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Assessing Caving Risk Related to Rockmass Bulking

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Abstract

Establishing how much or how little a rockmass bulks during caving is critical to assessing surface subsidence risk for civil tunnel and near-surface mining stope collapses, and to evaluating cave initiation and draw performance in block and panel cave mines. The volumetric expansion that occurs as a rockmass breaks up determines whether the cave back self-chokes or propagates progressively upward. Bulking depends on rockmass characteristics controlling block size and shape, as well as stress conditions, fall height of detached blocks and the fragmented rock debris maturity through comminution and compaction.

The excavation damage/yield zone geometry, fragmentation rates and stress redistribution further influence how the rock mass breaks and ultimately how the cave propagates. Insufficient understanding of these interacting processes has historically caused catastrophic tunnel and crown pillar collapses and major cave propagation difficulties in cave mining.

This paper reviews current modelling empirical method benchmarking methods for evaluating crown collapse risk and caveability, including Carter's Scaled-Span approach and Laubscher's MRMR hydraulic-radius framework. Particular emphasis is placed on the role of bulking in controlling void ratio, stress transfer and cave propagation. Guidelines for assessing bulking are presented, based on precedent case histories, laboratory data and numerical modelling insights.

Keywords

Risk, Caving, Crown Pillars, Bulking, Mining.

1 Introduction

One of the most risk-prone situations in both civil underground works and mining excavations is the potential for adverse surface impacts due to uncertain variabilityin competence of the overlying crown rockmass. Once a crown pillar rockmass fragments, collapse behaviour is commonly assessed using empirical rock mass classifications or span-based stability criteria. However, field evidence from crown pillar failures, filled stope back-break, cave hang-ups and cave subsidence demonstrates that neither span nor rock mass strength alone governs the system response. A critical, but often under-

emphasised, control is the volumetric response of the rock mass during its fragmentation, commonly expressed through bulking or swell factors.

For civil and mining tunnels, stope crown pillars, and cave backs, insufficient bulking of fragmented rock prevents self-choking and facilitates progressive upward migration of failure, potentially leading to breakthrough into overlying mine workings or the surface. In filled stopes, inaccurate swell estimation results in incomplete filling, stress concentration at the crown and progressive back-break. In cave mining the implications are broader and more complex, as bulking governs the void ratio within the broken column; and this void ratio governs stress transfer and arching; and stress transfer governs cave propagation rates, airgap development, cave hang-ups, and breakthrough timing.

Despite its significance, bulking is frequently treated as a constant parameter; often as a single swell factor defined at initiation and assumed constant throughout cave life. Such assumptions neglect the progressive evolution of the fragmented rock mass under increasing confinement, block rearrangement, crushing, fines generation and loading and unloading stress cycles. Bulking is stage-dependent and stress-dependent, varying spatially within the cave column and temporally as propagation conditions change. This paper presents a unified, risk-based framework linking bulking to void ratio, stress transfer and arching, applied to both crown pillar stability assessment and cave propagation.

2 Cave Mechanics and Caveability Assessment

Cave mechanics, and particularly the bulking behaviour of the fragmented rock mass, governs both the collapse processes around the cave back and the material flow behaviour in cave mines. Assessment of crown/cave back breakthrough risk requires an understanding of three primary factors:

1. Rock mass competence of the crown pillar/cave back.
2. Geometry of the crown pillar/cave back (span and void volume).
3. Fragmentation characteristics, and associated bulking behaviour.

For a given crown rock mass quality, caving likelihood is primarily span-controlled. In cave mining, this span is typically represented by the critical hydraulic radius (***HR$_{cr}$***) of the undercut (Laubscher, 1977, 1994, 2000; Fig. 1, right diagram x-axis). Where crowns must remain stable, thickness must also be considered, and the relevant parameter becomes the scaled crown span **(*Cs*)**, accounting for full three-dimensional crown geometry (Golder, 1990; Carter, 1992, 2014; Fig. 1, left diagram, y-axis).

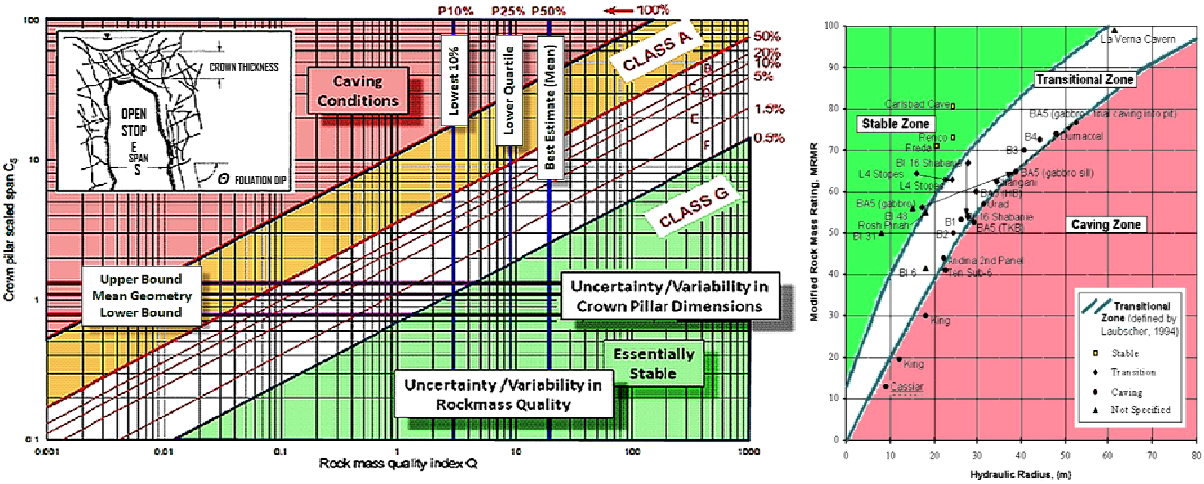


Fig. 1 Empirical Caving Charts: left – Scaled Span Crown Pillar Chart; right – MRMR Caving Chart.

For stoping mines, tunnels, drifts, or cavern assessments, crown breakthrough risk can be assessed by comparing the scaled span *Cs* with the critical span, *Sc* for the controlling rock mass quality (defined by *Q* or GSI/RMR_{76}), with the quotient *Sc/Cs* expressed as Probability of Failure (*PoF*) via the linear logistic regression lines from Carter et al. 2008, or directly from the critical span line $Sc = 3.3\ Q^{0.43}\ xsinh^{0.0016}(Q)$, which it will be noted is slightly non-linear with increasing rock competence. Although the rock quality vs. geometry axes are reversed between the two plots in Fig. 1, colour coding is set approximately equivalent, allowing direct caving comparison.

Critically, crown stability and cave propagation are also governed by the volume balance between available void space and the bulked volume of the fragmented rock. Collapse propagation will only arrest if the fragmented rockmass bulks sufficiently to fill the available void. If bulking is insufficient, progressive upward migration continues until breakthrough. Bulking, therefore, represents a critical parameter, linking fragmentation behaviour with collapse-driven instability.

3 Bulking

3.1 Fragmentation and Bulking Data

Bulking during caving depends not only on rockmass characteristics controlling initial block size and shape distributions, but also on in situ and induced stress conditions, airgap presence, fall height of blocks from the cave back, and fragmentation maturity through comminution and compaction. Supported and unsupported crown/cave back span at any time, and the geometry and depth of the yield/damage zone, also affect fragmentation block size and rate of fragmentation (break up).

Fig. 2 summarises collected bulking data from literature sources, subdivided by rock type. While most of the plotted data originates from evaluation of longwall coal gob collapse behaviour in sedimentary rock types, a significant number derive from hard-rock stope hangingwall failure and civil tunnels. The influence of fabric and rock strength is clear: competent, slabby strong rocks, such as slates break up with the highest Bulking Factors (*Bf%*), while weak, crushable mudstones, siltstones, claystones and schists show the lowest *Bf* values.

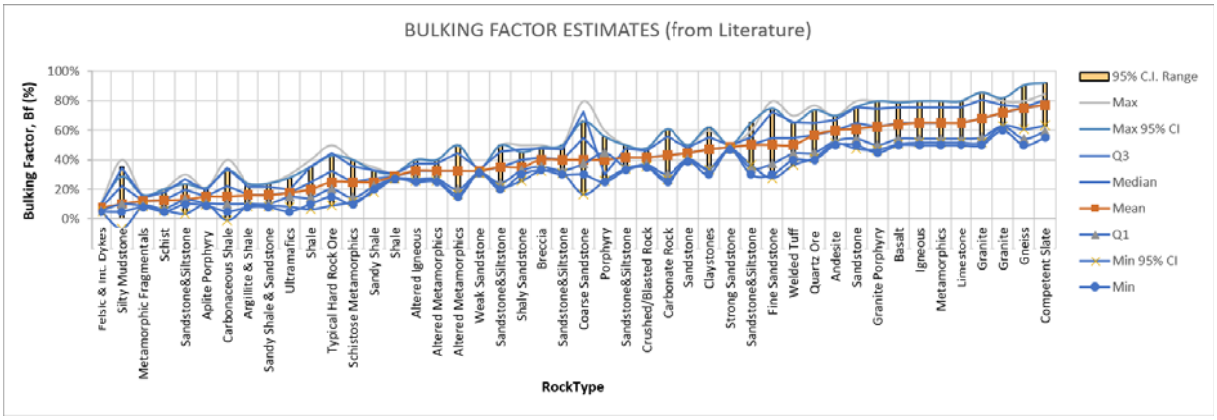


Fig. 2 Summary Box Plot of Bulking Factor (%) values, ranked by mean *Bf%* and rocktype.

Given the Hoek-Brown parameter m_i (Hoek & Brown, 1980) can be utilized as a useful intact rock type competence index, (Marinos & Carter, 2025), and noting that m_b reflects, not just rock type, but also rockmass brokenness (fracture intensity), a correlation to the mean trend of the data in Fig. 2,following earlier longwall coal, square root relationship formulations, can be postulated, suggesting:

$$B_f(\%) \cong 2.1 \cdot \sqrt{m_b \sigma_C},$$

where m_b and σ_C (UCS) need to be rockmass and rock type specific.

3.2 Swell versus Bulking

Swell refers to the initial volumetric increase of a fragmented rockmass relative to its in situ volume immediately following blasting or mechanical breakage, (primary fragmentation). ***Bulking***, by contrast, describes the volumetric state of the mobilized fragmented rock debris under a given stress condition, and thus evolves over time, reflecting block rearrangement, stress-dependent compaction and block breakage (secondary fragmentation).

In cave mining, this distinction is particularly important because the overall bulking factor derived from mass balance calculations evolves over the course of cave life. Initial (primary) fragmentation during undercutting produces *Bf* values of approximately 20–30% for most porphyry copper rock types. As confinement increases within the growing cave column, progressive compaction (secondary fragmentation) commonly reduces effective *Bf*'s to approximately 15–20%. After breakthrough, full column weight further compacts the fragmented mass, leading to long-term *Bf* values of approximately 8–12% (van As& Guest, 2020). Within actively flowing draw zones, shear dilation can produce local *Bf* values approaching 50–60%, while compacted zones outside the draw column may exhibit ≈10%.

This spatial and temporal variability - irrespective of rock type differences, explains much of the scatter in the case history bulking data plotted in Fig. 2, and demonstrates that estimating bulking for cave mining draw control design purposes cannot be adequately represented by a single constant value. For estimating choking balances for crown stability assessment purposes, taking mean values from Fig.2, may however, be considered sufficiently reliable, at least for first cut evaluation requirements.

4 Crown Collapse

4.1 Crown Stability and Caving Risk

Five principal mechanisms drive crown pillar/cave back collapses: plug failure, chimneying, caving, unravelling and delamination (Carter et al, 1989, Carter, 2014). Chimneying and plug failure both occur with little bulking, limiting any likelihood that choking of the void space will arrest collapse. For all other mechanisms, (when high PoFs are indicated from *Sc/Cs* checks), breakthrough likelihood will depend on rock type and on fragmentation-controlled bulking.

Extremely competent crowns (Q> 200, as in natural limestone cave geometries) will remain stable for millennia. More jointed rock masses remain stable for years, if spans are below the critical span, *Sc*, for that rockmass quality. At the other extreme, very poor-quality crowns ($Q \ll 0.1$) disaggregate rapidly, and thus, caving in these rock types frequently leads to surface breakthrough, as bulking is often insufficient to adequately fill and choke-off available void space, almost irrespective of crown thickness.

Weak rock types that fragment readily, and intensely jointed or faulted rock masses (such as shown across the lower row of Fig. 3), can be considered self-caving, and prone to chimney collapse mechanisms. Standup time relative to Q, based on civil and mining tunnel experience, can be estimated from Fig. 4 (Carter & Miller, 1996), and appropriate block size-specific caving rates can also be derived, by comparing that data with the crown pillar dataset. Chimney and plug caving are, however, very difficult to assess, as they can progress rapidly over a very narrow footprint, often with little warning, and frequently, as pointed out by van As & Guest, 2020), also with very low apparent overall *Bf* values (of around 4–5%), reflecting limited total breakage relative to cave volume.

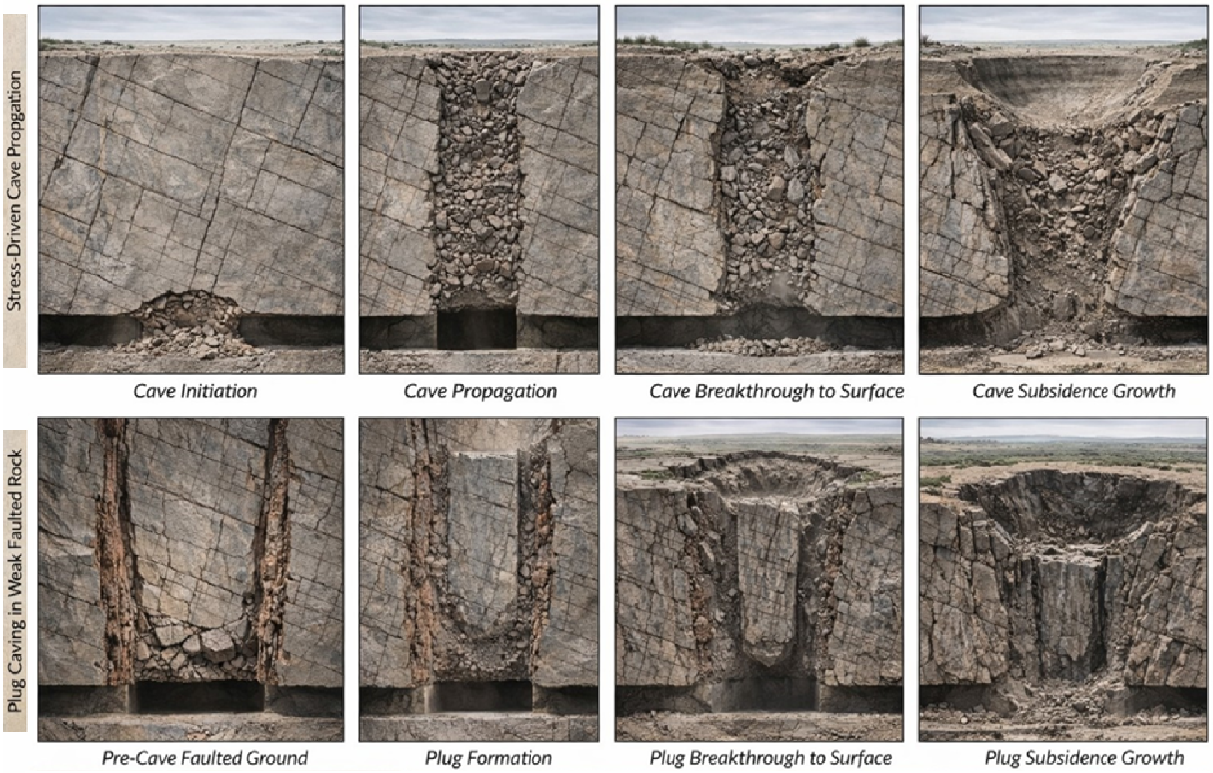


Fig. 3 Comparison– rockmass-controlled caving (top row) with chimney/plug mechanisms in faulted ground (lower row).

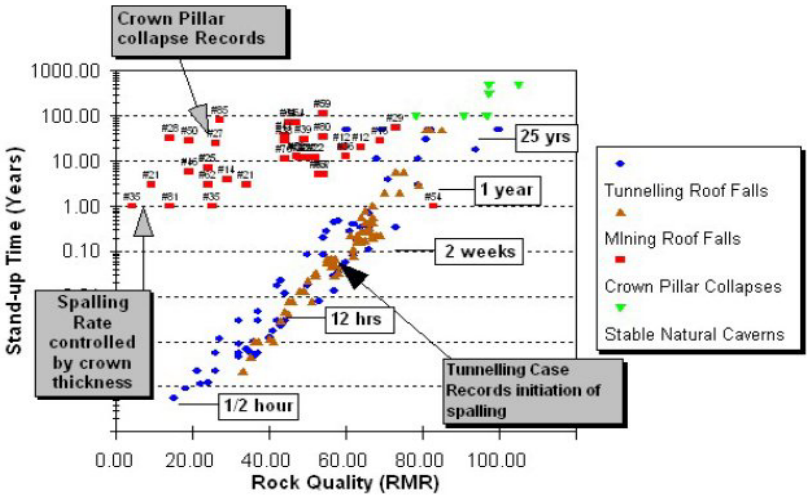


Fig. 4 Longevity for crown pillar collapses vs. stand-up time from tunnel and drift case records (Carter & Miller, 1996).

4.2 Choking Calculations and MRMR Caveability Estimates

Although bulking factors change significantly during cave propagation, advanced numerical modelling (Sainsbury et al., 2011; Sharrock et al., 2012; Cuello & Newcombe, 2014) confirms that, despite spatial variation in bulking/porosity across large cave footprints, a single rock type-specific bulking factor, such as can be extrapolated from Fig. 2, provides a reasonable approximation of overall column fragmentation for choking calculations. This is paralleled by longwall coal experience, where a single *Bf* approximation has proven reliable deeper into the gob, despite local variation near the coal face.

Benchmarking of cave onset from these advanced modelling approaches against the empirical methods outlined earlier suggests that the critical scaled span comparison with *Cs* provides a reliable threshold measure for assessing crown stability and rock mass caving likelihood, while determining the hydraulic radius of the undercut provides a better measure for defining overall caveability onset for thicker crowns where the crown thickness term, *T*, dominates the scaled span algebra. Evaluating the critical hydraulic radius (HR_{cr}) against a known rock mass quality using Laubscher's MRMR chart (Fig. 1, right) provides ready caveability likelihood assessment and allows initial estimates of the minimum undercut geometry dimensions required to initiate caving. It must though be noted that both the MRMR-*HR* and Scaled Span, *Cs* methodologies, although targeted differently, are conceptually analogous: comparing excavation geometry (*HR* or *Cs*) with a rock quality-dependent critical value (*HRcr* or *Sc*). Both methods however define only the initiation threshold for caving; as they implicitly assume that once the critical geometry is exceeded, the rock mass will propagate upward. In practice, post-initiation caving behaviour strongly depends on rock mass-specific levels of bulking. Where fragmentation produces sufficient fine cracking and dilation, stress transfer through the broken column is reduced and upward propagation proceeds readily. Where fragmentation is coarse and bulking is embryonic, efficient stress transfer promotes arching, potentially causing cave stall or hang-ups even when MRMR predictions suggest propagation should occur. Thus, while the critical hydraulic radius appropriately defines the geometric initiation threshold; bulking governs the subsequent mechanical evolution of the cave column.

5 Design Application

Two interrelated caveability design challenges require an in-depth appreciation of bulking: (a) crown pillar collapse risk evaluation, and (b) defining productive caveability for cave mining. Understanding site-specific bulking inter-relationships with rock type (Fig. 2) and stand-up time relationships per rock mass competence (Fig. 4) provides the basis of understanding for both.

5.1 Crown Pillar Surface Breakthrough Collapse Risk Assessment

The original Scaled Span methodology (Golder, 1990, Carter, 1992), which was originally developed from an extensive database of mainly subvertical stoping situations, was found in the late 1990's to be in need of modification for shallow dipping stoping (Carter et al, 2002), resulting in the standard procedures now incorporated in many guidelines, as summarized in Carter, 2014. More recently, with many mines transitioning from underground operations to super pits or, vice versa, going to cave mining from open pits, there has arisen a need to be able to better assess the influence on crown pillar stability of multiple steep orebodies and also complex on-seam and off-seam faulting patterns (Carter, 2019).

Depending on context, a recommended assessment workflow would therefore be as follows:

1. Define Crown Geometry – assess *Cs* (include shallow dip and/or multi-zone corrections).
2. Define Rockmass Quality – assess *Sc* (adjust for on-seam or off-seam faulting, if necessary).
3. Define Rock type controlling likely Caveability/Bulking – assess σ_C, *GSI*, m_i, hence m_b.
4. Assess bulking percentage by rock type – assess likely *Bf%* from σ_C and m_b.
5. Assess potential cave rate (m/year) per assessed most cave-prone rock type.
6. Establish available void space via CMS or similar ultrasonic survey if flooded.
7. Compare potential void volume vs. probable crown collapse volume (as bulked fill).
8. Assess potential breakthrough risk.

5.2 Evaluating Cave Propagation through Bulking Understanding

Cave initiation requires exceeding the critical hydraulic radius or minimum critical span. Sustained propagation and controlled cave growth, however, depends on the evolving bulking behaviour of the cave column. Fragmentation-dominated dilation governs early propagation; stress-dependent compaction governs long-term behaviour. Bulking must therefore be treated as a variable-state parameter, central to cave initiation, propagation, and operational control.

Three cave life-span phases are consistently identified from mass balance data: (1) undercutting phase - *Bf* ~20-30%, fragmentation-controlled; (2) propagation phase (post-*HRcr*) - *Bf* ~15-20%, with increasing confinement promoting partial compaction; and finally (3) steady-state post-breakthrough - *Bf* ~8-12%, full column weight mobilised. Local bulking in active draw zones may reach 50-60%, while surrounding compacted regions may be sub-10%. This spatial heterogeneity in bulking has direct implications for dilution management: the contrast between high-*Bf* draw zones and low-*Bf* compacted regions creates preferential flow paths that can accelerate dilution ingress from overlying waste, while isolated or poorly-drawn zones increase the risk of early mud or waste entry at breakthrough. Draw control strategies must therefore account for evolving void ratio distribution to minimise premature dilution and manage airgap formation. Since bulking is not directly measurable in situ (van As & Van Hout 2008), it must be derived from laboratory characterisation, field back-analysis or calibrated modelling. A suggested workflow, combining laboratory and field-testing methods would be thus:

1. Undertake laboratory testing ("swell" tests[*], confined compression and particle breakage studies) to provide mechanistic insight into initial dilation and stress-dependent compaction, and then calibrate against field behaviour.
2. Undertake calibrated modelling as basis for design, - benchmarked using initial MRMR, Lab data and cave mine operations experience, matching the three life-span phases identified above.
3. Conduct mass balance back-analysis: $Bf = (V_{cave} - V_{in\ situ}) / V_{in\ situ}$, (Brown, 2003,2006), where V_{cave} is obtained from CMS surveys or inferred from propagation height.
4. Carry out field measurements to improve understanding and calibrate modelling:
    - Complete a CMS/laser void scan to provide direct measurement of available void volume; for comparison with expected bulked collapse volume – to underpin calculations for crown breakthrough risk assessment;
    - Monitor drawpoints for block size and bulking (local *Bf*'s within flowing draw zones can reach 50–60% (plug flow) due to shear dilation, while compacted zones outside active flow may be only ~10%).
    - Implement cave marker and propagation tracking systems into the draw columns to help allow independent estimation of cave height vs. tonnage drawn, providing cross-checks on mass balance-derived bulking estimates.
5. Reassess caveability and cave propagation behaviour mechanics, and then update modelling, and if necessary, revise draw control strategies.

6 Conclusions

A combined understanding of cave mechanics, coupled with precedent knowledge of longevity-controlled rockmass degradation-driven crown pillar collapse behaviour, provides unique insight into the mechanisms governing excavation instability and potential surface impacts. For assessing surface impact from crown failure, and assessing propagation and operational control in cave mining, in-depth understanding is needed of rock-type-dependent bulking interrelationships with fragmentation stages.

[*] NB - here "swell" relates to "fragmentation-driven bulking", and should not be confused with "mineralogical swelling"

Empirical methods (scaled span, MRMR-hydraulic radius) define geometric and rockmass quality conditions for determining cave initiation and collapse potential but do not capture the specifics of the volumetric behaviour of fragmented rock that ultimately controls collapse propagation and cave performance. Bulking evolves systematically during cave development, from undercutting through cave propagation, but also continues to change after breakthrough. While bulking factors are strongly block-shape and rock-type controlled, local dilation within active draw zones may temporarily increase *Bf*s to levels significantly higher than baselines.

This evolving behaviour of bulking within a fragmenting rock mass, controls void ratio, stress transfer, arching, cave propagation rate, airgap development, hang-ups and cave material flow. For crown stability assessments, a single, representative early caving *Bf* provides a reasonable approximation for estimating collapse volume relative to available void. For cave mining design, however, bulking must be treated as a stage-dependent and stress-dependent state parameter of the cave column. Incorporating this behaviour into caveability assessment, mass balance analysis and draw control strategies thus provides the most realistic basis for predicting cave propagation and managing subsidence risk.

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