Simulating global deformation and assuring ongoing stability in a complex multi lode room and pillar mine

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ABSTACT: A widespread series of pillar failures occurred at the Kamoto Copper Mine in the early 1990's. Access to the affected areas was lost and an extended period of mine closure followed.
To constrain interaction between the past failure and future work areas, the current mine required careful considerations and interactions with the failed zones, and a barrier pillar has been retained to protect the future work areas from effects of the past failure. A system of access pillars and stabilization pillars and staging of extraction works to shape deformation, manage stress, and allow a sufficient degree of control over stability has been implemented.
Mine stability is maintained through an ongoing process of engineering design, simulation, observation, and analysis for a mine with a complex system of pillars, which is described in this paper.

Keywords: Room and pillar, global stability, pillar failure, observational programme.

1 INTRODUCTION

The Kamoto Copper Company (KCC) was formed in 2005, with Glencore becoming a majority shareholder in 2009. It is a world class operation located at the north-western end of the Democratic Republic of Congo (DRC) / Zambia copper belt approximately 10 km to the east of Kolwezi, DRC. The mine produces copper and is the world's single largest producer of cobalt. KCC includes two open pit mines (KOV and Mashamba East) and one underground mine (Kamoto underground, KTO). Underground production at KTO began in 1969 using a range of mining methods including room and pillar (R&P), sub-level caving, cut and fill, and sub-level open stoping.

From 1990, KTO experienced a succession of mine-scale instability events whilst mining in the central area with room and pillar. Kongolo, 1998 suggested that the pillar run occurred over a period of approximately 10 months. No personnel were injured in the collapse event, as the mine had evacuated and implemented an exclusion zone. This was initiated following early warning signs of the failure occurring. Access to the affected areas (approximately 900 m x 900 m in plan) was lost and an extended period of mine closure followed. Underground production restarted in 2007 in other areas of the mine.

2 BACKGROUND

2.1 *Geology*

The general geology consists of a sedimentary succession ranging from siltstones, sandstones, dolomites, and argillite. Mining is conducted over two superimposed orebodies of variable dip (10 to 65 degrees) and moderate thickness (10 to 15 m). These are the "Orebody Inferior" (OBI) and "Orebody Superior" (OBS), respectively. The orebodies are separated a 15 to 25 m thick middling "Roches Siliceuses Cellulaires (RSC), illustrated in Figure 1.

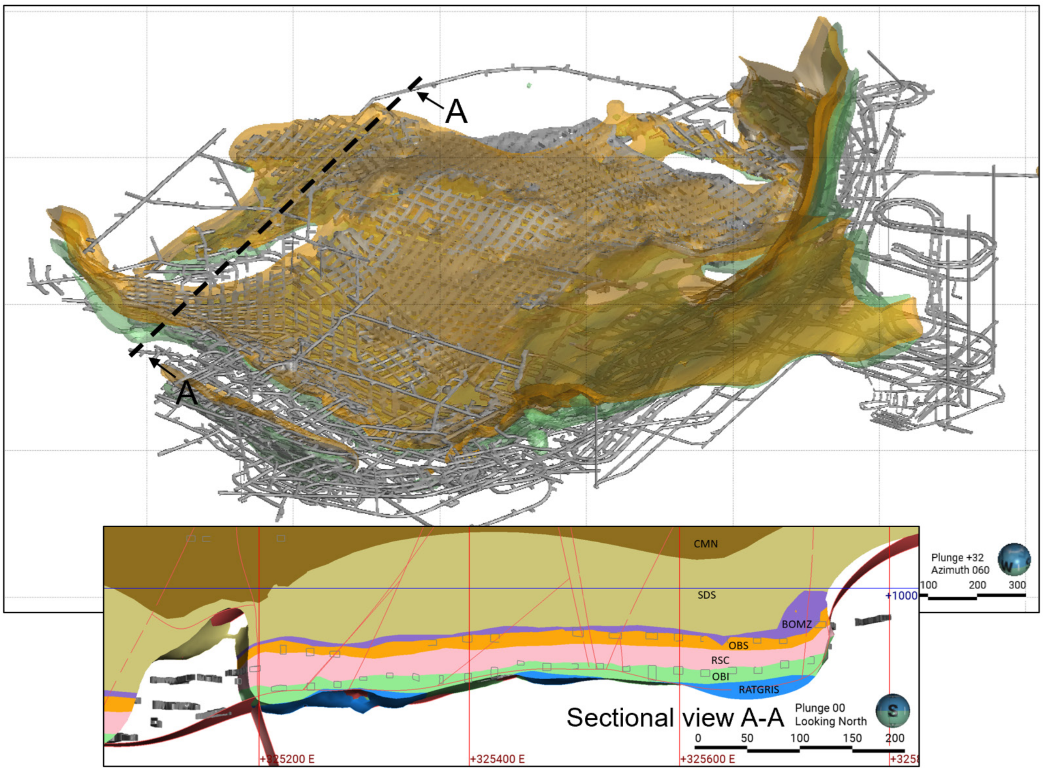

Figure 1. Isometric view north-east with the OBS (orange) and OBI (teal) orebodies, as-builts (grey) (top) and (bottom) cross section north with addition of major faults and fragment boundaries (red).

2.2 *Mining*

KTO is a fully mechanized underground mine (Figure 2), operating at a depth of 450 to 650 m, producing approximately 0.8 Mt of copper-cobalt sulphide ore per annum. The mining footprint dimensions are approximately 1500 m x 1400 m in plan with two orebodies superimposed.

The mining sequence for the R&P method at KTO is as follows:

- Parallel drives are mined at 6 m high and 7 m wide on a 25 m centre spacing, creating 18 m wide pillars; the hanging wall (HW) of the drive coincides with the HW of the orebody (OBS or OBI).
- The drive sidewalls are stripped to 12.5 m wide creating 12.5 m wide pillars (width to height (W:H) ratio of 2).
- The footwall (FW) is benched over the full width of the stope to a length of 75 to 100 m, to the contact of the orebody. This creates 12.5 m wide and 12.5 to 15 m high pillars (W:H ratio 0.85 to 1), which are then backfilled to the floor after extraction.

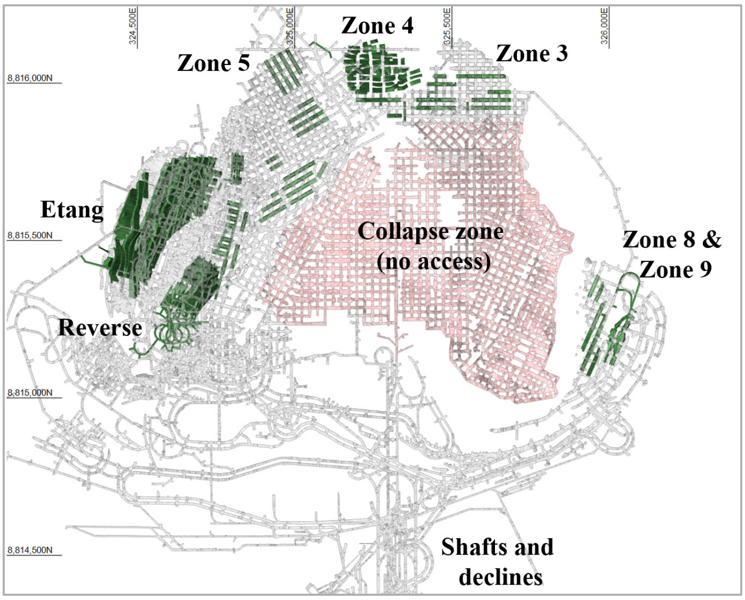

Figure 2. Plan view of the KTO mine with as-builts (grey), collapse zone (red) and future mining (green).

2.3 Geotechnical

2.3.1 Rock mass parameters

The OBI and OBS orebodies, including the RSC middling are characterized by generally low degrees of fracturing and high strength, described in Table 1.

Geotechnical features that have caused failures in the past include:

- The SDS2A unit in the OBS HW; a highly laminated, micaceous, and graphitic black shale. The unit has a dominant anisotropic fabric, which tends to initiate unravelling when exposed.
- Numerous faults that separate the fragments and cut across the orebody and bedding planes. Strain on the faults is associated with instability at a tunnel, stope and pillar scale and offsets lead to more complex geometries.
- Thinning of the RSC causing a narrow middling between the OBI and OBS orebodies. The closer proximity of the orebodies can contribute to higher interaction.
- Zones where the bedding is more broken, especially in the steeper dipping areas.

Table 1. KTO geotechnical domains with rock mass strength and classification data (KTO GCMP, 2022).

Geotechnical Domain	Location	Thickness (m)	UCS (MPa)	DRMS (MPa)	RMR89	GSI
SDS2B	Hanging wall	10 - 15	118	-	60	55
SDS2A	Hanging wall	3 - 5	153	-	53	48
BOMZ	Hanging wall	2 - 3	150	-	68	63
OBS	Upper orebody	10 - 15	138	44	68	63
RSC	Middling	15 - 25	150	56	77	72
OBI	Lower orebody	12 - 15	138	44	68	63
RATS	Footwall	+100	75	-	65	60

DRMS: Design rock mass strength (Laubscher, 1990)
RMR89: Rock mass rating (Bieniawski, 1989)
GSI: Geological Strength Index (Hoek, 1995)

2.3.2 *Stress field*

The stress state for KTO mine is described in Table 2. Mining occurs at shallow depths with low stress/strength ratios (0.2 to 0.3).

Table 2. Stress state for the KTO mine (KTO GCMP, 2022).

Stress Magnitude	**Trend**	**Plunge**
$\sigma\ 1 = 0.027d$	-	90°
$\sigma\ 2 = \sigma 1$	270°	0°
$\sigma\ 3 = 0.75\sigma 1$	180°	0°

3 MAINTAINING GLOBAL STABILITY

3.1 *Global stability strategy*

The KTO mining strategy describes the mining method, but also codifies the essential control measures relied upon to ensure mine stability is maintained. The main opportunities for improvements to the overall strata management and the observe-measure-analysis-design cycle are to clearly articulate the global stability strategy and to add process steps to ensure the global stability of new mine plans is confirmed in each planning cycle, and then tested in the field.

Generally, the new mining areas are divided into zones with similar characteristics, usually delineated by natural breaks in the orebody or changes in orebody topology. Carefully designed pillars are maintained between the zones, which are further sub-divided into blocks also separated by pillars. The block spans defined by inter zone and inter block pillars are designed to limit deformation within work areas, at the mining fronts and between work areas, to control HW to FW convergence (incremental and cumulative) and critically, in the event of a major failure in a part of the mine to prevent propagation of failure between blocks.

Access pillars have been designed and maintained between zones to ensure safe access. These major pillars also afford a degree of flexibility in inter block sequencing, though there are still inter block extraction sequencing constraints. A system of sub-stope scale rib and chain pillars are left within stoping blocks or rooms to maintain local instability.

3.2 *Operating rules*

The fundamental operating rules for achieving global stability include:

- Sufficient backfilling is essential to limit the propagation of collapses. It also influences the performance of some small pillars by providing confinement; however, fill is not a replacement for a pillar.
- For future stopes, the presumption should be that stopes will be filled, and where a stope will not be filled the effects should be sufficiently considered.
- OBS and OBI pillars should align to contribute to global stability.
- A pillar design is not sufficient unless the pillar capacity vs. demand has been assessed as sufficient for the service life of that pillar and maintains a sufficient safety factor.
- The roles and function of each pillar in the system needs to be defined and documented.

3.3 *Numerical Modelling assessment*

Beck Engineering Pty Ltd constructed a 3D mine scale, life of mine model incorporating all mine scale structures and known excavations. The numerical modelling used is LR4, which is a strain softening, dilatant, explicit Finite Element model.

3.3.1 Back analysis

Back analysis was able to replicate the lateral extent of the historic failure and indicates that the likely cause was over extraction during scavenging of remnants, with the effect being a succession of pillar failure between and on the OBS and OBI orebodies.

Strain and failures were likely shaped by major geological structures and that the degree of damage inside the collapse zone is highly variable. In some places pillar failures of 'pillar punching' would be the predominant failure mode, while in other areas stability problems would be concentrated along major rock mass defects.

3.3.2 Forward analysis

The rock mass damage scale (Beck Engineering, 2022) was used to evaluate the stability and performance of the pillar system. The damage scale is illustrated in Figure 3 and Figure 4 with the numerical model results, confirming that the pillar cores in the barrier, stabilization and access pillars are sufficiently stable and serviceable to the end of the mine plan. The entire system was further tested by increasing the load by an additional 100% (an increase of 2 times) without multiple adjacent pillar failures, indicating a 'global' Factor of Safety (FoS) of at least 2. Considering that this is a non-linear model, with explicit faults and all excavations and loss of pillar strength due to over stressing, this is a good result with a high level of confidence.

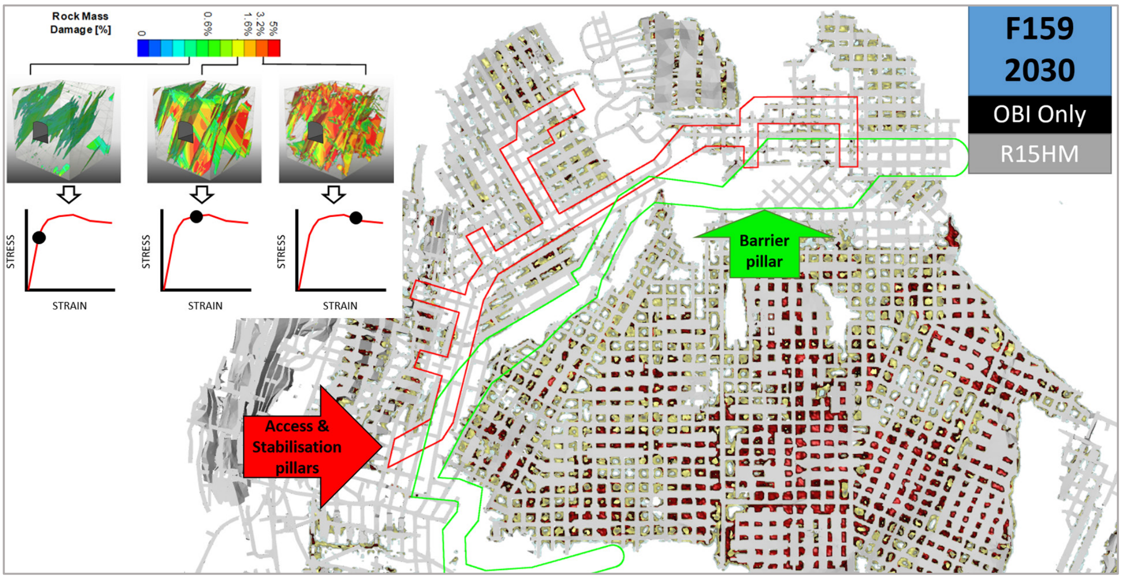

Figure 3. Model results in plan depicting rock mass damage at end of mining (2030) on OBI with the access and stabilization pillars (red outline), collapse zone barrier pillar (green outline) and rock mass damage scale (top-left).

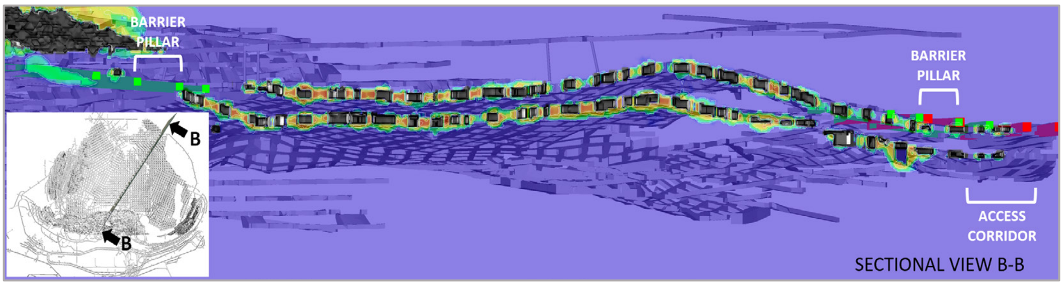

Figure 4. Model results depicting rock mass damage at end of mining (2030), cross section north-west.

3.4 Design verification

The following tools are regularly used as part of the pillar design verification process:

- Seismic monitoring to confirm mine stability
    - To remotely identify emerging potential instability
    - To confirm equilibrium is being maintained in failed areas
- Damage mapping
    - Targeting mainly the excavations along the stabilization and access pillars
- Critical excavation monitoring
    - Targeting a specific local hazard areas with extensometers such as large span intersections near the active mining front
- Pillar reconciliation:
    - Monitoring of the forecast vs. actual performance of the pillars

Deformation monitoring (Lidar) is planned to be undertaken in the critical pillars and accesses to identify emerging strain induced hazards.

4 CONCLUSION

The KTO mine has successfully constrained the historic failure from the current work areas, by carefully engineering a system of large, intermediate, and small-scale pillars. The extraction sequence works with the pillars to maximize the predictability of deformation and stress in work areas, and to retain operational flexibility to shape exposure and risk.

Sufficient 3D global non-linear modelling is used to support the mine plan, and the mine compares measured response to expected response to ensure stability is maintained. Potential adverse outcomes are appreciated, and measurements and observation to disconfirm their emergence are made.

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