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Discontinuity persistence as a key variable in caving: a three-dimensional numerical evaluation for a sublevel caving method

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Abstract

Discontinuity persistence influences and, in some cases, controls the strength and anisotropic behaviour of rock masses. In the context of caving methods, it affects deformation mechanisms, the direction of the caving propagation, and the geometry of the subsidence, while also participating in the release of energy, establishing a direct link with induced seismicity.

Current geotechnical sampling techniques limit the quantification of discontinuity persistence, particularly in complex geological environments accessed primarily through a limited number of drillholes. This introduces inherent biases of structural recognition at depth, resulting in a truncated representation of persistence at the caving scale and directly affecting the conclusions of caveability analyses used for design. This paper presents a numerical comparative study in which discontinuity persistence is identified as a key variable in sublevel caving, starting with an evaluation of the extraction footprint based on Laubscher's theoretical criteria, whose results revealed limitations in capturing the role of persistence in caving propagation.

The analysis presents a comparative numerical modelling approach, incorporating continuum (finite difference method [FDM]), discontinuum (distinct element method [DEM]), and hybrid models (finite–discrete element method [FDEM]), with the objective of assessing the limitations inherent to each approach and advancing towards a more consistent representation of the process (including discrete fracture network). Numerical results obtained from the discontinuum and hybrid approaches (DEM and FDEM) showed that discontinuity persistence, even under conditions of uncertainty, significantly controls caving propagation. This observation can only be made by explicitly capturing the connectivity and failure mechanisms associated with discontinuity features that are not adequately represented by simplified theoretical or purely continuum-based approaches.

The results presented in this paper confirm the need to consider discontinuity persistence not only as a theoretical concept, but as a practical input in the design of caving operations, particularly in scenarios where available structural information is limited and/or incomplete.

Keywords: *sublevel caving, three-dimensional modelling, discontinuity persistence, discrete fracture network*

1 Introduction

In the context of caving mining methods, the presence of geological structures such as faults, significantly impacts cave propagation, subsidence development, and energy release. These structures may act as preferential pathways or internal boundaries controlling the evolution of the cave (Brown 2003; Flores & Karzulovic 2003), although their spatial representation is typically constrained by limited and partial information during early project stages.

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Several studies developed by Karzulovic at El Teniente mine (Karzulovic 1999; Karzulovic et al. 1999; Flores & Karzulovic 2003) suggested the following:

1. The caving propagation is fundamentally due to the displacement of the rock mass blocks toward the undercutting levels; whether through falls, slides, overturns, and/or other modes of failure.
2. In accordance with this mechanism, caving will occur more easily as the number of key blocks (see Goodman & Shi 1985; Karzulovic 1998) in the rock mass increases. Since the only acting force in the caving process is the weight of the rock itself, the specific number of key blocks will depend solely on the orientation of the free face defining the sector of the cavity under consideration.
3. In accordance with point 2, the ease with which caving propagates cannot be uniform but rather changes as the cavity grows, potentially decreasing or increasing, not necessarily in a monotonic manner.
4. The cavity created by the caving process may be confined by larger structures, provided they are ‘properly’ oriented.
5. Depending on these main faults, the geometry of the block arrangement making up the rock mass, and the height of the mineralised block relative to the open basal area, the caving process could continue until it reaches the surface (or the crater floor), or it could stop upon reaching a state of equilibrium where no more critical blocks are produced (Figure 1).

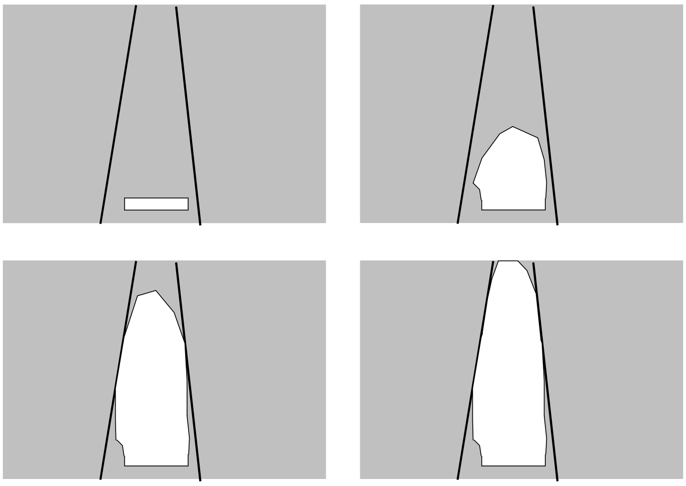


Figure 1 Sketch showing caving propagation in cases where the major faults are unable to completely contain the caving, resulting in a connection to the surface (modified from Karzulovic et al. 1999)

6. On the other hand, if the height of the rock column and the position of the main structures are such that they completely limit the progress of caving, then caving will stop once the cavity reaches a stable geometry and will not result in a connection to the surface, as illustrated in Figure 2.
7. The presence of discontinuities that define blocks induces anisotropic behaviour, which can become very pronounced and is usually defined by the direction of the weakest discontinuities in terms of strength, and by the direction normal to the softest discontinuities in terms of compressibility.
8. As the number of structural sets increases, the induced anisotropy tends to decrease, and the material’s behaviour becomes more isotropic. In fact, anisotropy is usually large when there is a single, clearly dominant discontinuity set.
9. Mechanical behaviour depends not only on the number of blocks but also on their geometry.
10. Depending on the boundary conditions, the geometric configuration, and the strengths of the intact rock and the discontinuities sets, the kinematics of the rupture may or may not be

influenced by the orientation of the discontinuities and may involve the intact rock and/or the discontinuities and/or a group of blocks.

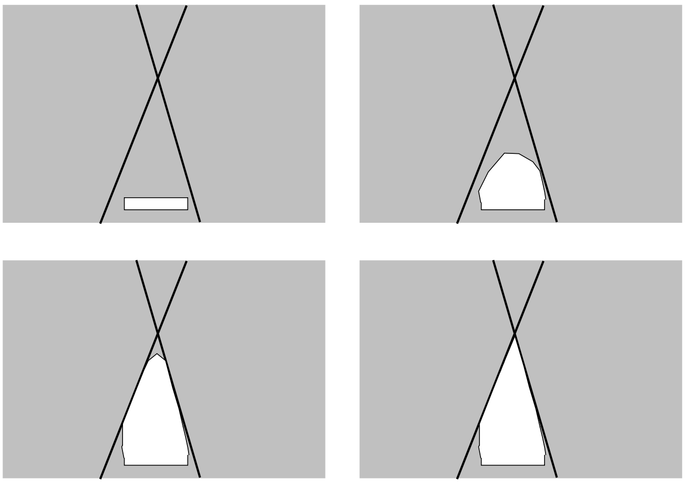


Figure 2 Sketch showing the caving propagation in the case where the major faults can completely limit the progression of caving, and it stops when the cavity reaches a stable geometry (modified from Karzulovic et al. 1999)

Although the identification of discontinuities depends on geological interpretation, their extent within the rock mass introduces a critical dependence of stability on structural detail. Available information – typically limited and incomplete – conditions how these structures are represented.

Under these conditions, discontinuity persistence emerges as the key geometric variable controlling structural connectivity and the kinematic freedom of rock blocks (Alejano 2024; Li & Bahrani 2024). Its influence extends beyond cave back propagation, modifying both mechanical anisotropy and cave geometry. However, persistence is difficult to quantify and is subject to bias due to incomplete drillhole and mapping data (Shang et al. 2018). As a result, geometrically plausible structural models may not be mechanically equivalent (Erharter & Elmo 2025), introducing uncertainty in geomechanical predictions.

Three-dimensional numerical modelling has become a primary tool to represent rock mass behaviour under caving conditions (Álvarez et al. 2020; Hormazabal et al. 2010, 2018). However, continuum approaches tend to average localised damage, underestimating structurally controlled propagation paths (Cumming-Potvin et al. 2018). In contrast, empirical methods, such as that of Laubscher (2001), do not explicitly account for structural connectivity or rock bridge failure. To address these limitations, it is necessary to incorporate stochastic representations of discontinuities, allowing structural connectivity and anisotropy to emerge explicitly (Severin et al. 2010; Maldonado et al. 2024; Álvarez et al. 2020).

Within this framework, this study evaluates whether uncertainty in structural persistence induces qualitative changes in the failure mechanisms governing caving behaviour. Using continuum, discontinuum, and hybrid approaches with discrete fracture networks (DFN), the analysis assesses whether persistence constitutes a critical variable controlling stability, cave geometry, and caving performance, and consequently defines the level of structural detail required in geomechanical models.

2 Design context and methodological limits

The analysis considers a representative sector of a mine operating under a sublevel caving (SLC) method, located at depths of 300 m and characterised by limited direct in situ stress measurements. From a geomechanical perspective, the sector includes primary rock units, secondary transition units, and an upper weathered domain. The primary units are mainly located below and around the footprint, particularly near its boundaries, where their higher competence may contribute to local confinement and arching effects. The secondary transition units are comparatively less competent and more relevant within the caving sector, providing more favourable conditions for cave initiation and propagation. For a detailed definition of these geotechnical zones, please refer to Russo & Ramirez (2023). The upper weathered domain was represented as a weak soil-like material and is mainly relevant to the response of the upper column rather than to the undercutting domain. Strength and deformability properties are summarised in Table 1. The values are expressed as mean values with a variability range.

For the primary and secondary transition units, strength parameters are reported based on the Hoek–Brown-derived estimate of equivalent rock mass compressive strength, useful for comparing their relative resistance. The upper weathered domain was represented using a simplified Mohr–Coulomb material.

Table 1 Summary of the geotechnical properties used in the numerical models

Domain/units	γ (g/cm³)	E_i (GPa)	ν	σ_{ci} (MPa)	m_i	GSI	σ_{cm} (MPa)	c (kPa)	ϕ (°)
Primary rock	2.9 ± 0.2	82 ± 17	0.20	155 ± 35	15 ± 5	70 ± 5	55 ± 19	–	–
Secondary transition	2.7 ± 0.2	46 ± 11	0.24	65 ± 30	9 ± 5	51 ± 6	16 ± 8	–	–
Upper weathered domain	1.8 ± 0.1	3 ± 1	0.25	–	–	–	–	75 ± 25	30 ± 2

Note: ϒ is the unit weight of the intact rock; σ_{ci} is the unconfined compression strength of intact rock; m_i is the Hoek–Brown parameter; GSI is the Geological Strength Index; *E* the rock mass Young's modulus; *v* is Poisson's ratio; σ_{cm} is the compression strength of the rock mass, *c* is the equivalent rock mass cohesion; ϕ is the equivalent rock mass internal friction angle.

The geometry of the upper level is defined by a maximum area of ~100,000 m^2, corresponding to a wide footprint adopted for numerical modelling. The numerical analyses were performed considering a staged undercut development sequence divided into 10 stages, representing approximately 40 months of progressive footprint development. Each stage corresponds to approximately 4 months of advance, during which the hydraulic radius increases from about 20 m at the initial stage to about 80 m at the final analysed condition. Figure 3 shows the depth of the upper level of SLC evaluated.

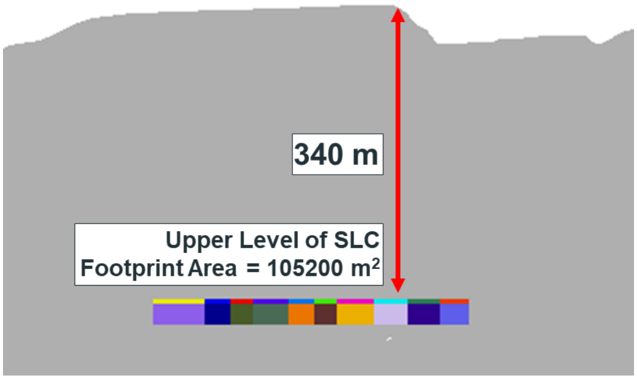
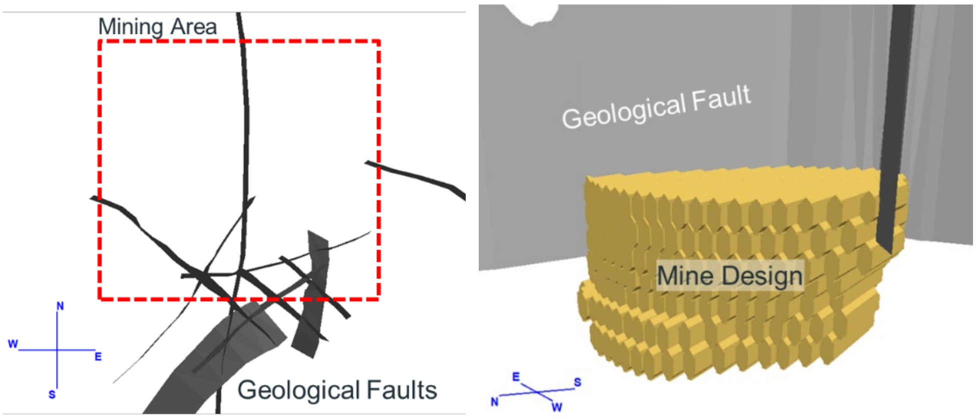


Figure 3 Depth of the upper level of sublevel caving (SLC) design

These stages are used to evaluate cave propagation, surface connection, and subsidence response under different discontinuity persistence scenarios. Although the design includes lower extraction levels, their influence on caveability is limited in the analysed condition.

The in-situ stress state is anisotropic, with horizontal-to-vertical stress ratios of 1.85 in the north–south direction and 1.5 in the east–west direction. Within the first 100 m of depth, the rock mass is highly weathered (saprolite), where an isotropic stress condition can be assumed ($K = \sigma_H/\sigma_V = 1.0$). These stress ratios were calibrated based on site measurements. The structural characterisation is based on surface mapping, drillhole logging, and preliminary project-scale structural models. Although major geological faults have been identified, their geometric representation within the volume of interest remains limited.

The structural information available from drillholes provides discrete intersections and local evidence of structural occurrence, but it does not allow a unique correlation of individual fault traces between boreholes or across the full caving-scale volume. Consequently, it is not possible to determine unequivocally whether separated intersections correspond to isolated discontinuities or to laterally persistent faults belonging to the same structural system; this condition reflects an inherent limitation of the pre-feasibility study stage. Figure 4 presents the available structural model.



(a) (b)

Figure 4 Three-dimensional structural model of the area, showing the interpretation of major faults within the mining sector. (a) Plan view, (b) Perspective view

Under these conditions, the available information constrains the presence and orientation of the main structural systems, but does not uniquely define their three-dimensional persistence, connectivity, or cross-cutting relationships at the caving scale. Therefore, alternative structural continuity scenarios may be mechanically plausible as sensitivity analyses to assess the impact of persistence on caving behaviour. For this purpose, this paper presents, through 3D numerical modelling, how the persistence of fault-related discontinuities may influence cave propagation, propagation height, and footprint development.

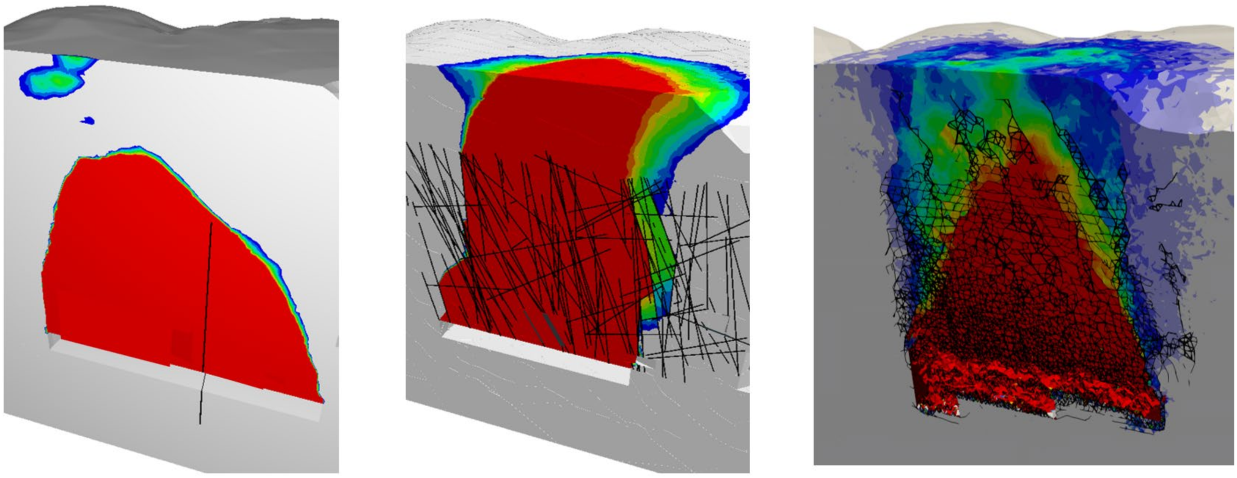
3 Numerical strategy and modelling approach

The numerical strategy adopted is based on a comparative approach between continuum (finite difference method [FDM]), discontinuum (distinct element method [DEM]), and hybrid (finite–discrete element method [FDEM]) models. This scheme was defined to evaluate how the rock mass response evolves as the level of structural representation increases, particularly regarding the role of persistence and fault connectivity in caving propagation. Figure 5 presents the general modelling workflow adopted in the study, illustrating the progressive sequence of analyses from a simplified continuum model to structurally explicit representations.

Figure 5 General workflow of numerical modelling used for caveability assessment

The continuum model represents an equivalent geomechanical response of the rock mass, usually idealised as isotropic. Its characterisation is derived from the estimation of rock mass quality based on the available information at the sampling scale, mainly from drillholes. In this representation, the spatial association, persistence, and connectivity of major faults are not explicitly included, as these structures may only be recorded as discrete intersections within drillholes, with limited influence on the equivalent estimation of rock mass quality.

Therefore, the discontinuum and hybrid models were used to address this limitation by explicitly incorporating structures under different persistence scenarios, without modifying the equivalent geomechanical quality assigned to the rock mass. Consequently, the explicit discontinuities should be interpreted as additional structural persistence scenarios, rather than as a duplicate representation of the discontinuities already implicit in the rock mass characterisation. The numerical results were also compared with the empirical caveability criterion proposed by Laubscher (2001). Three complementary numerical approaches were considered: the finite difference method with FLAC3D (Itasca 2022a), the distinct-element method with 3DEC (Itasca 2022b), and a hybrid FDEM scheme (Geomechanica Inc. 2024). Figure 6 compares the 3 numerical approaches used in this study.



(a) (b) (c)

Figure 6 Schematic comparison of the (a) continuous, (b) discontinuous, and (c) hybrid models used in the study

The purpose of this comparison was to evaluate how different mechanical formulations represent cave propagation, failure mechanisms, and structural connectivity. An aspect of particular interest is the capability of the hybrid FDEM model to combine explicit discontinuity representation with fracture initiation and propagation. Numerically, the Irazu hybrid approach uses six-noded cohesive elements (CE6), inserted along all element faces to approximate the existence and load-carrying capacity of the fracture process zone. These elements may yield and break in tension, sliding, or mixed mode, and can explicitly represent discontinuities (Figure 7).

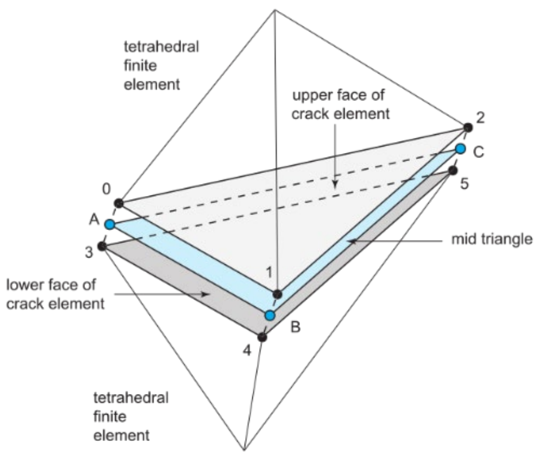


Figure 7 Scheme of six-noded cohesive elements with crack element

For the hybrid models, the DFN was not used to constrain the mesh (i.e. explicitly meshed), as doing so led to poor mesh quality due to the numerous acutely intersecting fractures. Instead, the DFN was incorporated as an approximate structural fabric mapped onto the numerical mesh. Therefore, where multiple DFN sets were locally present, the mapping was not interpreted as a one-to-one assignment of each fracture set to individual mesh nodes, but rather as an approximate representation of the pre-existing discontinuity network at the model scale.

4 Discrete fracture network construction and discontinuity persistence

The DFN was constructed from the available structural characterisation of the sector, considering the dominant orientations and relative occurrence of the main fault-related sets identified from geological interpretation. According to the available geological data, fault-related structures suitable for DFN representation were interpreted with representative spacing between 15 and 30 m. In the final DFN implementation, 217 fault-related entities were included within the competent rock mass domain associated with the caving propagation zone. Its representation is shown in Figure 8.

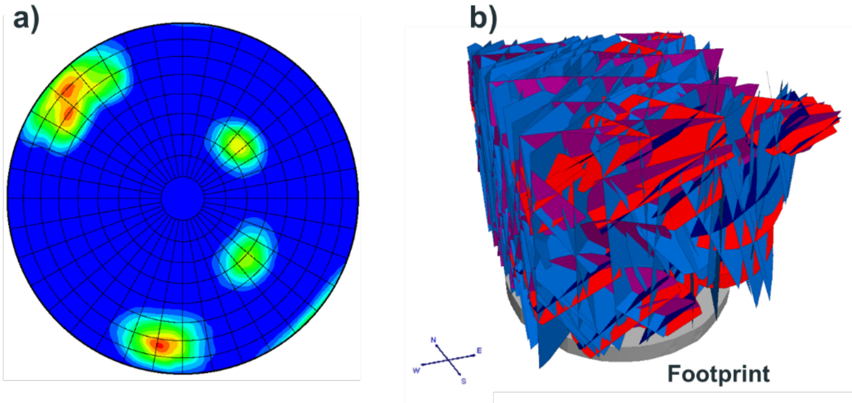


Figure 8 Discrete fracture network (DFN) used for the analysis based on available structural information. (a) Stereonet with principal sets; (b) Three-dimensional representation of the DFN

The DFN was not developed as a unique back-calculated reconstruction of all discontinuities intersected by boreholes, but as a controlled structural representation aimed at evaluating the mechanical influence of unresolved fault persistence and connectivity. For the intensity and spatial distribution, the P_{32} value was determined. P_{32} is defined as a fracture abundance measure (Mauldon & Dershowitz 2000) which relates the fracture surface area per unit volume of rock (m^2/m^3).

Stereological relationships, such as those proposed by Wang (2005), show that linear fracture intensity cannot be directly interpreted as volumetric fracture intensity without an orientation-dependent correction. In general form, the relationship between linear fracture intensity and volumetric fracture intensity may be expressed as:

$$P_{32,i} = C_{13,i} P_{10,i} \tag{1}$$

where:

P10,i = linear fracture intensity of set ‘i’

P32,i = volumetric fracture intensity of set ‘i’, defined as fracture area per unit rock mass volume

C13,i = orientation-dependent conversion factor between linear and volumetric fracture intensity.

However, this conversion provides an orientation-corrected equivalent intensity and does not uniquely define discontinuity persistence, size distribution, or DFN connectivity. This is particularly relevant in the present study, where the main uncertainty is not only the frequency of fault-related structures, but their effective persistence and three-dimensional connectivity.

In this study, the effective DFN intensity was instead evaluated directly from the explicit DFN geometry. The volumetric density of DFN entities was calculated as:

$$P_{30} = \frac{N_f}{V_m} \tag{2}$$

where:

P_{30} = volumetric density of DFN entities

N_f = number of DFN entities

V_m = volume of the model domain where the DFN was applied.

The DFN was applied within a modelling box of approximately 120 × 110 × 300 m: where the $P_{30} \approx 5.48 \times 10^{-5}\ \mathrm{m}^{-3}$. The volumetric fracture intensity of each persistence scenario was then calculated from the explicit area of the DFN entities:

$$P_{32} = \frac{\sum_{i=1}^{N_f} A_i}{V_m} \tag{3}$$

or, for equivalent DFN entities with a common representative disc area:

$$P_{32} = P_{30} A \tag{4}$$

where A is the area of one equivalent circular disc, calculated as:

$$A = \pi \left(\frac{D}{2}\right)^2 \tag{5}$$

For the 130 m equivalent-diameter scenario:

$$A_{130} = \pi(65)^2 \approx 13,273\ \mathrm{m}^2$$
$$P_{32,130} = 5.48 \times 10^{-5} \times 13,273 \approx 0.73\ \mathrm{m}^{-1} \tag{6}$$

For the 270 m equivalent-diameter scenario:

$$A_{270} = \pi(135)^2 \approx 57,256\ \mathrm{m}^2$$
$$P_{32,270} = 5.48 \times 10^{-5} \times 57,256 \approx 3.14\ \mathrm{m}^{-1} \tag{7}$$

Because fracture area scales with the square of the equivalent radius, increasing the radius from 65 to 135 m increases the effective structural area, and therefore the associated effective P_{32}, by approximately:

$$\frac{P_{32,270}}{P_{32,130}} \approx \left(\frac{135}{65}\right)^2 \approx 4.3 \tag{8}$$

Accordingly, the 270 m case should be interpreted as a limiting high-persistence condition at the footprint scale. Similarly, the resulting P_{32} values should be interpreted as effective values associated with DFN sensitivity scenarios used to evaluate potential structural connectivity.

A common mechanical parameterisation was assigned to all DFN sets, with cohesion of 25 kPa and a friction angle of 25°, to observe the effect of structural persistence without introducing additional variations in discontinuity strength. The DFN was applied within the rock mass domain associated with the caving propagation zone and was not extended through the upper weathered domain. The latter was represented as a weak soil-like material using a simplified Mohr–Coulomb formulation. This approach is consistent with the methodology proposed by Montiel et al. (2022), where persistence is controlled through explicit geometric modification of DFN entities. In the present study, this logic is applied to evaluate the influence of major fault persistence on caving propagation, allowing the transition from equivalent rock mass representations towards explicit representations of structural connectivity.

5 Results of evaluation using different numerical approaches

Based on the previously described methodology, the evaluation included the following numerical models:

- Continuum model (FLAC3D): this model does not incorporate DFN.
- Discontinuum model (3DEC): this model includes two DFN scenarios persistence at 50 and 100%.
- Hybrid model (Irazu): this model includes all three scenarios.

For all models, the propagation height of the unstable zone (caving) and vertical displacement in the subsidence zone were evaluated (Table 2).

Table 2 Results summary for cave condition at final stage of the numerical models

Numerical method	Persistence	Months until connection	Cave height (m)	Subsidence (m)
Continuous and discontinuous models	0%	–	81	0.02
	50%	–	157	0.08
	100%	24	338	2.30
Hybrid models	0%	–	105	0.04
	50%	–	287	0.15
	100%	24	338	1.80

Figure 9 shows results for the continuum and discontinuum models, while Figure 10 shows the hybrid model results. These results are expressed in terms of total displacement and numerical velocity, allowing visualisation of unstable zones and their relationship with surface displacement relative to the footprint.

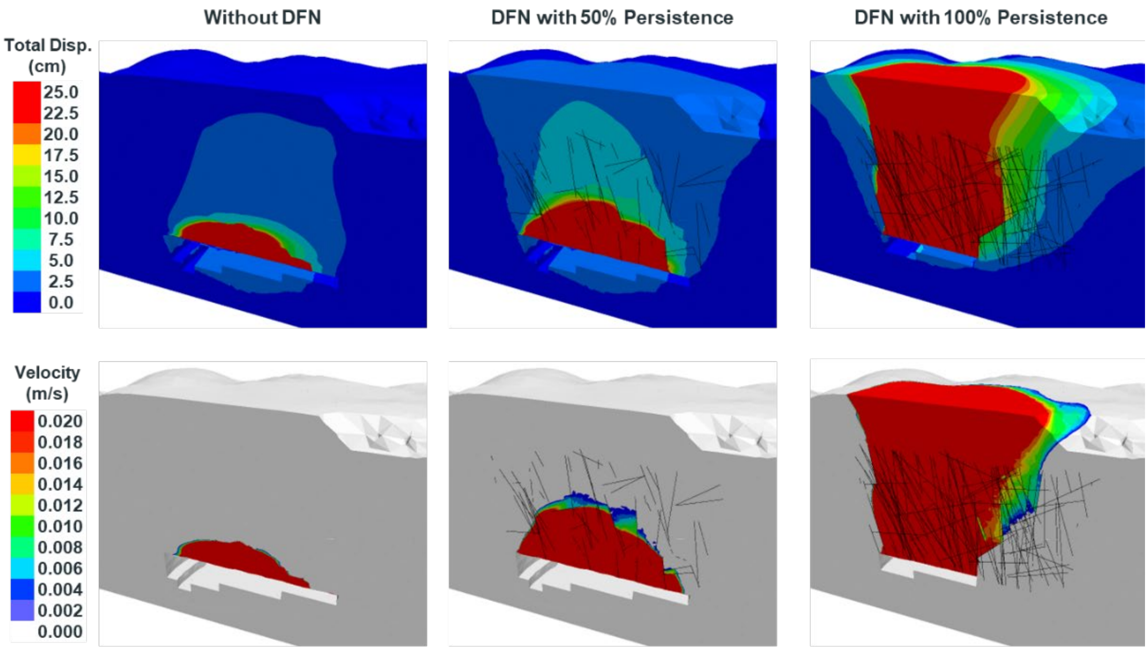


Figure 9 Continuous and discontinuous model results for discrete fracture network (DFN) persistence scenarios and their impact on cave propagation. Black lines represent the explicit discontinuities

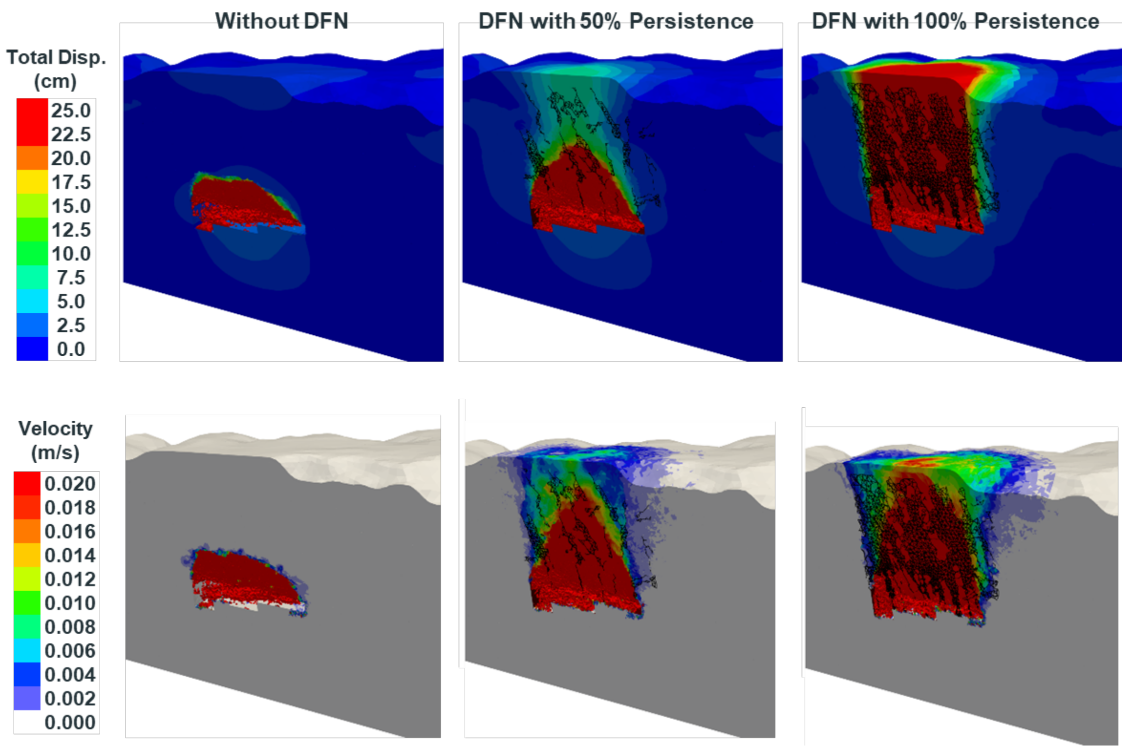


Figure 10 Hybrid model results for discrete fracture network (DFN) persistence scenarios and their impact on cave propagation. Black lines indicate the structural discontinuities represented in the hybrid model and their associated fracture development, whose apparent extension may differ from the initial DFN geometry because the FDEM formulation allows additional fracturing during the simulation

6 Discussion of results

Prior to the numerical analysis presented in the previous section, an initial caveability assessment was performed using Laubscher's empirical approach (2001), based on mean MRMR values derived from the available geomechanical characterisation.

According to this approach, the analysed footprint enters the caving range once the hydraulic radius reaches approximately 50 m, implying the need for significant footprint development to achieve favourable caveability conditions. However, this empirical criterion provides only an initial estimate of the conditions required for caving initiation and does not directly define cave propagation height, surface connection, or subsidence response.

The results presented in Table 2 indicate that the numerical models provide additional information that cannot be obtained from the empirical criterion alone. In scenarios with low structural density or without explicit structural persistence, caving propagation does not reach surface connection, even at the final stage of undercutting. This indicates that satisfying an empirical hydraulic radius condition does not necessarily imply the development of a continuous propagation path to surface.

This discrepancy highlights methodological differences that can be interpreted from both perspectives. From the empirical standpoint, the approach relies on a continuous representation of the rock mass and does not explicitly consider structural connectivity or fault geometry, limiting its ability to capture structure-controlled propagation mechanisms.

On the other hand, numerical models indicate that the rock mass possesses sufficient strength – given the footprint geometry and distribution of geotechnical units – to stabilise the cavity and prevent propagation to surface when structural persistence is absent or only partially developed. Based on numerical analysis, structural density plays a key role in caving propagation, as it reduces the overall strength of the rock mass and introduces block rotation mechanisms that extend the unstable zone in the models.

Within this context, the adopted numerical strategy allows differentiation between 2 levels of mechanical control:

- The continuum model evaluates the influence of equivalent overall rock mass strength, governed by intact rock parameters and geomechanical characterisation used for property scaling.
- The discontinuum and hybrid models explicitly capture structural connectivity and persistence, allowing the formation of continuous failure paths.

This distinction justifies the comparative modelling approach, emphasising each formulation's capability to represent physical mechanisms rather than merely reproducing overall response.

The results demonstrate that persistence does not act as a secondary geometric parameter, but as a variable that directly modifies mechanical connectivity within the rock mass. This is evident in Figures 9 and 10, where high-persistence conditions result in surface connection of the cave, unlike scenarios with medium persistence or without structural representation.

However, persistence should not be interpreted as a standalone determinant of immediate surface connection. Surface connection is obtained only in the highest persistence scenarios and only after sufficient area development, as indicated by the connection stage reported in Table 2. This suggests that persistence controls the potential for mechanical connectivity, but this potential must be mobilised together with the evolving undercut geometry, rock mass strength, and spatial arrangement of the structural system.

This interpretation is also relevant for the equivalent fracture intensity associated with the DFN scenarios.

Although increasing the equivalent discontinuity diameter substantially increases the effective structural area and, consequently, the equivalent P_{32} of the system, the results show that this increase does not translate linearly into cave height, subsidence, or surface connection. Therefore, P_{32} should be interpreted in this study as an indicator of potential structural connectivity, rather than as a direct predictor of caveability. Its mechanical effect depends on whether the structural network is favourably arranged and sufficiently mobilised by the progressive development of the footprint.

When hybrid models are incorporated, a greater propagation height is observed compared with continuum (+23%) and discrete (+45%) approaches, according to Table 2. These variations should be considered in the estimation of the mobilised material volume and the remaining thickness of the crown pillar. In addition, this difference can influence decision-making aimed at mitigating risks associated with nearby infrastructure, interpreting the microseismical response, and defining operational monitoring criteria.

7 Conclusion

This study evaluates the role of discontinuities persistence as a controlling variable in caving propagation through a comparative numerical analysis using continuum, discontinuum, and hybrid models. Discontinuities persistence is a critical variable controlling caving propagation, directly influencing mechanical connectivity within the rock mass.

Variations in persistence and cross-cutting relationship can induce qualitative changes in failure mechanisms, including the development of preferential propagation paths and the potential for surface connection. The results show that persistence influences surface connection but does not act as a standalone determinant of immediate cave propagation. The explicit incorporation of discontinuities, primarily through DFN, provides a more robust framework for evaluating caving under structural uncertainty.

Continuum-based modelling approaches relying solely on equivalent rock mass strength are insufficient to represent failure mechanisms controlled by structural connectivity. Equivalent fracture intensity, such as P_{32}, should be interpreted as an indicator of potential structural connectivity rather than as a direct predictor of caveability, since its mechanical effect depends on the spatial arrangement and mobilisation of the discontinuity network.

In early project stages, where structural information is limited, persistence should be treated as an explicit modelling variable rather than an implicitly defined parameter.

The adopted modelling strategy demonstrates that different numerical formulations capture different aspects of rock mass behaviour, and their combined use is necessary to identify controlling mechanisms. In this context, discontinuities persistence is not merely a secondary modelling parameter, but a fundamental aspect of rock mass characterisation, with direct implications for caving performance interpretation and the level of detail required in future engineering stages and operations.

Use of artificial intelligence disclosure statement

In preparing this work, the authors used GPT-5.5 Thinking to improve the language, clarity, and readability of the manuscript. The authors reviewed and edited the AI-assisted content where necessary and take full responsibility for the final version of the work.

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