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Multi-criteria analysis of construction methodologies and lining options for deep bored shaft excavations

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ABSTRACT: The design and construction of shafts for underground ventilation and access requires a nuanced approach to decision-making, balancing safety, constructability, schedule, resource availability and cost-effectiveness. This study presents a method for Multi-Criteria Analysis (MCA) of construction methodologies and lining options for deep bored shaft excavations. The objective is to evaluate multiple, often conflicting performance criteria to weigh the relative risks and benefits of each option. The goal is to identify which method should be advanced to detailed design. The analysis integrates field data from a real-world ventilation shaft project and offers a practical framework for comparing excavation and lining techniques. It demonstrates how informed decisions can reduce project risks, improve delivery efficiency, and support long-term performance. The MCA process highlights the value of structured stakeholder engagement and transparent risk evaluation in geotechnical design. This approach supports confident, defensible decision-making in complex subsurface environments.

1 INTRODUCTION

The construction of vertical shafts for underground coal mining—particularly for ventilation and access—presents complex engineering and logistical challenges. These stem from heterogeneous ground conditions, fluctuating groundwater regimes, and the high capital cost of shaft infrastructure. Decisions made in early project phases carry substantial implications for safety, schedule, and long-term performance.

To support structured and transparent decision-making under such conditions, Multi-Criteri-Analysis (MCA), also known as Multi-Criteria Decision Analysis (MCDA), offers a robust evaluation framework. MCA allows systematic comparison of alternatives based on multiple, often competing criteria. Its application spans various engineering fields, including infrastructure development and geotechnical design (Saaty, 1980; Dodgson et al., 2009).

The fundamental steps involved in undertaking an MCA process typically include (Dodgson et al., 2009):

– Defining the decision-making problem and its objectives.
– Identifying the potential alternatives.
– Establishing relevant performance criteria.
– Gathering quantitative and qualitative information on each option.
– Assigning preference weightings to the criteria based on their relative importance.
– Evaluating alternatives against these criteria.
– Selecting the most appropriate solution.

This paper presents a case study that demonstrates the application of MCA in the context of a deep bored shaft constructed for a Central Queensland underground coal mine. The purpose of the MCA was to evaluate excavation and lining options for two key shaft segments—upper and lower—underpinning design decisions that balance geotechnical, operational, and cost-related risks.

One of the principal challenges encountered in MCA application is the inherent subjectivity associated with assigning risk scores and weightings. Variability in expert judgement, incomplete information, and differing stakeholder priorities can lead to bias or reduced transparency. To address this limitation, a structured MCA workshop was convened, engaging representatives from multiple disciplines including geotechnical engineering, construction, mine operations, and cost estimation. The collaborative format enabled collective scrutiny of risks and facilitated alignment of perspectives. As a result, scoring was grounded in site-specific evidence and operational insight, thereby increasing confidence in the robustness and defensibility of the selected solutions.

2 CASE STUDY – LINING OPTIONS FOR DEEP BORED SHAFT EXCAVATIONS

This case study illustrates the practical application of MCA to a real-world shaft excavation project undertaken in the Bowen Basin, Central Queensland. The primary objective of this case study is to evaluate the relative performance of a range of excavation and lining methods for a deep bored shaft, which was required to serve as the primary ventilation and access point for an underground coal mine. The case was selected due to its representative ground conditions, operational complexity, and the need for a structured decision-making framework. By implementing the MCA methodology in a project environment characterised by variable geology, high groundwater potential, and stringent operational timelines, the study demonstrates how multi-criteria assessment can guide the selection of robust, cost-effective and constructible design solutions.

2.1 *The proposed shaft development*

The MCA case study described here focuses on the construction of a bored ventilation shaft for an underground coal mine. The planned final depth of the shaft was 80 m and the planned final internal diameter was 4.5 m.

For the purposes of the geotechnical design and construction, two distinct zones were defined within the shaft, including:

(1) Upper Shaft – (US) – comprising the zone between ground level and the top of moderately weathered Permian rock; and

(2) Lower Shaft – (LS) – the zone below the top of moderately weathered Permian rock.

The MCA approach involved systematically weighing up the relative advantages and disadvantages of a range of prospective shaft excavation and lining method options. It considered the complex interplay between multiple criteria to ensure that decision-making aligned with the project's predefined objectives. The ultimate objective of the MCA was to identify which option or options were to be carried forward to the detailed analysis and design stages of the project, and ultimately be applied in the construction of the shaft.

2.2 *Site Investigation and Ground Model Development*

The project site is located within the Early Permian to Middle Triassic Bowen Basin; a major coal-bearing geological basin that extends for approximately 600 km from Collinsville in the north to Theodore in the south. The site location is underlain by surface deposits of unconsolidated Quaternary alluvium (CLAY, Clayey SAND and Sandy CLAY), which are in turn underlain by poorly lithified Tertiary aged sediments (typically weathered to CLAY and Sandy CLAY). Tertiary aged basalt flows are also known to occur in the area, however these were not encountered at the shaft location. Underlying the Quaternary and Tertiary deposits are the Permian-aged Fort Cooper and Moranbah Coal Measures of the Blackwater Group.

Given the critical role of ground conditions in construction method feasibility and risk management, a detailed understanding of the subsurface profile was essential. Site characterisation involved a phased investigation strategy incorporating regional geological review, surface mapping, and targeted drilling. The centrepiece of this effort was a fully cored geotechnical borehole extending to 95 m depth, providing high-resolution data on lithology, rock mass quality, weathering profiles, and groundwater conditions. These data were foundational to both preliminary design development and to the MCA framework, ensuring that each construction and lining option could be robustly assessed against realistic subsurface scenarios.

Ground conditions encountered in the fully cored geotechnical borehole drilled to investigate the planned shaft location are summarised in Table 1. These data informed the stratigraphic interpretation and were critical in defining geotechnical boundaries relevant to construction risk and shaft segmentation.

Table 1. Summary of ground conditions.

Stratigraphy	From Depth (m)	To Depth (m)	Thickness (m)	Strength	Weathering
Quaternary Alluvium (CLAY & Sandy CLAY, Clayey SAND)	0	8.8	8.8	VSt-H/ L-MD	N/A
Tertiary Sediments (CLAY & Sandy CLAY)	8.8	12.95	4.15	VSt-H	N/A
Extremely Weathered Permian Interbedded Sandstone & Mudstone	12.95	13.6	0.65	L	XW
Weathered Permian Sandstone	13.6	20.7	11.9	L-M	HW-MW
Fresh Permian Sandstone, Mudstone & Coal	20.7	95	69.5	M-H	SW-FR

2.3 *Shaft zoning and functional requirements*

Based on the stratigraphy, geological sequence, and geotechnical properties revealed by the site investigation, the shaft was subdivided into two distinct functional zones to guide the construction methodology selection:

- Upper Shaft (US): Extending from ground level to the top of moderately weathered Permian rock (~19 m depth), this zone is dominated by weak, highly weathered materials including alluvial soils and Tertiary sediments. The design focus in this zone was on minimising groundwater inflow and ensuring excavation stability.
- Lower Shaft (LS): Commencing at the base of the Upper Shaft and extending to the final shaft depth (80 m), this zone is characterised by more competent Permian rock, including interbedded sandstone, mudstone, and coal seams. Construction in this zone required methods that could accommodate hard rock excavation, potential methane gas emissions, and maintain interface compatibility with underground mine workings.

These zone definitions were critical in framing the MCA, as they required consideration of construction methodologies capable of addressing different ground behaviours, support requirements, and interaction with the mine's operational timeline.

3 CONSTRUCTION AND LINING OPTIONS

Based on the defined shaft zoning and prevailing ground conditions, a set of construction and lining options was developed for both the Upper Shaft and Lower Shaft. Each option was designed to address the unique geotechnical, hydrogeological, and operational challenges associated with its respective shaft segment. The following options were identified and assessed:

3.1 *Upper shaft options*

Four alternative methodologies were considered for the excavation and support of the Upper Shaft:

- US-1: Box Cut with Steel Pre-Sink Collar. Excavation of a box cut to 17.1 m depth, installation of a steel pre-sink collar, and backfilling with stabilised sand. A concrete surface slab would then be constructed to accommodate the blind bore or raise bore rig.

- US-2: Secant Pile Ring Wall. Installation of a secant pile ring wall to 19 m depth using a guide wall and temporary platform. The piles are integrated with a surface concrete slab and capping beam.
- US-3: Box Cut with Micro-Pile Ring Wall. Combination of box excavation to 14 m depth and vertical micro-pile reinforcement from 14 m to 19 m depth. Stabilised sand backfill and concrete slab construction follow.
- US-4: Contiguous CFA Pile Wall with Shotcrete Support. Construction of a CFA pile wall to 19 m depth with reinforced concrete capping beam at surface level. Excavation inside the pile wall proceeds in stages to 17.1 m depth, with permanent shotcrete lining applied progressively.

3.2 *Lower shaft options*

Four alternatives were considered for the deeper, rock-dominated Lower Shaft:

- LS-1a: Raise Bore with Selective Shotcrete Support. Following pilot hole drilling and raise boring, selective areas of the shaft are stabilised using steel fibre reinforced shotcrete. Target areas for shotcreting are selected based on video inspection.
- LS-1b: Raise Bore with Full Steel Liner. A continuous steel liner is installed following raise boring. The annulus is back-grouted for full contact and corrosion protection.
- LS-2a: Blind Bore with Staged Shotcrete. Blind boring with drilling fluid support, staged dewatering, and sequential application of shotcrete at intermediate and final excavation depths.
- LS-2b: Blind Bore with Full Steel Liner. Full-depth blind boring with drilling fluid support, followed by installation of a steel liner and back-grouting to secure the lining and prevent groundwater ingress.

Each of these construction and lining options formed the basis of the MCA evaluation discussed in the following section.

4 MCA METHODOLOGY

The MCA process was structured to assess the relative merits and risks of each proposed construction and lining option. A two-stage evaluation was implemented:

- Stage 1: Performance Risk Scoring – Each option was scored qualitatively against a predefined set of performance criteria using a scale of 1 to 5, where 1 indicated very low risk and 5 indicated very high risk. A score of 99 denoted a fatal flaw.
- Stage 2: Importance Weighting – Key criteria were assigned weighting factors (1 for neutral importance, 2 for high importance) to reflect their relative impact on project success.

4.1 *Performance criteria*

The following performance criteria were used to evaluate each construction and lining option during the MCA process. These criteria reflect the critical technical, financial, and operational risks relevant to deep shaft excavation in complex ground conditions:

- Geotechnical Risk: Likelihood of instability or deformation of the shaft walls due to varying soil and rock conditions, particularly in zones with weak or weathered materials.
- Groundwater Risk: Risk of water inflow during or after construction, influencing excavation safety, lining integrity, and long-term maintenance requirements.
- Financial Risk of Contingency Measures: Potential cost exposure from unplanned remedial measures required to address unexpected ground behaviour or construction complications.
- Ease of Mobilisation and Set-up: Practical challenges and time requirements associated with assembling equipment, infrastructure, and workforce at the site.
- Impact on Critical Path Activities: Influence on the overall project timeline, particularly on activities that directly control project completion.
- Mine Schedule Alignment: Compatibility with mining operations and sequencing, including whether shaft completion enables or delays key underground development milestones.
- Construction Cost (CapEx): Estimated upfront capital expenditure required for shaft excavation and lining.

- Whole-of-Life Cost: Combined cost of construction, inspection, maintenance, and potential rehabilitation over the shaft's operational life.
- Availability of Qualified Contractors: Market availability and scheduling flexibility of specialist contractors capable of delivering each method to specification.
- Confidence of Successful Implementation: Likelihood that the method will be executed on time, within budget, and without major construction or operational setbacks.
- Impact on Underground Operations: Degree to which shaft construction interferes with existing or planned underground activities, such as requiring access from underground or causing downtime in adjacent mining zones.

To address potential subjectivity in the evaluation process, a structured MCA workshop was conducted involving representatives from geotechnical design, construction planning, mining operations, and commercial management. This multidisciplinary input ensured that scoring and weighting were grounded in both technical knowledge and practical constraints. Discussions during the workshop enabled clarification of assumptions, exploration of risks, and consensus on performance expectations.

The resulting matrix of risk scores and weightings formed the quantitative basis for ranking each construction and lining option.

4.2 *Qualitative risk rating system*

To support the MCA scoring process, a qualitative risk rating system was adopted to ensure consistency and clarity in the assignment of scores. This system defined risk levels across a scale from 1 to 5, with an additional score of 99 used to represent fatal flaws. Each rating corresponds to a general level of concern based on likelihood, severity, and potential impact:

- Rating 1: Very Low Risk – Negligible likelihood or impact; no contingency required.
- Rating 2: Low Risk – Limited likelihood or impact; manageable with routine controls.
- Rating 3: Moderate Risk – Reasonable likelihood and/or moderate impact; mitigation measures required.
- Rating 4: High Risk – High likelihood or impact; significant contingency measures anticipated.
- Rating 5: Very High Risk – Very high likelihood or severe impact; unacceptable without major risk reduction.
- Rating 99: Fatal Flaw – Option is not viable due to prohibitive technical, safety, or operational reasons.

These ratings allowed stakeholders to articulate and quantify risks based on their domain of expertise while preserving a consistent scoring structure across all criteria.

4.3 *Importance Weighting of Performance Criteria*

To reflect their differing levels of criticality, each performance criterion was assigned an importance weighting. This weighting allowed the MCA process to prioritise those criteria deemed most influential in determining the success of the shaft construction. Two weighting levels were adopted:

- Weighting 1 – Neutral Importance: Assigned to criteria considered relevant but not disproportionately influential to the project's outcomes.
- Weighting 2 – High Importance: Assigned to criteria with high impact on project feasibility, safety, operability, or cost.

The weighting structure was agreed upon by consensus during the MCA workshop to ensure balanced representation of technical, commercial, and operational priorities.

4.4 *Key assumptions*

The MCA was developed and applied under a set of defined assumptions that reflect known site conditions, anticipated operational needs, and broader project delivery constraints. These assumptions were agreed upon during the MCA workshop to ensure a common understanding and to avoid scoring discrepancies due to differing expectations. Key assumptions included:

- The shaft would have a finished internal diameter in the range of 4.0 m to 4.5 m.

- The operational life of the shaft would be approximately 10 years.
- The shaft would serve as the primary ventilation conduit for the underground mine, requiring continuous operability.
- Construction of the Upper Shaft would likely coincide with the wet season, implying elevated groundwater levels in near-surface strata.
- Specialist shaft construction contractors and equipment would be available but potentially constrained by procurement lead times.
- The shaft construction program would need to align with the broader mine schedule to avoid delays to critical underground access milestones.

These assumptions informed both the technical evaluation and the practical feasibility assessments of the alternative design and construction options.

5 MCA RESULTS AND DISCCUSSION

The MCA produced a clear ranking of the evaluated construction and lining options based on weighted performance scores. In addition to identifying technically feasible solutions, the process enabled the early exclusion of options carrying unacceptable risk profiles.

One key feature of the methodology involved the use of a 'fatal flaw' rating. Score 99 was assigned to any criterion where an option exhibited a non-negotiable failure risk. This ensured that options presenting insurmountable challenges—such as unacceptable whole-of-life maintenance liabilities or unmanageable groundwater ingress—were systematically removed from consideration. For example, shotcrete lining options were excluded due to concerns around adhesion under wet conditions, risk of degradation over time, and limited ability to safely perform repairs without disrupting mine operations.

Two critical differentiators in the MCA were whole-of-life costs and confidence of success. These provided valuable insight into long-term viability and delivery risk.

Whole-of-life cost considerations extended beyond initial capital expenditure to include recurring inspection, maintenance, and potential rehabilitation demands. Shotcrete-based options were significantly penalised due to anticipated ongoing inspection and remedial requirements—with any video inspections, surveys or remedial shotcrete application activities all necessitating interruptions to the shaft (and therefore mine) operation— posing poor maintainability and high operational risks. In contrast, steel-lined solutions were favoured for their durability and low maintenance profile, reducing total lifecycle costs.

Confidence of success reflected constructability under expected ground conditions, availability of proven construction methodologies, and contractor familiarity. Shotcrete-supported designs scored poorly due to known performance issues in wet environments—related to poor adhesion and washout of the shotcrete—and execution difficulties in deep, confined shafts—related to electrical safety challenges with the operation of the remotely operated shotcreting rig within the potentially explosive gas (methane) environment. Blind bored steel-lined options, in contrast, demonstrated alignment with established techniques, providing greater assurance in delivery.

Table 2 summarises the risk scores and criteria importance weightings derived for each option. The results highlighted significant variability in performance, particularly in relation to lifecycle cost exposure, constructability confidence, and groundwater or geotechnical risk.

Table 2. summary of risk scores by performance criteria.

Performance Criteria	Unweighted Qualitative Ratings				Importance Weighting	Weighted Qualitative Ratings			
Upper Shaft (Ground Level to 17.1 m bgl[1])									
Option Number	US-1	US-2	US-3	US-4	-	US-1	US-2	US-3	US-4
Geotechnical Risk	3	2	3	2	2	6	4	6	4
Groundwater Risk	5	1	5	3	2	10	2	10	6
Financial Risk	4	1	4	3	1	4	1	4	3
Ease of mobilisation	1	3	3	4	1	1	3	3	4
Critical Path Impact	5	3	5	4	2	10	6	10	8
Mine Schedule	1	1	1	1	1	1	1	1	1
Construction Cost	1	4	3	4	2	2	8	6	8
Whole-of-Life Cost	1	1	1	1	1	1	1	1	1
Avail. of Contractors	1	3	2	3	1	1	3	2	3
Conf. of Success	3	1	3	4	1	3	1	3	4
Imp. on Underground	1	1	1	1	1	1	1	1	1
Total Scores:	26	21	31	30	-	40[2]	31	47[3]	43
Lower Shaft (17.1 m to 80 m bgl)									
Option Number	LS-1a	LS-1b	LS-2a	LS-2b	-	LS-1a	LS-1b	LS-2a	LS-2b
Geotechnical Risk	3	3	2	1	2	6	6	4	2
Groundwater Risk	4	3	2	1	2	8	6	4	2
Financial Risk	4	4	2	2	1	4	4	2	2
Ease of mobilisation	4	4	2	2	1	4	4	2	2
Critical Path Impact	3	2	4	3	1	3	2	4	3
Mine Schedule	4	4	1	1	1	4	4	1	1
Construction Cost	3	4	3	4	2	6	8	6	8
Whole-of-Life Cost	99	2	99	2	2	198	4	198	4
Avail. of Contractors	2	2	3	3	1	2	2	3	3
Conf. of Success	99	1	99	1	1	99	1	99	1
Imp. on Underground	5	5	1	1	2	10	10	2	2
Total Scores:	230	34	218	21	-	344[4]	51	325[4]	30

*Notes:

1. m bgl = Metres below ground level.
2. For Upper Shaft Option 1, if the blind bore method were adopted for the Lower Shaft, the Box Cut depth could be reduced to 14 m bgl and the risk score would be ≤40.
3. For Upper Shaft Option 3, if blind bore were adopted for Lower Shaft, the requirement for micro-piles between 14 to 19 m bgl could be eliminated and the risk score would be ≤40.
4. Lower Shaft options incorporating shotcrete support were assigned Fatal Flaw ratings due to: (1) “Whole-of-life costs” and (2) Low “Confidence of Success”.

5.1 *Upper shaft results*

Among the Upper Shaft options, US-2 (Secant Pile Wall to 19 m) emerged as the preferred solution. This option offered high confidence in construction success, robust groundwater exclusion, and minimal interface complexity. Other options, such as US-1 and US-3, were associated with higher risks due to reliance on temporary support systems and uncertain ground behaviour in the upper strata.

5.2 *Lower shaft results*

For the Lower Shaft, LS-2b (Blind Bore with Steel Liner) scored significantly better than the alternatives. It offered the highest level of construction reliability, minimal dependence on underground development, and reduced risk of failure due to groundwater or methane ingress. Shotcrete-based options (LS-1a and LS-2a) were penalised for the aforementioned performance issues, execution difficulties, poor maintainability and high operational risks, receiving fatal flaw ratings in several criteria.

5.3 *Lessons Learned from MCA Process*

The structured MCA process enabled comprehensive evaluation of construction and lining options by integrating technical performance, stakeholder input, and implementation risk. The workshop format proved especially valuable, surfacing practical issues that might have been overlooked in a conventional assessment. Incorporating lifecycle and constructability considerations allowed the team to distinguish between options with theoretical merit and those with proven, repeatable execution outcomes.

6 CONCLUSIONS

This study highlights the effectiveness of a structured Multi-Criteria Analysis (MCA) process in guiding complex shaft construction decisions. The framework enabled transparent evaluation of diverse technical and operational options amid uncertainty and competing priorities.

Success relied on active stakeholder engagement through a collaborative workshop, where assumptions were tested, risks clarified, and consensus reached. Key challenges—including subjectivity in scoring, future maintenance uncertainty, and schedule alignment—were openly addressed.

By using agreed performance criteria and importance weighting, the team identified solutions that were both technically feasible and operationally reliable. Lifecycle and constructability considerations were effectively integrated, helping to eliminate options with fatal flaws.

The process provided a shared decision-making foundation and allowed the project to move into detailed design with confidence and alignment across all disciplines.

7 REFERENCES

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