Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)

doi:10.36487/ACG_repo/2645_15

Energy distribution criteria for drawbell blasting in block caving based on post-blast scanning and back-analysis

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Abstract

Drawbell blasting is a critical activity in block caving operations as it directly controls excavation geometry, fragmentation, and cave initiation conditions. Defining suitable explosive energy distribution criteria is challenging due to variable confinement, drilling deviations, and differences between designed and actual explosive charging and blasting by phases.

This paper presents a methodology to determine energy distribution criteria for drawbell blasting using a back-analysis approach that integrates post-blast scanning, measured drilling deviation data, and real explosive charging information. The methodology compares the actual excavated geometry obtained from post-blast scanners with numerical simulations of explosive energy distribution generated using real drilling and charging data.

By correlating simulated energy contours with scanned drawbell geometries, an energy threshold is identified that best represents the excavation limits achieved in practice. This approach allows the definition of phase-dependent energy criteria for phased drawbell blasting.

Application of the methodology per phases shows that a Phase 1 blasting (slot or initial centre), characterised by high confinement and limited free face, requires an average explosive energy close to 4.3 MJ/t to ensure adequate rock fracturing and material movement. In contrast, Phases 2 or 3, which benefit from increased free faces and reduced confinement, require significantly lower energy levels, around 2.26 MJ/t.

The results highlight the strong influence of confinement conditions on energy demand and demonstrate that energy-based blast design criteria, supported by real post-blast data, can improve blast predictability, excavation quality, and operational safety in block caving drawbell construction.

Keywords: *block caving, drawbell blasting, energy distribution, post-blast analysis*

1 Introduction

The construction of drawbells in block caving operations is critical, as the geometry and quality of the cavity determine initial cave propagation, mineral fragmentation, extraction capacity, and safety at undercut and production levels. Traditionally, drawbell design has heavily relied on empirical rules and operational experience, with methods ranging from multi-phase excavations (2 or 3 blasts) to attempts at single-shot execution to enhance productivity and reduce personnel exposure (Jofré et al. 2000; Silveira et al. 2005; Altamirano et al. 2014; Music & San Martín 2010).

However, the literature reveals several critical limitations in the state-of-the-art:

1. Load recommendations and powder factors are often expressed in practical terms (kg/m^3 or kg/t) without proper normalisation to specific explosive energy (MJ/t), complicating comparisons across sites and products.

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2. Wave propagation and damage models (e.g. Holmberg-Persson) are widely used to predict PPV and distant damage, yet the quantitative link between simulated energy contours and actual excavated geometry remains unestablished (Persson et al. 1994; Onederra 2013).
3. There is no accepted operational criterion differentiating energy demand between the initial phase (Phase 1: slot or initial centre with high confinement and limited free face) and subsequent phases (Phase 2/3: greater free face), despite their distinct mechanical and energetic behaviours.

In practice, a general evaluation threshold – often cited as ≈2 MJ/t (commonly attributed to Bill Adamson's work [Adamson 1996]) – is applied uniformly across different phases. However, the source and validity of this criterion have not always been publicly verified, and its uniform application may lead to under-excavation or inadequate fragmentation in Phase 1, where confinement elevates the real energy demand.

Recent advances in instrumentation and post-blast analysis (borehole deviation surveys and 3D scans) open the possibility of addressing this gap. Experiments and experiences in recent projects (e.g. Chuquicamata underground) have demonstrated that precise measurements and energetic modelling enable the evaluation of excavated geometry, fragmentation, and actual volumes against theoretical design, and calibration of attenuation models (k, α) under field conditions (Morales & Olivares 2014; Paredes et al. 2019; Rodríguez et al. 2020; Henríquez et al. 2024). However, few studies formalise a back-analysis procedure linking simulated energy contours (expressed in MJ/t) with the surfaces effectively achieved by the blast, and deriving phase-specific energy criteria.

Faced with this gap, this study proposes to:

- recognise the dependence of drawbell energy demand on execution confinement and phase, and the insufficiency of a single energy threshold for all phases
- implement a back-analysis methodology integrating:
  - post-blast 3-D surveys (excavated geometry)
  - actual drilling data (deviations, lengths)
  - energy distribution simulations (Holmberg & Persson model [H&P model] or JKSimBlast / I-blast softwares) to identify phase-specific energy thresholds (MJ/t) that best correlate with field excavation limits.
- normalise criteria by converting practical powder factors to specific energy (MJ/t) using the explosive's energy per mass, facilitating inter-site comparisons and criterion transfer.

This review summarises the evidence and positions the methodological proposal to derive phase-dependent energy criteria by correlating simulated energy contours with post-blast scanned geometries, aiming to improve design predictability, excavation quality, and operational safety in block caving drawbell construction. The following sections describe the proposed methodology, field data employed for demonstration, and results supporting phase-specific operational criteria.

2 Site description

The case study was carried out in a major underground block caving operation in South America. Due to confidentiality agreements with the mining company, specific location and site identification are withheld.

The general rock site parameters are described in Table 1.

Table 1 Rock parameters (Rock A)

Geomechanical parameter	Value
Rock density (γ) (t/m^3)	2.72 ± 0.04
Porosity (η) (%)	0.71 ± 0.28
Uniaxial compressive strength (UCS) (MPa)	162 ± 29
Tensile strength (Ti) (MPa)	13 ± 3
Young Module (E) (MPa)	49 ± 4
Poisson Module (υ)	0.23 ± 0.03
P-wave velocity (V_p) (m/s)	5,078 ± 653
S-wave velocity (V_s)(m/s)	2,936 ± 262
Intact rock parameter (m_i)	12.5
UCS for intact rock (σ_{ci}) (MPa)	153
Tensile strength for intact rock (σ_{ti})(MPa)	13
Cohesion (c) (MPa)	30
Angle of friction (ϕ) (°)	47

3 Methodology

The proposed methodology is based on a 3-stage analysis: design, execution, and post-blasting analysis. Figure 1 provides a schematic overview summarising the considered workflow.

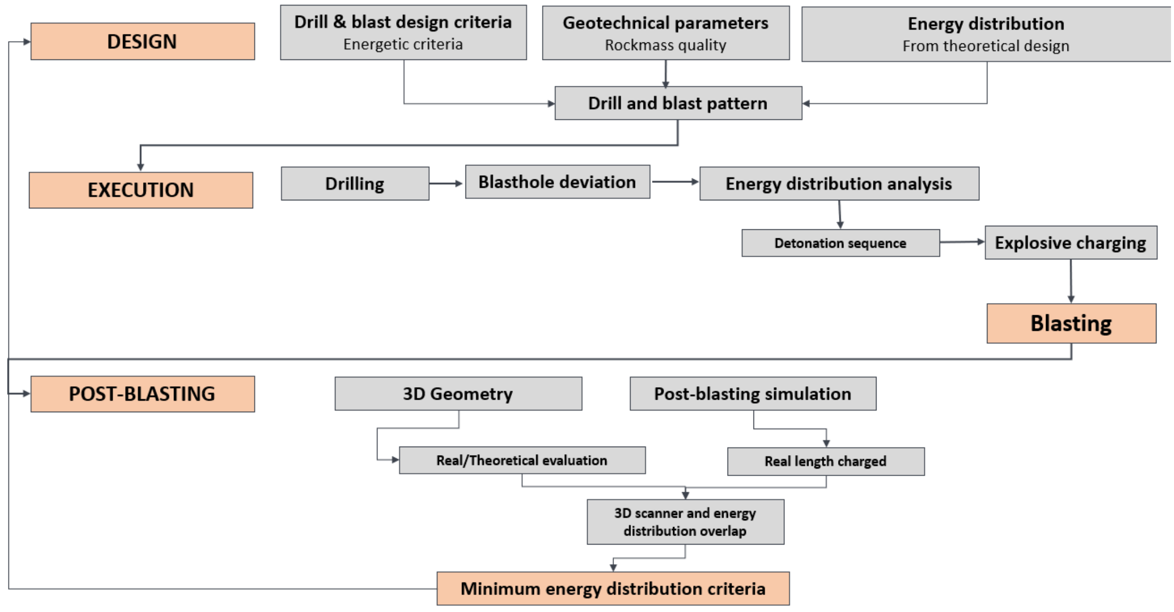

Figure 1 Proposed methodology

3.1 Design

The initial drawbell blast designs are established using theoretical formulations to determine primary burden and spacing parameters. These parameters are calculated based on standard empirical and analytical methods, taking into account the expected rock mass properties. A first theoretical design is estimated, considering stemming distribution, explosive charges and detonation sequences. Following this, the initial layout undergoes validation through numerical simulation or specialised blast modelling software, which incorporates site-specific rock mass parameters (e.g. uniaxial compressive strength, modulus of elasticity, and level of jointing). The goal of the simulation stage is to identify regions within the planned excavation with potential over-concentration or deficient distribution of explosive energy. If areas with excessive or insufficient energy are detected, iterative adjustments are made either by increasing or reducing the number of drill holes, or by modifying burden and spacing, to optimise the energy distribution while ensuring compliance with operational safety limits.

In this stage, the number of phases is stablished regarding to the available void volume for receiving the blasted material. When this total blasted volume – due to rock expansion after blasting – is greater than the available void volume in the receiving system (slot raise + drawbell + projection). This mismatch is caused by the difference between the in situ rock density (~2.6 t/m³) and the post-blast loosened density (~2.0 t/m³), which results in approximately 35% volume increase. As a solution, a multi-stage blasting approach is adopted (Figure 2).

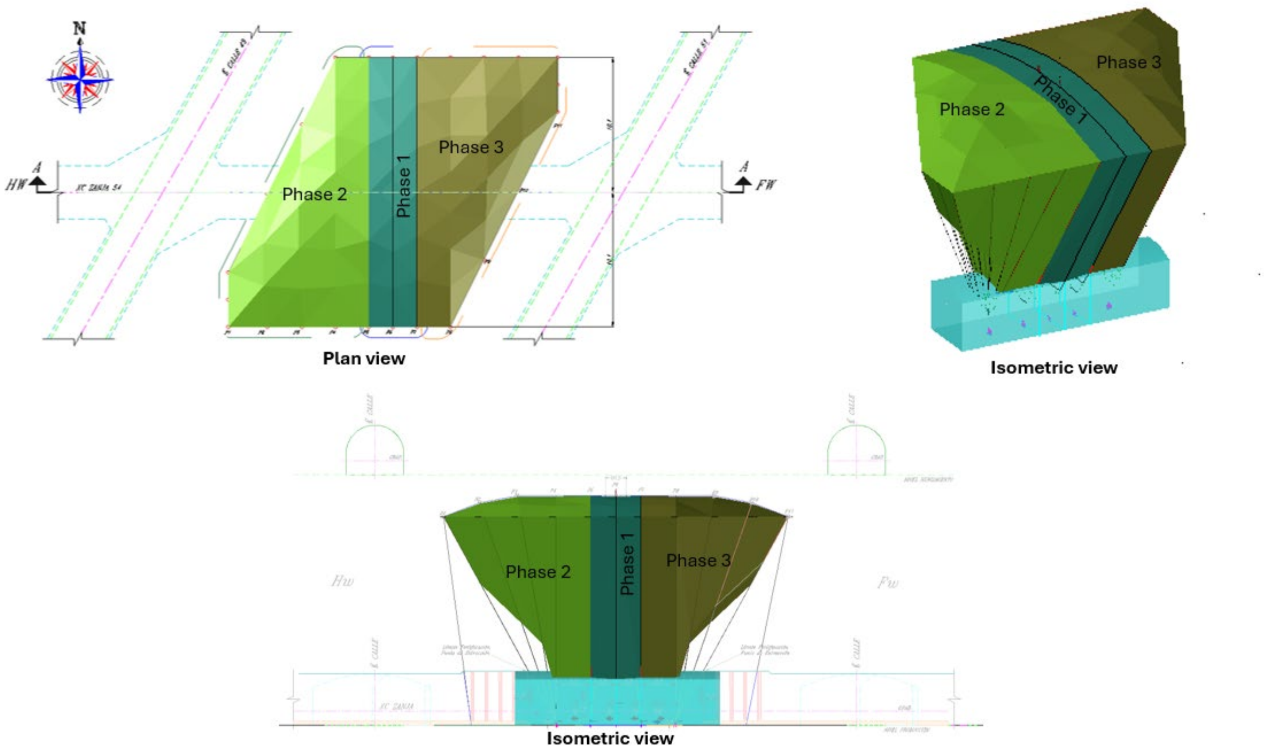

Figure 2 Proposed methodology

3.2 Execution

During the execution phase, the drill pattern is implemented onsite according to the design. Precise borehole deviation measurements are performed (e.g. with a REFLEX system) to capture the true three-dimensional as-drilled geometry of each hole. This real drilling data forms the basis for a refined analysis of explosive energy distribution, considering the actual spacing and burden generated by errors and deviations from the original design (Henríquez et al. 2024). Zones of low energy interaction can thus be visualised, highlighting possible regions of poor fragmentation or incomplete breakage either due to short holes or bottom deviations. Unless a locally calibrated energy criterion is available, a minimum threshold of 2 MJ/t, as referenced in standard practice, is typically adopted for preliminary analysis.

Utilising the measured depth and location data for each borehole, the actual detonation sequence is established, prioritising shortest distances from explosive charges to the evolving free face. Explosives charging and blasting are then executed based on this real pattern and timing.

As a scope study, it is important to note that the simulation shown in this paper is static (it does not consider detonation sequence). In any case, the timing sequence that is considered for each blasting considers the real distance to the dynamic free face to avoid confined drillhole detonation.

3.3 Post-blasting analysis

Post-blasting evaluation involves repeating the analytical procedures of the pre-blast stage but now incorporating both the actual loading parameters and the three-dimensional survey of the post-blast excavated cavity (via 3D laser scanning or LiDAR). At this stage, the modelled energy contours, derived from the as-drilled and as-charged data, are overlaid and compared with the true limit of the excavated volume. The key methodological step is the identification of the energy threshold which best matches the real post-blast cavity, maximising the spatial coincidence between simulated energy contours and the surveyed boundaries. This analysis is repeated and adapted for each blast phase, enabling validation and, if necessary, calibration of energy criteria across different drawbells and operational cycles.

4 Results

4.1 Phase 1

The drilling parameters for phase 1 is shown in Table 2. As an initial result, the distribution energy analysis of Phase 1 for a drawbell prior to blasting execution is presented. At this stage, no locally calibrated minimum energy criterion is available; therefore, a provisional threshold of 2 MJ/t is employed, following common industry practice. The outcomes of this preliminary evaluation are shown in Figures 3 and 4. In both figures, it can be observed that the predictive simulation closely matches the target excavation geometry throughout most of the volume. However, at phase 1 shoulders or edges, there is a slight energy deficit, resulting in limited predicted underbreak in those areas. In terms of overall height, the simulated energy contours indicate that the design geometry would be largely achieved.

Table 2 Drill and blast parameters

Parameter	Value
Diameter	3 inches
Rock type	Rock A
Number of drillholes	22
Burden	1.8 – 2.7 m
Toe distance	3.2 – 3.4 m
Volume blasted	567.5 m^3
Drilling factor	0.6 m/m^3
Emulsion	1,348.3 kg
ANFO equivalent	1,083.1 kg
Powder factor	2.38 kg/m^3

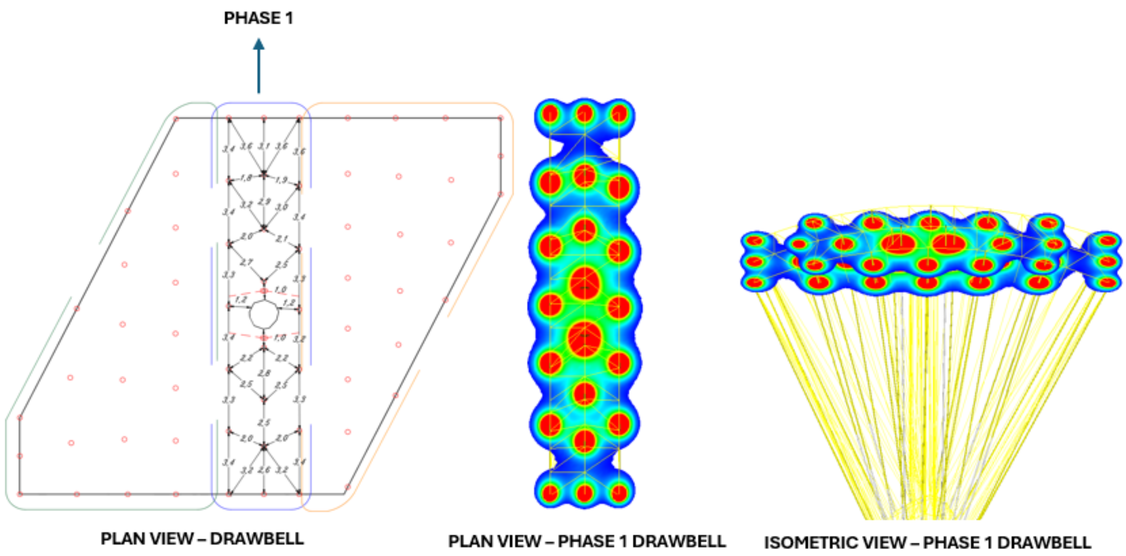

Figure 3 Energy distribution for Phase 1: minimum criteria 2 MJ/t (plan and isometric view)

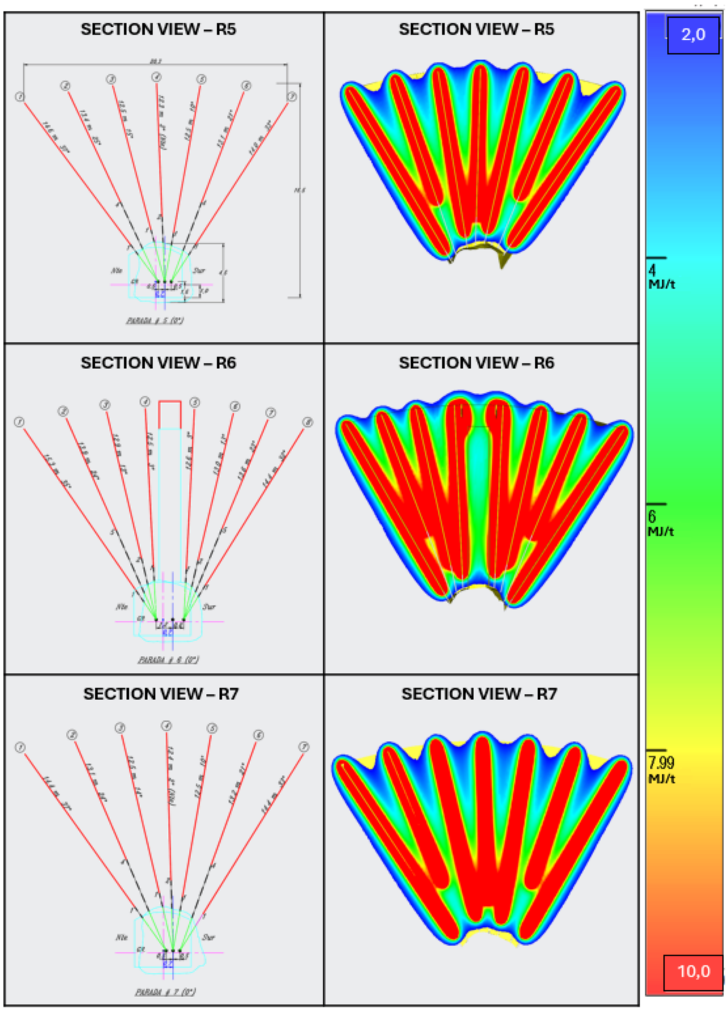

Figure 4 Energy distribution for Phase 1: minimum criteria 2 MJ/t (section view)

However, a common result observed during the actual execution of the design is illustrated in Figure 5. This figure shows that the blast successfully achieved breakthrough and upward movement in the central slot raise, but the lateral or shoulder zones did not fully break or displace. Typically, these shoulder areas remain as 'frozen' rock, which may only collapse during subsequent blasts. In some instances, this behaviour is attributable to limitations in the initial design or in the blasting execution leaving solid zones that subsequently require a supplemental regularisation blast. This extra stage increases both the total cost and the time required to bring the drawpoint into operation. In this case, the minimum energy threshold of 2 MJ/t was not sufficient to accurately predict the outcome of the blast.

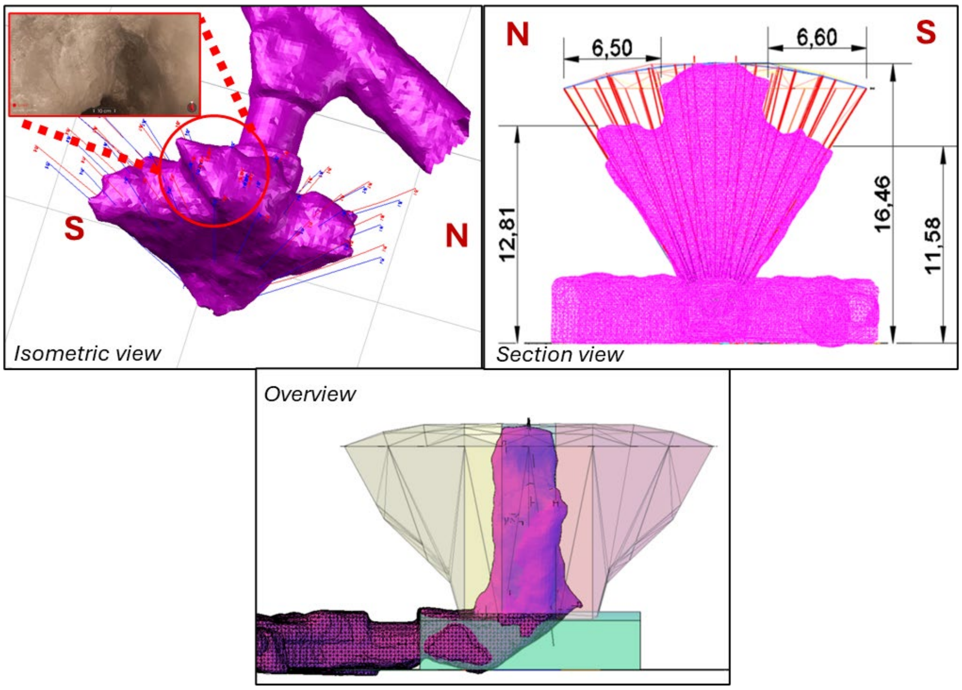

Figure 5 3D scan for Phase 1

When the minimum energy threshold is increased in the simulation, the predicted energy contours are found to align more closely with the actual post-blast excavation boundaries, particularly in the regions where different energy halos intersect. As illustrated in Figure 6, this adjustment reveals a probable excessive spacing, specifically towards the shoulder areas that failed to break during blasting. The improved correlation between simulated energy distribution and the measured excavated geometry supports the interpretation that inadequate energy input – due to either insufficient borehole density or suboptimal charge placement – contributed to the incomplete breakage observed at the shoulders. Consequently, a recommended corrective action would be to revise the Phase 1 blast design, introducing additional or repositioned boreholes to reinforce these critical shoulder zones and ensure more uniform breakage across the entire drawbell profile.

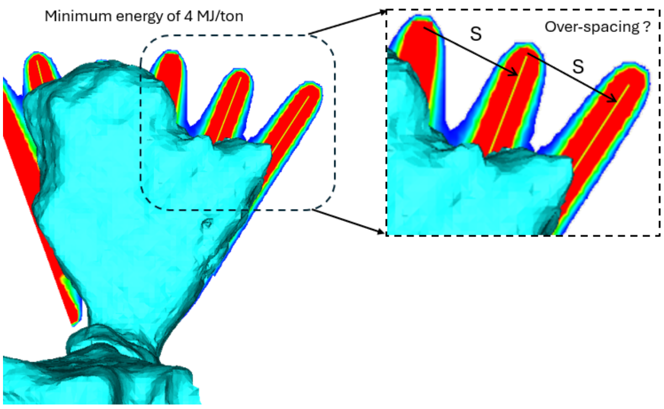

Figure 6 3D scan for Phase 1 considering a minimum energy distribution of 4 MJ/t

4.2 Phase 2 or 3

For Phases 2 and 3, it is assumed that the free face created during Phase 1 has been fully established, providing sufficient space for blasted material to displace. In the analysed cases, this free face was either successfully developed in Phase 1 or achieved through a supplemental regularisation blast to attain the required geometry.

As previously described, a post-blast analysis was conducted by adjusting the simulated energy contours to match the actual excavated volume captured in the post-blast scan. As shown in Figures 7 and 8, this calibration demonstrates that the best fit between predicted and actual excavation boundaries is achieved at a minimum energy threshold close to 2 MJ/t, a value consistent with common industry practice. This analysis was performed using both plan view and cross-sectional profiles, providing a comprehensive assessment of the correlation between energy input and excavation outcome across multiple geometries. These results reinforce the observation that, once an effective free face is available, the energy required to achieve successful breakage in subsequent phases is significantly reduced compared to Phase 1.

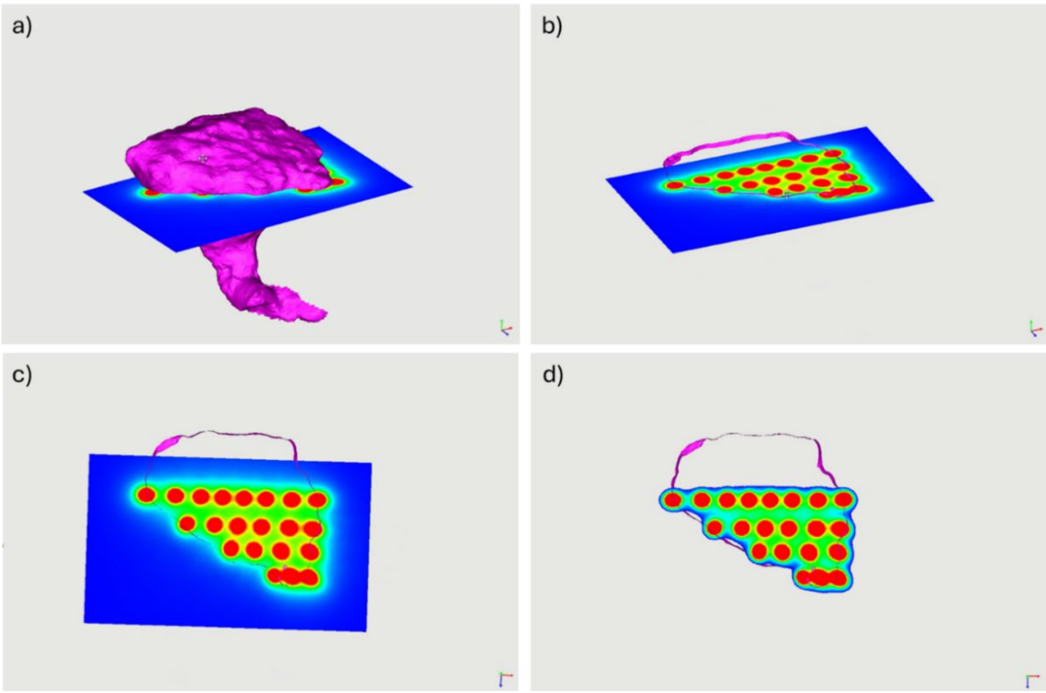

Figure 7 3D scan for Phase 2 and energy distribution adjusting in plan section: 2 MJ/t

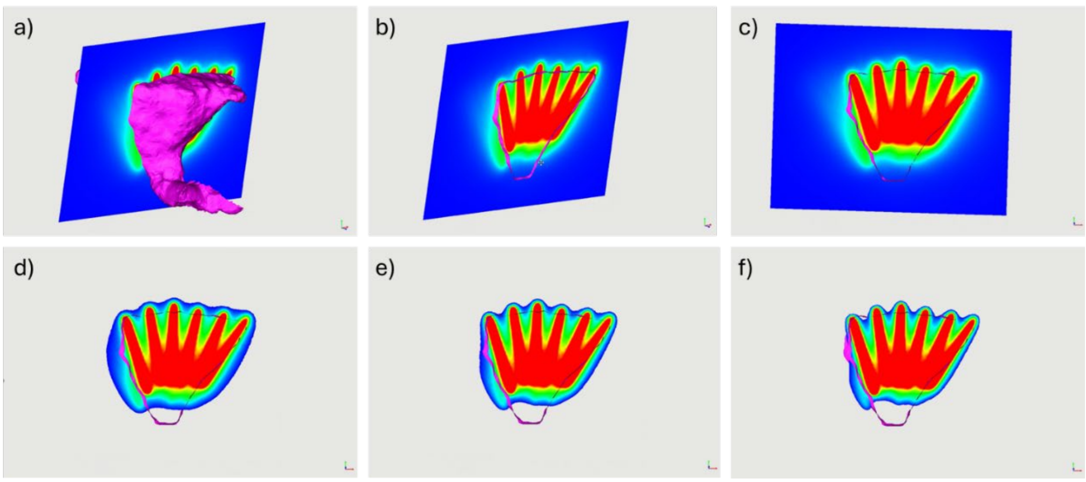

Figure 8 3D scan for Phase 2 and energy distribution adjusting in section: 2 MJ/t

4.3 Summary of the results

To better understand these results and assess the presence of a systematic trend, a back-analysis was conducted on a series of drawbell blasts for which both post-blast scan data and actual explosive charging records were available. The outcomes of this analysis are summarised in Figure 9. Several key findings can be highlighted:

- For Phase 1 blasts, the minimum specific energy required for design is higher than 2 MJ/t. This higher energy demand is attributed to elevated confinement and the absence of a developed free face, necessitating higher charge factors and energy input to achieve sufficient rock fragmentation and displacement.
- To find a proper threshold value, further back-analysis needs to be conducted. At this stage of the research, a range of 3.9–4.8 MJ/t may be used as an initial design input.
- In contrast, for Phases 2 and 3, the minimum energy required to achieve satisfactory breakage was significantly lower, averaging approximately 2.3 MJ/t. This reduction corresponds to the increased free face and improved blasting conditions provided by the preceding phase/s, in line with theoretical expectations and common industry practice.
- It should be noted that areas effectively broken and displaced in the post-blast results are considered in the analysis; zones that failed to break may be influenced by extrinsic factors, such as local borehole conditions or structural anomalies, and are not used to calibrate the energy thresholds reported here.

These findings are consistent with prior literature (e.g. Paredes et al. 2019) that emphasise the strong dependence of required explosive energy on local confinement conditions and phase sequence. The observed distinction in energy criteria between the initial and subsequent phases reinforces the need for phase-dependent design approaches, rather than the use of a uniform minimum value across all stages of drawbell blasting.

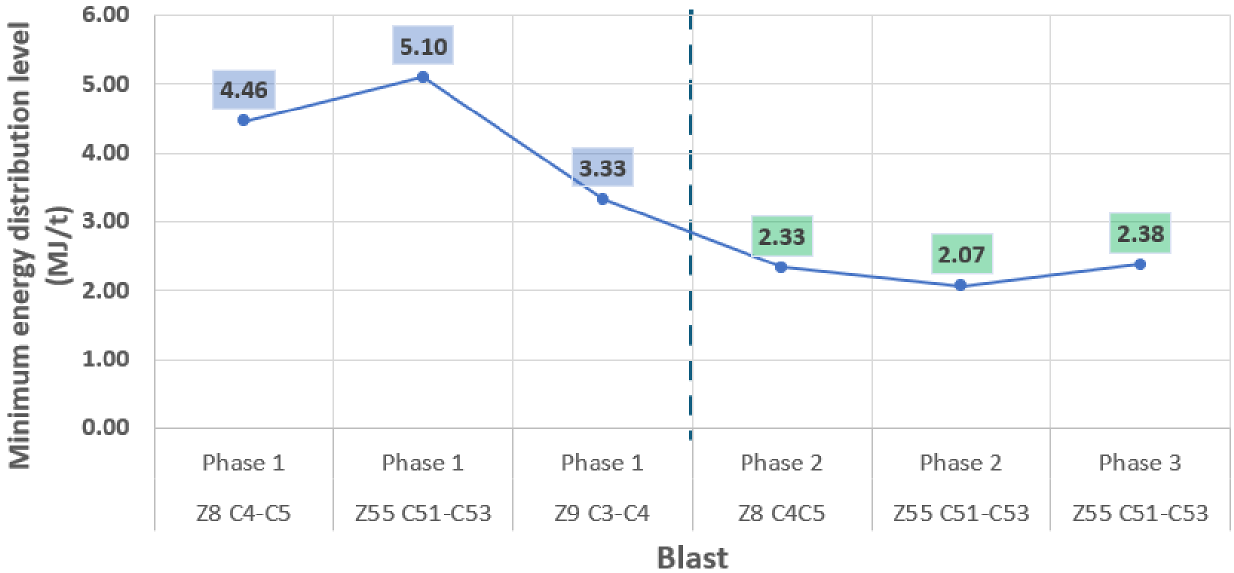

Figure 9 Summary of the blast analysed

5 Recommendations of the study

Given that the principal difference in energy requirements is observed in Phase 1, it is recommended that future drawbell blast designs specifically address the higher energy demand associated with this initial phase. To ensure successful breakage in Phase 1, the design should incorporate an increased number of boreholes, particularly oriented to reinforce the shoulder zones where underbreak was previously noted. By adopting a higher minimum specific energy criterion – initially 3.9–4.8 MJ/t – for Phase 1 and strategically enhancing the drilling pattern in critical areas, the likelihood of achieving the desired excavation geometry in a single blast is significantly improved. The proposed reinforced design (Table 3), developed in light of these findings, is illustrated in Figures 10 and 11.

Table 3 Drill and blast parameters

Parameter	Value
Diameter	3 inches
Rock type	Rock A
Number of drillholes	26
Burden	1.9–2.7 m
Toe distance	2.6–2.8 m
Volume blasted	567.5 m^3
Drilling factor	0.7 m/m^3
Emulsion	1,619.7 kg
ANFO equivalent	1,301.10 kg
Powder factor	2.85 kg/m^3

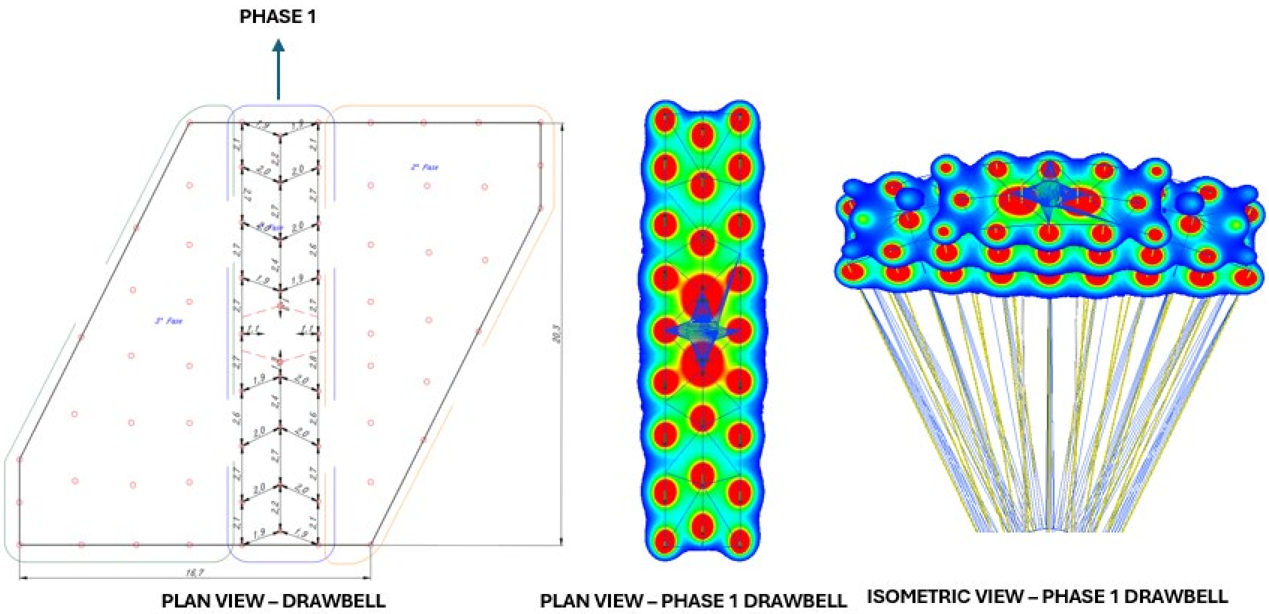

Figure 10 Energy distribution for Phase 1: reinforcement drillholes (plan and isometric views)

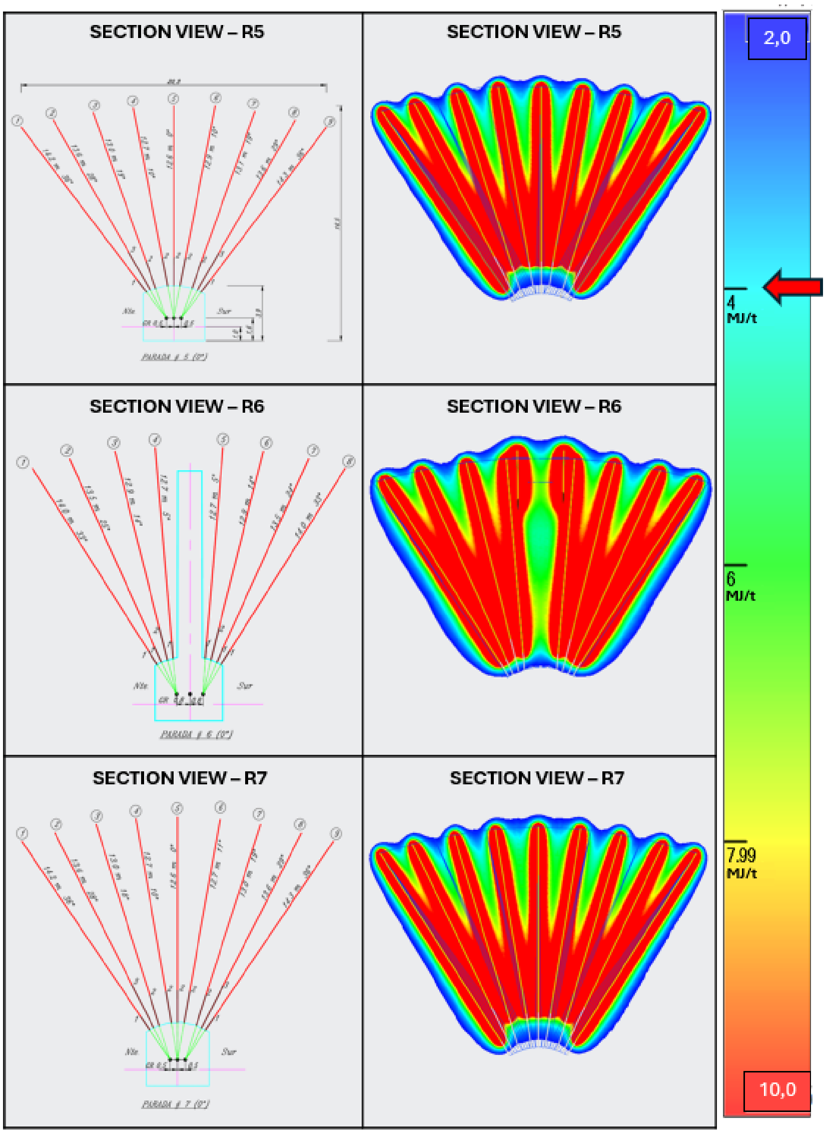

Figure 11 Energy distribution for Phase 1: reinforcement drillholes (section view)

6 Conclusion

This study presents a methodology for defining phase-dependent specific energy criteria for drawbell blasting in block caving operations, based on post-blast scanning, drilling deviation surveys, and back-analysis of simulated energy distribution. The main conclusions are as follows:

- The research confirms a clear distinction in energy requirements between blast phases. Phase 1 – characterised by high confinement and scarce free face – consistently demands a higher minimum specific explosive energy, while subsequent phases (2 and 3), benefiting from greater free face and reduced confinement, require significantly lower energy input (≈2.3 MJ/t). Uniform application of a generic 2 MJ/t threshold is insufficient for reliable Phase 1 blasting outcomes.
- Correlating simulated energy contours (from as-drilled and as-charged conditions) with detailed post-blast 3D scan data effectively predicts actual excavation performance. Back-analysis enables the calibration of energy thresholds that best match achieved blast geometry, supporting their operational use as phase-specific design targets.

- The findings advocate for reinforcing Phase 1 designs by increasing borehole density, particularly in shoulder zones vulnerable to underbreak. This strategy, informed by the new energy criterion, enables improved predictability of excavation geometry, reduced need for corrective re-blasting.
- Adoption of a phase-dependent minimum specific energy approach, grounded in real data and supported by post-blast verification, is recommended for future drawbell designs. Regular calibration using post-blast scanning and deviation-measured charge distributions can further enhance blast reliability.

While results are robust across the cases analysed, broader validation in diverse geological and operational settings is encouraged. Future work should investigate the integration of this methodology with automated design tools and its applicability to other sublevel caving or blasting contexts.

For future work, more back-analysis should be considered and match the results with dynamic burden analysis (considering the real distance to the free face according to detonation sequence).

In summary, the methodology enables data-driven, phase-dependent energy criteria for drawbell blasting, supporting safer, more predictable, and cost-effective construction in block caving operations.

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