Ground Support 2026 - D Cumming-Potvin & J Wesseloo (eds.)
© 2026 Australian Centre for Geomechanics, Perth
doi:10.36487/ACG_repo/2625_24

Industry benchmarks for ground support quality assurance/ quality control practices

Ruth Michelle Stephenson [a,*], **Christopher Richard Moulding** [b]

[a] *Mine Mentor Pty Ltd, Australia*

[b] *Operational Geotechs Pty Ltd, Australia*

Abstract

Quality assurance and quality control (QA/QC) is key to achieving the support's intended performance. Significant effort can be spent on support design, but if the design is not well implemented, much of this effort is undermined, and the design Factor of Safety should be increased potentially leading to conservative designs. Quality assurance is ensuring that a task is adequately completed, preventing poor quality. Quality control is a validation to detect poor quality.

There are 3 major components to QA/QC which are before, during, and post-installation. All 3 are critical to the implementation of geotechnical designs at any underground operation. QA/QC programs are typically designed with consideration to the key issues with each type of support element, testing frequency, acceptance criteria, and reporting of the results.

Global industry benchmarking data for test types, frequency, acceptance criteria, among other aspects, were compiled from recent ground control management plans from various underground operations around the world. These are presented to assist operations in the design or review of the ground support QA/QC programme, consistent with established industry practice.

Keywords: *quality assurance, quality control, QA/QC, ground support, Benchmarking*

1 Introduction

Considerable effort is required for the design, selection, and installation of ground support systems in underground mines. However, this effort may be undermined if the support is not installed to the required standard. As such, ground support quality assurance and quality control (QA/QC) programs are commonly implemented to:

1. ensure installation activities are completed to the required standard, preventing poor quality (quality assurance).
2. verify the installed support to identify any deficiencies (quality control).

Both elements are required in combination for a QA/QC program be effective (Yeni 2024).

The extent of the program would be designed with personnel exposure in mind. High consequence excavations, such as crib rooms and major accesses would justify a more extensive programme than an area with limited exposure such as inactive headings. The cost and time associated with QA/QC effort would be balanced against risk reduction.

Ground support QA/QC programs are widely used as a critical control to help ensure support is installed in accordance with designs to achieve the intended performance. In some jurisdictions, such as Ontario, Canada, QA/QC requirements are legislated (Section 73 of Ontario Regulation 854 [Government of Ontario

* Corresponding author. Email address: ruth@mine-mentor.com

2025]). In Western Australia, ground control guidance incorporates both quality assurance and quality control, highlighting the importance of adequate personnel training and supervision to support the effective installation of ground support (Western Australian Department of Mines, Industry Regulation and Safety 2019). This also extends into principal mine hazard plans, which are becoming more common requirements for licenses to operate and mine-specific risk-based assessments (e.g. *Work Health and Safety (Mines) Regulations 2022 (WA)* [Government of Western Australia 2022], Schedule 19 - Principal Mining Hazard Management Plans, Clause 1: Geotechnical Structure Instability).

2 QA/QC programs

QA/QC programs are typically designed with consideration of the dominant failure mechanisms and installation sensitivities associated with each support type. Ground support QA/QC programs comprise 3 primary components:

- Pre-installation: excavation quality, procurement of the correct support elements, verification of supplied materials, and appropriate storage conditions.
- During installation: observation of installation practices and the application of technologies such as scanning.
- Post-installation: testing of support elements, inspection of installed support (including rehabilitation requirements), and assessment of corrosion.

All 3 components are critical to the effective implementation of geotechnical designs in underground operations. Some aspects, particularly inspections, are closely linked to ground support monitoring practices.

To be effective, a QA/QC program defines the frequency and methods of testing for all support elements, acceptance criteria, responsibilities for QA/QC activities, systems for recording and managing data, and communication protocols for reporting results and addressing identified issues.

Key QA/QC focus areas include:

- Friction bolts: verification of hole diameter (e.g. bit gauges or drive time correlations) and bolt installation quality (e.g. bolt angles and spacing).
- Fully encapsulated bolts: confirmation of adequate encapsulation (Figure 1).
- Cable bolts: grout consistency, full encapsulation, and plate tensioning (Figure 2).
- Shotcrete: early-age strength, coverage, and thickness, with flexural strength becoming increasingly important in higher stress environments.
- Mesh: coverage and overlap requirements (Figure 3).



Figure 1 Examples of poor encapsulation for resin bolts



Figure 2 Example of poor encapsulation for cable bolts

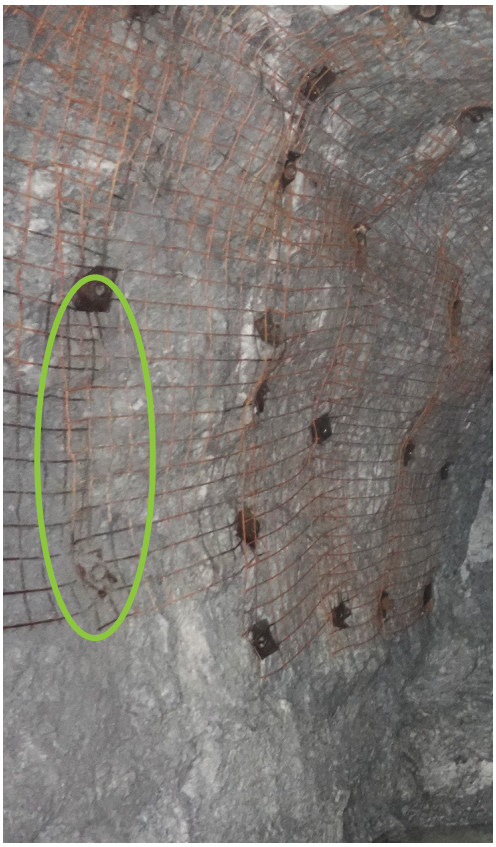


Figure 3 Example of poor-quality mesh overlaps (one square instead of 2)

2.1 Prior to installation

Prior to installation, the QA/QC measures implemented include excavation quality and the procurement, quality, and storage of support elements.

Poor blasting practices, inadequate scaling, and excessive overbreak can adversely affect ground support performance. Where excavation quality exceeds design assumptions, a review of ground support requirements is often undertaken. Maximum excavation dimensions specified on ground support plans can be verified for compliance on a routine basis.

Controls would be in place to ensure that support elements specified in the design are procured and available in sufficient quantities to meet operational demand. Test certificates are typically supplied with each batch of support elements to verify supplier quality control. Supplier accreditation may also be required. In the

event of identified defects, ideally installed elements are traceable to allow for potential recall and the supplier notified. These processes might be subject to periodic audit.

Support elements are to be stored in conditions that minimise degradation, including protection from direct sunlight and precipitation. Where stored underground, areas should be dry, well ventilated, and maintained within suitable temperature ranges (particularly for resins and cementitious materials). Resin use-by dates are monitored, and expired materials assessed for suitability prior to use, with records maintained for audit purposes. These controls might be implemented on a routine basis.

2.2 During installation

During installation, the QA/QC measures implemented typically include task observations. Ground support installation activities might be routinely observed by ground control personnel to verify compliance with design and procedures. Typical checks may include:

- measurement of spin and hold times for resin-anchored bolts
- verification of resin use-by dates at the face
- confirmation that bit gauges are used for friction bolts and that bolts are not overdriven
- validation of bolt spacing and angle of support elements
- identification of excessive shotcrete rebound
- verification of hydroscaling pressures prior to shotcrete application
- monitoring of accelerant dosage rates for shotcrete
- verification of full-column grouting of cable bolts and inspection of cable condition prior to installation
- visual assessment of water-to-cement ratio for cable bolt grout
- verification of grout curing times prior to cable bolt tensioning.

Fibrecrete thickness measurement (scanning) may also be implemented during installation if available. Scanning technologies such as LiDAR may be used to assess shotcrete thickness through pre-application and post-application surveys (Figure 4). Ideally, results are reviewed promptly to identify areas of under-application, allowing remediation prior to subsequent support installation (e.g. bolting). Therefore, this data would be made available to ground control personnel for review. This process might be implemented on a routine basis where such systems are in use.

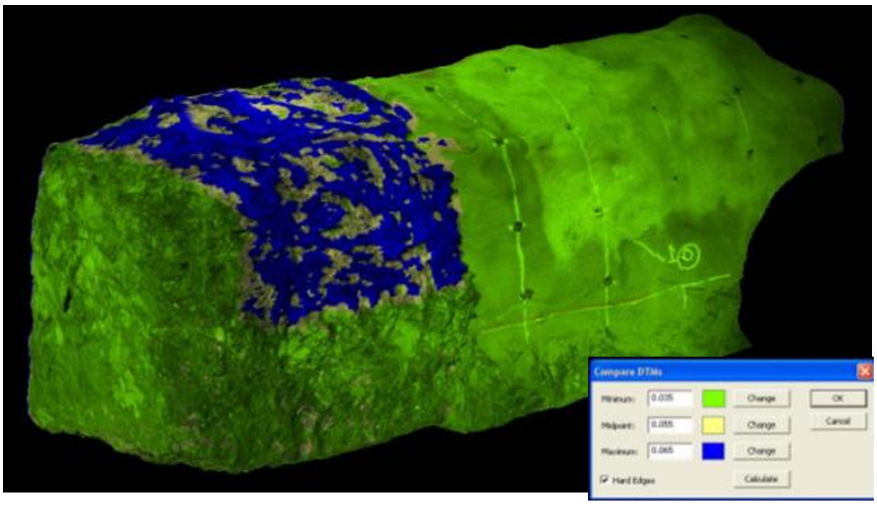


Figure 4 Example of shotcrete thickness scan results (after Loncaric et al. 2025)

2.3 Following installation

Following installation, the QA/QC measures implemented often include testing support elements and inspection of installed support.

Routine testing verifies support performance against design assumptions. Typical tests may include:

- pull testing of rockbolts. For fully encapsulated bolts, testing is generally limited to the near-collar region (approximately 0.3 m), although results may indicate broader encapsulation issues
- grout strength testing for cable bolts (as pull testing cable bolts is generally considered unsafe)
- shotcrete testing, including compressive strength (cylinders or cubes) and flexural strength (round determinate panel [RDP] tests)
- shotcrete thickness measurements if scanning technology is unavailable.

Routine inspections confirm that ground support has been installed in accordance with design. Typical checks include:

- verification of bolting pattern and installation angles
- verification that cable bolts are plated and tensioned
- identification of potential encapsulation deficiencies (where exposures are available)
- assessment of fibrecrete and/or mesh coverage
- confirmation of mesh overlaps
- ensuring that bolt plates are seated firmly against the rock surface.

As noted by Yeni (2024), it is good practice to increase the inspection/testing frequency if issues are identified. This might be outlined in clearly explained trigger action response plans (TARPs) showing the acceptance levels (triggers), frequencies (actions), reporting requirements, and accountabilities (responses).

Where QA/QC issues are identified, increased monitoring and reporting might be maintained until performance improves and compliance with requirements is demonstrated.

3 QA/QC benchmarking data

Benchmarking data was compiled from 24 recent ground control management plans (GCMPs) from a range of underground operations in Oceania, North America, Asia, and Africa to provide an indication of current industry practice across operations. The results are presented to allow operations to compare QA/QC programs against these benchmarks.

Although there are multiple aspects to ground support QA/QC as described above, some of these practices are not consistently documented in GCMPs for comparison in the benchmarking exercise. This includes practices such as the procurement, quality, and storage of support elements, task observations for support installation, and conducting inspections of installed support.

3.1 Pull testing

The pull testing benchmarking data is presented in Figure 5, which shows the accepted pull testing capacity for each bolt type.

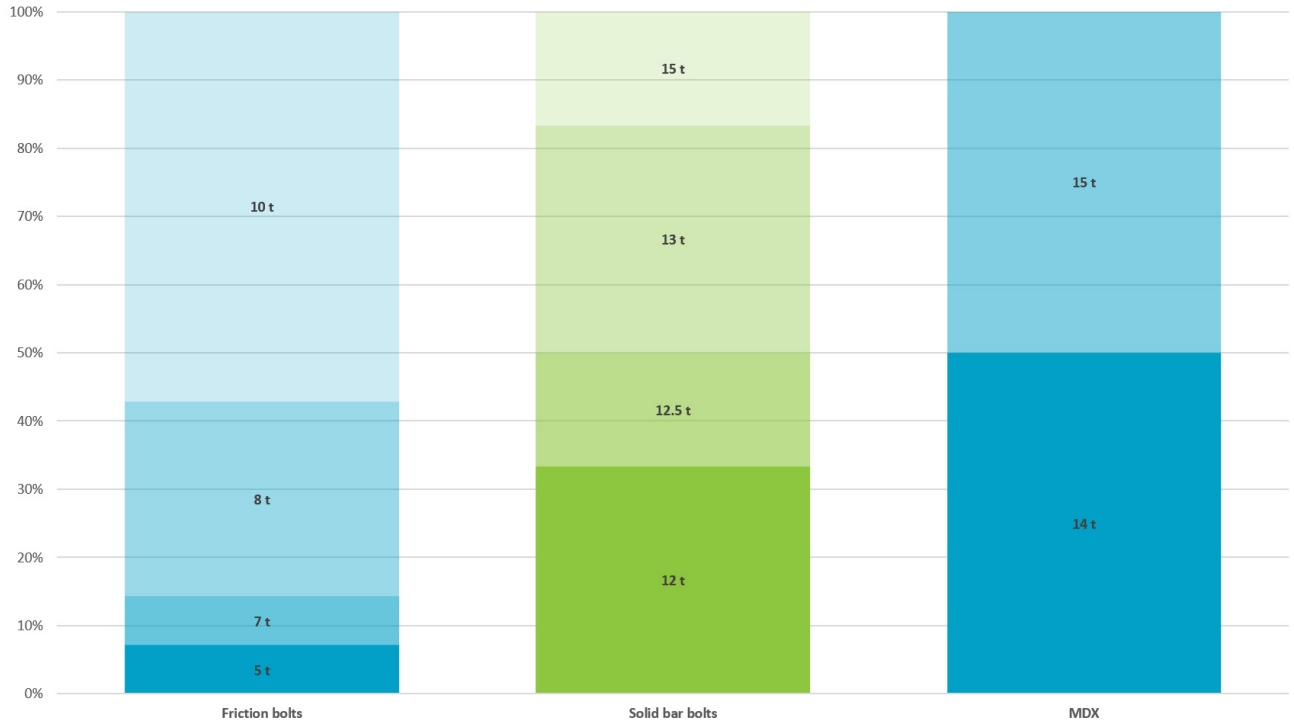


Figure 5 Pull testing benchmarking data

Further insights from the pull testing benchmarking dataset include the following:

- The pass criteria are typically 80–95% passing for each bolt type.
- In some cases, acceptance criteria are defined as a proportion of yield load rather than an absolute load value, typically ranging from 75–80% for new reinforcement and 67% for corroded reinforcement.
- Sample sizes at the majority of operations was specified at 1% of installed bolts, with very few operations adopting values outside of this (e.g. 0.35 and 3%). Rationales for the selection of sample size were not typically stated in the GCMP documentation.
- Testing frequency varies from monthly to ‘as required’, reflecting differing site-specific risk profiles and practices.

3.2 Fibrecrete testing

Fibrecrete testing benchmarking data, including unconfined compressive strength (UCS), beam testing, RDP testing, and thickness testing frequency are presented in Figure 6. All reported strength and energy criteria are based on 28-day test results.

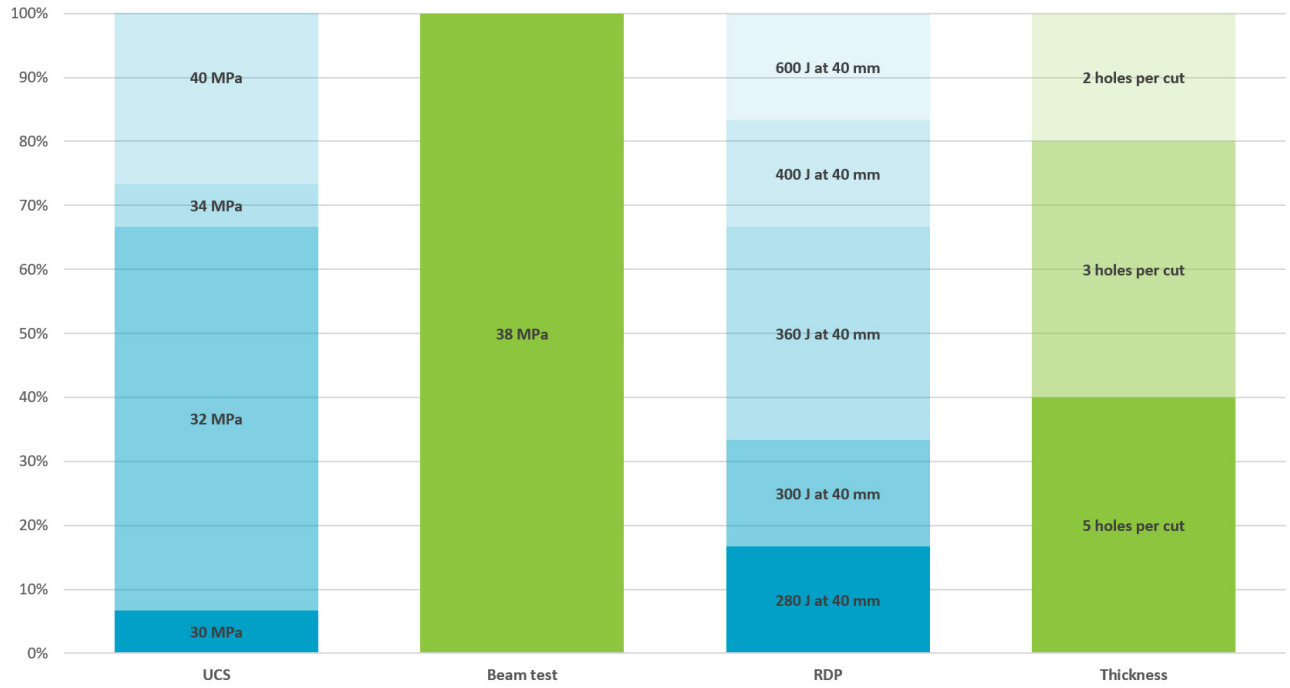


Figure 6 Fibrecrete testing benchmarking data

Further insights from the fibrecrete testing benchmarking dataset include the following:

- Slump test acceptance criteria are typically defined as a range, with reported values varying from 8–16 cm to 17–23 cm across operations.
- Slump testing frequency varies significantly, from one test per batch to one test per week.
- Strength testing frequencies range from weekly to monthly and are often influenced by the volume of fibrecrete applied.
- RDP testing frequencies vary from event-based testing (e.g. changes in mix design) to regularly scheduled monthly testing.
- Fibrecrete thickness criteria vary between operations and include requirements such as ≥80% compliance with design thickness, nominal design thickness, tolerances of ±10 mm, and allowable ranges of −10 to +30 mm relative to design.

Criteria for early-age strength to permit re-entry also vary and include:

- Time-based requirements (e.g. 2 hours for bolting and 4 hours for personnel access).
- Strength-based requirements of 0.8–1.0 MPa at 1–2 hours, to 1 MPa at 24 hours.

One GCMP specified timing requirements for fibrecrete installation in areas of weak ground (Table 1). Such requirements may also be incorporated into ground support plans.

Table 1 Guide for support installation timing

Ground conditions	First pass installation timing
‘Good’	Within 72 hours
‘Fair’ to ‘poor’	Within 24 hours
Self-mining/unravelling	Fibrecrete priority for immediate spraying

3.3 Cable bolt grout testing

Cable bolt grout testing benchmarking data regarding ‘acceptable’ strength criteria is presented in Figure 7 and is based on 28-day test results.

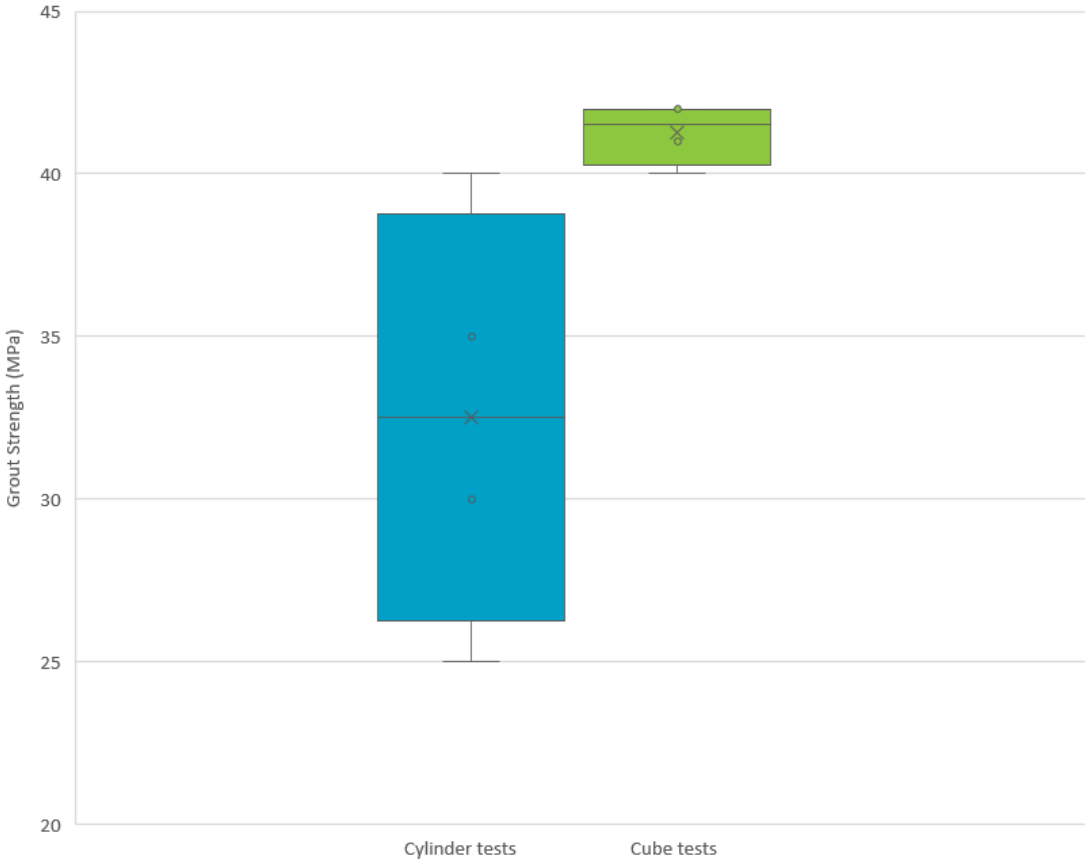


Figure 7 Cable bolt grout testing benchmarking data

Further insights from the cable bolt grout testing dataset include the following:

- Strength testing frequency varies from weekly testing to the commonly-adopted 3 tests per grouting task.
- The allowable time for firing following installation of grouted cable bolts is frequently specified as 12 hours.
- One GCMP stated a grout strength of 2.6 MPa at 8 hours and no other criteria specified.

3.4 Bolt dump angles

A review of bolt dump angle installation benchmarking data was conducted from GCMPs, ground support standards and QA/QC or inspection forms. This indicated a wide range of angle tolerances in the industry, as demonstrated in Figure 8.

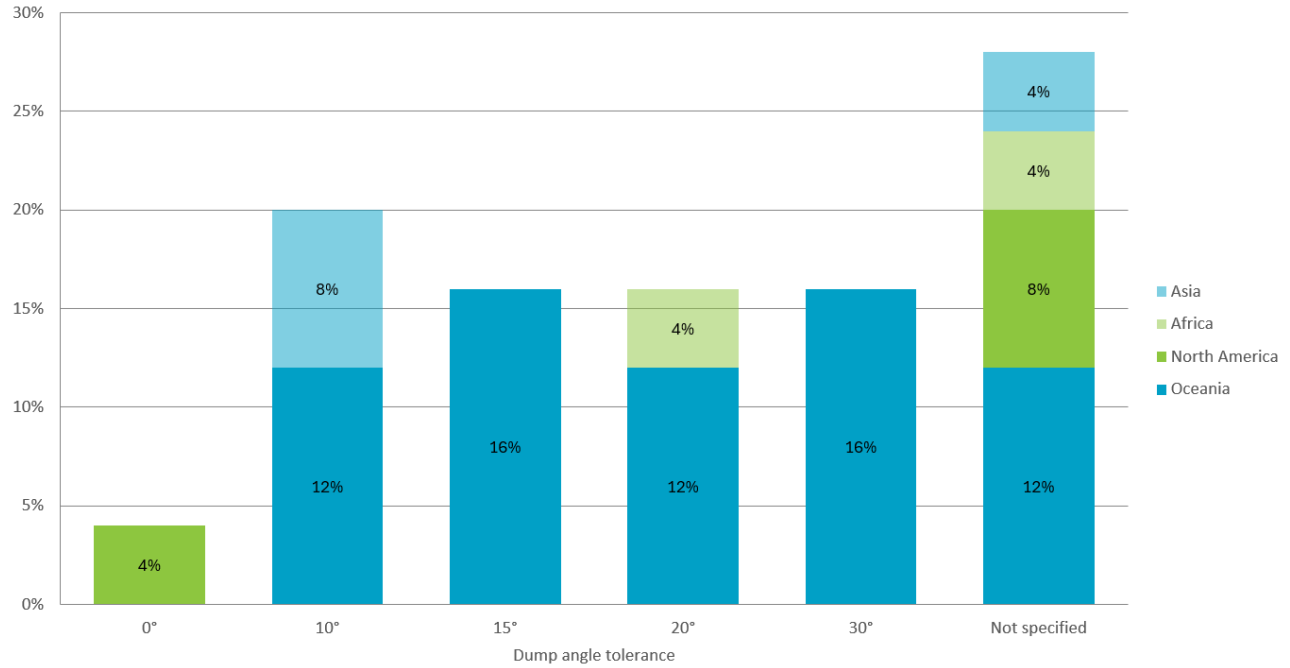


Figure 8 Bolt dump angle tolerance benchmarking data

Further insights from the dataset include the following:

- Bolt dump angle tolerance data ranged between 0–30°, with 76% of sites documenting dump angle tolerances.
- Dedicated bolt angle checks as part of QA/QC or inspection forms were noted from 36% of the dataset (e.g. geotechnical department forms, jumbo audits, or shift supervisor inspection forms).
- Geotechnical analysis and rationale using Unwedge and a design Factor of Safety (FOS) to assess dumped bolts were documented in 8% of the dataset, primarily from sites with smaller development dimensions constraining equipment installation angles.

The basis for bolt angle tolerances is summarised in Table 2.

Table 2 Basis for tolerance

Basis for bolt angle tolerance	Proportion of dataset (%)	Comments
Documented analysis	8	Primarily due to development dimensions/equipment constraints
Stated tolerances, no analysis documented	60	Bolt dump tolerance specified, no rationale provided
Tolerances mentioned, but no angle provided	4	References QA/QC or audit process, but no stated tolerances
No tolerances documented	24	Bolt dump angles not addressed in any documentation
Not applicable/perpendicular installation required	4	No allowance permitted by design

3.5 Additional testing criteria

Additional QA/QC criteria identified in the benchmarking dataset include the following:

- Mesh overlap requirements are typically specified as 2–3 squares. The criteria would usually depend on the ground conditions (2 squares may be appropriate for 'good' ground and 3 squares would be the minimum for poorer ground conditions).
- Verification frequencies range from weekly to monthly.
- Overbreak tolerances are generally defined between 10–15%, commonly documented in underground services contracts and design schemes. Compliance is assessed either on a per cut basis or at monthly intervals. In some cases, absolute development dimensions are specified as trigger criteria (e.g. a maximum excavation width of 7 m), beyond which additional support is required.

4 Discussion

The benchmarking of QA/QC practices across a range of geographical regions including Oceania, North America, Asia, and Africa, noted common verifications that are conducted before, during, and after support installation. These practices included rockbolt pull testing, fibrecrete slump, compressive and flexural strength, fibrecrete thickness, cable bolt grout testing, mesh overlap, bolt angle verification and development overbreak tolerances.

The benchmarking data indicate considerable variability in QA/QC practices across underground operations, particularly in testing frequency, acceptance criteria, and implementation. This is evident across all support types and in terms of acceptance criteria, suggests a lack of consistent industry standards. In terms of testing frequency and implementation, this is more likely to be associated with the size of the operation and ability to resource the work.

For pull testing, differences in acceptance criteria (absolute load versus proportion of yield) and sampling rates (typically 1% but ranging from 0.35–3%) reflect varied approaches to performance verification. Fibrecrete and cable bolt grout testing show similar variability in testing frequency and strength criteria. Additional measures, such as overbreak tolerances, also demonstrate inconsistent approaches, including the use of both percentage-based and absolute trigger limits.

Variability often reflects differences in the scale, resourcing, operator skill level, and ground conditions of operations. Smaller operations, or those installing relatively low volumes of support, may adopt lower testing frequencies while still maintaining an appropriate level of QA/QC coverage. Similarly, operations with relatively favourable ground conditions and lower geotechnical risk may justify reduced testing intensity compared to mines operating in more challenging ground. In contrast, larger operations with high installation rates or more complex ground conditions typically state more frequent and systematic testing to achieve comparable confidence in support performance. As such, QA/QC requirements are proportional to the scale of activities, prevailing ground conditions, and the associated level of risk.

These differences have important implications for ground support design. Where QA/QC programs are inconsistent or insufficient, uncertainty in the performance of installed support increases. In such cases, increased design conservatism should be adopted. For example, a FOS of approximately 1.5 may be appropriate where there is high confidence in the geotechnical model and QA/QC practices are rigorous, including routine task observations. Where it is less well controlled, ad hoc, or poorly resourced, higher FOS values should be considered regardless of confidence in the geotechnical model.

Conversely, well-defined and consistently implemented QA/QC programs reduce uncertainty in support performance and allow designs to be applied with greater confidence. This highlights the importance of integrating QA/QC into the design process, rather than treating it as a compliance-based activity. The use of risk-based tools, such as TARPs, could also be employed by increasing testing and inspection where

deficiencies are identified. These programs form an integral component of the overall geotechnical design framework.

Despite variability in practices, the benchmarking data indicates convergence in acceptance criteria. Pull test criteria are commonly clustered at around 80% of the yield load. Fibrecrete UCS criteria are predominantly clustered between 32–40 MPa. Cable bolt grout strengths typically cluster between 30–40 MPa, indicating broadly consistent performance expectations across operations.

Pull testing frequency appears to be more strongly influenced by operational scale, ground conditions, and resourcing, with sampling rates for bolt testing most commonly around 1% of installation. QA/QC frameworks also reflect a mix of prescriptive and performance-based approaches, with inconsistent implementation across operations. In some cases, broad acceptance ranges may permit inconsistency in installed quality, and the lack of standardisation may result in both over-testing and under-testing.

Bolt dump angle tolerance data illustrates relatively clear inconsistencies. The benchmarking information for bolt dump angles is often well-documented; however, it is rarely supported by geotechnical analysis or formally documented in QA/QC inspection checks. The wide range of reported angle tolerances (0–30°) suggests limited consistency in the justification as to why one value is considered more acceptable than another. This observation is further reinforced by 25% of the dataset that does not specify tolerances. Collectively, these findings highlight a potential blind spot in geotechnical design and post-installation validation practices and raise questions as to whether established tolerances are supported by engineering justification or simply reflect the acceptance of legacy ‘standard practice’ perpetuated across sites over time.

5 Conclusion

QA/QC is fundamental to achieving the intended performance of ground support systems. While significant effort is invested in design, its effectiveness depends on consistent implementation.

QA/QC practices were reviewed from 24 GCMPs from Oceania, North America, Asia, and Africa. The review indicated that these practices typically include a combination of monitoring the excavation quality, checking the procurement, quality, and storage of support elements, conducting task observations of support installations, and testing and inspecting the quality of installed support. A final summary of the collated benchmarking data, together with other general information gathered from the GCMPs (where stated) is presented in Table 3. The practice criteria were often well stated, but the frequency was not always stated. Therefore, the data is biased towards operations with well-documented QA/QC plans.

Benchmarking results show considerable variability in QA/QC practices across operations, reflecting differences in scale, ground conditions, and resourcing. Where practices are robust and consistently applied, confidence in support performance is increased, allowing efficient design application. Where it is less well controlled, uncertainty increases and greater design conservatism is required. In this context, FOS values of 1.5 may be appropriate where QA/QC is stringent, and higher values are required where it is ad hoc or insufficient.

The benchmarking data highlights an opportunity for the industry to improve consistency in QA/QC development. Increased standardisation of acceptance criteria could improve confidence in installed support performance, reducing unnecessary testing and design conservatism. The greatest variance was observed in practice frequency, which appeared to be linked to the scale of the operation, or varied according to risk. This is considered to be appropriate for both reasons.

Future work might focus on expanding the benchmarking database to include more operations and mining jurisdictions, incorporating additional data on operation size and location. This larger dataset could be used to determine relationships between QA/QC intensity, ground support performance, and geotechnical risk. As the benchmark dataset expands, it could provide a foundation for the development of risk-based industry guidance and more standardised approaches to ground support QA/QC.

Table 3 Collated QA/QC information

Practice	Typical criteria	Typical frequency
Measure excavation size	10% compliance or absolute trigger value	Per cut to monthly
Procure correct support	Procurement controls	Per order
Supplied material quality	Test certificates	Per batch
Monitor storage conditions	Dry and ventilated	Per month to per quarter
Shotcrete slump test	Range of values from 8–23 cm	Per batch or week
Task observations	Each type of installation	Per month to 2 per quarter
Fibrecrete thickness scanning	≥design	Per cut
Pull tests	80–95% passing about 80% of yield load	1-3% of bolts
Shotcrete compressive strength	30–40 MPa	Per week or month
Shotcrete flexural strength	280–600 J at 40 mm deflection	Per mix design to monthly
Shotcrete thickness	80% compliance, ±10 mm, -10 to +30, ≥design	Per cut
Cable bolt grout strength	25–50 MPa (cylinders) or 40–42 MPa (cubes)	Per task or weekly
Bolt dump angle tolerances	10–30°	Per shift to week
Installation inspections	Bolt spacing and angle, support coverage, mesh overlaps	Per shift to week, per cut to every 3 cuts

References

Government of Ontario 2025, *Ontario Regulation 854: Mines and Mining Plants, R.R.O. 1990, under the Occupational Health and Safety Act*.

Government of Western Australia 2022, *Work Health and Safety (Mines) Regulations (WA) 2022*.

Loncaric, AJ, Delaney, C & Singh, U n.d., 'Control and measurement of shotcrete thickness using modern technology', Stratacrete Pty Ltd, viewed 7 April 2025, https://stratacrete.com/wp-content/uploads/Control-and-Measurement-of-Shotcrete-Thickness-using-Modern-Technology.pdf

Western Australia Department of Mines, Industry Regulation and Safety 2019, *Guideline – Ground Control Management in Western Australian Mining Operations*, Perth.

Yeni, O 2024, 'A proposal for determining fall of ground potential risk in underground mines through numerical QA/QC and geotechnical risk rating method', in P Andrieux & D Cumming-Potvin (eds), *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 881–888, https://doi.org/10.36487/ACG_repo/2465_55