Rock slope design and residual risk management for Aktogay Copper Mine, Kazakhstan

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ABSTRACT: Aktogay is a large open pit copper mine in Kazakhstan. Several geotechnical investigations have been completed from initial scoping and feasibility studies to continuous improvement studies during mining. Rock slope design has involved several phases of stability analyses for various stages and the life-of-mine open pit. With the progression of mining in the pit, ground conditions at the mine are becoming more apparent and uncertainty is progressively reduced. This paper briefly describes the slope stability modelling approaches used to understand and communicate geotechnical risks and opportunities for integration with a complex mine plan and sequence. A combination of 3D limit equilibrium and finite element analysis was incorporated into slope stability assessments for future slope excavation stages. The models have been developed with the intention of being digital twins to actual mine progression, with routine updating as engineering geological features are validated and updated with new exposures and additional site investigations.

Keywords: 3D slope stability analysis, risk management, digital twin, mining.

1 INTRODUCTION

Aktogay copper mine is located in south-eastern Kazakhstan, approximately 470 km to the north-east of Almaty, and 250 km west of the border with China. Mining operations commenced in 2015 and mine life is expected to be at least another 25 years.

The Aktogay deposit is located on the western part of the Central Asian Orogenic Belt (Li et al. 2018). It is confined to the eastern part of the Central Aktogai raft of volcanics and the enclosing pluton. The raft is intruded by Early Carboniferous, porphyritic granodiorite which also cross-cuts diorite and granodiorite of the Koldar pluton with the orebody striking west to north-west in an elliptical shape (Zvezdov et al. 1993). Major geological structures present in current and future pit slopes also follow this trend (Figure 1). Argillic-sericite alteration is focused on the core of the porphyry system and decreases outward (LeRiche et al. 2022).

A comprehensive geotechnical model has been developed from lithology, alteration, major structure and rock mass models as illustrated in Figure 1. These models were developed from a comprehensive data set from several site investigation campaigns including 162 geotechnicallylogged diamond cored boreholes, 130 boreholes with machine learning core photograph classification and over 1700 geomechanical laboratory tests (LeRiche et al. 2022).

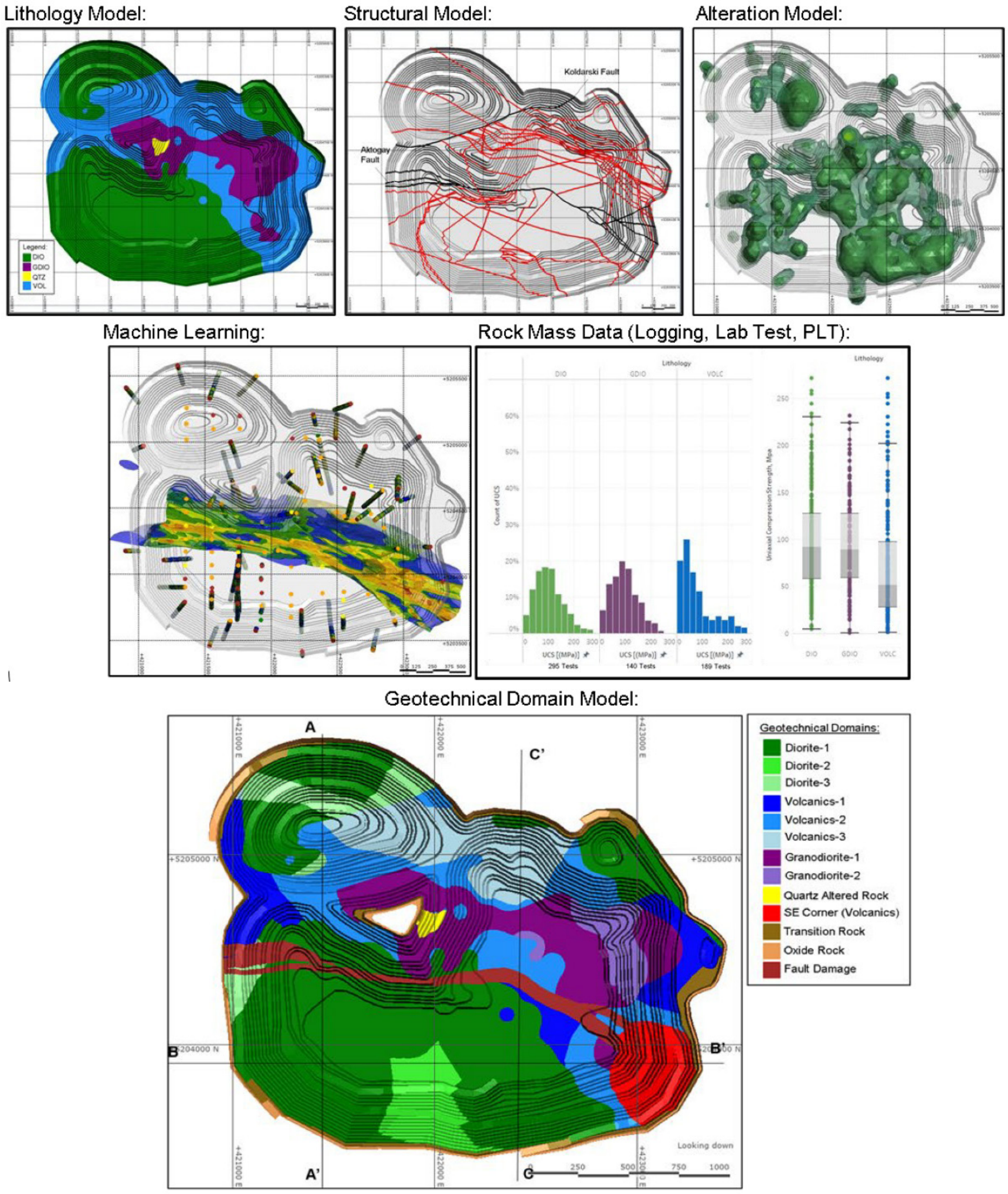

Figure 1. Aktogay Life of Mine Pit Shell and Geotechnical Model developed from Lithology, Structural and Alteration models using Rock Mass Data and Machine Learning (after LeRiche et al. 2022).

Average annual precipitation at Aktogay is less than 200 mm with a maximum of 297 mm being recorded in 1957 (Sagintayev et al. 2015). Snowfall at Aktogay usually lasts for approximately five months between November and March with an average annual snowfall of 268 mm.

Groundwater management during initial mining stages only involves surface water management (sumps and pumps to remove water from the pit floor). Horizontal drains are planned for deeper mining stages. Pore pressures behind the slopes are well understood through a network of vibrating wire piezometers. Higher pore pressures are observed during the snowmelt period (Spring).

During the initial mining stages at Aktogay, slope performance has been excellent with only a few multi-bench instabilities. As shown in Figure 2, bench performance has also been very good as a result of a focus on operational excellence for blasting and excavation.

Slope stability analysis in earlier studies was completed using two dimensional (2D) cross-sectional analysis. Limitations of 2D analysis for open pit mines include (Bar & Weekes, 2017; Bahsan & Fakhriyyanti, 2018; Chakraborty & Goswami, 2021; Bar et al. 2022; McQuillan & Bar, 2023):

- Spatially or laterally varying geological conditions as seen in Figure 1.
- Spatially varying material strengths, including anisotropic behavior.
- Non-linear slope geometry and pit curvature as seen in Figure 2.
- Persistent geological structures, striking and intersecting slopes at various angles (i.e. not representable using a 2D cross-section).
- High variability in 2D results within close spatial proximity to each other.
- Inability to understand potential failure sizes for operational risk management purposes.

This paper describes the development and use of three-dimensional (3D) limit equilibrium (LE) and finite element (FE) models for slope design review and residual risk management at Aktogay.

Figure 2. Aktogay Copper Mine Stage 2 Pushback: Looking South. Left: September 2021 (Autumn). Right: December 2022 (Winter).

2 THREE-DIMENSIONAL SLOPE STABILITY ANALYSIS

A 3D slope stability model was developed in 3D LE and 3D FE modelling software packages, Slide3 and RS3 of Rocscience Inc, respectively.

The model geometry was based on the geotechnical model in Figure 1 and isotropic material properties from Table 1 were applied. The 3D model developed is 2.35 km long, 1.85 km wide, and approximately 0.65 km deep, which allows for fast assessments of different slope design geometries.

A total of 45 known geological faults were included as *weak layers* or interfaces (Figure 3).

Pore pressures were simulated based on current mine dewatering practices comprising perimeter pumping wells and surface water pumping. Monitored pore pressure data, from a network of over 40 vibrating wire piezometers, enabled the derivation H_u coefficients assigned to a phreatic surface that considered both typical and elevated pore pressures during the snowmelt period during spring.

Table 1. Material Properties.

Geotechnical Domain	UCS	GSI	m_i	D	c'	ϕ'	H_u
Unit of Measure	[MPa]				[kPa]	[°]	
Diorite	50 - 98	42 - 57	23 - 24	0 - 0.7	-	-	0.80 - 0.83
Granodiorite	66 - 90	46 - 59	19 - 20	0 - 0.7	-	-	0.77 - 0.80
Volcanics	32 - 88	42 - 56	16 - 19	0 - 0.7	-	-	0.79 - 0.86
SE Corner & F.D.	24	42	16	0 - 0.7	-	-	0.80
Quartz Altered Rock	90	46	20	0 - 0.7	-	-	0.77
Transition Rock	15	39	12	0 - 0.7	-	-	0.80
Oxide Rock	-	-	-	-	100	35	0.80
Fault Damage Zone	24	42	16	0 - 0.7	-	-	0.80
Discrete Fault	-	-	-	-	15-75	15-25	1.00

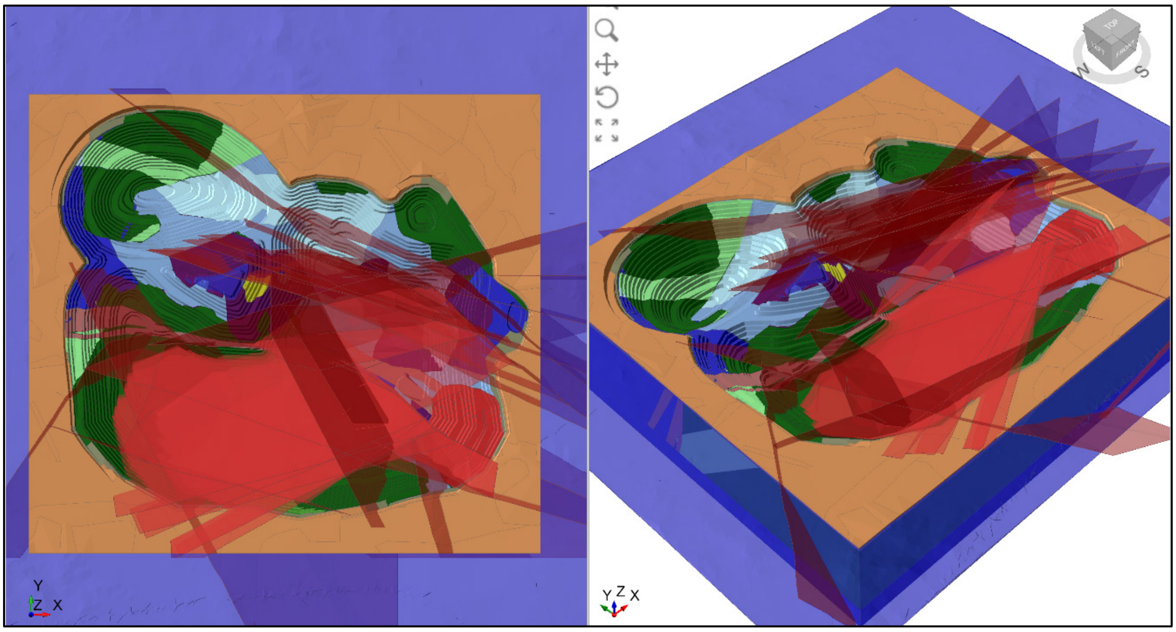

Figure 3. 3D Slope Stability Model for Aktogay Ultimate Pit. Semi-translucent red surfaces show discrete geological faults from the structural model incorporated into the models as weak layers. Semi-translucent blue surface represents the phreatic surface used to apply H_u coefficients and replicate monitored pore pressures.

Slope stability analysis using 3D LE methods identified potential risk areas or design hazards on the southern slopes of the ultimate pit design as illustrated in Figure 4 (based on inputs from Table 1). The low FoS (Factor of Safety) areas identified were all associated with adversely oriented discrete faults and formed one-, and two-sided wedges in the upper part of the slope. No significant risk areas were identified elsewhere in the design.

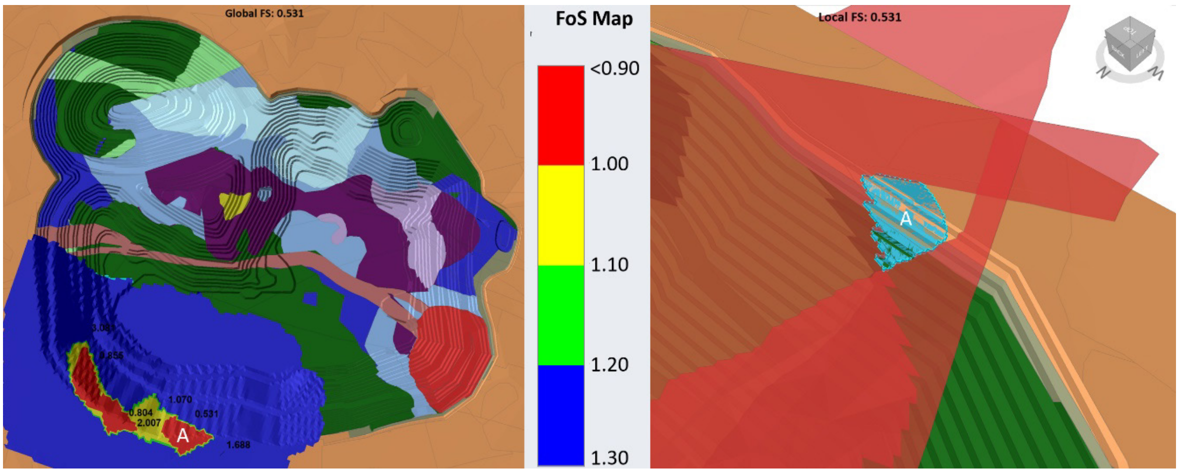

Figure 4. 3D LE Slope Stability Model for Aktogay Ultimate Pit Southern Slopes. Left: FoS Map with Potential Risk Areas and Design Hazards. Right: Looking South-East at Wedge 'A' formed by two adversely oriented discrete faults intersecting in the upper slope.

3D FE was used to validate the results of 3D LE modelling. Wedge 'A' was identified and is shown in Figure 5. Elastic analysis was run to determine the slope areas most susceptible to deformation based on modelled geological structure and material properties.

Results were then compared to 3D LE to verify predicted failure mechanisms and identify potential risk areas and design hazards. Contours of higher maximum shear strain were observed at the intersections of modeled faults. This confirms expected behavior in such ground conditions. 3D FE modeling identified the potential for ductile deformation on the central north slope (Figure 5), not identified with 3D LE methods, where this upward movement is less likely to be identified using limit equilibrium methods. 3D LE and 3D FE modeling was completed in tandem to provide a comprehensive review of potential risks and hazards using multiple analysis methods.

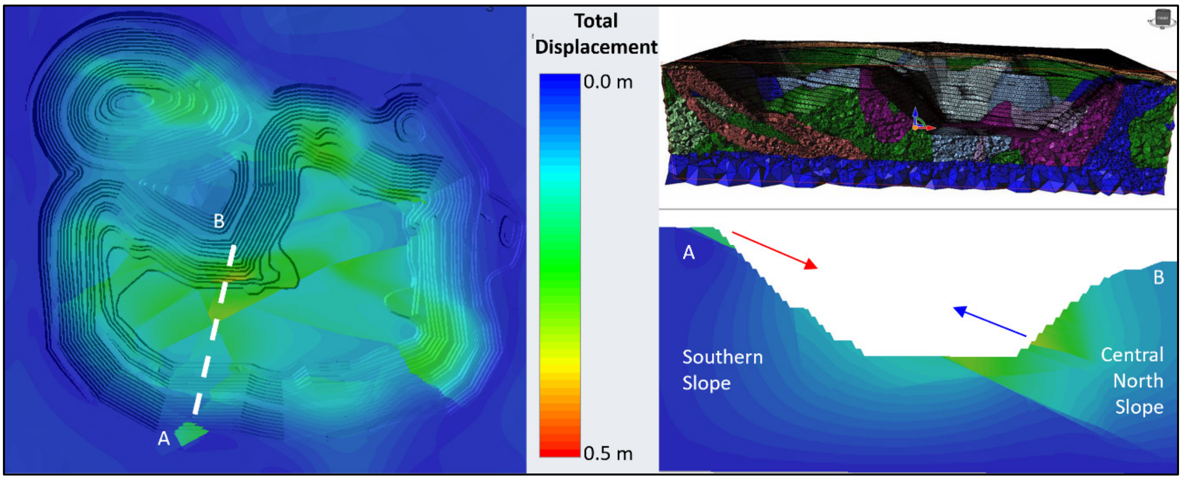

Figure 5. Elastic 3D FEM Slope Stability Model for Aktogay Ultimate Pit Southern Slopes. Left: Total Displacement. Upper Right: Section cut displaying 4-noded tetrahedral finite element mesh applied to 3D FE model. Lower Right: Cross-Section Looking West with Wedge 'A' on southern slope and ductile deformation upward on faults on the central north slope.

3D LE and FE models were also analyzed using a series of different sensitivity scenarios to understand input parameter sensitivity, particularly relating to discrete fault shear strengths and pore pressures. It was identified that most of the potential risks or design hazards on the southern side of the ultimate pit could be stabilized with slope depressurization (pore pressure reduction). By way of example, Figure 6 demonstrates improved FoS and fewer risks, using FoS as hazard criteria, (compared to Figure 4) with reduced pore pressures (H_u=0.60) that can be achieved using horizontal drains and confirmed with additional vibrating wire piezometers on successive pushbacks.

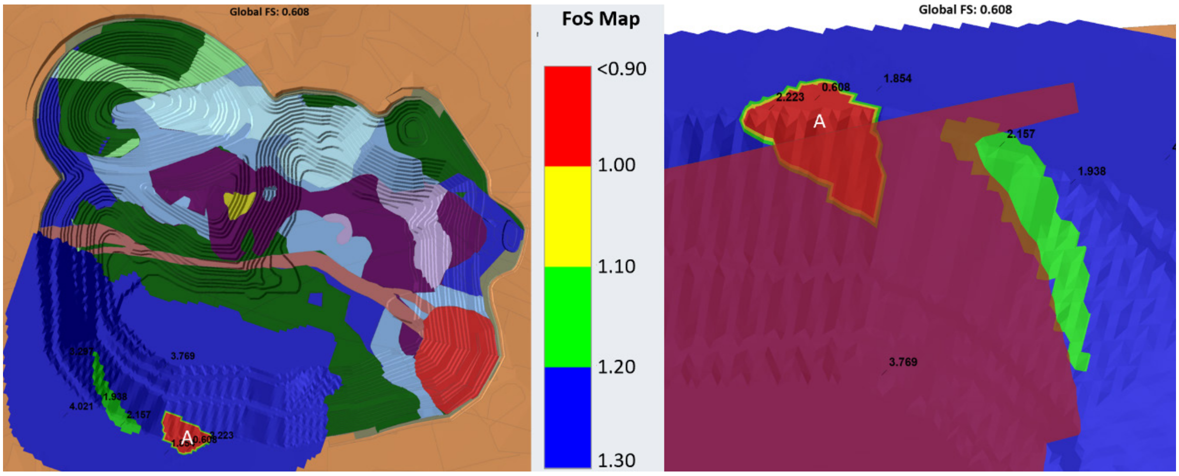

Figure 6. 3D LE Slope Stability Model for Aktogay Ultimate Pit Southern Slopes with reduced pore pressure (H_u=0.60) applied. Left: FoS Map with Potential Risk Areas and Design Hazards. Right: Looking South at Wedge 'A' and a second *low*-FoS one-sided wedge.

Wedge 'A' from Figures 4 and 6 is formed by two adversely oriented discrete faults, which even if depressurized, remains unstable with a potential failure volume of 0.46 million m^3 (approximately

1.2 million tonnes). Being positioned at the pit crest (top of the slope), this design hazard can be easily managed through a minor design change to drastically unload, or completely remove the wedge. Further site investigations are warranted to improve the characterization of the discrete faults and confirm their orientation, continuity and character. Doing so has the potential to reduce additional material movement needs.

3 KEY FINDINGS

The 3D slope stability models have been developed based on the geotechnical model incorporating major geological structures. These 3D models provide insights into potential design hazards associated with structurally-driven and complex failure mechanisms, both spatially and in magnitude (size), which remains impractical to impossible using 2D analysis.

This enhanced understanding of residual risk has helped guide control measure development, specific future site investigation objectives and sets targets for slope depressurization. It also enables a cost-benefit analysis of various control measure options (e.g. unloading or shallower slope angles versus horizontal drilling for depressurization).

3D slope stability models also have the ability to serve as digital twins. That is, they can be updated quarterly or annually to include any updates to the geotechnical model such as the inclusion or amendment of any geological faults, pore pressures, etc., updating of mine plans and forecasting risk and recent slope performance against the models both qualitatively in the case of LE, and quantitatively for FE.

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