering geological setting

Groundwater model:

- $H_u = 0$ would indicate a dry soil or rock mass. Pore pressure will be zero
- $H_u = 1$ would indicate fully saturated, hydrostatic conditions
- $H_u > 1$ would indicate pore pressures higher than hydrostatic conditions (e.g. high pressure in an artesian aquifer)

Groundwater considerations for the model :

- H_u coefficient of 0.75 is applicable when considering all available data from the spring season during the snowmelt period where geotechnical risks associated with pore pressures are at their highest
- The top 50 m of ground beneath the surface in proximity to the pit, which mainly consists of clay and saprolite domains, is considered dry with $H_u = 0.00$

Three-dimensional back analysis

- Focus on sedimentary domain to refine material properties
- 3D limit equilibrium software *Slide3* from RocScience Inc was utilised for the back-analysis

Validations :
- Spatial validation: replicates the correct failure location and shape
- Material property validation: used attain a Factor of Safety (FoS) = 1.00 ±0.02

Slide3 failure back-analysis :
- Analysis used a general limit equilibrium (GLE) method of columns. Additional checks using Bishop and Janbu.
- A generalised anisotropic strength model was applied to the sediments domain with the bedding strength following an anisotropy surface defined by the basal contact of the sediments. Generalised anisotropic variability parameters A = 15° and B = 30° were adopted based on previous work in sedimentary rock masses by Bar & Weekes (2017).
- Isotropic material strength properties were applied to the remainder of the soil and rock masses.
- Known geological faults as weak layers.
- The groundwater table followed the external surface with customising H_u coefficients.
- Sensitivity analysis for the potential variation of pore pressures using H_u coefficients was also completed.
- Probabilistic input parameters were used in *Slide3* along with the particle swarm method for slip surface generation, with additional surface altering optimisation to find a range of plausible material strengths that result in equilibrium conditions.

Three-dimensional back analysis

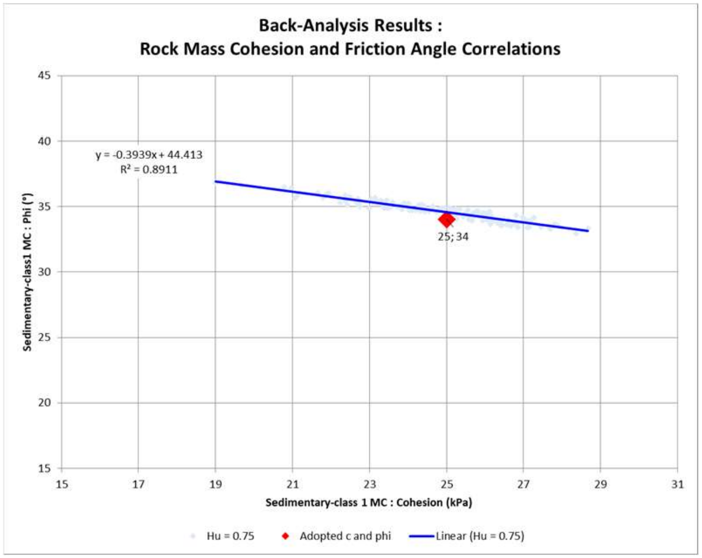
Spatial validation with IBIS ArcSAR radar data :
- Assessed the influence of faults in the model. Most were sub-vertical and had negligible influence on the outputs.
- The output was compared against the actual displacement data.
- Model inputs and re-run models were adjusted as appropriate until a spatial match was achieved.

The original slope component parameter for strongly altered sedimentary domain at Sector 6 :
- 55° bench face (batter) angle
- 10 m bench height
- 7.5 m berm width
- 34.6° Inter-ramp angle (IRA)

The probabilistic analysis was performed that meet FoS as close to 1.0 (FoS ≈ 1.0).
Initial values for bedding strength are based on mean average laboratory data with a plausible range in cohesion of ±6 kPa and a friction angle of ±6°.

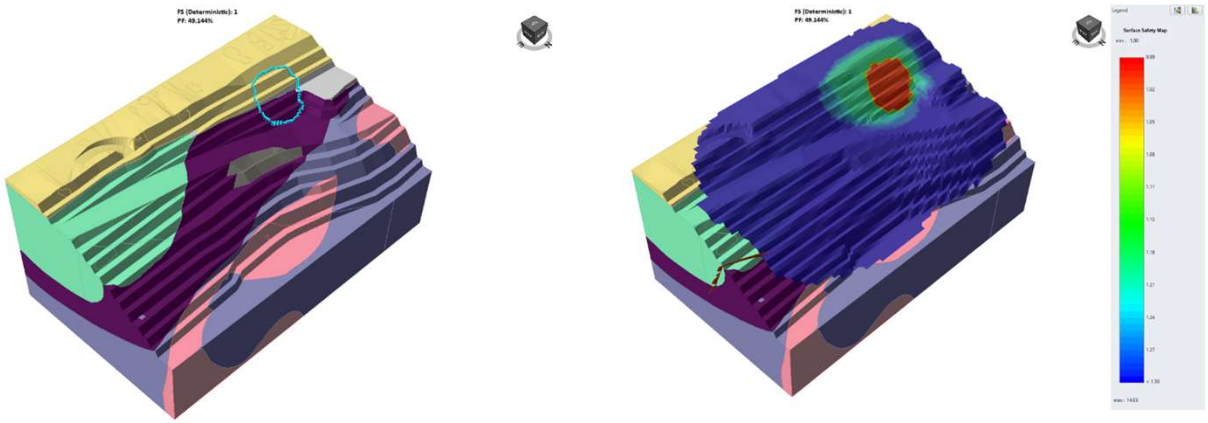
Three groundwater scenarios were tested:
- H_u = 1.00: assumption of fully saturated conditions, although considered very pessimistic.
- H_u = 0.75: based on the available VWP data (main consideration)
- H_u = 0.00: assumption of fully depressurised conditions, although considered very optimistic.

Three-dimensional back analysis



Correlation of back-analysed rock mass cohesion and friction angle with FoS ≈ 1.

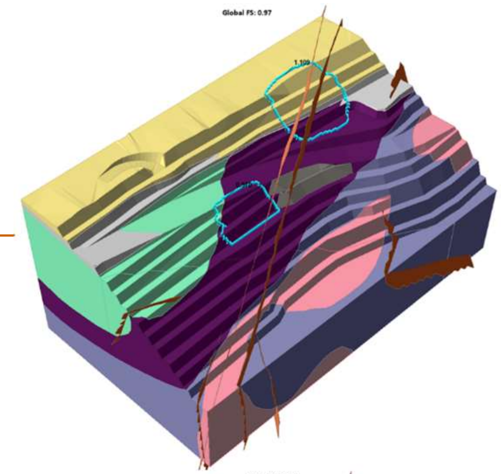
Back-analysis with failure surface contour reflecting the area of cracks and settlement at the upper bench adjacent to the main haulage ramp



The back-analysis results :

- Rock mass strength : cohesion of 25 kPa and friction angle of 34°
- Bedding strength : cohesion of 5 kPa and friction angle of 16°

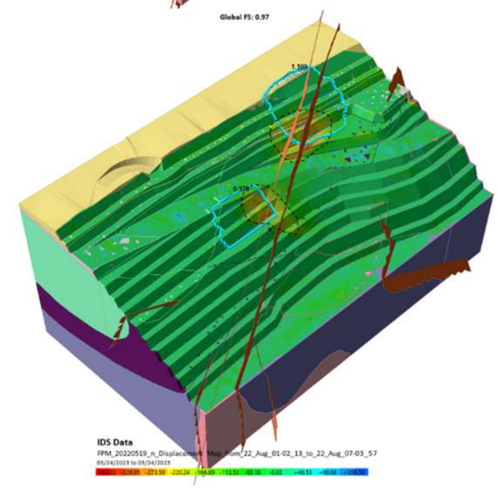
Three-dimensional back analysis



Model validation :

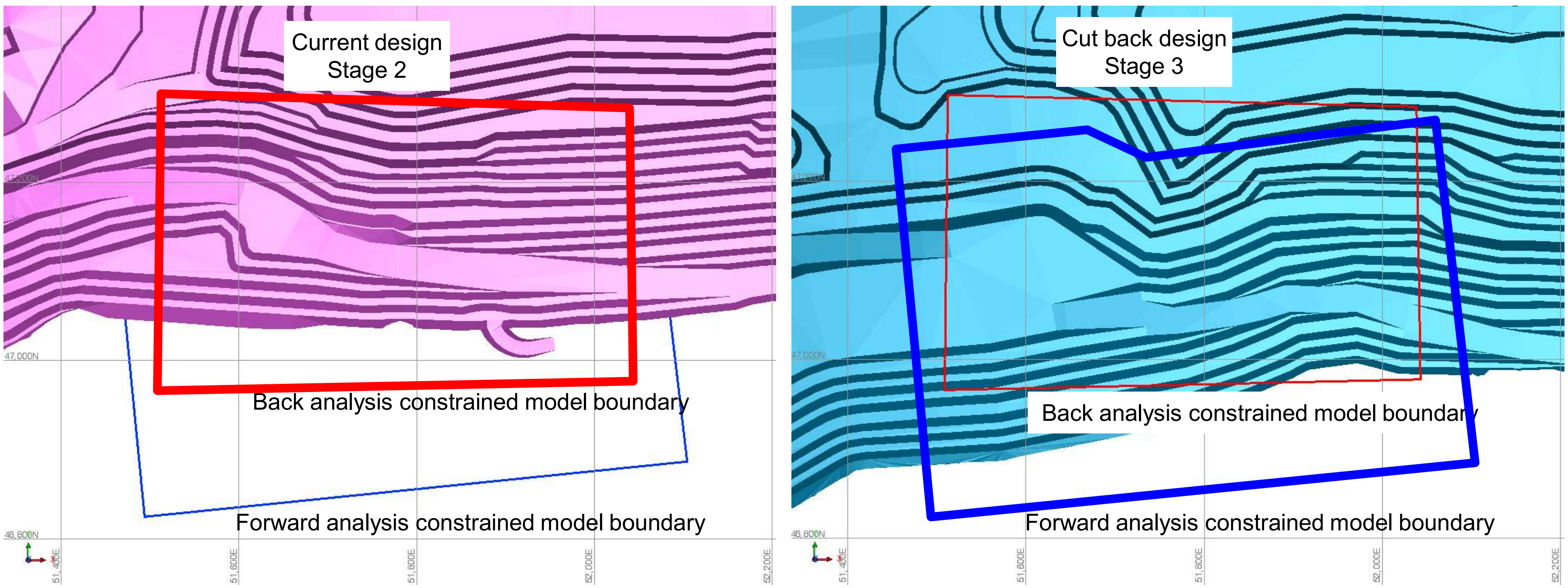
- Overlaying back-analysed *Slide3* outputs with deformation data from slope stability radar.
- Cracks and settlement occurred at two locations; spatial model validation was completed for both.
- Remediation works (design changes) have not been considered in the back-analysis.

IDS GeoRadar – IBIS ArcSAR



- Sub-vertical geological fault modelled as weak planes had limited effect on results.
- The modelled failure surfaces area is in general agreement with overlaid deformation contour captured by slope stability radar monitoring.

Three-dimensional forward analysis



Three-dimensional forward analysis

Forward analysis for proposing stable slope design configuration :
- Plastic analysis for determination of FoS : 3D limit equilibrium – *Slide3*
- Elastic analysis for validation and to investigate the potential for a complex failure mechanism : 3D finite element - *RS3*.

Design Acceptance Criteria (DAC) :
- Adopted shear strength parameters were used for the base case.
- Back-analysed shear strength parameters for sedimentary-class 1 were used for sensitivity analyses

		Design Acceptance Criteria		
Slope scale	**Consequences of Failure**	**FoS (min) (Base Case)**	**FoS (min) (Sensitivity)**	**PoF (max) P[FoS≤1]**
Bench	Low-high	1.1	NA	25-50%
Inter-ramp	Low	1.15-1.2	1.0	25%
	Moderate	1.2	1.0	20%
	High	1.2-1.3	1.1	10%
Overall	Low	1.2-1.3	1.0	15-20%
	Moderate	1.3	1.05	10%
	High	1.3-1.5	1.1	5%

Adjusted from Read & Stacey (2009)

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Three-dimensional forward analysis

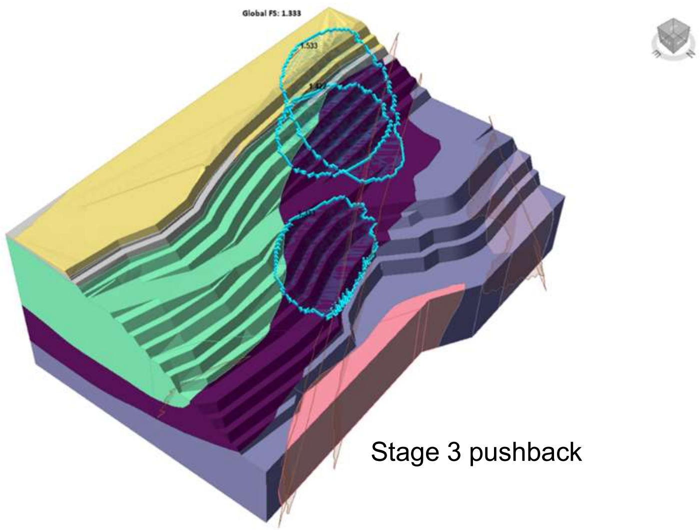
- Variations of H_u = 0.75, H_u = 0.60 and H_u = 0.50 were assessed to investigate the influence of the groundwater table
- H_u = 0.75 (base case) assumes Stage 3 pushback implements the slope geometry adjustment only, without any slope depressurisation effort
- H_u = 0.60 and H_u = 0.50 further assess for groundwater sensitivity on slope stability with the premise to set up depressurisation targets to improve FoS.
- For an inter-ramp slope with a moderate consequence of failure, the DAC requires a minimum FoS = 1.2 for the base case.

Slope component parameter comparison

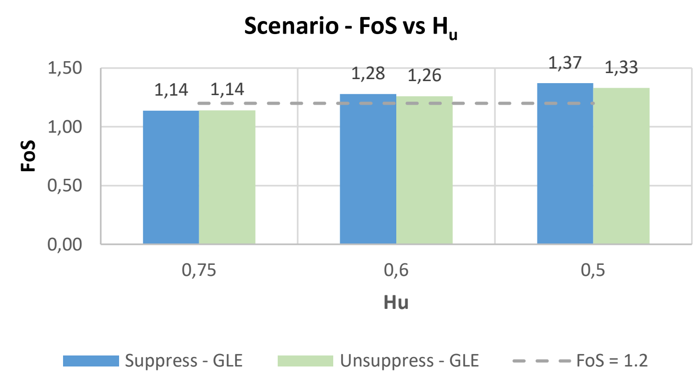
Domain	Design	Batter angle (^{0})	Bench height (m)	Berm width (m)	Inter-ramp angle (^{0})
Sedimentary-class 1	Stage 2	55	10	7.5	35 (34.6)
	Stage 3 pushback	45	10	7.5	30 (29.7)

Three-dimensional forward analysis

- Faults as weak planes are modelled as suppressed and unsuppressed to figure out their influence on stability and investigate whether any potential failure could be controlled by structures.
- FoS for each H_u scenario are obtained for each suppressed and unsuppressed faults model by using *Slide3* software.



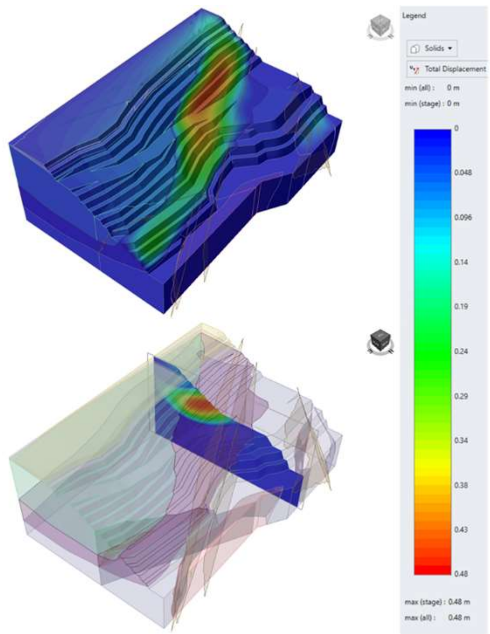
H_u	FoS Supressed faults	FoS – Unsuppressed faults	Remarks
0.75	1.14	1.14	Marginal stability
0.60	1.28	1.26	Achieved static acceptance criteria
0.50	1.37	1.33	Achieved static acceptance criteria

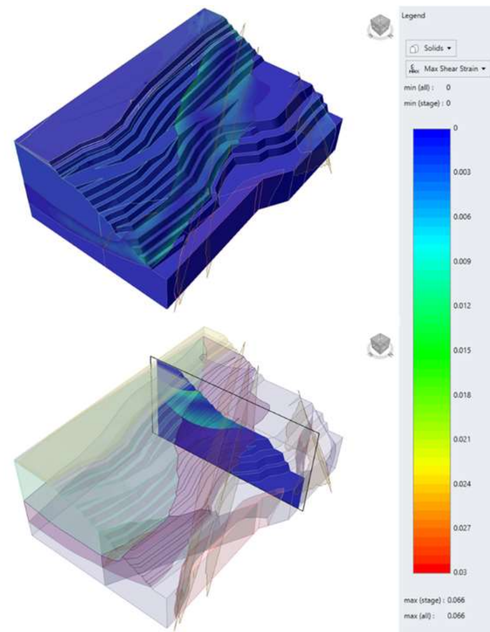


- Sub-vertical geological faults have negligible impact on slope stability.
- Slope depressurisation has the potential to significantly improve FoS.

Three-dimensional forward analysis

- Total displacement and maximum shear strain are displayed for elastic analysis in *RS3* to validate the *Slide3* results.
- No additional complex failure mechanisms were identified using finite element analysis.





Three-dimensional forward analysis

Full pit scale using the 3D limit equilibrium method was completed as part of a LoM study :

- Understanding potential inter-ramp and overall slope scale risks and opportunities associated with rock mass failure modes and structurally driven failure modes.
- All slip surfaces were bounded to have a minimum slip surface at a depth of 30 m below the external boundary to avoid analysing for local and operationally manageable bench instabilities.
- A total of 45 discrete geological faults were included in the full pit scale model.
- All slip surface were subsequently optimised using surface alteration algorithms to find the lowest FoS.
- Faults were included as weak layers that intersect the rock mass and pit slope geometry at various locations and orientations.

Ellipsoidal slip surfaces were generated using:

- A particle swarm search for assessing multiple low FoS slip surfaces comprising both rock mass failure and structurally driven failure modes.
- A cuckoo search for 10 overlapping spatial domains for assessing the lowest FoS slip surface within each domain comprising both rock mass failure and structurally driven failure modes.

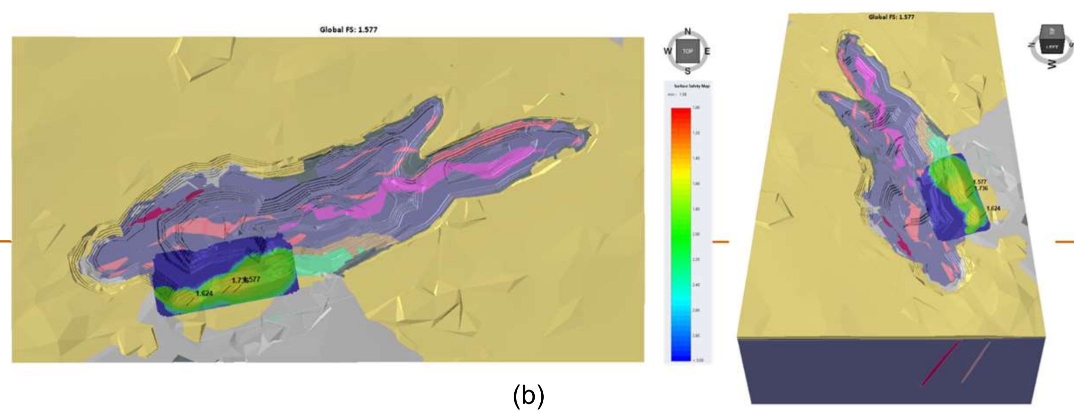
The results indicated the FoS exceeds DAC for both the particle swarm search and cuckoo search (FoS > 1.2) for inter-ramp slopes

All 3D limit equilibrium was validated with 3D finite element

Three-dimensional forward analysis

Slide3 output for full pit scale to assess rock mass failure modes by using particle swarm presenting (a) multiple failure surfaces and (b) a FoS heat map

(a)

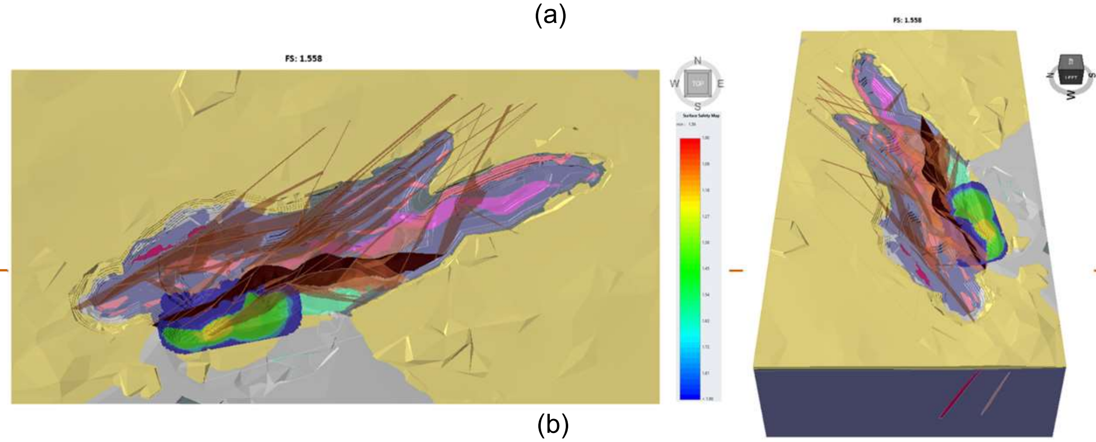


(b)

Three-dimensional forward analysis

Slide3 output for full pit scale to assess structurally driven failure modes by using a cuckoo search presenting (a) a global minimum failure surface and (b) a FoS heat map

(a)



(b)

Conclusion

Based on the back-analysis results and subsequent forward analysis on local and global models, the following recommendations were proposed to improve slope stability for further Stage 3 pushback design and LoM mine plans:

- Within the sediments-class 1 domain, reducing inter-ramp angle to be 29.7º (from 34.6º) by implementing 45º bench face angles, 10 m bench height, and 7.5 m berm width for long-term stability.
- Improve the stability by reducing pore water pressure. This requires a high-density network of VWPs and the commencement of horizontal drilling to depressurize the south wall slopes.
- Additional geotechnical site investigations including additional diamond drilling and borehole geophysics to further refine our geomechanical understanding of the sediments domain.

The challenging slope stability conditions at Bozshakol pit south wall particularly on strongly altered sedimentary domain have been safety and economically managed through a comprehensive monitoring and response processes and ongoing remedial works.

In this study, the south wall instabilities have been back-analysed to refine material properties for a more reliable future prediction, which has resulted in a minor slope design change for the upcoming Stage 3 pushback. It has also demonstrated the need for slope depressurisation and helps to demonstrate the economic value of horizontal drilling.

The use of 3D limit equilibrium analysis has been integrated into the geotechnical workflow and is now used as part of annual LoM design reviews and for slope reconciliation processes.


Thank you
Спасибо
Рахмет