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Development of a probabilistic performance assessment method for frictional anchors

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Abstract

The traditional approach to performance assessment of frictional anchors involves campaign pull testing of recently installed bolts, where the results are sorted into pass/fail categories usually based on a set nominal pull resistance value. A detailed analysis of the pull-out data was undertaken at a Western Australian underground mine during a supplier change. The results showed that the distribution of pull testing results has a distinct bi-modal appearance. This paper offers a simple explanation of the mechanism causing the bi-modality and describes the new approach to recording and processing of the pull testing results, adopted at the mine. Also, a model for performance simulation and acceptability criteria are discussed. The proposed interpretation of the pull testing results as a combination of 2 groups, each following a normal distribution, and allows for use of the results in a probabilistic analysis of ground support performance.

Keywords: *friction bolt, split set, testing, performance*

1 Introduction

Friction bolts – also known as split sets or friction rock stabilisers (FRS) – have been the staple of ground support in many hard rock mines in Australia and all over the world. Many manufacturers and suppliers follow the same or similar principal product design, with minor differences. Numerous research works have been published over the years, investigating influence of a number of parameters of rockbolts, rock mass and their interface, as well as environmental conditions on performance of the frictional anchors and various aspects of design of ground support systems (Hadjigeorgiou & Tomasone 2018; Varden et al. 2023, Nicholson & Hadjigeorgiou 2018; Agrensa et al. 2024; Tomory et al. 1998; Tomasone 2018; Hadjigeorgieu 2023; and many others).

Pull testing has long been accepted as the main way of assessing the performance of frictional anchors, and an ASTM International (2013) standard test method exists. In many Western Australian mines, pull testing is done in regular campaigns, often outsourced to the suppliers' representatives. Commonly, the results are assessed based on a percentage of tested bolts clearing a set threshold value, which is, in turn, linked to a nominal value expected for this type of bolt.

However, the typical industry's practice in relation to recording, processing and interpreting the results of such testing has some shortcomings. A number of these drawbacks became evident during a process of ground support supplier change at a gold mine in Western Australia in 2025. These sparked a re-think of the approach to pull testing at the mine, followed by a year-long campaign of data collection and processing, in collaboration with the supplier's representatives.

2 Initial findings

The mine uses 2.4 m long, 47 mm diameter friction bolts as their primary ground support element. The mine decided to change the supplier of ground support, and to ensure that the new supplier's products achieved an equivalent performance to those provided by the old supplier, a program of pull testing was conducted to evaluate the performance of frictions bolts provided by both. To avoid bias towards either the old supplier

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(Supplier A) or the new one (Supplier B), pull testing of the newly installed Supplier B's frictional anchors was performed by a third party contractor. The results of pull testing were recorded to the nearest 1 kN, i.e. approximately 0.1 tonne-force (commonly referred to as 'tonnes', a convention that will be used further in the paper due to its simplicity and widespread utilisation in the industry, e.g. '1 tonne' refers to 1 tonne-force or 9.81 kN), which is much finer resolution than what is typically reported by suppliers' testing in Western Australian mines (generally, assumed rounded to the nearest tonne). Pull testing results during Supplier A's tenure at the mine were reported to the nearest 1 tonne.

The first batch of results indicated a significant gap in performance between actual and expected, where the expectations were based on the typical historical test results from Supplier A (when tested by the supplier's representative), conducted at the mine regularly during the previous 8 years. The distributions of both are shown in Figure 1. Generally, the accepted pull-out capacity of a 2.4 m long, 47 mm frictional anchor in a hard rock mine is 10 tonnes, and as far as it's known the testing would commonly be stopped at this point, with only about 1% of bolts pulled to load greater than that.

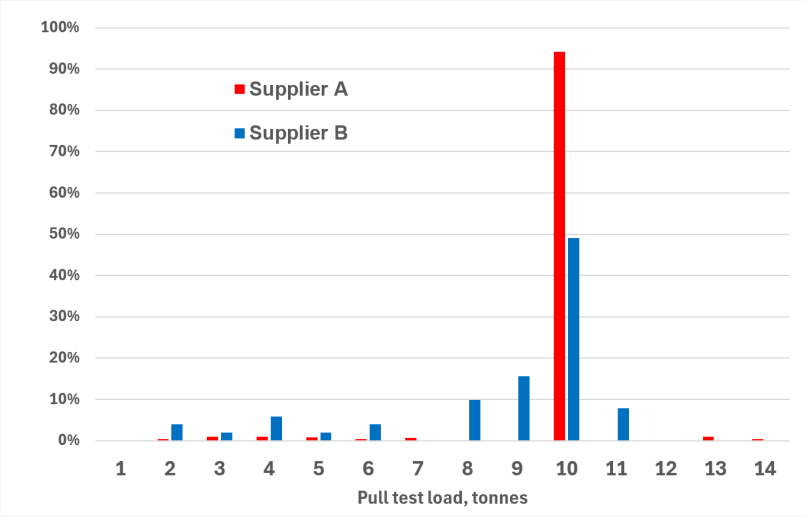


Figure 1 Comparison of the first batch test results to historical data at the mine

However, in-depth analysis of Supplier A's historical results showed that the distribution of pull test values did not appear realistic, where out of 2,934 tests only 2 bolts recorded 9 tonnes, 3 tested at 8 tonnes, and 2,764, or 94.2%, tested at perfect 10 tonnes, and none at 11 or 12 tonnes. Consequently, a re-testing of Supplier A's recently installed split sets was conducted by the same third party which yielded a much more convincing distribution of test results (Figure 2). The bolts were pulled to slip and a total of 31 bolts were tested.

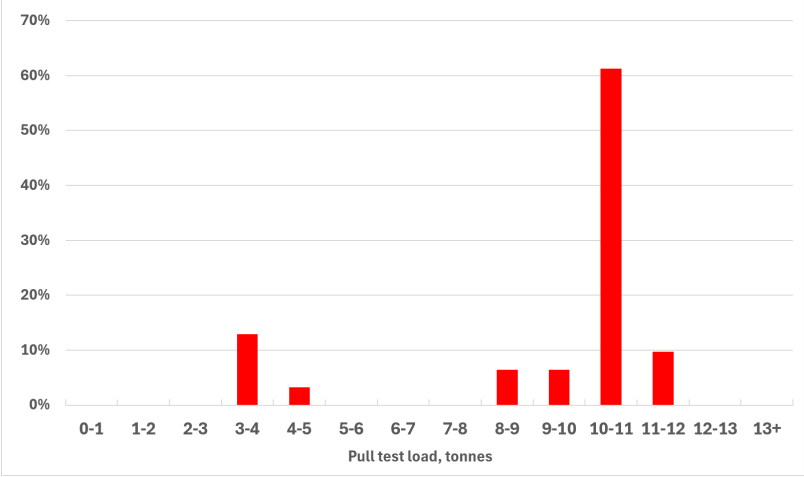


Figure 2 Supplier A, re-test by third party

3 Mechanism causing bi-modality

One of the most intriguing findings of testing bolts from both suppliers, including the historical test data as well as recently installed bolts, tested by a third party, was a very distinct bi-modal distribution of the results, with a large proportion of bolts having capacity around the nominal value (in this case, between 8 and 12 tonnes), and a separate subset with values generally between 2 and 7 tonnes. Visual assessment of the test results distribution indicated that there was an apparent minimum of bolts with pull-out capacity between 7 and 8 tonnes, suggesting the threshold value of 8 tonnes as the boundary between the 2 groups. It was also noted during testing that generally the bolts in the main (higher capacity) subset were relatively straight in the hole, while the other (lower capacity) group was showing significant spiralling/twisting after installation, as assessed and reported by test personnel. After the mine has conducted a trial of different bits and optimised the hole size for the new product, the bi-modal character of the test results remained, and was observed consistently during regular test campaigns in the subsequent 12 months.

However, all testing of friction anchors to date (from both suppliers) suggested that product parameters such as wall thickness, ultimate tensile strength (UTS), Young's modulus of steel, split tube geometry, etc., were consistent, and nothing indicated such variability in the performance, particularly its bi-modal character. This led to the hypothesis that a certain mechanism can be activated during installation, where a bolt's cross-section loses stability and instead of deforming in plane, a three-dimensional deformation takes place, which includes twisting/spiralling, and a smaller final diameter of the bolt in the hole is achieved at much lower radial load on its walls. This is similar to the process known as lateral-torsional buckling, observed when trying to bend a beam along its major axis (Figure 3).

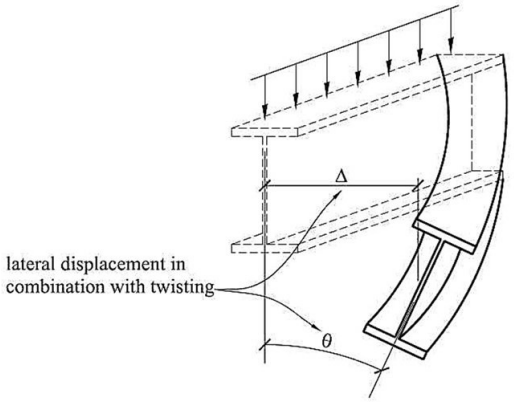


Figure 3 Lateral-torsional buckling illustration (Al Zaidee & Al Hasan 2017)

While development of a detailed model of such process (applicable to split tube frictional anchors) goes beyond the scope of this paper, some of the potential causes that can initiate such detrimental behaviour can be suggested. An obvious one would be the application of rotational torque on the bolt by jumbo operators at installation. Despite every relevant safe working procedure (or equivalent document) known to the author expressly prohibiting the use of rotation during installation, it has been observed at times and cannot be completely excluded. However, if rotation were used habitually, in that case the high frequency of spiralled bolts would easily be traced back to the offending party. Instead, the occurrence of such bolts appears to be random, which suggests that a different mechanism may also be responsible for the onset of spiralling.

A possible hypothesis to explain this behaviour is that excessive 'indexing', i.e. angular misalignment between the borehole and bolt axes, may be a reason for spiralling onset, when the bolt's split tip makes one-sided contact with the inside of the borehole, as shown in Figure 4. The resultant shearing force translates into twisting, propagating along the length of the bolt. During installation, it sometimes manifests as a 'kink' on one of the sides of the split.

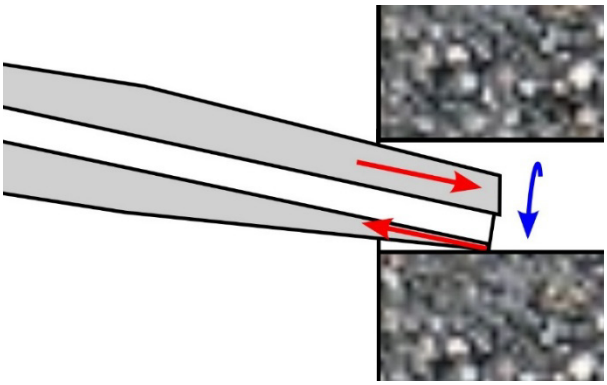


Figure 4 Suggested mechanism of spiralling onset induced by 'indexing'

The issue of indexing is difficult to mitigate using today's typical installation techniques, where one jumbo boom is used for drilling boreholes and the other is used for installation of the bolts. Even if the drilling boom is used as an indicator of the hole direction, visual alignment is not perfect, particularly in the plane parallel to the line of sight. Some improvement may come with operator's experience, however the issue can hardly be eliminated. Therefore, using current bolting methods and principal design of the bolt, some proportion of bolts can be expected to undergo spiralling at installation. This problem is likely to be exacerbated if other elements of installation technique are poor, such as using torque/rotation at insertion, driving the bolts with excessive speed, or use too much feed pressure while boring, causing hole deviation.

4 Revised methodology of data recording and interpretation

Based on the above considerations, the mine requested the supplier's representatives to change testing and recording procedure, to apply pull-out force until 14 tonnes are reached or the bolt slips, whichever comes first, and record the result with rounding to the nearest kilonewton or 0.1 tonne. The interpretation of the results also changed. Instead of the previous trend of marking all bolts with pull-out resistance less than the nominal 10 tonnes as 'failed', the results were split into 2 groups: 8 to 14 tonnes (labelled 'good') and 0 to 7.9 tonnes ('poor'). For simplicity, the distributions of the values in each group were treated as independent distributions, and for each group a mean and standard deviation values were determined, as well as the percentage of the bolts falling into the 'poor' group. From visual assessment of the histograms, both groups appeared close to normal distributions. Additional tests were conducted to confirm the normality of each. Q-Q plots (Figures 5 and 6) for both 'good' and 'poor' subsets indicated that the distributions can be accepted as normal, with some abnormal outliers evident, particularly in the 'good' group.

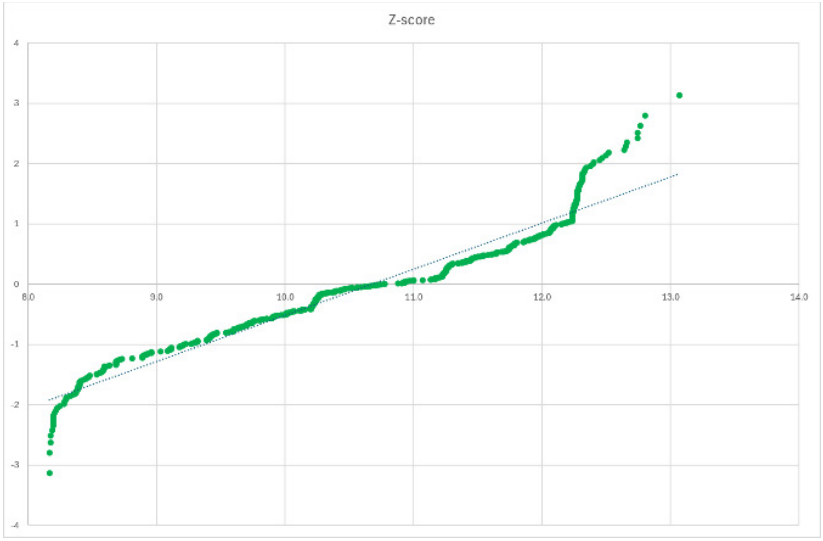


Figure 5 Q-Q plot for 'good' group

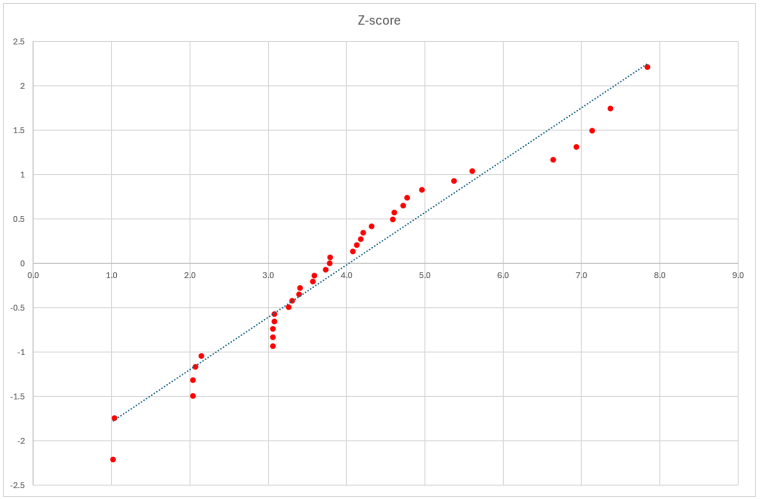


Figure 6 Q-Q plot for 'bad' group

Further evaluation was done, calculating skewness and kurtosis for each subset of data. For the 'good' group, skewness of −0.3 and kurtosis of −1.07 were calculated, which indicated that the dataset is approximately normal and acceptable for most standard statistical tests (Minsa 2026), with slightly flatter peak and fewer outliers. The 'bad' group had skewness of 0.55 and kurtosis 0.2, which were interpreted as moderately right-skewed and almost perfect bell-curve tails.

The data obtained during the 12-month trial strongly indicated that the bi-modal character of the test results was consistent from month to month, with summary of the trial shown in Figure 7.

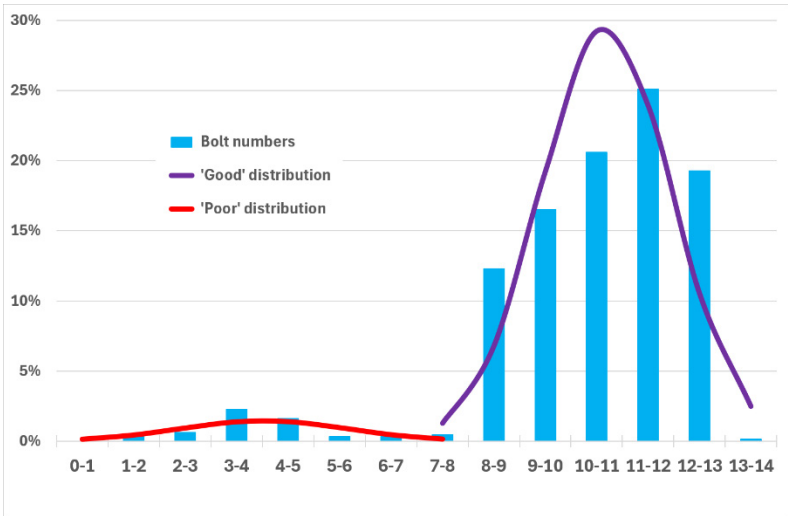


Figure 7 Summary of 12-month trial

Overall, the 'good' group represented 94% of the total number of tested bolts, with mean of 10.7 tonnes, and standard deviation of 1.27 tonnes. 'Poor' group had mean of 4.0 tonnes, and standard deviation of 1.63 tonnes. The results of the trial support the hypothesis that bolts with significant spiralling form a distinct group with severely affected pull resistance, and the methodology to represent the results as 2 groups with separate normal distributions is acceptable.

On the basis of the 2 normal distributions obtained from the test data as described above, a probabilistic model was built, estimating the probability of a single bolt failure (PoF), using the most common ground support standard parameters (drive geometry, bolt positions and angles in the ring, spacing between rings) at the mine. This model used assumptions that are common in the industry – depth of the stable arch, depth of blast damage, etc., to estimate the load demand on each bolt, also taking into account different modes of

loading for the bolts in the backs and walls. It was also assumed that the shear resistance of the bolt would not be affected by spiralling, as the cross-section remains unchanged.

Specifically, the model accepted for the typical conditions seen in the mine included a standard 5 × 5m drive geometry with arched backs, where the height of the backs' arch was 1 m, and assumed common industry values for depth of blast damage of 0.4 m (calculated as 2 times the practical damage radius for decoupled perimeter charges used at the mine), depth of unstable ground arch in the drive's backs one-third of the drive span for fair ground, rock mass specific gravity of 2.7, depth of unstable ground in the walls was estimated as 1 m. The frictional capacity of each bolt was assigned randomly, using the distributions determined during the pull testing for the period, and shear strength of each bolt was assumed equal 8 tonnes, based on the bolt's cross-section and steel parameters. The mine's most frequently used bolting pattern is shown in Figure 8.

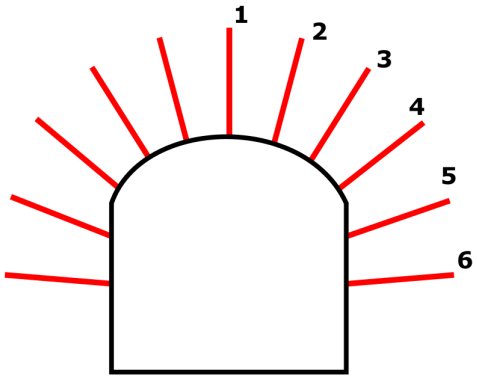


Figure 8 Bolting pattern used in the model

The loading on the bolts was a combination of cross-shearing and axial load. Each bolt was assigned an attributed unstable block of rock, with the volume being a product of bolts spacings (along and across the drive) and the depth of unstable ground at the particular bolt's location. Each of these blocks was considered sliding along the most feasible plane depending on geometry. This plane was assumed vertical for bolts 1 and 2, blocks supported by bolts 3 and 4 were assumed sliding along a plane dipping at 60° from horizontal, and bolts 5 and 6 at 45°. The dip of the plane was selected such that the load conditions would be judged the most disadvantageous for the particular bolt.

A bolt was deemed failed if the modulus of vector of gravity exceeded that of the sum of the vectors representing the retaining forces. Pull-out force (Fp), acting along the bolt's axis (limited by frictional capacity of the 'active' portion of the bolt, anchored in the stable ground), normal force on the sliding plane and friction resistance on the contact (Fn and Ft), where Ft = k × Fn, and shearing resistance of the bolt (Fs) (Figure 9).

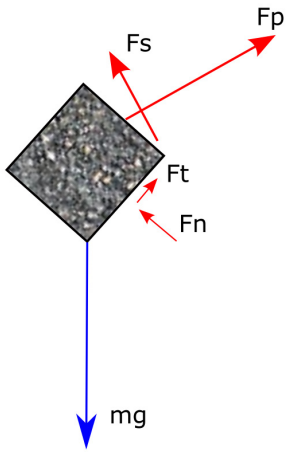


Figure 9 Schematic of forces acting on the unstable block normal. Force on the sliding plane and friction resistance on the contact = Fn and Ft, shearing resistance of the bolt = Fs

The outcome of the modelling, while not necessarily representing the true PoF for the mine, is a useful parameter for tracking the overall performance of the split sets installed in the mine (or a particular section of the mine), as well as overall adequacy of the selected bolting pattern to the ground conditions. A sharp increase in PoF can be used for flagging a significant deterioration of ground support installation process, and prompt a more detailed investigation, where the calculated distribution parameters can provide useful insight into the issue. For example, increase of 'poor' bolts percentage would indicate potential issues with installation technique – indexing, use of rotation during bolt installation, excessive speed of insertion, high feed pressure during boring, etc., while a decrease in mean value or increase in standard deviation for 'good' bolts may suggest issues with boring bits sizing, or a change in rock mass parameters causing a change in borehole diameter.

5 Potential spiralling mitigation methods and future work

Today, a standard mine site practice most often includes a process of drill bit size optimisation for the prevailing ground conditions and the supplied product, which is often performed by installing and pull testing the bolts in a well established area, where the installation procedures are strictly followed, and chances of bolts twisting due to indexing or other reasons are minimal. One of the possible areas of future investigation would be looking at correlation (or lack thereof) between the borehole diameter and the rate of excessive spiralling. It appears reasonable to suggest that the proposed mechanism of the onset of bolt twisting may be realised more readily, or have lower chances of self-correction in smaller borehole diameter, with everything else being equal. So, the optimal bit size for local conditions may not only be determined based on the straight bolts pull-out resistance, but also from the proportion of twisted bolts.

The ability of the operator to align the bolt with the axis of the borehole is currently dependent on the visual indications, which, as discussed earlier, have their limitations. The use of a boom alignment and tracking system could be more effective, viability of such technology is currently being evaluated.

Alternatively, an amended design of the frictional anchor can be considered, which would eliminate or significantly reduce the tendency of the bolts to twist upon installation.

6 Conclusion

In consultation with the supplier's representatives, the mine changed the procedure of testing friction bolts (pulled to slip or 12 tonnes, whichever occurs earlier) and recording of the results (in 0.1 tonne increments). It was deemed that for temporary mine openings a PoF of 3% for a single bolt was acceptable. Also, the mine amended the acceptable performance criterion, with a requirement that the mean of all tested bolts in the 'good' group has to be no less than 10 tonnes. In addition, the mine will require periodic testing of recently installed friction bolts by a third party.

The revised approach to analysis and interpretation of pull testing results allowed obtaining more realistic data, eased supplier representatives' concerns and perceived pressure to report only good results, as well as allowed the mine to better identify the root causes of split set performance issues. It also helped to establish better working relationship with suppliers and track the combined performance of ground support using one simple calculated parameter.

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