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Empirical charting for dynamic ground support at Flying Fox and Spotted Quoll mines

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Abstract

Empirical charting of ground support performance in dynamic conditions using easily available mine site data is a method applied at Flying Fox and Spotted Quoll nickel mines in Western Australia. The focus is on identifying the limiting largest seismic event magnitude for which a given ground support scheme would be expected to sustain damage to a tolerable level.

The method has been used previously with success at Long Shaft and Hamlet mines to guide the selection of support in dynamic conditions. Charting defines the relationships between three easily determined factors: the dynamic disturbance (via the seismic event magnitude); the level of ground support damage caused; and the type of installed ground support. Most Flying Fox and Spotted Quoll events are crush events, for which the use of magnitude as a proxy for the dynamic disturbance is suitable.

At the mines, installed ground support is broadly classified into three schemes: conventional friction bolt and mesh; fibrecrete with mesh and bolts; and custom high-performance seismic. At Flying Fox mine, 224 data points were available for the preparation of charts for these schemes, while at Spotted Quoll there were 137 data points. Events as large as M_L2.2 at Flying Fox and M_L2.9 at Spotted Quoll were recorded. Despite the two mines being only 6 km apart, their geomechanical environments were different and a corresponding difference in the empirical charts was evident.

Strong advantages of the empirical approach are recognition of the site-installed bolts, seismicity, geology and support performance. This makes the results calibrated to the mine. The approach does not require estimation of ground motion or site effect (for crush-type events) at the precise location of a support element, nor estimation of energy and load capacities of elements during dynamic disturbances. However, the approach has limitations as described in the paper, and the charts are not transferable between mine sites.

Empirical charting should provide site engineers with a defensible support selection method for seismic conditions described by an expected or forecast upper event magnitude. The process is simple, transparent and attractive in that it takes into account all of the factors that can negatively impact the actual capacities versus design capacities. It is hoped that the descriptions in this paper will encourage engineers to explore similar work for their sites.

Keywords: *ground support system, ground support scheme, dynamic, support selection, support performance, seismicity, empirical chart, mining*

1 Introduction

Site engineers need to know the limiting largest seismic event magnitude for which a given dynamic ground support scheme would be expected to remain functional while sustaining damage to a tolerable level. The aim of empirical charting is to identify this magnitude. This method provides an alternative means of dynamic support selection as site engineers may not have the benefit of advanced computer models, or of all the data needed to populate various analytical methods for support selection.

Empirical charting provides guidance on the performance of a particular ground support scheme in dynamic conditions if the necessary historical performance data is available. This paper demonstrates this process for the Flying Fox and Spotted Quoll mines operated by IGO Limited in Western Australia (WA).

The empirical approach accounts for the actual installed bolts, seismic events, site geology and bolt performance, making the results calibrated, and applicable, to the mine. Input parameters are used to represent the following:

- The intensity of the seismic disturbance impacting a support element.
- The type of installed ground support scheme.
- The degree of damage sustained by the ground support.

Historically, several attempts were made at Flying Fox over the past 12 years to compile empirical charts capturing the performance of ground support under dynamic disturbances. These past attempts were important steps in enabling the method and the input data preparation procedures to be steadily refined as new knowledge was identified. The result is a high level of confidence in the current charts.

It is important to be aware that for various reasons, empirical charts are not transferable between mines. It is hoped that this paper will encourage engineers to explore similar work for their sites.

2 Geomechanics background

2.1 Flying Fox geomechanical environment

Flying Fox nickel mine has been operational since 2006 and has now reached more than 1,300 m below surface. The deposit is a typical komatiite-associated nickel deposit. The ore is hosted in both ultramafic and non-ultramafic rocks, chiefly felsic metasedimentary schists. The sequence is intruded by a composite of granitoid bodies (pegmatite, granite, granodiorite). The deposit is bounded to the north by a thick proterozoic dolerite dyke.

Mineralisation thickness is very variable up to 20 m as a result of the many phases of faulting and remobilisation.

Local structure comprises strong contact-parallel banding and schistosity developed in the footwall metasedimentary rocks. A few discrete faults are interpreted from the offset of the mineralisation and lithological contacts, and from the truncation of stratigraphy.

The strongest rock type is the silicified metasediment with an average uniaxial compressive strength (UCS) of 384 MPa, and under load it accumulates comparatively more strain energy than other rock types. At high stress, and especially at contacts with other rock types, it is more prone to bursting. The weakest rock type is the ultramafic with an average UCS of 83 MPa.

The stress field is lower than may be expected in comparison with other mines in the WA Yilgarn block. Underground observations confirm the relative lack of stress damage in most rock types other than the ultramafic at depth.

Flying Fox mine started to show seismic activity from about 750 m below the surface. An Institute of Mine Seismology seismic monitoring system is installed. Significant seismicity tends to be located within the foliated metasediments, at the orebody contacts, and in the barren areas in the granite and ultramafic rocks. Fracturing of intact rock is the typical source mechanism.

Damage modes in workings manifests as bulking behind mesh or fibrecrete, buckling in foliated rock mass or strainburst where the rock mass is more competent (especially the silicified metasediment).

2.2 Spotted Quoll geomechanical environment

At Spotted Quoll, the nickel sulphide orebody is hosted by mainly sedimentary rocks in both the footwall and hanging wall. There is occasional ultramafic exposure on the hanging wall, and felsic intrusions which mostly offset the orebody. The felsic rock type is the strongest with an average UCS of 202 MPa, and the ultramafic is the weakest at 139 MPa, i.e. much less of a difference compared to the large range at the Flying Fox mine. Spotted Quoll mine is currently over 1,000 m deep.

The orebody is divided into three mining zones based on the orebody dip. The upper Stage 1 has a 50–70° dip, then the dip flattens to 20–40° in the T0 Fault Zone. In Stage 2 the dip is more complex and variable, ranging from 40–80°.

Felsics are a major cause of seismicity in the deeper Stage 2 workings. In the lower levels of Stage 2, felsics are exposed on the footwall side of the orebody in the northern section, and there are a few oredrives where the felsic intrusions completely cut off the orebody in the middle sections of the lode. A top-down longhole stoping method is followed with paste backfill, and the stopes are retreated from north to south following an echelon of 45°.

3 Advantages and limitations of the empirical chart approach

Early empirical chart work was reported by Mikula (2012). Mikula & Gebremedhin (2017) provided a detailed discussion of several advantages and limitation of the empirical chart method. Some key aspects are summarised here.

3.1 No need to estimate a site effect factor or amplification of peak particle velocity

The empirical approach for crush-type events uses magnitude as the input parameter to represent the seismic disturbance. The rationale is that the worst damage coincides with the near-field of events where the ground motion is highest, and that motion is directly correlated with magnitude. Avoiding the estimation of a peak particle velocity (PPV) bypasses numerous complexities and errors in the following:

- Selecting a site effect factor.
- Determining the near-field–far-field boundary.
- Determining the true source-damage distance (the point within the source that emitted the strongest radiation towards the damage location is hard to identify).

3.2 No need to quantify capacity of installed support

The empirical chart method avoids the awkward problem of combining the performance of several hardware components to calculate the energy, load or deformation capacity of the support. The chart assumes that the capacities applying at any one damage site are representative of the capacities elsewhere in the mine for the same ground support scheme. Then it becomes sufficient to only identify the type of scheme that is installed.

This simplification is also a restriction, being valid only for the mine concerned and the support systems for which data is available.

Determining the in situ energy or load capacity of a support scheme in dynamic ground is a very complex area, being difficult to test, both in the laboratory and field. Many variables influence dynamic performance, including rate of loading, duration of loading, intensity of loading, variable quality of installations, imperfections in the ground support element, type of anchorage, borehole–rock interface and the type of instrumentation used to measure the performance.

Support scheme capacity is not the sum of capacity of its component parts. The rock mass and support together form a complex composite system in which performance depends on interactions between the installed support, the rock mass and the dynamic disturbance, which cannot be predicted. Scheme capacity is affected by weak links, which occur for a multitude of reasons, and a common experience is mesh tearing away from bolt collars.

The load demand on bolt elements is a function of imposed strain and strain rate, while the energy demand on bolts is a function of potential or kinetic energy associated with a failing section of rock mass. A final static load demand also exists. These need not be in proportion to each other in any particular case. The determination of scheme capacities is uncertain to the extent that it does not take all this into account.

3.3 Unknown consumed capacity of ground support

This is an important aspect that can negatively affect the empirical chart method. Ground support capacity may be partially consumed due to prior ground movement, seismic or aseismic. If a chart data point represents an element with a high degree of consumed capacity at the time of the seismic disturbance, damage at the location of the element could be worse than expected. An assessment of this factor should be part of the data collected during investigation of each instance of damage.

4 Input data statistics

Flying Fox data was from the period October 2010 to April 2023, and Spotted Quoll data from May 2018 to March 2023. The final Flying Fox damage database contained 224 data points (from 156 seismic events), and the final Spotted Quoll database had 139 data points (in this case also from 139 events).

Some data points were removed from the databases as being doubtful, for reasons including corrosion of the ground support hardware, extensive damage (capacity consumption) prior to the seismic hit, multiple overlapping events in a short time period preventing clear association of a damage level to a particular event, the effects of squeezing, the effects of blast damage, and the inability to validate due to insufficiently detailed records.

The charts are not reliable until adequate numbers of data points are available, i.e. at least 20 per ground support type and geomechanical environment. This can take years (empirical charting data has been collected for 13 years at Flying Fox and five years at Spotted Quoll) and requires diligence by engineers collecting the required data. Ultimately, the site engineers need to be satisfied that worst-case damage has been observed and recorded.

5 Review of seismic source mechanism and location

An important part of the chart validation process was to check whether charts could be compromised by the inclusion of events with different types or modes of event source mechanisms, i.e. some fracturing/crush types and some slip types. It was possible that the different types may have imposed different levels of damage on ground support, although every event is likely a mixture of both types of mechanism.

Accordingly, the Hudson Charts for the mines were reviewed, showing that crush mechanisms were clearly dominant. Also, the S:P energy ratio was reviewed as a rough indicator of event source type.

Flying Fox data:

- Average S:P ratio was 6, and 17% of events exceeding 20.
- For the potentially damaging subset $M_L > 0$, the average S:P ratio was 3, with 1% exceeding 20.

Spotted Quoll data:

- Average S:P ratio was 7, and 13% exceeding 20.
- For the potentially damaging subset $M_L > 0$, the average S:P ratio was 5, with 11% exceeding 20.

This indicates that self-initiated strainbursts and crush-type events are the dominant form of seismic failure at both mines, as is observed, while slip-type events are rare, so the overall datasets are not compromised. Importantly, for the subset of points defining the critical trendlines on charts, no points had high S:P ratios.

Regarding event location, the notional distances from source to damage observations varied widely. Excluding points with S0 damage that could be at any distance, the distances were as follows:

- Flying Fox: average 23 m, majority range from 2–45 m, and six events from 53–155 m.
- Spotted Quoll: average 20 m, majority range from 1–45 m, and one event 70 m.

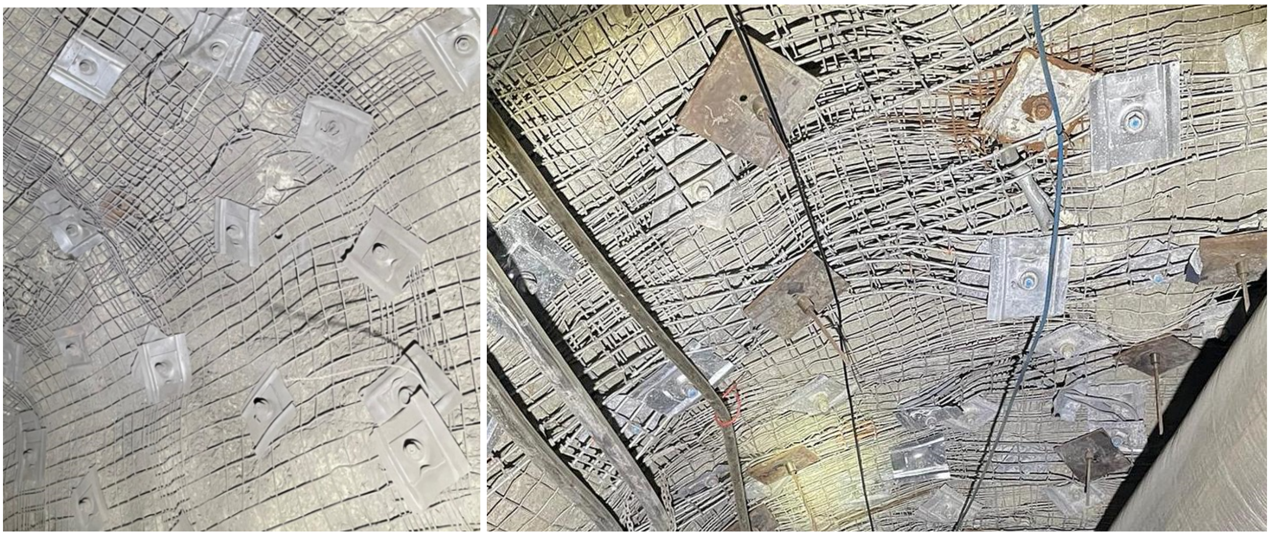
Those are notional distances, which suffice only to associate an event to a specific damage site. Actual distances are unknown for several reasons: larger events are not point sources; waveform processing errors; and a simplified velocity propagation model. A sensor upgrade at Spotted Quoll 'moved' events by over 50 m. Therefore, it is considered invalid to allocate events as near-field or far-field on the basis of computed distance away. Rather, as is described by Malovichko & Rigby (2022), it is considered that crush events and damage spatially coincide.

6 Ground support schemes

Each data point is linked to one of the various ground support schemes installed at the site of damage. Scheme data is shown in Table 1. Examples of the heavy and ultra heavy schemes are shown in Figure 1.

Ideally at least 20 data points per scheme should be available. The light seismic and ultra seismic scheme numbers were too few to permit trend lines to be defined. The light scheme is essentially no longer used so it is unlikely more data points will become available; however, more ultra points may yet be collected and enable future chart updates.

One of the main flaws of the medium seismic scheme is that failure often happens at mesh joins, and sometimes by friction bolt plate removal rather than tearing of the mesh. This reduces capacity, resulting in S4–S5 damage. With the heavy seismic scheme, the usual failure mode is tearing of the mesh as the MD bolt plates do not get removed with such ease.



(a) (b)

Figure 1 Examples of dynamic ground support schemes: (a) Heavy seismic; (b) Ultra heavy seismic

Table 1 Ground support scheme data

Ground support scheme	Scheme component description	Wall support coverage	Instances represented: Flying Fox	Instances represented: Spotted Quoll
Friction bolts and weldmesh	Friction bolt 2.4 m at 1.4 × 1.0 m spacing Mesh galvanised 100 × 100 mm 5.6 mm gauge	1.5 m from floor	43	30
Fibrecrete	Fibrecrete 50mm Friction Bolt 2.4 m at 1.4 × 1.0 m spacing	1.5 m from floor	26	0
Fibrecrete, bolts and mesh	Fibrecrete 50 mm Friction bolt 2.4 m at 1.4 × 1.0 m spacing Seismic mesh reinforced galvanised 100 × 100 mm 5.6 mm gauge	1.5 m from floor	41	32
Light seismic	Fibrecrete 75 mm Friction bolt 2.4 m at 1.0 × 0.7 m spacing Seismic mesh reinforced galvanised 100 × 100 mm 5.6 mm gauge	To floor	6	0
Medium seismic	Fibrecrete 75 mm Friction bolt 2.4 m at 1.4 × 1.0 m spacing MD bolts 2.4 m at 1.4 × 1.0 m spacing Seismic mesh reinforced galvanised 100 × 100 mm 5.6 mm gauge	To floor	90	56
Heavy seismic	Fibrecrete 100 mm MD bolts 2.4 m at 1.0 × 0.7 m spacing Seismic mesh reinforced galvanised 100 × 100 mm 5.6 mm gauge	To floor	18	13
Ultra seismic	Fibrecrete 100 mm MD bolts 2.4 m at 1.0 × 0.7 m spacing Seismic mesh reinforced galvanised 100 × 100 mm 5.6 mm gauge Osro straps 6 m long laterally across backs of drive at 1.4 m spacing, pinned with 2.4 m MD bolts at 2 m bolt spacing, and 3 × 6 m dynamic cable bolts at 2 m bolt spacing Osro straps also on both walls pinned with 2.4 m MD bolts at 1.4 m spacing	To floor	0	6
Totals			224	137

7 Input parameter: damage sustained by ground support

Failure of ground support components is readily observable and is operationally recorded as an unwanted outcome, so charting using the ground support damage parameter is practicable. It is important to verify that any damage instance was in fact due to the seismic event and not to prior blasting, squeezing, consumed capacity or other factors.

Damage sustained by ground support is distinguished from rock mass damage. For a crush-type event, the amount of energy resulting from the seismic event must be dissipated by either ground support yielding/damage or by rock mass fracturing damage. The authors consider that a more effective ground support scheme would shed a greater portion of loads and energy to the rock, causing more rock failure rather than resulting in lesser rock fracture but broken hardware components. The charts certainly demonstrate less ground support damage for the more enhanced schemes.

The details of ground support damage sustained during a seismic disturbance are unique in every instance, so it is necessary to adopt a generalised method of describing support damage. The general method adopted was described by Mikula & Gebremedhin (2017) and is shown in Table 2.

The performance levels in Table 2 are as follows:

- Acceptable: damage classes S0 to S2. The disturbance does not compromise the functionality of the ground support, so mine production may continue uninterrupted. No rehabilitation is required.
- Tolerable: damage class S3. The ground support requires some repair, rehabilitation or replacement, but the extent of damage does not present a major threat to personnel or equipment. Support prevents fall of ground (other than small scats through mesh). Some production interruption (rehabilitation) is likely necessary.
- Intolerable: damage classes S4 to S5. The safety of personnel and equipment is compromised and production is significantly impacted. Support has lost functionality to the point that a fall of ground has occurred.

The distinction between acceptable (S2) and tolerable (S3) performance is a site-based, semi-qualitative engineering judgement based on observations such as:

- Whether or not bolts were broken.
- Whether or not mesh was bagged to capacity.
- Whether or not bolt bearing plates were heavily loaded.
- Whether or not rehabilitation of the damage was carried out.

Table 2 Support damage scale rating summary guidelines for damage caused by a seismic event, modified from Kaiser et al. (1995), with performance level indicators

Rating	Steel support damage guideline	Performance level
S0	No damage	Acceptable
S1	First signs of distress	Acceptable
S2	Loaded, plates deformed, mesh bagged but functional	Acceptable
S3	Heavy loaded, few broken, mesh bagged, some torn/open	Tolerable
S4	Major damage, broken bolts, mesh failed or bagged to capacity, rock ejected	Intolerable
S5	Complete failure of support components	Intolerable

8 Input parameter: event magnitude

Magnitude characterises both the amplitude and the rate of elastic convergence of the excavation surface during the dynamic disturbance, so it is a valid proxy for the intensity of crush-type events. The driver of the damage is high tangential strain of the surface. The location of rock mass damage (typically significant bulking of stress-fractured ground on the excavation perimeter) usually coincides with the seismic source. The radiated waves are initiated by the sudden elastic convergence of the rock mass surrounding the burst location.

In contrast, radiated wave parameters such as PPV may be more suitable than magnitude for characterising intensity of slip-type event sources occurring at some distance from a damage location.

There is no standard for which magnitude scale or equation should be used for mine seismic monitoring. A moment magnitude scale (from Ben-Zion & Zhu 2002) is used at both mines because some prior work at Flying Fox suggested that scale provided a good relationship between magnitude, PPV and damage for this site. Under this scale the local magnitude is as defined in Equation 1.

$$M_L = \log_{10}(\text{Moment}) - 9.76 \tag{1}$$

Using magnitude distinguishes between near- and far-field events since far-field events cause less damage for the same magnitude event. One event can damage multiple places in a mine, some nearer than others to the source. Early empirical charting work (Mikula 2012) based on PPV rather than magnitude demonstrated this well, showing less PPV and less damage from far-field events. Thus they were not critical demarcation points.

9 Chart construction process

The charting process is not a black box but is transparent: the data scatter is clearly indicated on the chart. Several processes contribute to inherent data scatter, for example:

- Ground support installation: the installed instances of each of the schemes are not identical. The actual installed ground support scheme varied locally from the intended scheme. Typical variables include bolt spacing, anchorage strength, installation quality, consumed capacity due to prior events and the geomechanical details of the rock mass.
- Magnitude variability: inherent variability exists between seismic disturbances that happen to be recorded as having identical magnitudes. Each is unique, and not identical in other attributes.
- Variable vulnerability to damage: the complex interactions among the energy transmission process, the rock mass and the ground support result in variable damage from events of the same magnitude.

Other processes result in computational data scatter, including:

- Possible magnitude scale deficiencies: higher magnitudes may saturate if the seismic sensor array in the mine is deficient, i.e. the recorded magnitudes may be less than the actual magnitudes. This would cause a certain level of damage to be associated with an apparent lesser magnitude of event in the chart. However, this is a conservative error and as such is tolerable.
- Near- or far-field: if damage in a particular case happens to be in the far-field, the damage will be less than would have happened in the near-field. So the data point will plot in a lower position on the chart and not be a critical point for defining the worst-case damage demarcation line.
- The waveform processing may have some error, resulting in an incorrectly allocated magnitude.
- The visual estimate of damage class could be in error.

The datasets represent damage influenced by all the above factors. With statistically adequate case numbers, a significant proportion of cases can reasonably be expected to represent challenging or worst-case performance conditions for the ground support. The method only requires some of the total pool of points to demonstrate worst-case performance. Any of the critical data points defining the lower-bound envelope could be in error for several reasons, so it is essential to double-check the validity of each such point. This is an essential requirement for the success of the empirical charting method, which depends on inclusion of worst-case data points.

Once all data points are validated and plotted, a lower-bound envelope is fitted to the data points to define the lower-bound, worst-case or minimum performance of the ground support. It is noted that mine geotechnical personnel normally do take effort to record the most adverse damage outcomes from larger events occurring in their mines, so it is reasonable to expect that worst-case performance points will be included in statistically adequate datasets.

Minimum ground support performance is the result of the most adverse combinations of attributes, such as cases where ground support installation quality was lacking, where some capacity was consumed prior to the seismic disturbance or where an event of a given magnitude resulted in a particularly intense disturbance.

Some cases were observations of zero damage while at Flying Fox, multiple damage sites resulted from the one event. No distinction is made in the charts between damage in the backs or in the walls, as prior assessments suggested there was not much difference between the two. More observations should be added as they become available over time, which will increase the confidence in the results of the process.

Where multiple data points happened to be superimposed, they were allocated small perturbations in the y-axis value to enable them to be visible in the charts.

10 The demarcation lines

Demarcation lines (or lower-bound envelope lines) defining critical performance of the various ground support schemes are fitted to the chart data.

The primary aim of a demarcation line is to define the magnitude dividing S3 and S4 damage, called the S3.5 magnitude. That represents the functional limit of a given scheme. If the forecast magnitude at a location exceeds that magnitude then that scheme should give way to a higher scheme.

Positioning of the demarcation lines is not a trivial exercise. The following considerations are relevant:

- Number of data points with S1 damage (the lower end of the damage scale). Since smaller magnitude events are more frequent, lower levels of damage should be frequent. While S0 damage (no damage) may not be recorded, S1 damage usually is. So the lowest S1 position in the chart is likely to be a critical point, i.e. a reliable point for demarcation.
- Possible absence of critical S3, S4 and S5 points if data for higher damage levels is sparse. If only S1 and S2 points are available then just fitting a line to the worst-case S1 and S2 points can be misleading – it can give too high an estimate for the critical S3 and S4 magnitudes.
- Damage classes do not equate to a linear increase of damage. A shift from S1 to S2 may be quite small (a few extra cracks in fibrecrete), while a shift from S4 to S5 can represent a very large amount of additional damage. Therefore, the demarcation lines need not be linear – but currently straight lines are used due to lack of guidance on this aspect.
- Magnitude is also not linear. Depending on the particular magnitude scale used, an increase of magnitude by one unit equates to the order of 30 times an increase in radiated energy. A small increase in magnitude can potentially result in a large increase in damage.
- Only a few events were large enough to generate significant damage to the higher capacity ground support schemes, so some schemes may not be well represented in the data.
- Any of the data points defining demarcation lines could be in error for reasons noted previously so, once identified, the critical points require rechecking.

11 The charts

Charts were prepared with indications of the lower-bound scheme performance for the site moment magnitude scale. The site damage tolerance is defined as the S3.5 magnitude separating S3 and S4 damage.

- Flying Fox: friction bolt, fibrecrete and mesh schemes (Figure 2).
- Flying Fox: light, medium and heavy seismic schemes (Figure 3).
- Spotted Quoll: friction bolt, fibrecrete and mesh schemes (Figure 4).
- Spotted Quoll: medium, heavy and ultra seismic schemes (Figure 5).

For ease of comparison, the demarcation lines from all four charts are collated in Figure 6. These lines on the charts can be interpreted in two equivalent ways:

- For a given event magnitude, damage sustained will not be worse than a given damage class.
- Events of intensity less than a given magnitude will have damage less than a given damage class.

Note the discordant points arrowed in Figure 5. These are suspect, and ignored, as they indicate performance grossly inferior to all other observations and site expectations based on experience. Site records indicate that the ‘medium seismic’ M_L0.29 point could have been blast or squeezing damage, and the M_L0.63 point could have been squeezing. The ‘heavy seismic’ M_L0.69 point was an area under stress prior to the event and mesh was bled in an adjacent zone, so it is considered that support capacity was already consumed in this zone.

12 Chart summary demarcation lines

Figure 6 enables comparison of all the chart results via a compilation of the demarcation lines. Table 3 compares the prior and new performance limits for the mines. It is considered that:

- The Spotted Quoll limits seem accurate based on site practice.
- Spotted Quoll limits are all 0.2–0.3 higher in magnitude than Flying Fox limits. This is judged to be due to the different geological and geomechanical environments.
- The heavy seismic lines in both cases do not have sufficient higher damage points so the trends of those lines are carried parallel to the medium seismic lines. The heavy seismic limits are about as expected from prior work.
- The Flying Fox medium seismic limit M_L1.4 is much lower than the prior limit M_L2.1. While this limit seems low, there have been instances that justify this number. In most cases, medium seismic performance is acceptable up to M_L1.5 or 1.6, but this M_L1.4 scenario outlines the advantage of this work in that the charting takes into account all of the intricacies that can negatively impact the actual capacities versus design capacities. Even if the Flying Fox trendline was to be adjusted somewhat, the medium limit would not change very much. All Flying Fox limits are less than Spotted Quoll limits, so the Fox medium limit should certainly be less than M_L1.7.
- Upgrade from light to medium seismic schemes improves performance by 0.8 or 0.9 M_L points.
- Upgrade from medium to high seismic schemes improves performance by 0.55–0.6 M_L points.

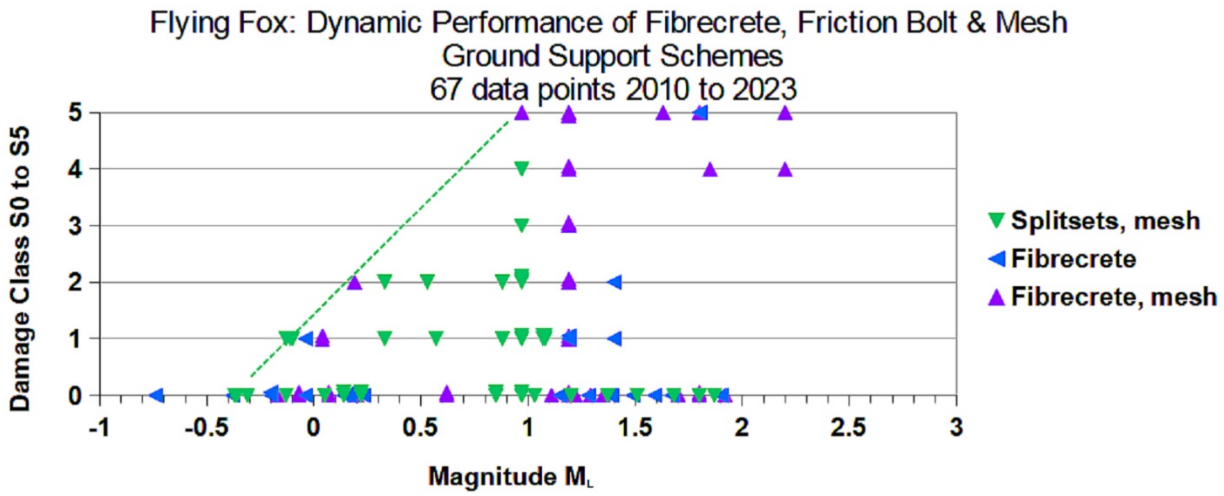


Figure 2 **Flying Fox – Friction bolt, fibrecrete and mesh schemes. The site damage tolerance S3.5 magnitude for all schemes is M_L0.6**

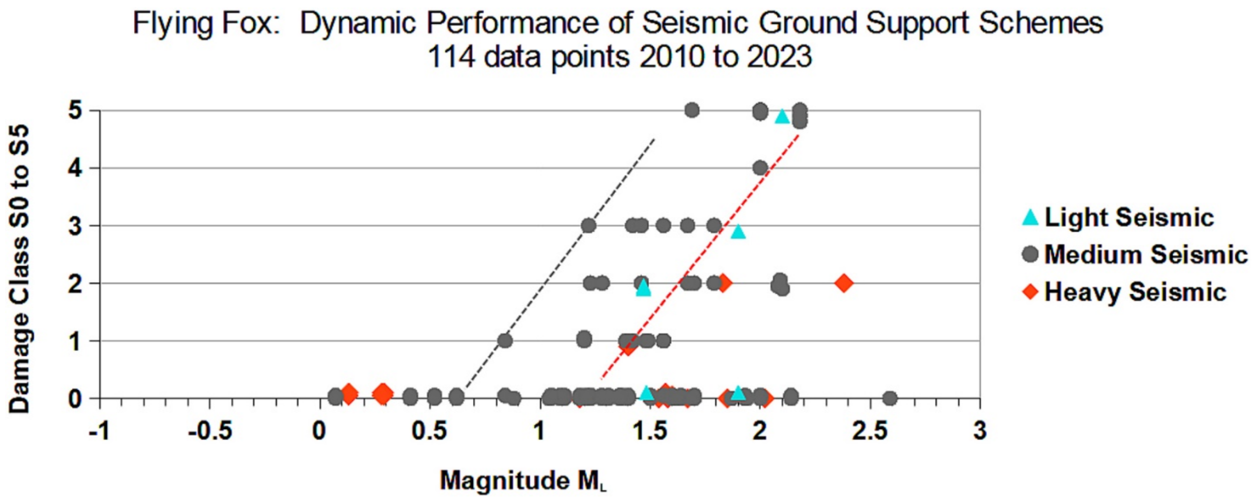


Figure 3 **Flying Fox – light, medium and heavy seismic schemes. The site damage tolerance S3.5 magnitude is medium seismic = M_L1.4, heavy seismic = M_L2.0**

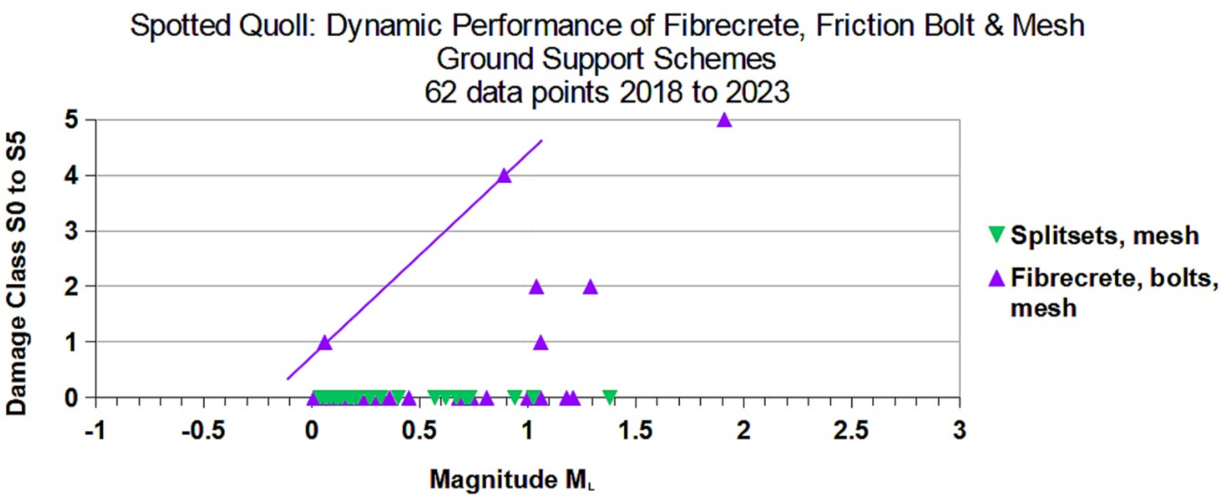


Figure 4 **Spotted Quoll – Friction bolt, fibrecrete and mesh schemes. The site damage tolerance S3.5 magnitude for all schemes is M_L0.8**

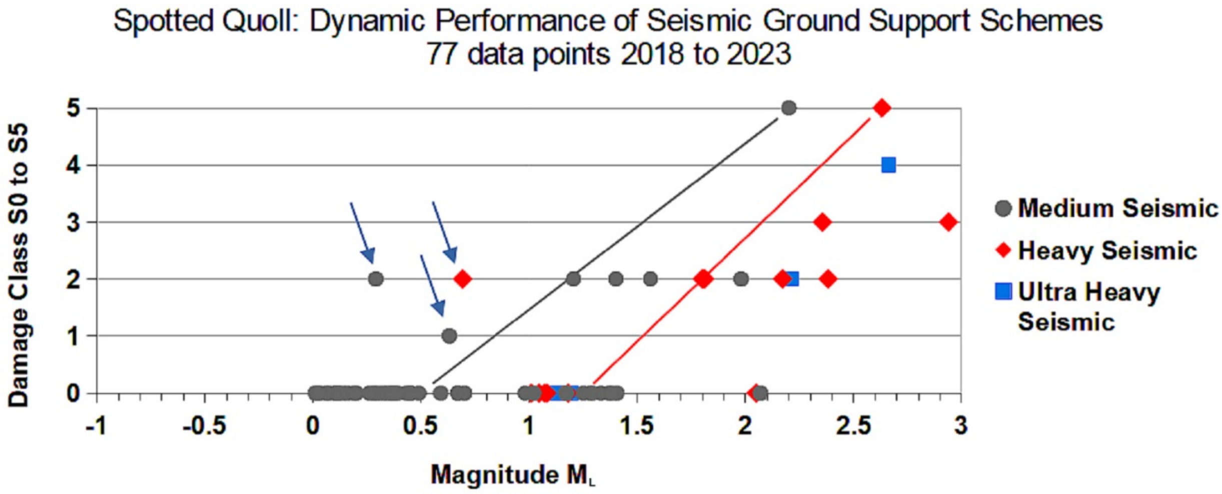


Figure 5 **Spotted Quoll – medium, heavy and ultra seismic schemes. The site damage tolerance S3.5 magnitude is medium seismic = M_L1.7, heavy seismic = M_L2.25. No limit can be identified as yet for the ultra scheme**

Table 3 **Comparison of prior (2018) and new (2023) upper limits for ground support schemes**

Edition	**Type of limit**	**GSP4A**	**Light seismic**	**Medium seismic**	**Heavy seismic**
Prior Flying Fox	Damage class versus M_L	M_L0.2	M_L0.8	M_L2.1	$M_L > 2.1$
New Flying Fox	Damage class versus the S3.5 M_L point	M_L0.6	n/a	M_L1.4	M_L2.0
New Spotted Quoll	Damage class versus the S3.5 M_L point	M_L0.8	n/a	M_L1.7	M_L2.25

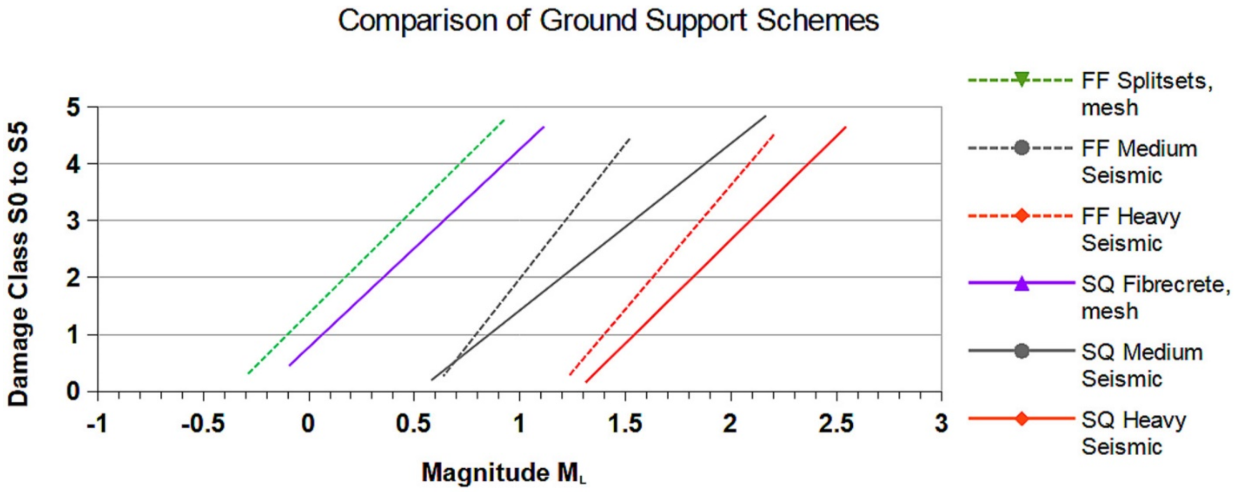


Figure 6 **Flying Fox and Spotted Quoll – compilation of demarcation lines**

13 Practical use of the charts

The charts have several applications. They are useful for routine operational ground support assessment, e.g. where and how to upgrade in response to seismic activity, or what level of ground support to specify for a new area.

Engineering assessment is required regarding the applicability of the charts for scoping or feasibility studies, such as for a new mining block in an existing mine. This depends on the extent to which the new conditions are similar to the existing.

The charts are also useful to quantify how different ground support schemes perform relative to each other.

To use the charts for selection of an appropriate support scheme it is necessary to estimate an expected largest event magnitude that may occur in a given location. That estimation is outside the scope of this paper. These estimates are conducted in various ways, but essentially they are obtained from site seismic history for the area together with some means of estimating the next highest event expected.

An assessment is required as to whether worst-case data points are sufficient in number to confidently define worst-case demarcation lines. If they are not, the charted demarcation line may not be worst case. Engineering judgement should then be used to adjust to a more conservative ground support requirement.

At present, the charts are only applicable to the support schemes in use at the mine. If the mine adopts alternative schemes, future performance data will be used to expand the charts to include those schemes. The use of any bolt type in seismic conditions is subject to a design review to ensure its suitability for conditions in the areas in which it is to be used. The charts should be reviewed and updated periodically as new data becomes available.

A future task will be to extend charting to analyse rock mass damage data in the form of deformation of the excavation surface. This parameter is being measured routinely by more and more mines before and after seismic damage occurs.

14 Non-transfer of empirical charts to other mines

A practitioner would need to prove that a chart is transferable to another site. Factors mitigating against transferability include:

- Differences in seismic waveform collection, processing, interpretation and magnitude scales.
- Different geomechanical environment (stress fields, rock types, structures).
- Different mining environment (voids, mining method and sequence).
- Different ground support types and installation practices.
- Different assignment of damage classes.
- Differences in event mechanisms (fracture or fault slip) and damage (strainburst, ejection, shakedown or combinations).

Correlation with other industry experience is awkward due to the significant influence of all the above factors. Practitioners would likely expect to observe rock mass damage from events starting at about M_L1, but rock mass damage and support damage are quite different. For example, for Hamlet mine (Mikula & Gebremedhin 2017) the friction bolt scheme S3.5 damage point was $M_L1.4$. This may be compared with $M_L0.6$–0.8 in Table 3 above for a similar scheme for the Flying Fox and Spotted Quoll mines.

15 Conclusion

This paper shows how the empirical chart method provides useful guidance for dynamic support selection at Flying Fox and Spotted Quoll. It indirectly accounts for variables including source-damage distance and variable installation of the GSS schemes. The charts provide the guidance for the seismic magnitude ranges for which ground support regimes are appropriate. The focus is on identifying the limiting largest seismic event magnitude for which the schemes would be expected to sustain damage to a tolerable level.

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