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Integrating analytic hierarchy process/analytic network process for seismic hazard assessment in block/panel caving assessment

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Abstract

Currently, many block/panel and sublevel caving mines are operated in deep, high-stress and challenging geotechnical environments where mining-induced seismicity can compromise safety, infrastructure and production continuity. Evolving cave footprints alter hazards via stress redistribution, activation of geological structures and cave maturity. Decisions require a framework integrating operational demands with rock mass characteristics, modelling, monitoring and engineering judgement to manage risk.

This paper outlines a novel approach that couples the analytic hierarchy process (AHP) and the analytic network process (ANP) to turn heterogeneous evidence and factors into transparent, ratio scale priorities that directly support planning, re-entry and exposure management and seismicity hazard.

AHP structures seismicity decisions into a hierarchy – goal, criteria, subcriteria and factors – offering disciplined expert knowledge capture. It ensures traceability and consistency by making technical-factor rankings explicit, enabling judgements to be audited and updated as new data arrives. When criteria are treated as independent across levels, AHP yields clear, consistent prioritisation, strengthening decision-making and maintaining methodological transparency throughout the process overall.

ANP extends AHP for caving, modelling real-world interdependent clusters – planning and operations, monitoring and analysis, and controls and exposure – that influence one another. It uses a supermatrix of influence to capture mutual associations and avoid distortions from uniform cluster weighting. The outcome is long-run priorities that show how changes propagate across the system, helping to safely eliminate risks from plans before implementation.

Embedded in the mine's seismic hazard assessment plan, AHP/ANP aligns data collection, seismic response analysis, control measures and risk assessment into a single decision layer. It complements geomechanical workflows and modern microseismic systems by converting evidence and expert judgement input into action-oriented priorities, improving transparency of trade-offs and the robustness of planning, re-entry and exposure rules.

Keywords: *block and panel caving; mining-induced seismicity; analytic hierarchy process; analytic network process; supermatrix; microseismic monitoring; geological characterisation; induced stress; seismicity hazard*

1 Introduction

The management of seismic hazard in underground mining – particularly in high-stress caving operations – is widely recognised as a complex systems engineering challenge. The seismic response of a rock mass is not governed by geological conditions alone; it is the result of a dynamic, non-linear interaction between inherent

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rock mass characteristics (faults, lithology, stress field), the mine design (macro-sequence, undercut strategy, footprint geometry) and operational execution (draw compliance, production rates, sequencing).

Risk, in this context, differs from hazard. While seismic hazard refers to the probability of a potentially damaging event occurring within a specific volume and time, risk is defined as the potential for adverse consequences expressed as the hazard (potential for an event that can cause damage) multiplied by the vulnerability and exposure. Consequently, a robust assessment framework must account not only for the physical mechanics of rock rupture but also for the operational controls and decision-making processes that mitigate exposure.

Current industry best practice typically relies on two distinct analytical streams: statistical analysis of historical seismic data and deterministic numerical stress modelling. While these methods are fundamental for due diligence and defining the hazard envelope, they possess inherent limitations when attempting to integrate qualitative factors – such as data confidence, operational readiness or workforce exposure – into a holistic risk model.

This paper presents a comprehensive framework for seismicity hazard assessment utilising the analytic hierarchy process (AHP) developed by Saaty (1990, 2000, 2008) and the analytic network process (ANP) of Saaty & Vargas (2013). The objective is to provide a structured multi-criteria decision-making (MCDM) tool that integrates quantitative geotechnical data with qualitative operational factors to support transparent, auditable and risk-based decision-making. The practical implementation of this framework is demonstrated through a deep panel caving case study (the hypothetical 'El Temblante' mine).

2 Analytic hierarchy process/analytic network and multi-criteria decision-making process methodologies applied to seismic hazard assessment

Seismic risk in underground mining – especially caving operations – arises from a complex interaction of geology, mining-induced stress changes, data quality, modelling capability, operational exposure and the effectiveness of controls. These drivers are measured in different units and levels of certainty, and they often influence one another (e.g. extraction sequence affects stress, which affects seismicity, which affects exclusions and production). As a result, relying on a single metric or purely qualitative judgement can lead to inconsistent prioritisation, hidden trade-offs and decisions that are difficult to justify to operators, executives or regulators.

MCDM deals with decision problems where there are two or more criteria or objectives that need to be considered simultaneously. These criteria can be diverse and may include quantitative and qualitative factors such as cost, time, quality, risk and environmental impact, and social considerations.

A structured MCDM framework using AHP/ANP provides a disciplined way to integrate quantitative evidence (seismic catalogues, monitoring performance, modelling outputs) with expert judgement (data confidence, ground support performance, protocol maturity). AHP is well suited to hierarchical decompositions (e.g. data collection → seismic response → control measures → risk assessment), while ANP strengthens the approach where interdependencies and feedback loops exist (e.g. monitoring quality influencing hazard confidence and operational controls).

Implementing an AHP/ANP-based MCDM model delivers tangible governance and operational benefits: transparent weighting of drivers, consistency checking of judgements, repeatable scoring across sites and time, and defensible prioritisation of investments (e.g. sensor upgrades versus support enhancements versus planning changes). It also enables scenario testing and sensitivity analysis, showing which factors most influence risk and where controls provide the greatest reduction per unit cost or disruption. Overall, the approach converts fragmented information into a clear, auditable decision pathway that supports proactive seismic risk management and aligns safety and production objectives.

2.0 Analytic hierarchy process

AHP decomposes complex decision problems into a structured hierarchy: goal => criteria => subcriteria => alternatives/factors, as shown in Figure 1. AHP is particularly useful where multiple criteria (technical, operational, safety, financial) must be balanced and where transparency and governance discipline are required. It utilises pairwise comparisons, allowing experts to systematically evaluate the relative importance of diverse drivers (e.g. stress conditions versus draw rate). A critical engineering feature of AHP is the consistency ratio (CR), which mathematically checks for logical contradictions in expert judgements, ensuring robust and defensible weightings.

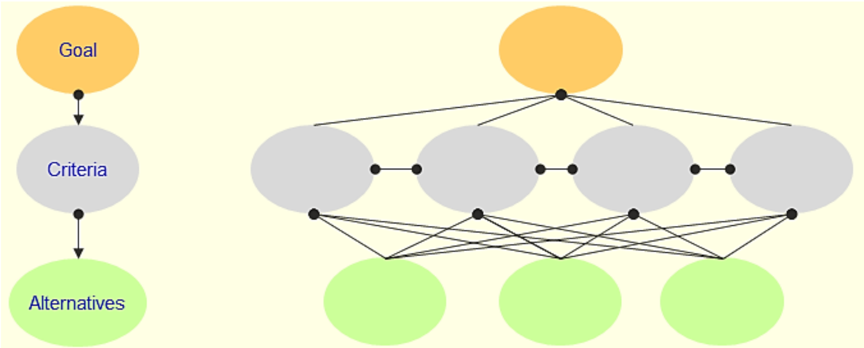

Figure 1 Analytic hierarchy process

2.1 Analytic network process

Because mining systems involve highly coupled variables (e.g. induced seismicity affects production rates, which in turn alters the extraction sequence and future seismicity), ANP extends the AHP framework. by modelling interdependencies and feedback loops through a network structure (supermatrix), ANP accurately reflects the complexities of geotechnical systems. These interconnections are illustrated in Figure 2.

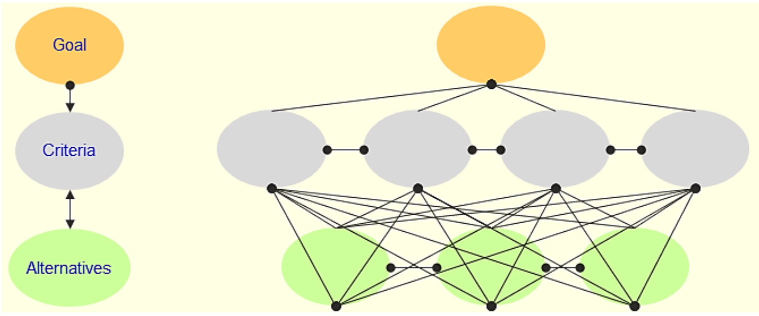

Figure 2 Analytic network process

The AHP and ANP methodologies do not replace geomechanical analysis; rather, they serve as the decision engine that integrates rigorous technical findings with operational realities. By providing a mathematical framework that leverages pairwise comparisons and strictly validates expert judgement through CR, AHP and ANP transform fragmented, multidisciplinary data into a transparent, repeatable and auditable governance tool. This ensures that hazard prioritisations and capital allocation for risk mitigation are technically defensible and devoid of the hidden biases inherent in unstructured qualitative assessments.

To justify the use of the AHP/ANP framework it is necessary to rigorously compare it against the established methods. Table 1 summarises the key differences between the statistical seismology and numerical modelling approach, the Hudson Interaction Matrix and the Saaty AHP/ANP methodologies.

Each technique has its own strengths and weaknesses and is therefore not replaceable. However, for the MCDM context of seismic risk assessment there are distinct advantages to the AHP/ANP methodology. As highlighted in Table 1, conventional methods are excellent for quantifying mechanical interactions but struggle to account for the operational context. Seismic risk management is rarely about finding a single correct answer; it is about making the best trade-off under uncertainty. Decisions such as defining exclusion zones, selecting ground support regimes or choosing between preconditioning methods involve conflicting objectives. An MCDM approach using AHP/ANP offers tangible governance benefits such as auditability, focus on critical controls and bias reduction.

Table 1 Comparison of seismic hazard assessment methodologies: analytic hierarchy process (AHP) and analytic network process (ANP)

Characteristic	Statistical /numerical modelling	Hudson Interaction Matrix	Saaty AHP/ANP
Core purpose	Determine M_{max} and occurrence rates; simulate physical stress response	Map and quantify interactions and causal loops between factors	Establish relative priorities/weights for decision-making and risk ranking
Model structure	Numerical mesh or statistical probability distributions	Symmetric matrix (N × N) focusing on cause/effect	Hierarchical (AHP) or network (ANP) structure
Input data	'Hard' data: rock properties, stress tensors, seismic catalogues	Relative interaction values (expert judgement, 0–4 scale)	Pairwise comparisons (expert judgement supported by evidence)
Operational factors	Difficult to incorporate; models are idealised physics engines; they ignore human/process factors	Can be included as factors in the matrix	Explicitly included as decision criteria (e.g. 'workforce discipline')
Consistency check	N/A (calibration required)	None	Yes (consistency ratio), ensures logical coherence
Mathematical rigour	High (calculus/statistics)	Low (simple summation)	High (eigenvector calculation)
Best use case	Quantifying mechanical interactions and hazard baselines	Initial screening and understanding system behaviour	Holistic risk assessment, prioritisation of controls and complex decision-making

3 Seismic hazard hierarchical overall framework

The seismicity hazard hierarchy provides a structured, multi-criteria framework that integrates geological conditions, mining activities, monitoring systems and risk controls into a unified decision-making model. By organising these elements into clear, traceable layers, the structure enables consistent evaluation of seismic drivers and the effectiveness of operational controls. A key task in applying the AHP/ANP methodology is therefore to define the overall framework for the assessment.

3.0 Selection of criteria to characterise the problem

The overall goal of the framework is to assess seismic hazard in underground caving operations. This is the highest-level statement of the problem. This is followed, as shown in Figures 1 and 2, by the criteria, subcriteria and individual factors that influence the seismic response of the rock mass. In this context, the words 'goals' and 'criteria' are the terminology used in the AHP/ANP analysis as opposed to their more familiar usage in geomechanics.

For the case of seismic hazard, the first level criteria are the broad areas within which the engineering domains that influence seismicity exist. These are defined as:

- site characterisation, which represents the foundational inputs, i.e. data collection. It defines the inherent seismogenic setting in terms of structures, stress regime and rock mass behaviour that govern how energy accumulates and releases
- mine planning and operations, which defines the stress behaviour and energy release forcing of induced seismicity imposed by mining geometry, sequencing, production rate, blasting and the evolving cave boundary
- monitoring and analysis, which defines how well the mine can detect, locate, characterise and interpret seismicity/stress/deformation, i.e. the reliability of the hazard representation and its ability to be managed dynamically
- controls and exposure management, which defines how effectively consequence (preconditioning/support) and exposure (remote, triggered action response plans [TARPs], re-entry, traffic lights) can be reduced.

The second level subcriteria represent the engineering domains, i.e. what must be captured within the first level criteria, e.g. geological structures, data collection, stress conditions, mine planning and layout, mining operations, seismicity (network design, seismic analysis), preconditioning or exposure management.

The third level contains the technical factors, such as how variables might be scored, e.g. persistence of geological features, stress magnitude, rock mass brittleness, macro-sequence, cavefront length, network sensitivity, deformation monitoring, stress change, reporting frequency and completeness, numerical modelling, hydraulic fracturing, support strength or TARPs.

Level 3 converts the hierarchical structure from a conceptual decision model into a fully evidence-based engineering framework, ensuring that seismicity-related decisions are supported in verifiable, site-specific and technically defensible information. The complete hierarchical structure for seismic hazard evaluation is shown in Figure 3.

3.1 Description of factors influencing seismic response of the rock mass

In selecting the criteria and factors shown in Figure 3, a combination of standard knowledge regarding factors affecting the seismic response of the rock mass in mines (e.g. Brown 2007; Mendecki 2016; https://acg.uwa.edu.au/srmp) plus site-specific expert judgement are used. This latter aspect of factor selection is critical in capturing site characteristics that are relevant at the specific mine as opposed to simply using generic factors, since each mine will have different drivers of seismicity and these must be reflected in the evaluation. For example, at one mine the faults may exert a controlling influence on the seismic response, whereas at another mine, due to the nature of the faults and their orientation relative to mining, they may have little influence. The weight assigned to factors will also be site-specific. For this reason, documentation of the factor selection and reasons for their inclusion becomes part of the set-up process for the AHP/ANP analysis, which also provides the paper trail for the analysis to use in future reviews, and possible modification if conditions should change. To illustrate this stage of the methodology, Table 2 shows a partial description of factors that will be used in the example later in this paper.

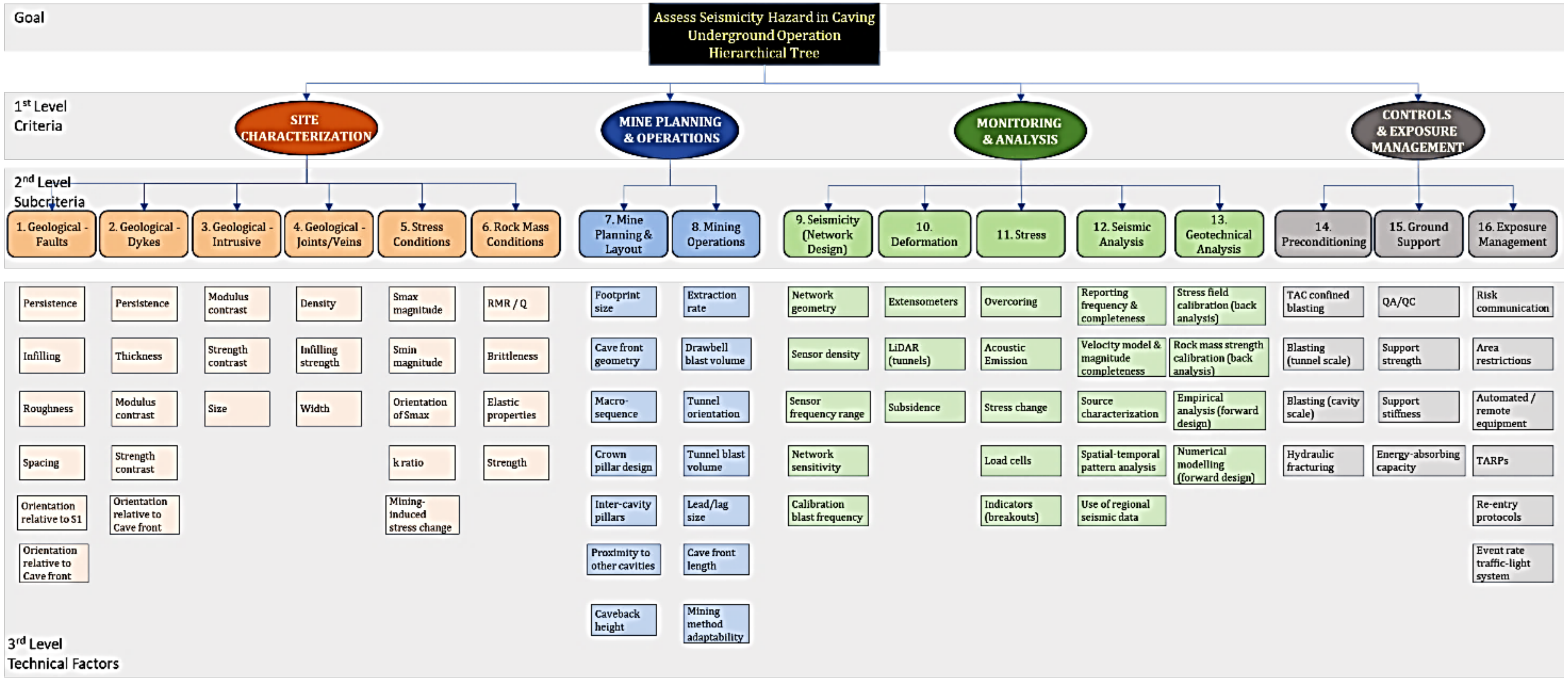

Figure 3 Hierarchical structure applied to seismic hazard assessment

Table 2 Example of criteria (left column) and factors that form part of site characterisation

A1 **Geological – faults**	A1.1 Persistence A1.2 Infilling A1.3 Roughness A1.4 Spacing A1.5 Orientation to S1 A1.6 Orientation to cavefront	Faults are potential slip surfaces. Their connectivity, strength and orientation relative to principal stress and excavation govern the likelihood of unstable shear and large events. More continuous → higher potential for larger slip spots • Weak clay/gouge can reduce stick-slip potential (more stable sliding) but may also reduce confinement locally; it sets direction based on observed behaviour at the site • Rough faults can lock and release in larger stick-slip; smooth faults may slide more easily but perhaps less violently – site specific • Closely spaced faults can segment slip (smaller events) but also create complex interactions • Favourably oriented for shear under current stress → higher slip potential • Structures daylighting or intersecting abutments/pillars can localise damage
A2 **Geological – dykes**	A2.1 Persistence A2.2 Thickness A2.3 Modulus contrast A2.4 Strength contrast A2.5 Orientation to cavefront	Dykes often create sharp stiffness/strength contrasts, causing stress concentrations and differential deformation – common nucleation sites for seismicity near cave abutments • Higher modulus contrast (stiff dyke in softer host or vice versa) → higher stress gradients → higher hazard • Greater thickness/persistence → more volumetrically significant stress perturbation • Strength contrast can create 'strong inclusions' that store elastic strain and fail violently
A3 **Geological – intrusive**	A3.1 Modulus contrast A3.2 Strength contrast A3.3 Size	Large intrusive bodies (e.g. porphyry phases) can behave as competent, brittle blocks with higher energy-release potential • Bigger + stronger + stiffer intrusive → higher potential for brittle rupture and larger events, especially if surrounded by weaker rock that transfers load
A4 **Geological – joints/veins**	A4.1 Density A4.2 Infilling strength A4.3 Width A4.4 Brittleness A4.5 Elastic properties A4.6 Strength	The joint/vein network governs whether deformation is distributed (many small cracks) or localised brittle failure (fewer, larger ruptures) • Large-event potential focus: lower joint density + strong/locked joints → more intact rock → more stored energy → higher hazard • Activity/rate focus: higher joint density → more sources for small seismic events → higher activity • Infilling strength and width influence shear/normal stiffness and slip tendency

In each of the level 2 subcriteria, several additional factors could have been included, but experience with multi-factorial AHP/ANP analysis shows that exclusion of factors with lesser importance does not change the outcome of the analysis. This emphasises the importance of expert judgement review in the initial phase of problem set-up so that factors with the most impact are not accidentally excluded. Also, for this example problem, there are 76 factors overall. The importance of each additional minor factor will therefore be heavily diluted by the presence of this large number of factors that are considered to have high importance.

3.2 Implementation of the analytic hierarchy process and analytic network process methodology

Figure 4 shows the general flow of tasks in implementing the AHP analysis methodology. Definition of the hierarchical structure is shown in Figure 3 and a sample of the factors influencing the seismic hazard are shown in Table 2. The next step in the AHP methodology is assignment of scores of importance in a pairwise comparison of factors. This is done using a judgement scale defined by Saaty (1990) representing the intensity with which one element dominates another with respect to the parent attribute. The scale is: 1 = equal dominance; 3 = moderate; 5 = strong; 7 = very strong; and 9 = extreme (2,4,6,8 are intermediate values).

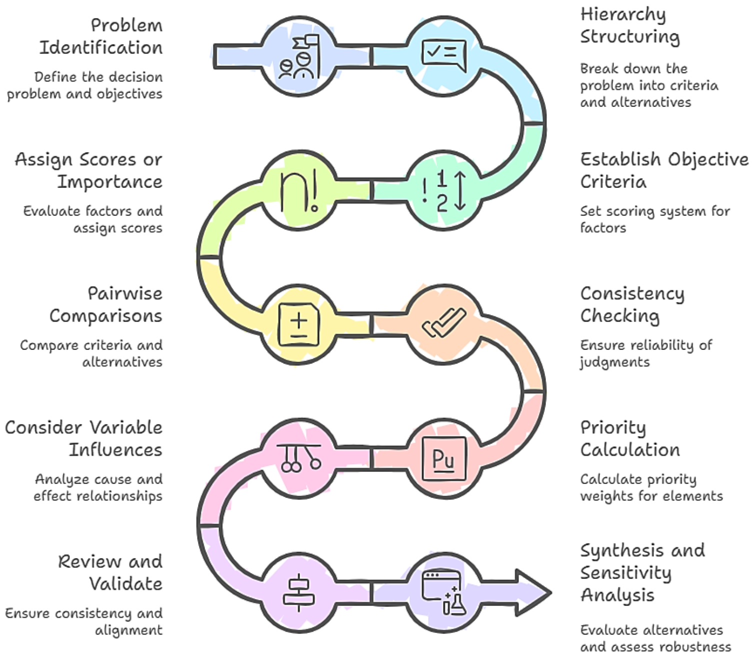

Figure 4 Generalised description of the analytic hierarchy process

4 Analytic hierarchy process and analytic network process assessment of a hypothetical mine

To fully illustrate the AHP/ANP analysis we describe the hypothetical El Temblante mine, for which the pairwise importance rating of factors will be carried out. In describing the mine, the structure outlined in Figure 3 is used, together with the descriptions of factors shown in Table 2. For brevity, only factors related to site characterisation will be described. It should be noted that the generic description of factors is provided for illustration purposes. If the site characterisation, operations, monitoring and controls (see Figure 3) vary across the mine, each 'domain' should be assessed separately and not averaged. Furthermore, the methodology is not exclusive to cave mines but applies to any mining method.

4.0 Site characterisation – geological factors

The main geological features of the El Temblante mine consist of fault, dykes, intrusive bodies, joints and veins from the deposit stockwork, state of stress and rock mass conditions. Each of these must be described in sufficient detail to enable an importance ranking of the constituent factors (Figure 3 and Table 2) to be determined.

Geological faults: faults are primarily sub-vertical, relatively young and show no signs of displacement, i.e. they have no infilling, fault surfaces are clean and rough, and the aperture is minimal. They have little to no associated damage zone surrounding the fault traces. The strike is principally northeast-southwest, although some local splays may vary significantly from this. Their spacing is variable, but in the tens of metres for intermediate faults and over 100 m for major faults. Based on mapping in tunnels and correlation across the macroblock footprint, major fault traces persist for hundreds of metres in all cases, and intermediate to minor faults may disappear across the footprint. For this particular macroblock, the cavefront will advance in a northwest direction, i.e. approximately perpendicular to the major fault systems. In other areas of the mine, faults have been found to be sources of large seismic events but, unless influenced by mining, they are not inherently seismically active.

Intrusive bodies: there are numerous intrusive bodies at the El Temblante mine. They are steep sided and in plan view have irregular external profiles. There are several that intrude into the footprints of the new deep projects. Since some extend to upper levels of the mine and have been encountered, experience shows that they are of concern for induced seismicity. Like the dykes, they tend to be massive (few joints) and of high contrast to the host rock in both strength and elastic properties. Rockbursting in the mine has been associated with both faults and intrusive bodies in approximately equal proportions. Their dimensions are highly variable in plan view, extending from tens of metres to over 100 m in some cases, and they are scattered almost randomly across the macroblock footprints so that there is no most-favoured orientation of cavefront that will minimise approach issues.

Similar detailed descriptions are compiled for each of the factors defined in the hierarchical structure shown in Figure 3. From these descriptions, a global 1–9 scoring meaning table for site characterisation is developed using Saaty's scale that applies consistently across the six subcriteria and is explicitly based in the technical-factor logic and interpretations.

4.1 Scoring of criteria

Two levels of scoring are subsequently carried out. Firstly, a scoring of each of the level 2 criteria is carried out to rank the importance of faults versus dykes versus stress conditions, etc. This provides the higher level of how the factors below each of these criteria are rated relative to each other in the global assessment (Table 3). Similarly, each of the level 3 subcriteria below each of these criteria is ranked in terms of importance (Table 4). An example of the weighting of factors for geological faults is shown in Table 4.

In the global assessment, the rating of the higher-level criteria is applied to all the lower-level subcriteria, so, in effect, subcriteria do not carry equal weight but are pro-rated according to how important that particular group of factors is within the overall context of its influence on seismic hazard.

Table 3 Global 1–9 scoring meaning for site characterisation

Score	Global scoring meaning	Site characterisation interpretation (using the technical-factor logic across A1–A6)	Typical evidence
9	Extreme hazard potential	Multiple strong drivers align for large-event potential: highly persistent/favourably oriented faults relative to stress and cavefront (A1); major stiffness/strength contrasts from dykes or intrusives (A2/A3); stress state with high deviatoric driving force and adverse orientation/anisotropy plus significant mining-induced stress change potential (A5); rock mass is strong, stiff and brittle with high elastic energy-storage capacity (A6); joint network tends towards fewer/locked structures enabling stored-energy release (A4)	High-confidence structural model (fault continuity/orientation); dyke/intrusive mapping with quantified contrasts; stress measurements indicating high Smax/deviatoric stress/anisotropy and strong sensitivity to Δσ; lab/field-derived strength, modulus and brittleness indices; structural fabric indicating potential for larger ruptures
7	High hazard potential	Clear predisposition for seismicity and/or large events, but not all drivers are simultaneously 'worst case', e.g. faults are present and favourably oriented but less continuous; contrasts are material but spatially limited; stress magnitudes/orientations are adverse but not extreme; rock mass energy-storage potential is high in key domains	Credible structural and lithological model; stress regime indicates elevated driving force; modulus/strength contrasts documented; rock mass properties show meaningful brittleness/stiffness; joint/vein attributes support stored-energy potential in some domains
5	Moderate baseline hazard potential	Baseline hazard exists but is generally bounded: faults/dykes/intrusives present but not strongly aligned; stress and confinement conditions are moderate; rock mass may be less brittle or less stiff; jointing may promote more distributed deformation (more small events rather than large ruptures)	Structural mapping shows limited continuity or unfavourable orientation; contrast features are smaller/less significant; stress state moderate with less adverse anisotropy; rock mass properties imply moderate energy storage; expected seismicity mainly small to moderate
3	Low hazard potential	Conditions generally favour small, localised events (or low activity overall) rather than damaging seismicity: faults are discontinuous/unfavourably oriented; contrasts minimal; stress state and confinement reduce brittle rupture likelihood; rock mass not strongly brittle/stiff	Limited major structure continuity; weak contrasts; moderate-to-low stress driving force; rock properties show lower modulus/brittleness; joint density and infill characteristics consistent with distributed deformation
1	Minimal hazard potential	Baseline hazard potential is negligible under the characterised conditions: the site lacks the structural/stress/material preconditions for significant seismic energy release	Consistent evidence that faults are not seismogenic (poor continuity/unfavourable orientation), contrasts negligible, stress driving force is low and rock mass behaviour is dominantly dissipative rather than brittle

Table 4 Evaluation of importance of factors related to geological faults

L2_SC subcriterion	Technical factor	Score guidance (1/3/5/7/9)	Final factor score
A1 Geological – faults	A1 Persistence	9: Very persistent/continuous faults; high large slip potential 7: Persistent faults common; large slip credible 5: Moderate persistence; slip possible but bounded 3: Discontinuous/segmented; large slip unlikely 1: Very limited persistence; minimal slip potential	8
	A2 Infilling	9: Infill/conditions promote unstable behaviour; high hazard contribution 7: Infill contributes to slip potential 5: Mixed/uncertain influence 3: Infill tends to reduce violent slip potential 1: Infill indicates minimal seismic slip hazard	2
	A3 Roughness	9: Rough/locked with high stick-slip potential 7: Moderately rough; stick-slip credible 5: Mixed roughness; bounded 3: Smooth/low locking; reduced large-event potential 1: Very smooth/creeping; minimal large-event contribution	6
	A4 Spacing	9: Spacing/interaction likely promotes damaging events 7: Spacing supports significant interaction 5: Mixed; bounded 3: Segmented/benign spacing; limits large events 1: Spacing suggests minimal hazard contribution	4
	A5 Orientation to S1	9: Strongly favourable for shear under current stress 7: Generally favourable; slip credible 5: Moderately favourable; bounded 3: Mostly unfavourable; slip unlikely 1: Unfavourable; negligible slip potential	3
	A6 Orientation to cavefront	9: Highly adverse relative to cavefront/abutments; strong localisation 7: Adverse; credible localisation 5: Mixed; bounded 3: Limited interaction with cavefront 1: No meaningful interaction with cavefront	9

4.2 Pairwise comparison and evaluation of factor importance

A central feature of the AHP/ANP methodology is its matrix format and the ability to subsequently calculate consistency diagnostics. There are many papers, including the original Saaty (1990) paper that outline the mechanics of the calculation process in detail, so they are not repeated here. Instead, a simplified description is provided to illustrate the main steps in the process.

The initial pairwise matrix $A = [a_{ij}]$ is formed with each element a_{ij} representing the relative importance of factor *i* relative to factor *j*. The diagonal elements are always 1, since *i* = *j*, i.e. it is the importance of a factor relative to itself.

The second step in the matrix evaluation process is to normalise the matrix, which is carried out such that $\sum w_i = 1$, where w is the weight of each pairwise comparison.

Finally, the consistency statistics are calculated. The CR evaluates the logical reliability of the decision-maker's evaluations by comparing the consistency of their normalised factor weight matrix against the expected consistency of a randomly generated matrix of the same size, ensuring their judgements are intentional and not arbitrary. If this value is less than 0.1 the result is acceptable, 0.10 < CR ≤ 0.20 is borderline and CR > 0.20 requires re-evaluation. For this study the process is implemented in a Power BI dashboard to facilitate graphical output for interpretation.

4.3 Results of analytic hierarchy process and analytic network process seismic hazard analysis of the El Temblante mine

4.3.0 Analytic hierarchy process seismic hazard assessment

The AHP analysis results for the El Temblante mine are shown in Table 5 and in more detail in Figure 5. The main results can be summarised as follows:

- In the AHP (pure hierarchy), the mine's intrinsic predisposition to seismic hazard (structures, stress, brittleness, contrasts) dominates the hazard picture; controls and monitoring are important, but secondary; operations/layout is the lowest contributor in this configuration.
- At the L2 (criteria) level, the AHP hierarchy is strongly dominated by site characterisation.
- CR/reliability of judgements are values indicating that the weightings are coherent and suitable for interpretation and decision support.
- AHP pairwise comparisons are internally consistent, with CR values in the low-single-digit (<10%).

Table 5 Analytic hierarchy process model results for the El Temblante mine

Criteria (level 2)	Hierarchical weighting	Consistency reliability
Site characterisation	54.43%	3.54%
Controls and exposure management	23.99%	2.37%
Monitoring and analysis	14.97%	3.69%
Mine planning and operations	6.62%	0.00%

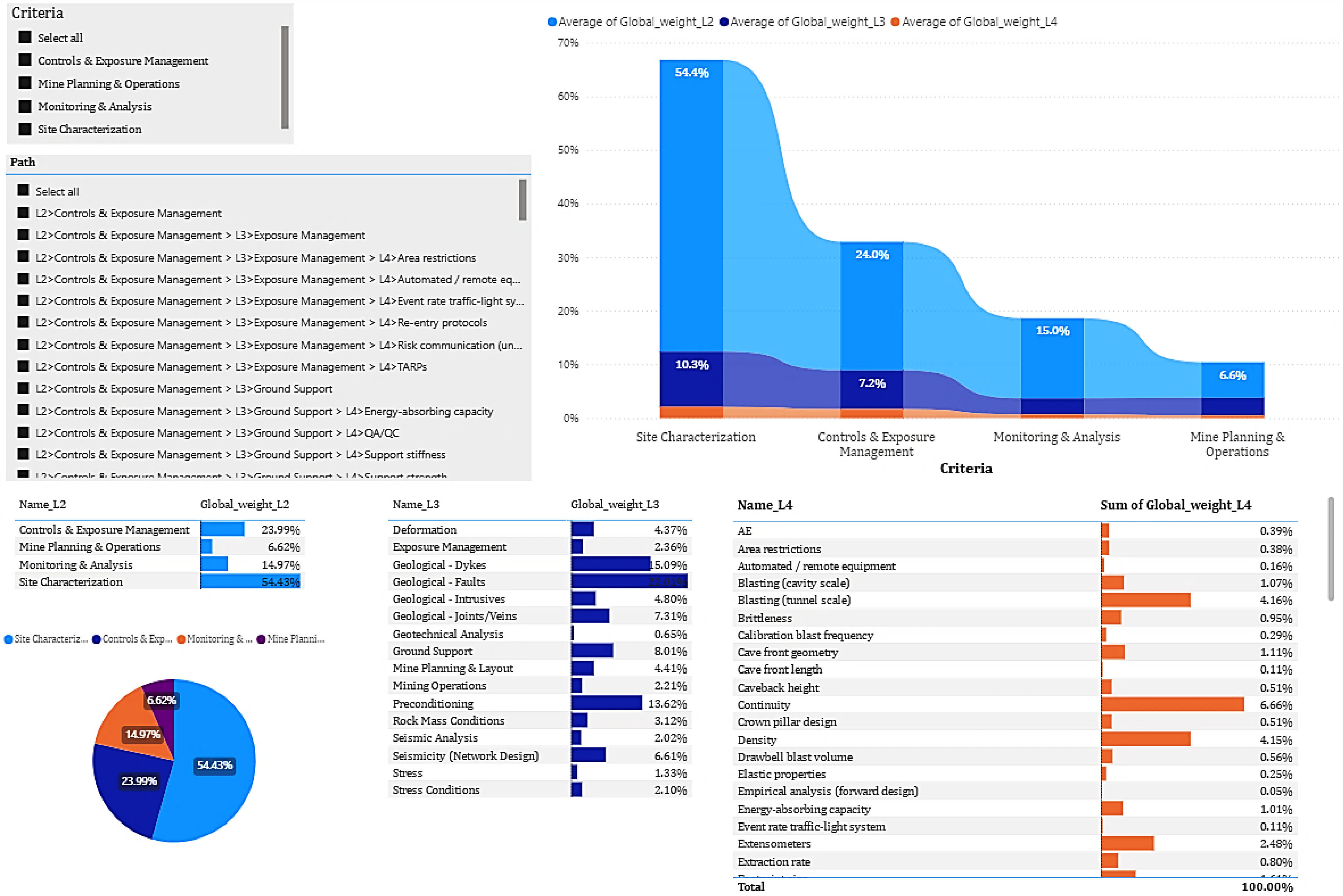

Figure 5 Seismic hazard analytic hierarchy process overall assessment

For the case of site characterisation, which has the largest overall influence, the specific factors are shown in Table 6. The AHP model shows that the biggest 'natural' hazard drivers are faulting and dyke-related contrasts (i.e. strong stiffness/strength contrasts and related stress concentrations), with joints/veins and intrusives as secondary but meaningful contributors. Large-event predisposition is primarily controlled by structure continuity/persistence, material contrasts, and energy-storage capacity drivers (stress magnitude + brittle/stiff rock), consistent with the site characterisation description of geological factors related to induced seismicity (Section 4.1) and the importance ranking of fault persistence (Table 4).

Table 6 Site weighting of site characterisation factors (subcriteria level 3)

Subcriteria (level 3)	Hierarchical weighting
Geological – faults	40.43%
Geological – dykes	27.72%
Geological – joints/veins	13.44%
Geological – intrusives	8.82%
Rock mass conditions	5.74%
Stress conditions	3.85%

4.3.1 Analytic network process seismic hazard assessment

When interdependencies are included (ANP), the relative importance becomes more balanced, indicating that monitoring capability and the effectiveness of controls and operational responses are almost as influential as the inherent site conditions in determining the realised seismic hazard.

The ANP implementation introduces interactions (dependencies/feedback) via the influence/ interaction matrix and then calculates integrated weights across the network. As a result, the top-level balance shifts markedly, as shown in Table 7 and detailed in Figure 6.

This is the classic ANP effect: dominance reduces and weights become more distributed across interacting clusters (L2/L3/L4).

In the ANP model, the interpretation indicates that, since monitoring, controls and operational decisions influence each other (and influence the hazard trajectory), the system's ability to detect, interpret and manage hazard becomes nearly as important as the baseline geology/stress.

Table 7 Analytic network process results model (level 2)

Criteria (level 2)	Hierarchical weighting
Site characterisation	34.61%
Controls and exposure management	29.12%
Monitoring and analysis	18.54%
Mine planning and operations	17.74%

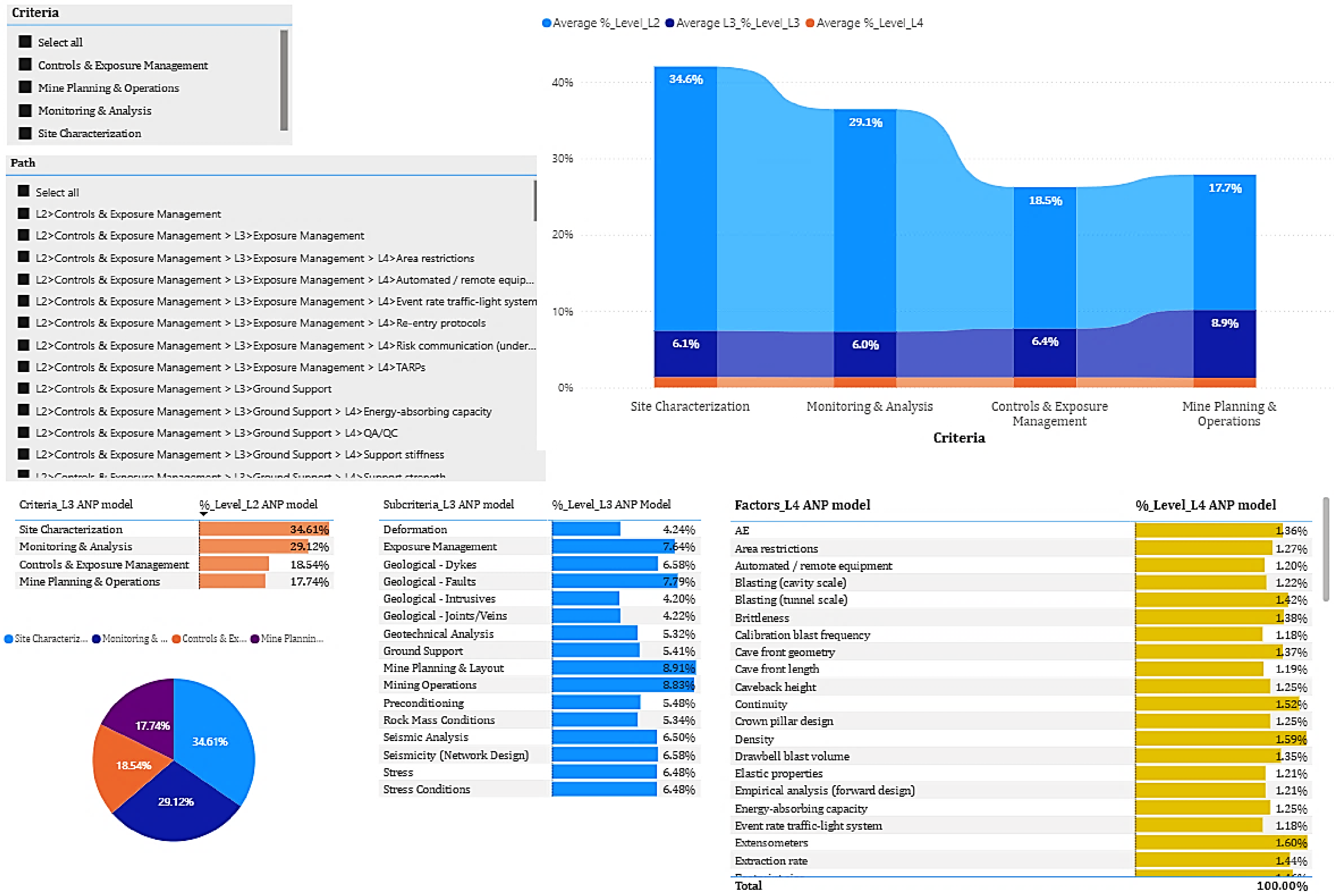

Figure 6 Seismic hazard analytic network process overall assessment

4.4 Interpretation of results

Across AHP and ANP, the model consistently identifies a high-influence set of themes. Their comparative weightings are shown in Table 7 and these results can be interpreted as:

- Structural and contrast-driven sources matter most. Faults, dykes, intrusives and vein/joint characteristics consistently carry high weight because they govern where stress localises and where large events can nucleate.
- Monitoring quality is not optional. Seismic network geometry/density and timely reporting/pattern analytics are repeatedly highlighted as critical decisions.
- Controls that change response and strong support remain central. Preconditioning and support capacity are high contributors in both the AHP hierarchy and the ANP integrated system view.

It should be noted that the interpretation of results is based strongly on the assignment of importance factors, which is in turn based on experience and knowledge from the site being assessed. These results are therefore specific to the hypothetical El Temblante mine and may differ from general experience.

Table 8 Hierarchical versus integrated assessment: analytic hierarchy process (AHP) versus analytic network process (ANP)

L2 criteria	AHP Hierarchical weights	ANP Integrated weights
Site characterisation	54.43%	34.61%
Controls and exposure management	23.99%	29.12%
Monitoring and analysis	14.97%	18.54%
Mine planning and operations	6.62%	17.74%

5 Conclusion

Current industry best practice for seismic hazard assessment typically relies on two distinct analytical streams: statistical analysis of historical seismicity and deterministic numerical stress modelling. While foundational for defining the hazard envelope, these conventional methods are unable to account for many factors known to influence seismic hazard. These limitations may be overcome by using MCDM frameworks such as the analytic hierarchy process (AHP) and analytic network process (ANP).

Statistical methods, primarily based on Gutenberg-Richter magnitude-frequency relations and activity rate monitoring (e.g. 'traffic light' systems), are inherently backward-looking and heavily assume historical stationarity: the premise that future rock mass response will mimic past behaviour. In rapidly evolving cave environments where extraction fronts intersect new geological domains, this assumption is often invalid. Furthermore, statistical parameters function as lagging indicators, detecting hazard state changes only after the rock mass has begun to deteriorate. They are also devoid of any specific geological information or operational factors.

Deterministic numerical models (boundary element or finite element methods) address the predictive shortfall of statistics by simulating stress redistribution, and estimating fault slip via excess shear stress, maximum seismic event magnitude (M_{max}) through slip displacement, and energy release. Numerical models are strict physical idealisations that cannot incorporate operational factors that heavily influence risk, such as workforce exposure, draw control compliance or the quality of ground support installation. Additionally, these models are deeply reliant on precise calibration; uncalibrated models offer only relative scenario comparisons and are plagued by the epistemic uncertainty of input parameters (e.g. in situ stress, fault friction angles).

Past attempts at including seismic data analysis results with geological site conditions and operational factors have been made e.g. Dunn & Laas (1999) and Disley (2014). Based on the authors' experience, similar methods have been developed locally at various mines. However, such methods have not been widely adopted. The principal differences between these methods and the AHP lie in their theoretical foundations, methods for deriving weights, handling of measurement scales and the measurement of logical consistency. While AHP is a highly structured, mathematically rigorous theory of relative measurement, these methods are empirical, heuristic-based engineering tools heavily reliant on subjective assignment. There are additional differences in the assignment of weights, which are calculated mathematically in the AHP methodology as opposed to arbitrary mathematical functions (e.g. Dunn & Laas 1999). Furthermore, the AHP methodology makes use of specific ratio scales to preserve the relative strength between factors, does not rely on arbitrary adding or multiplying weights but uses rigorous matrix algebra, can handle many more factors in the evaluation and includes a consistency check to identify which judgements should be revised to improve consistency.

The AHP and ANP bridge the critical blind spots of conventional methods by integrating hard quantitative data (e.g. stress tensors, seismic catalogues) with qualitative expert judgement (e.g. operational design execution, seismic hazard protocols) into a unified MCDM framework.

The AHP and ANP methodologies do not replace geomechanical analysis; rather, they serve as the 'decision engine' that integrates rigorous technical findings with operational realities. By providing a mathematical framework that leverages pairwise comparisons and strictly validates expert judgement through a consistency ratio, AHP and ANP transform fragmented, multidisciplinary data into a transparent, repeatable and auditable governance tool. This ensures that hazard prioritisations and capital allocation for risk mitigation are technically defensible and devoid of the hidden biases inherent in unstructured qualitative assessments.

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