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Geomechanical behaviour of underground excavations under squeezing conditions: damage mapping and multi-instrumental monitoring

Bruna de Almeida Pires Souza [a,*], Michel Melo Oliveira [b]

[a] *Cuiabá mine, AngloGold Ashanti, Brazil*

[b] *CPGEM, Universidade Federal de Minas Gerais, Brazil*

Abstract

Cuiabá mine, owned by AngloGold Ashanti and located in the Quadrilátero Ferrífero (Brazil), operates at depths of approximately 1,600 m, where increasing stress conditions impose significant geomechanical challenges. In this context, the Balancão (BAL) orebody has gained production importance while exhibiting pronounced squeezing behaviour, characterised by progressive and time-dependent deformation of the rock mass surrounding excavations.

This study focuses on the main ramp of the BAL orebody, aiming to understand the geomechanical response of the rock mass and the performance of support systems as a function of mining-induced stress changes. The approach integrates multi-instrumental monitoring and field observations, including (i) systematic mapping of support damage, (ii) convergence measurements, (iii) multiple point borehole extensometers (MPBX), (iv) LiDAR scanning, and (v) geological and geomechanical characterisation. Deformation patterns were analysed in relation to the evolution of nearby stoping activities.

Results indicate a spatially heterogeneous and time-dependent deformation response along the ramp. Convergence data reveal recurrent deformation phases, often delayed relative to mining activities, with alternating periods of acceleration and stabilisation. Support damage mapping demonstrates progressive degradation correlated with deformation intensity and proximity to active stopes. The observations highlight a transition from rigid to more ductile support strategies to accommodate ongoing squeezing conditions.

The integration of monitoring data and field mapping provides a robust framework for interpreting deformation mechanisms and support response under deep mining conditions. The findings contribute to improving geotechnical understanding of support performance in squeezing environments and support more effective design and operational decision-making in similar underground settings.

Keywords: *squeezing, underground geomechanics, geotechnical monitoring, numerical modelling, Cuiabá mine*

1 Introduction

The Cuiabá underground gold mine, operated by AngloGold Ashanti and located in the Quadrilátero Ferrífero, Brazil, is currently developed at depths approaching 1,600 m, where high stress conditions impose significant challenges to excavation stability and long-term ground support performance. Among the mine orebodies, the Balancão (BAL) narrow vein system has gained increasing production relevance in recent years, despite being associated with complex geomechanical conditions.

Geologically, the deposit is hosted within the Rio das Velhas Supergroup, comprising metavolcanic, metavolcaniclastic, and metasedimentary sequences metamorphosed under greenschist facies conditions. The lithostratigraphy is characterised by metabasalts, banded iron formations (BIF), and carbonaceous

* Corresponding author.

schists, with gold mineralisation primarily associated with sulphide-bearing BIF and quartz vein systems. Widespread hydrothermal alteration introduces significant spatial variability in rock mass properties, particularly in non-mineralised host rocks where most underground infrastructure excavations are developed. Structurally, the mine is characterised by multiple deformation phases, which resulted in a complex framework of folds, shear zones, and discontinuities. The dominant structures include foliations (S1 and S2) and a later crenulation cleavage (S3), which exert strong control on rock mass anisotropy and deformation mechanisms. These structural features play a critical role in governing deformation patterns under high stress conditions.

At such depths, excavation-induced stress redistribution combined with ongoing mining activities leads to progressive damage in both the rock mass and installed support systems. In particular, the occurrence of squeezing, characterised by large time-dependent deformations resulting from the gradual adjustment of the overstressed rock mass following excavation, represents a critical challenge for maintaining excavation stability. Under these conditions, support systems must not only ensure immediate post-blast stability but also accommodate sustained deformation throughout the excavation life cycle. Field observations in the BAL ramp indicate that deformation is strongly influenced by the interaction between stoping activities, geological structures, and stress redistribution. The observed displacements are driven by mining-induced stress changes associated with stoping activities and modulated by the presence of geological structures. This interaction often results in spatially heterogeneous and temporally delayed deformation responses, complicating both prediction and support design. In addition, mining-induced seismicity may contribute to further damage, particularly in regions of high stress concentration and stiffness contrast.

Despite the availability of extensive monitoring data and documented support degradation, current approaches often treat deformation, mining sequence, and support performance as partially decoupled processes. As a result, a consistent and integrated understanding of how mining-induced stress changes control the spatial and temporal evolution of deformation, and how these affect support system behaviour remains challenging to establish and apply across different deep mining environments.

This study contributes to the understanding of these processes by investigating the geomechanical behaviour of the main ramp of the BAL orebody through the integration of multi-instrumental monitoring and systematic support damage mapping. The objective is to elucidate the mechanisms governing deformation under squeezing conditions and to assess the influence of mining activities on the evolution and performance of ground support systems in deep underground excavations.

1.1 Local geological context

According to Vial (1980) and Fernandes et al. (2016), the stratigraphic sequence is composed of metabasalts interlayered with schists at the base, overlain by chemical sedimentary rocks, including BIF and ferruginous chert. Carbonaceous schists and metabasalts occur above these units, while the upper sequence is represented by schists and metavolcaniclastic rocks.

Gold mineralisation at the Cuiabá mine is primarily associated with shear zones (Vitorino 2017) and occurs as massive, banded, or disseminated sulphides within BIF, as well as in quartz veins and veinlets. Gold is mainly linked to pyrite, occurring as inclusions or along fractures, and may also be associated with pyrrhotite. The host rocks are strongly affected by hydrothermal alteration, resulting in chloritized, carbonatized, and sericitized zones (Barbosa 2011), which exhibit gradual contacts and significant heterogeneity. Although mineralised zones are well studied, most underground excavations are developed in non-mineralised host rocks. In narrow vein orebodies, ramps and infrastructure are predominantly excavated in metapelites and metapsammites, which are weaker than the mineralised rocks. The lithostratigraphic column for the normal limb is presented in Figure 1, while the sequence is reversed in the inverted limb.

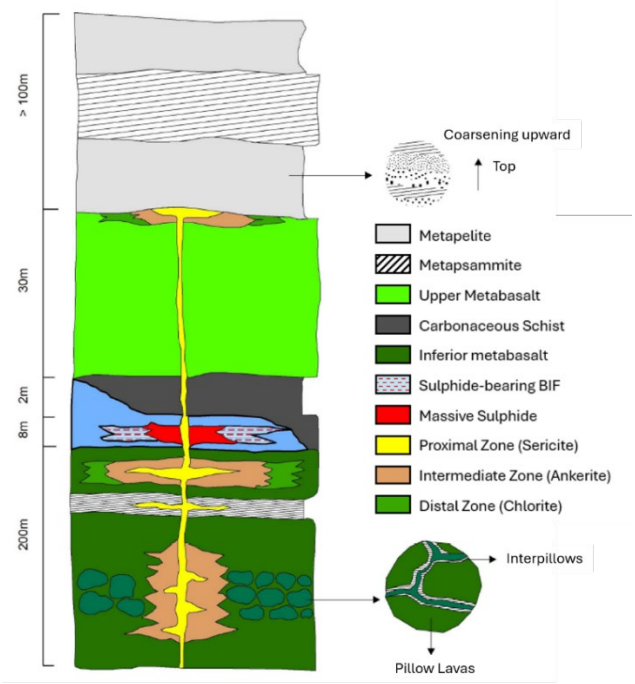


Figure 1 Lithostratigraphic column of the Cuiabá deposit, including associated hydrothermal alteration zones (modified from Fernandes et al. 2016)

The mine is structurally dominated by a large tubular anticline plunging to the southeast, with an inverted northern limb and a normal southern limb. The structural framework developed through 3 main deformation phases (D1–D3) (Vial 1980; Toledo 1997; Xavier et al. 2000). D1 is characterised by bedding-parallel shear zones associated with mylonitic foliation and stretching lineation, while D2 represents a coaxial phase marked by the development of thrust faults and continued deformation. D3 corresponds to a later compressional phase, generating folds with North–South orientation and crenulation cleavage. The orientation of the main discontinuity sets is summarised in Table 1.

Table 1 Orientation of the main discontinuity sets identified in the rock mass at Cuiabá mine (AngloGold Ashanti 2024)

Structural discontinuities	Dip (°)	Dip direction (°)
S1	35	152
S2	33	146
S3	45	93

1.2 Geomechanical properties of the metapelite

Uniaxial compressive strength (UCS), elastic modulus (E), and Poisson's ratio for the metapelite were determined from laboratory tests performed on drill core samples. For this study, average values derived from 10 samples were adopted, together with minimum, maximum, and statistical dispersion indicators (Table 2). The statistical analysis reveals a heterogeneous geomechanical behaviour. UCS values range from 25 to 93MPa, with a coefficient of variation (CV) of 40%, indicating moderate to high variability. The elastic modulus shows a more consistent response (CV of 12%), whereas Poisson's ratio presents high dispersion (CV of 52%), reflecting greater uncertainty in lateral deformation. These results highlight the inherent heterogeneity of the analysed material.

Table 2 Summary statistics of uniaxial compressive strength (UCS), elastic modulus (E), and Poisson's ratio for the metapelite

Parameter	Average	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
UCS (MPa)	65	26	93	26	40
E (GPa)	85	74	99	11	12
Poisson's ratio	0.16	–	–	0.08	52

1.3 In situ stress field

The in situ stress field of the mine is based on the stress model developed for Cuiabá mine by ITASCA S.A. (2018). The model was calibrated using stress measurement campaigns and numerical back-analyses conducted at the mine. Based on this calibration, the vertical stress (σv) corresponds to the intermediate principal stress, while the maximum principal stress (σH) is defined as a function of the vertical stress. The minimum principal stress (σh) corresponds to approximately 30% of the vertical stress. The magnitudes and orientations of the principal stresses are presented in Table 3.

Table 3 Stress state at the mine based on ITASCA S.A. (2018) in situ tests and modelling

Magnitude	Dip (°)	Azimuth
σv = ρ g h	90	0
σH = 0.5 σv + 15	0	316
σh = 0.3 σv	0.0	226

σv = vertical stress; σH = maximum horizontal stress; σh = minimum horizontal stress; ρ = density; g = acceleration due to gravity; h = depth

1.4 Balancão orebody

The BAL orebody is described as a continuous homoclinal structure located on the inverted limb of a large tubular fold, with greater extent along the down-plunge direction than along strike. The orebody dip is subparallel to the regional foliation, trending northeast-southwest with dips ranging from 25 to 35°. Toward the northeastern extremity, the progressive closure of the fold results in steepening of the orebody, with dips increasing to 65–90°. At greater depths, significant variations in dip are expected, with a tendency toward lower inclinations.

Mineralisation in the BAL orebody is primarily hosted within BIF and is strongly controlled by hydrothermal fluid flow and structural features associated with D1 and D2 deformation phases. Gold occurs mainly as disseminated sulphides within metasedimentary rocks, generally subparallel to bedding. The D3 phase, developed under a ductile–brittle regime, generated a crenulation cleavage (S3), which is widely observed in the BAL region.

The lithological model distinguishes key domains, including BIF, metandesite, metabasalts, metasediments, and carbonaceous schists, as well as their alteration zones. Approximately 78% of primary development in BAL is hosted in metasediments, while secondary excavations (ore drives) are distributed among carbonaceous schists, BIF, and altered domains.

1.5 Squeezing and damage evolution in the Balancão ramp

The BAL ramp has exhibited a progressive and time-dependent deterioration of the support system, consistent with squeezing conditions. Historical damage records indicate that degradation of the original

support system is spatially heterogeneous and closely associated with the evolution of nearby mining activities. As shown in Figure 2, the BAL ramp is in close proximity to several stoping areas, with distances ranging from approximately 30 to 45 m, suggesting a strong influence of mining-induced stress changes on the observed deformation behaviour.

Initially, damage was primarily characterised by cracking and local detachment of shotcrete, accompanied by minor convergence. As mining advanced and stress redistribution intensified, the severity and extent of damage increased, with the development of wider cracks, shotcrete debonding, and exposure of reinforcement elements. The observed deformation was initiated by mining-induced stress changes but continued to develop over time, suggesting a coupled mining-induced and time-dependent deformation process. In several sections, damage evolved from localised deterioration to extensive zones requiring partial or complete rehabilitation of the support system. Temporal analysis of the damage evolution shows that deformation and support degradation do not occur instantaneously after excavation, but rather present a delayed response linked to stoping activities. This behaviour suggests a strong interaction between excavation sequence, stress redistribution, and the progressive mobilisation of deformation mechanisms in the rock mass.

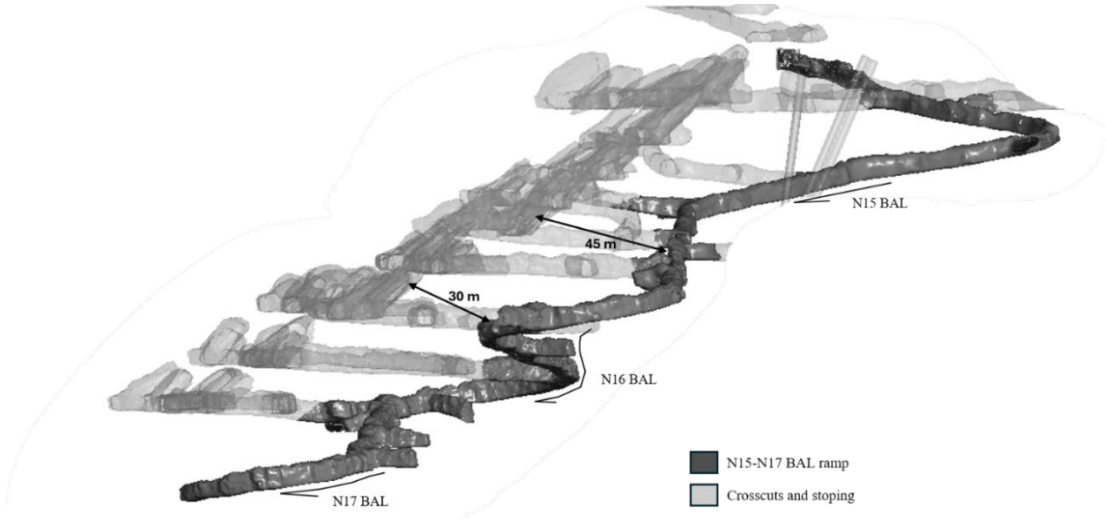


Figure 2 Spatial relationship between the Balancão (BAL) ramp (N15-N17) and adjacent stopes, showing the approximate distances between the excavation and mining fronts

More recent observations indicate a transition in support response, with rigid systems proving insufficient to accommodate ongoing deformation. As a result, more ductile support strategies have been progressively implemented to improve system performance under sustained squeezing conditions. Overall, the damage history along the BAL ramp highlights the cumulative and progressive nature of deformation-driven deterioration, emphasising the need for continuous monitoring and adaptive support design in deep mining environments.

2 Methodology

This study is based on an applied case study conducted at the main ramp of the BAL orebody at Cuiabá mine, focusing on the geomechanical response of the rock mass and support systems under squeezing conditions. The methodological approach integrates field observations, geotechnical monitoring data, and support damage mapping, allowing for a comprehensive interpretation of deformation mechanisms in relation to mining activities.

2.1 Study area and scope

The analysis was carried out along the main ramp of the BAL orebody, between Levels 15 and 17, where a significant history of deformation and support damage has been recorded. The study period spans from

February 2022 to April 2026, covering multiple mining stages and enabling the evaluation of the temporal evolution of deformation in response to excavation and stoping activities.

2.2 Geomechanical characterisation

Geomechanical parameters for the rock mass were obtained from laboratory tests performed on drill core samples, including UCS, E, and Poisson's ratio. These data were used to characterise the mechanical behaviour of the dominant lithologies, particularly metapelite, which host a large portion of the excavations. Statistical descriptors, including minimum, maximum, mean values, and CV were considered to account for variability in rock mass properties.

2.3 Support damage mapping

Damage mapping was systematically conducted along the BAL ramp (Levels 15–17) between February 2022 and April 2026 to assess the evolution of support system degradation under squeezing conditions. The methodology was adapted from Costa et al. (2019) and Souza et al. (2024) and consisted of periodic field inspections, photographic documentation, and georeferenced damage records. The assessment was based on a scoring system that quantified the condition of the support system using 3 parameters: (i) percentage of damaged shotcrete area, (ii) crack thickness in shotcrete, and (iii) bolt exposure or mesh loading, depending on the support type installed. Individual scores were assigned to each parameter and summed to obtain a global damage index ranging from 0 to 100.

Based on the final score, support conditions were classified into 5 categories: no damage (80–100), low damage (60–80), moderate damage (40–60), high damage (20–40), and extremely high damage (0–20). The methodology was adapted over time to accommodate changes in support standards, particularly the transition from shotcrete-dominated systems to more ductile support solutions incorporating mesh.

The original damage mapping methodology developed by Costa et al. (2019) was based on the evaluation of damaged shotcrete area, crack thickness, and bolt exposure. Scores assigned to each parameter were combined to generate a support damage index, as summarised in Table 4.

Table 4 Parameters and corresponding scores used in the first version of the damage mapping methodology (adapted from Costa et al. 2019)

Damage area (%)	Score	Shotcrete crack thickness (cm)	Score	Bolt exposure (cm)	Score
0	40	0	40	No exposure	20
0–20	30	<0.5	30		
20–40	20	0.5 < e < 1	20	<30 cm	10
40–60	15	1 < e < 2	15		
60–80	10	2 < e < 4	10	>30 cm	0
80–100	5	>4	5		

As squeezing conditions became more severe and mesh support was progressively incorporated into the ground support standard, the original damage mapping methodology was updated by Souza et al. (2024). In the revised version, bolt exposure was replaced by mesh loading, allowing a better assessment of support performance under large deformations. The damage index continued to be calculated from the combined scores assigned to the damaged shotcrete area, shotcrete crack thickness, and mesh loading, providing a quantitative measure of support deterioration (Table 5).

Table 5 Parameters and corresponding scores used in the revised damage mapping methodology, including shotcrete and mesh loading (adapted from Souza et al. 2024)

Damage area (%)	Score	Shotcrete crack thickness (cm)	Score	Mesh loading (cm)	Score
0	40	0	40	<100	20
0–20	30	<0.5	30		
20–40	20	0.5 < e < 1	20	100 < c < 200	10
40–60	15	1 < e < 2	15		
60–80	10	2 < e < 4	10	>200	0
80–100	5	>4	5		

For sections supported exclusively by mesh, a simplified version of the damage mapping methodology was adopted. In this approach, support conditions were evaluated using 2 parameters: the percentage of damaged area and the degree of mesh loading. Because shotcrete was not present in these locations, the weighting of mesh performance was increased to ensure that the damage index accurately reflected the level of support deterioration under squeezing conditions. The scoring criteria used for these areas are presented in Table 6.

Table 6 Parameters and corresponding scores used in the damage mapping methodology for areas where mesh was the only surface support element

Damage area (%)	Score	Mesh loading (cm)	Score
0	40	<100	60
0–20	30		
20–40	20	100 < c < 200	30
40–60	15		
60– 80	10	>200	0
80–100	5		

As shown in Table 7, the final support condition was classified according to the total damage score, ranging from no damage to extremely high damage. This classification was applied consistently throughout the study to compare damage severity between different monitoring periods and ramp sectors.

Table 7 Classification of support system damage severity according to the final score obtained (adapted from Costa et al. 2019)

Final score	Damage classification
80–100	No damage
60–80	Low damage
40–60	Moderate damage
20–40	High damage
0–20	Extremely high damage

2.4 Multi-instrumental monitoring

Convergence monitoring was conducted through the installation of 14 monitoring stations along the BAL ramp between Levels 15 and 17. Each station consisted of reference pins fixed to the excavation surface, enabling periodic measurements between opposite points of the excavation. The collected data were used to quantify excavation closure, calculate displacement rates, and identify sectors exhibiting higher deformation activity over time.

To investigate deformation within the rock mass, a 15 m long multiple point borehole extensometer (MPBX) equipped with 6 anchors was installed in a critical sector of the ramp. The anchor configuration allowed displacement measurements at different depths, making it possible to identify the location and extent of the active deformation zone and distinguish shallow excavation-related movements from deeper rock mass responses.

Three-dimensional deformation monitoring was performed using periodic LiDAR surveys covering approximately 560 m of the ramp. Point clouds acquired during successive campaigns were compared to generate deformation maps and representative cross-sections, providing continuous spatial coverage of the excavation and enabling the identification of localised convergence and expansion zones that could not be captured by conventional point-monitoring techniques.

The datasets obtained from convergence monitoring, MPBX measurements, and LiDAR surveys were integrated with damage mapping and mining activity records to evaluate the spatial and temporal evolution of deformation and its relationship with nearby mining operations. Figure 3 illustrates the position of each monitoring element.

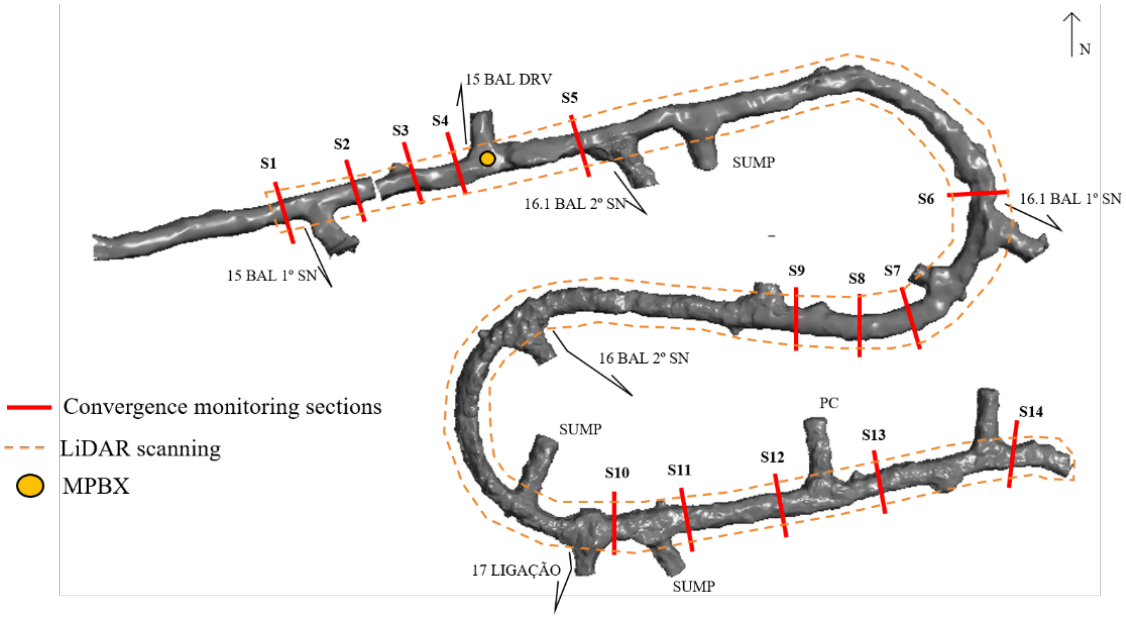


Figure 3 Layout of the Balancão (BAL) ramp showing the location of the monitoring instruments used in this study, including convergence monitoring sections (S1–S14), the multiple point borehole extensometer (MPBX) installation, and the LiDAR scanning coverage

3 Result and discussion

3.1 Evolution of support damage

Damage mapping revealed a progressive deterioration of the support system along the BAL ramp during the monitoring period. Figure 4 compares the initial survey conducted in February 2022 with the final survey performed in April 2026. At the beginning of the monitoring program, damage was concentrated in isolated

sectors of Level 15 and was predominantly classified as low to moderate. By 2026, damaged areas had become more extensive, affecting a greater portion of the ramp and exhibiting higher damage classifications.

The observed damage mechanisms included shotcrete cracking, mesh loading, localised support failure, and repeated rehabilitation requirements. As the support system was progressively exposed to ongoing deformation, several sectors required rehabilitation and the adoption of more deformable support configurations to maintain excavation stability.

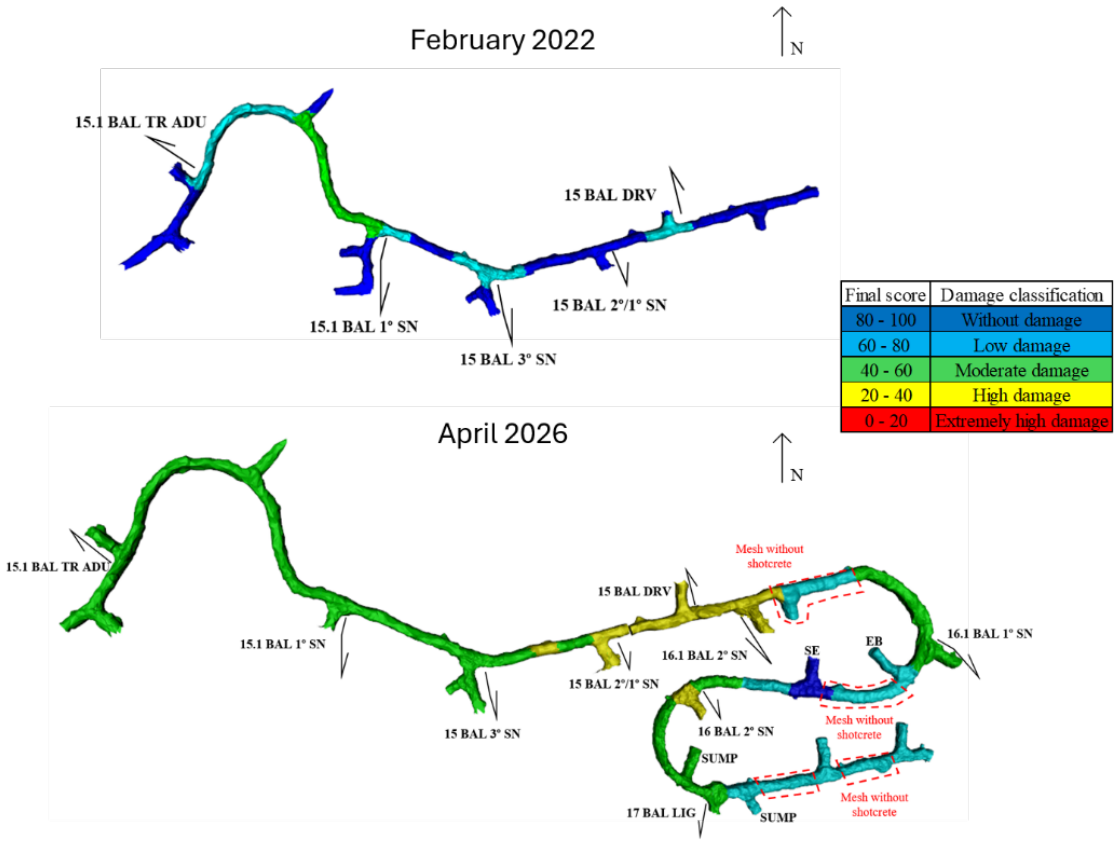


Figure 4 Comparison of support damage mapping results obtained in February 2022 and April 2026 along the Balancão (BAL) ramp

3.2 Convergence monitoring

Convergence monitoring revealed a heterogeneous distribution of deformation along the BAL ramp. Both the accumulated displacement and displacement rate varied significantly between monitoring stations, indicating that deformation was concentrated in specific sectors rather than being uniformly distributed throughout the excavation. The results obtained for each monitoring section are presented in Figure 5. Maximum accumulated displacements exceeded 100 mm in the most critical locations, while other sections exhibited substantially lower deformation levels. Similarly, displacement rates showed considerable variability along the ramp, reflecting differences in the intensity and timing of ground response.

Several monitoring stations exhibited periods of accelerated displacement followed by phases of relative stabilisation, demonstrating that deformation evolved progressively throughout the monitoring period rather than occurring as a single event. The persistence of measurable displacement over time indicates ongoing rock mass adjustment around the excavation. The spatial variability observed in the convergence measurements highlights the non-uniform nature of the deformation process and emphasises the importance of continuous monitoring to identify critical sectors and assess the performance of the support system.

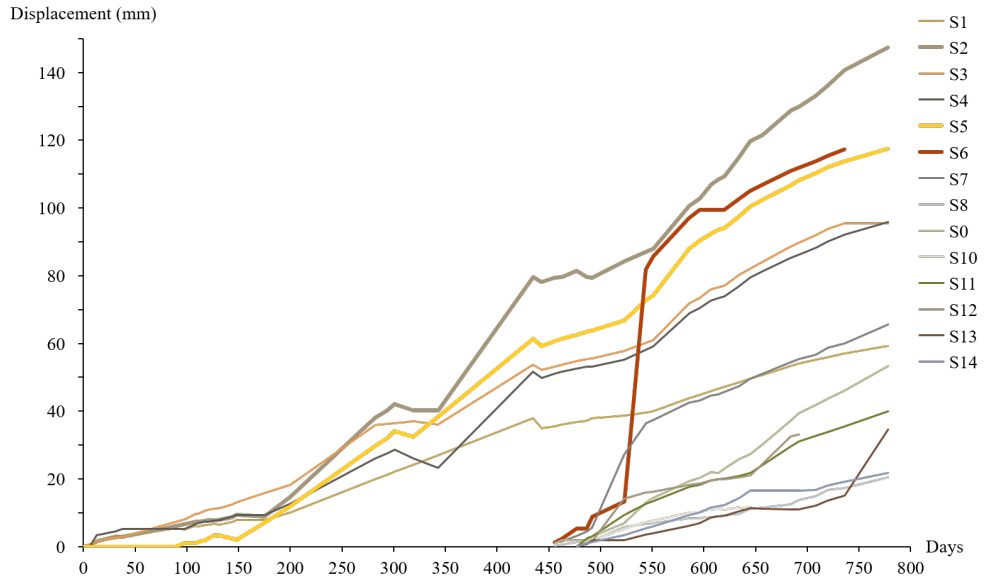


Figure 5 Accumulated displacement and displacement rate measured at the convergence stations installed along the Balancão ramp

3.3 Multiple point borehole extensometer response

A MPBX installed in a critical sector of the BAL ramp was used to assess the distribution of deformation within the rock mass. The recorded displacements were predominantly concentrated near the excavation boundary, with movement decreasing significantly with increasing depth. As shown in Figure 6, the highest deformation was measured at the collar region of the instrument, while the deeper anchors exhibited comparatively small displacements throughout the monitoring period. The maximum recorded displacement reached approximately 25 mm at the shallowest measurement point, whereas movements at greater depths remained limited.

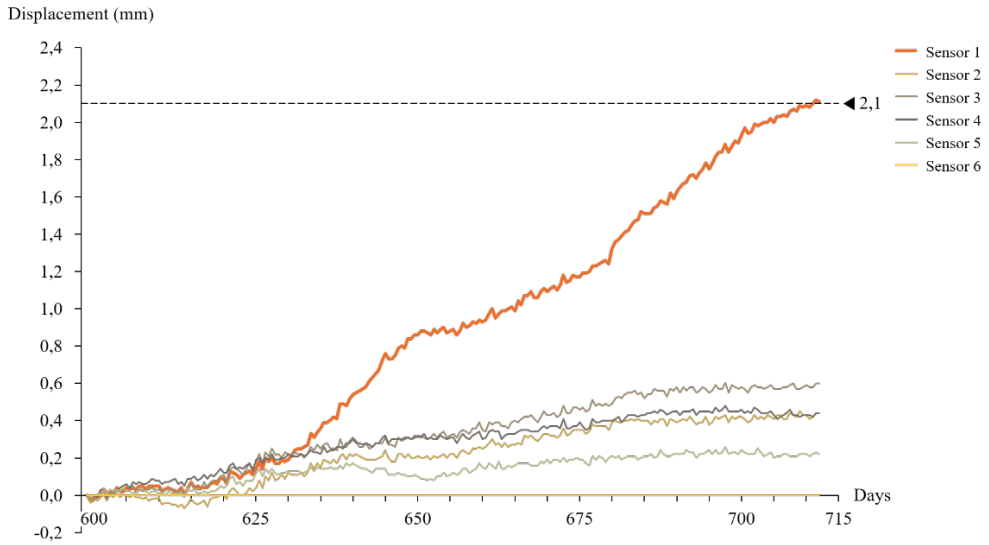


Figure 6 Multiple point borehole extensometer displacement measurements showing the evolution of rock mass deformation with depth along the Balancão ramp

The displacement profile suggests that most of the deformation was restricted to the near-field rock mass surrounding the excavation, with limited propagation into the rock mass at depth. This behaviour indicates the development of a relatively shallow active deformation zone associated with excavation-induced stress redistribution and squeezing-related ground response.

3.4 LiDAR monitoring

LiDAR surveys provided a continuous spatial assessment of deformation along the BAL ramp. Comparison of successive point clouds revealed that deformation was not uniformly distributed throughout the excavation, with convergence concentrated in discrete sectors of the monitored area. The deformation maps generated from the LiDAR surveys identified localised zones of elevated convergence, while other sections remained comparatively stable during the monitoring period. As shown in Figures 7 and 8, the magnitude and distribution of deformation varied considerably along the ramp, highlighting the heterogeneous nature of the rock mass response.

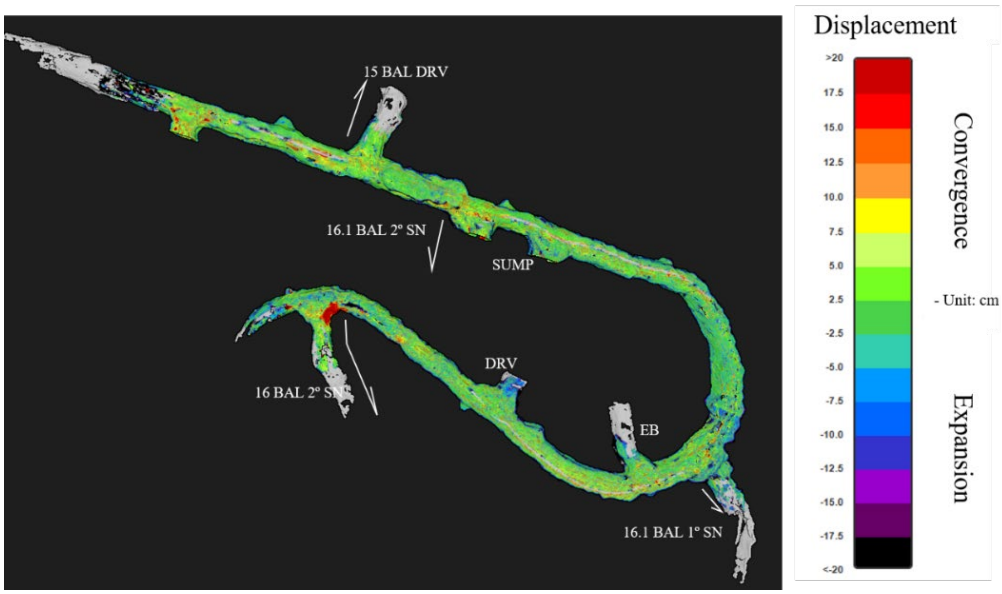


Figure 7 LiDAR-derived deformation map of the upper section of the Balancão (BAL) ramp. Colours indicate the magnitude and direction of displacement between successive surveys, with warm colours representing convergence and cool colours representing expansion

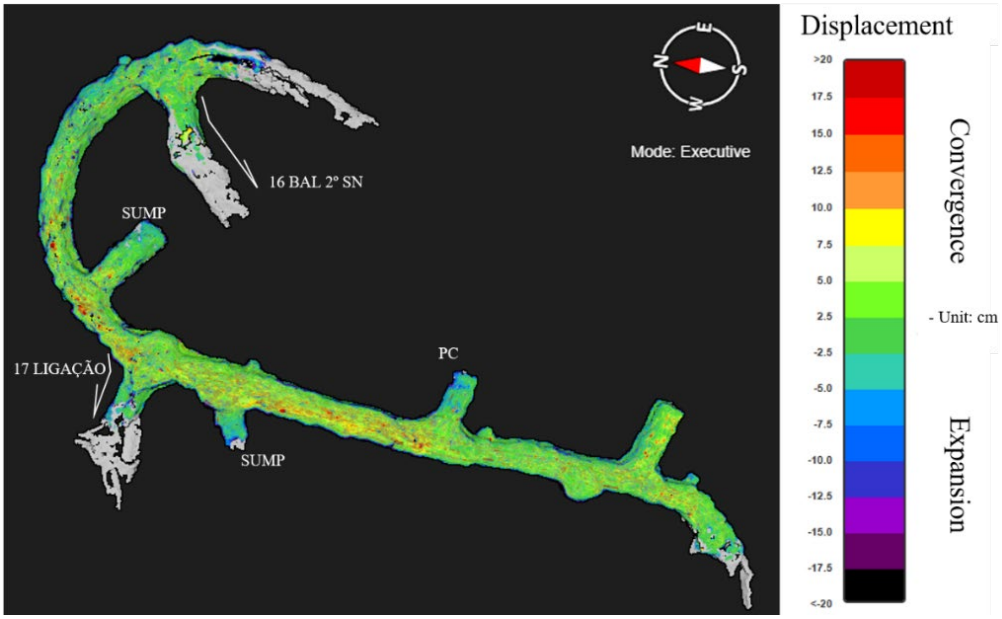


Figure 8 LiDAR-derived deformation map of the lower section of the BAL ramp. Localised zones of convergence and expansion are highlighted through comparison of successive point clouds, illustrating the spatial variability of deformation along the excavation

Representative cross-sections extracted from critical locations confirmed that deformation was concentrated in specific areas and was often associated with visible support deterioration. The 3D visualisation provided by LiDAR allowed a more comprehensive assessment of excavation performance than conventional point-monitoring techniques, facilitating the identification of deformation hotspots and critical sectors requiring increased geotechnical attention.

3.5 Integrated assessment of deformation behaviour

The integration of damage mapping, convergence monitoring, MPBX measurements, and LiDAR surveys demonstrated that deformation along the BAL ramp is governed by a combination of squeezing mechanisms and mining-induced stress redistribution. All monitoring techniques consistently identified the same critical sectors, strengthening confidence in the interpretation of the deformation processes.

Furthermore, the results suggest that the rock mass exhibits a time-dependent response to nearby mining activities, characterised by alternating periods of acceleration and stabilisation. The progressive deterioration of the support system and the persistence of deformation even after rehabilitation interventions indicate that squeezing remains the dominant mechanism controlling excavation performance in the study area.

4 Conclusion

The integrated monitoring program implemented along the BAL ramp provided valuable insights into the deformation processes affecting the excavation under squeezing conditions. Damage mapping identified a progressive deterioration of the support system over the monitoring period, characterised by shotcrete cracking, mesh loading, recurrent rehabilitation requirements, and the progressive adoption of more deformable support systems.

Convergence measurements, MPBX monitoring, and LiDAR surveys consistently indicated that deformation was spatially heterogeneous and seems to be strongly influenced by the mining sequence. The results demonstrated that nearby stoping activities directly influenced both the onset and the magnitude of squeezing, with sectors located closer to active mining areas experiencing higher deformation levels and increased support damage.

The combined dataset also revealed that the rock mass response was time-dependent, with alternating periods of accelerated deformation and relative stabilisation. In several cases, deformation continued after mining activities had progressed, suggesting a delayed geomechanical response associated with stress redistribution around the excavation. MPBX measurements indicated that deformation was primarily concentrated near the excavation boundary, while LiDAR surveys successfully identified localised deformation zones and complemented conventional monitoring techniques by providing continuous spatial coverage of the ramp. The most severe deformation was observed in sectors where mining-induced stress changes interacted with structurally controlled and relatively weaker rock mass domains, promoting progressive damage accumulation and support deterioration over time.

Overall, the results demonstrate that squeezing development in the BAL ramp is closely associated with mining-induced stress changes. The observed relationship between deformation, support degradation, and mining proximity highlights the need for further evaluation of the current stand-off distances adopted between stoping activities and permanent excavations. These observations indicate that the magnitude and evolution of deformation are strongly influenced by the interaction between mining-induced stress redistribution and local geomechanical conditions. Such analyses may contribute to establishing more appropriate geotechnical criteria for mine planning, minimising deformation impacts, optimising support requirements, and improving the long-term stability of critical infrastructure.

As a next step, the monitoring database developed in this study should be used to correlate a 3D numerical model capable of reproducing the observed deformation patterns. Once calibrated, the model could be applied to assess the influence of future mining sequences, evaluate alternative stand-off distances between stopes and the ramp, and support geotechnical decision-making for long-term excavation stability.

References

AngloGold Ashanti 2024, *Cuiabá Mine Geotechnical Database and Structural Mapping Records*, AngloGold Ashanti, Sabará.

Barbosa, FP 2011, *Geologia e alteração hidrotermal do depósito Cuiabá (Geology and hydrothermal alteration of the Cuiabá deposit)*, Universidade Federal de Minas Gerais, Belo Horizonte.

Costa, F, Silva, R & Oliveira, M 2019, *Development of a damage mapping methodology for underground excavations under squeezing conditions*, internal technical report, AngloGold Ashanti, Sabará.

Fernandes, G, Lobato, LM, Pereira, LM & Carvalho, P 2016, 'Geological controls on gold mineralization at Cuiabá Mine, Quadrilátero Ferrífero, Brazil', *Brazilian Journal of Geology*, vol. 46, no. 3, pp. 345–362.

ITASCA S.A. 2018, *3D Numerical Modeling for Cuiabá Mine*, Santiago de Chile.

Souza, BA, Padula, R & Lima, TCA 2024, *Revision of support damage mapping methodology for squeezing environments at Cuiabá Mine*, internal technical report, AngloGold Ashanti, Sabará.

Toledo, CLB 1997, *Evolução estrutural do depósito Cuiabá, Quadrilátero Ferrífero, Minas Gerais (Structural evolution of the Cuiabá deposit, Quadrilátero Ferrífero, Minas Gerais)*, Master's thesis, Universidade Federal de Ouro Preto, Ouro Preto.

Vial, DS 1980, *Geologia estrutural do depósito Cuiabá (Structural geology of the Cuiabá deposit)* internal report, Mineração Morro Velho, Nova Lima.

Vitorino, GC 2017, *Structural controls on gold mineralisation at the Cuiabá deposit,* Master's thesis, Universidade Federal de Minas Gerais, Belo Horizonte.

Xavier, RP, Lobato, LM, Vieira, FW & Alves, JV 2000, 'Structural evolution and gold mineralisation in the Rio das Velhas Greenstone Belt, Quadrilátero Ferrífero, Brazil', *Ore Geology Reviews*, vol. 18, no. 1–2, pp. 95–114.