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Evolution of parabolic arch design rationale for intersection support and variations between sites

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Abstract

Cable bolting is commonly used in most underground mines in Australia to support large spans and intersections. The assessment methodology currently employed by many mines adopts a 'parabolic arch' design rationale to support a tension arch of estimated volume with known rock mass density. Once the weight is determined, a number of cables are applied to the span. These are typically evenly-spaced and include allowance for a Factor of Safety.

During routine review work, the author has observed 6 differing versions of intersection support design rationale including 4 different versions of 'parabolic arch' design across mine sites in Australia. Calculations across multiple mine sites vary for cable bolt capacity, rock mass density selection, measuring of intersection span, cable bolt spacing, and tension arch depth to span ratio. Each assessment method observed has varying advantages and disadvantages for different ground conditions, excavation geometry, structural settings, rock mass properties and stress regimes.

This paper aims to collate and contrast the methods for intersection design – which are currently employed by multiple sites – to offer junior engineers a point of reference for intersection support. It is hoped that rather than copying and pasting the same intersection cable bolting design spreadsheet across operations, engineers may pick and choose between different design approaches based on the most relevant failure mode and ground conditions observed at each mine.

Other observations are noted regarding current trends in cable bolting installation, QA/QC testing, plate and tensioning, smart cable installation, intersection excavation sequence, closure pillar intersection management and historical failures.

Keywords: *intersection, cable bolting, parabolic arch*

1 Introduction

Before discussing the various versions of parabolic arch design available for intersection support, it is important to note some fundamentals surrounding parabolic arch area and volumes.

1.1 Parabolic arch volumetric considerations

The area under a 2D parabolic arch can be defined as:

$$A = 2/3 \times B \times H \quad (1)$$

where:

- A = area under a 2D parabolic arch (m^2)
- B = the length from one side of the parabolic arch to another (m)

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H = the height of the parabolic arch (m).

From an intersection design perspective, this can also be expressed as a function of the intersection diameter (D) and is shown schematically in Figure 1:

$$A = 2/3 \times D \times D/y \quad (2)$$

where:

A = area (m^2)

D = intersection diameter (m)

y = parabolic arch to depth ratio as a function of D.

Half of the area under a parabolic arch (or a quadrant) can be expressed as;

$$A = ½ \times 2/3 \times D \times D/y \quad (3)$$

Multiplication of this area (or quadrant) around the centroid of the area and 2π to create a volume under the paraboloid arch leads to:

$$V = ½ \times 2/3 \times D \times D/y \times 2\pi(3D/16) \quad (4)$$

$$V = (12\pi D^3)/(96y), \text{ or } \pi D^3/8y$$

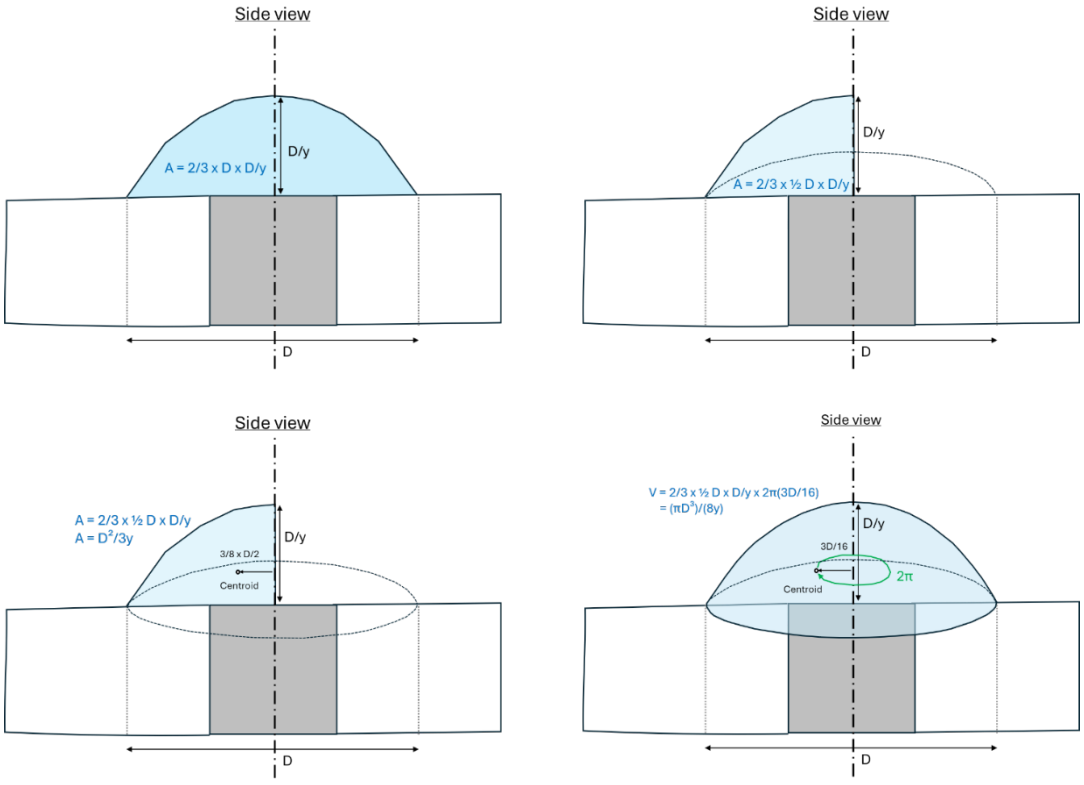


Figure 1 Area and volumetric considerations for parabolic arch relative to intersection diameter

Several published versions of parabolic arch design are available with varying levels of design approach, these can be summarised as follows.

1.2 Rosengren (2006)

A memorandum to Argyle Diamond Mines describes a standard method for calculating reinforcement requirements for wide spans and intersections in kimberlite (Rosengren 2006), and this design method is also

later described in detail by Potvin & Hadjigeorgiou (2020). The original Rosengren memorandum discusses 2 depths of parabolic arch based on the maximum inscribed circle within the intersection span (D). These are:

- Type A (⅓ × D) parabolic arch depth (general access or low stress conditions).
- Type B (½ × D) parabolic arch depth (strategic openings or high stress conditions).

Due to the potentially unfavourable grout to kimberlite bond strengths around the grout annulus (host rock kimberlite potentially being <<32 Mpa), a 3 m minimum embedment on each cable bolt was recommended (Rosengren 2006). In the author's experience, this is uncommon in many other hard rock mines where typical rock uniaxial compressive strength are >100 Mpa or even >200 Mpa. The Argyle memo (Rosengren 2006) goes on to recommend cable bolt ultimate capacity as 25 t for single strand cables, and 50 t for twin-strand cables, with a FoS of 1.2 applied to the cable bolt capacity to downgrade the tendon.

Other key considerations from the Argyle memo include:

> *"In very large intersections, it may be necessary to mine the intersection in two or more stages, with installation of additional cablebolts between stages."*
>
> *"The parabolic arch is simply a design concept and does not necessarily infer that the potential failure will follow this shape."*

The mass (M) to be supported by the reinforcement, per metre length of drive, is given by:

$$M = K \times \rho \times D^2 \tag{5}$$

where:

K	=	arch factor (Type A or Type B)
Type A (D/3)	=	2/9
Type B (D/2)	=	1/3
P	=	rock bulk density (t/m³)
D	=	roof or intersection span (m).

While arch factor (K) is not defined in the original memorandum (Rosengren 2006), a D/4 tension arch would require an arch factor of K = 1/6. Illustrations for the parabolic tension arch are shown in Figure 2.

It is important to note that M represents a t/m² value along a given tunnel length, rather than a typical intersection parabolic dome.

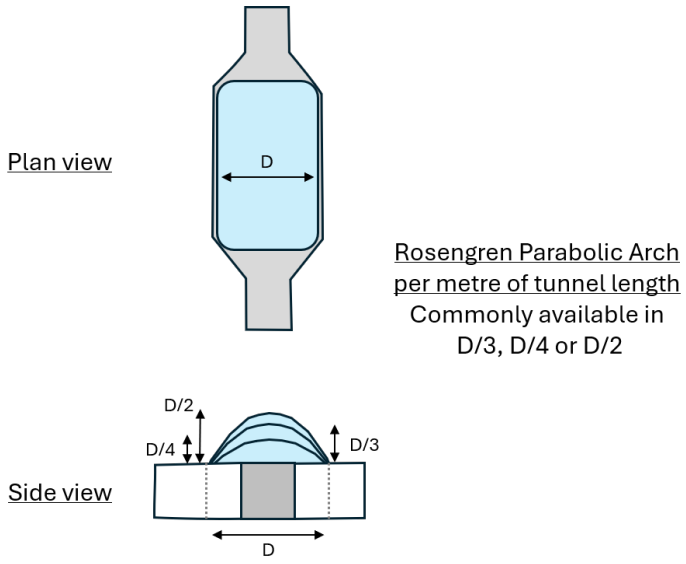


Figure 2 Overview of Rosengren Parabolic arch

1.3 Hills et al. (2015)

Hills et al. (2015) discusses the difference between parabolic arch along a wide span length of drive versus parabolic dome assessments for intersection support (Hills et al. 2015). Hills provided several worked examples for ground support at Challenger Gold Mine (CGM).

Key points for parabolic arch intersection designs within this paper are summarised as:

- 40 t twin-strand cable bolt capacity used at CGM, being the onset of inelastic yield, as suggested by Hutchinson & Diederichs (1996)
- D/3 tension arch
- Intersection volume (V) = $\pi D^3/24$
- Factor of Safety (FoS) = 1.5
- 2 m minimum embedment on cable bolts beyond fracture zone
- Cables should be installed at 90° ± 15°.

The author goes on to acknowledge:

> *"Where possible, the standard cable bolt designs allow for single pass cable bolting. This is not possible in order to achieve an adequate coverage of reinforcement in four-way intersections, and the mining of these intersections is avoided if at all possible, as a matter of good practice."*

and

> *"Standard cable bolt patterns may not be valid in the vicinity of intrusive dykes and sills; appropriate site-specific design is recommended on those occasions."*

1.4 Davison (2016)

This paper discusses several ideas and applications for the introduction of the Stiff Splitset Bolt and other ground support methods that may aid in the speed up of underground jumbo development. Intersection support methods are summarised with parabolic arch estimation, Unwedge analysis and empirical charts considered.

Davison (2016) suggests that, for smaller intersection spans in favourable ground conditions, a tight pattern of 3 m long friction bolts may be applicable for wedge support and be a viable alternative to cable bolting. This is in line with observations from current underground mines that utilise a mechanically anchored friction bolt for small intersection spans in good ground conditions, such as a Kinloc, MD, MDX or Mech-Lok bolt.

Davison (2016) acknowledges that parabolic arch estimation may be overly-conservative in some instances, particularly for static loading"

> *"…the paraboloid is considered a dead weight with no rock adhesion, no friction between rock and no clamping from depth induced stress."*

Further,

> *"It is very easy to throw more steel, concrete and time at mining problems. It is more challenging to determine what is the correct amount of steel, concrete and time that a project should take."*

1.5 Dolinar (2000)

A paper published by the National Institute for Occupational Safety and Health (NIOSH) from the USA (Dolinar 2000) discusses the introduction of cable bolting support in coal mines for longwall gate roads.

Failure modes for large spans within coal mines are discussed, including detached block on sedimentary layers, pressure arch and flexural beam loading due to the yielding coal pillars, as shown in Figure 3.

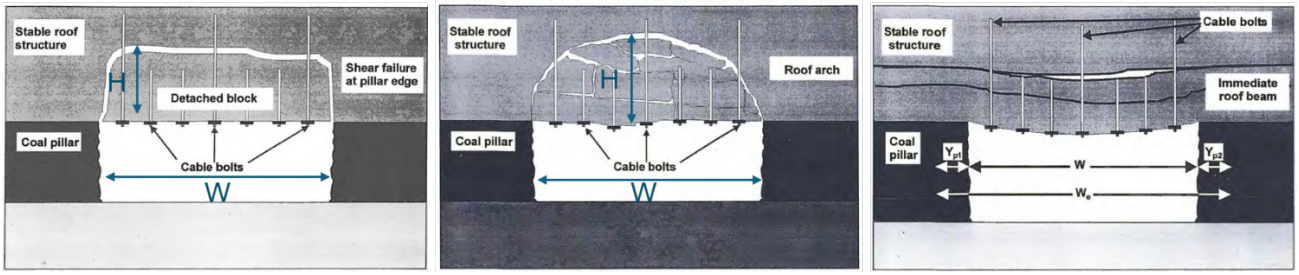


Figure 3 Overview of failure modes described by Dolinar (2000) in USA coal mines

The 'detached block' scenario equates to a failure volume approximated by,

$$F = W \times H \times \rho \tag{6}$$

where:

F = weight of rock to be supported per linear metre of gate road (t)

W = excavation width (m)

H = detached block depth (m)

ρ = rock density (t/m³).

Calculation of the Roof pressure arch weight per metre of gate road is the same and given by;

$$F = \pi/4 \times W \times H \times \rho \tag{7}$$

The tension arch depth in this scenario equates to a depth slightly greater than a D/3 tension arch and is an almost identical method to Rosengren (2006). Other notable mentions for bulbed cable bolts installed in resin and grout mediums from Dolinar (2000) include:

> *"Laboratory pull tests on short 76.2 cm column grout anchors have shown that anchor [bulb] components embedded in the grout significantly increase anchorage capacity over that of a cable without any [bulbs]."*

and

> *"Laboratory and field tests have shown that 1.2 m and 1.5 m of resin embedment will achieve the ultimate capacity of a cable if properly grouted."*

These testing observations for cable bolt critical embedment in coal mining (1.2 to 1.5 m) are generally half of those proposed for very poor ground conditions such as kimberlite (3 m) (Rosengren 2006). While this may be in part due to the influence of resin as a grouting medium, pull testing of early-strength cable bolts (Evans 2015) in cementous grouts indicates that a 1 m section of grouted bulbed cable bolt in a ~76 mm hole may be sufficient to generate full strand rupture.

The variance of critical embedment lengths between published authors from 3 m, 2 m, 1.5 m and 1 m is likely in line with the improved grout annulus to rock bond shear strength behaviour between different ground conditions.

2 Evolution of parabolic arch design for underground intersections and variations between sites

During routine review work and site coverage, the author has observed several adaptations of the parabolic arch design methods for intersection support that are discussed previously in this paper. To the author's knowledge, some of these adaptations are unpublished, however, are rather useful for different ground

conditions and intersection development methods in Australian hard rock mines. A summary for each adaptation is given below.

2.1 Half ellipsoid

This adaptation is an approximation of the tensile zone of instability, given by half an ellipsoid. Generally, this is more conservative than a parabolic arch dome assessment due to additional volume being incorporated near the edges of the intersection. This method has been used where concerns with adverse ground conditions have been raised, ground conditions are unknown, or repeated QA/QC issues with a mining contractor workforce were unable to be rectified for cable bolting installation.

The potential failure volume can be described by:

$$V = 2/3 \times \pi \times D/2 \times D/2 \times D/y \quad (8)$$

$$= \pi D^3/6y$$

where:

- V = tensile volume (m^3)
- D = intersection diameter (m)
- y = tension arch depth ratio as a function of D.

A schematic overview of this method is shown in Figure 4.

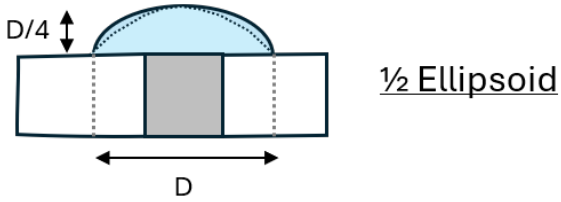


Figure 4 Overview of ½ ellipsoid tension arch dome for intersection support

2.2 Reduced parabolic arch method 1: Andrews arch

This is an adaptation from Rosengren (2006), where the outer ring of the tensile zone is subtracted. The rationale for doing this is that this outer ring is being supported by normal rockbolts from the development cycle, providing sufficient embedment and/or the positive influence of the shoulders of the drive. This method can be used in conjunction with D/4, D/3 and D/2 failure depths based on the range of stress conditions and ground conditions. Care should be taken to ensure that the outer ring annulus considers the details of the primary bolting support, such as bolt capacity, bolt critical embedment, and bolt spacing. An overview of this method is shown in Figure 5. For example, the outer ring to be subtracted would vary between development supported with a 2.4 m × 47 mm friction stabiliser versus a 2.4 m T20 resin bolt due to both variations in bolt capacity and critical embedment.

This method can be applicable across a wide range of ground conditions, e.g. poor to very good ground conditions (Q >1).

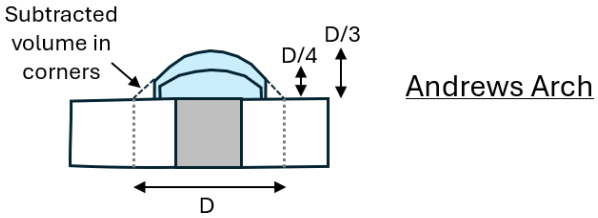


Figure 5 Overview of Andrews arch tension arch dome for intersection support

2.3 Reduced parabolic arch method 2: Reimnitz reduction

Another adaptation from Rosengren (2006) is where a natural overbreak zone is created when developing the intersection with a development jumbo and can be subtracted from the tension arch volume. In cases where some arching is realised, the modelled weight demand is reduced. In cases where poor profile is realised (e.g. bellied intersection backs), the modelled weight is increased. Whilst it is generally more conservative to assume flat backs for planned intersections, this method can easily be used to reassess actual factors of safety for realised excavations, i.e. as-built intersections based an actual realised spans, installed cables and excavation profile.

To use this method for planned intersections and cable bolting support, this author proposes the following excavation sequence to generate a natural overbreak zone in an intersection span containing good ground conditions in a favourable stress environment:

1. Square off the drag location shoulder when developing up to the intersection location and confirm suitable ground conditions for turnout location.
2. Fire the strip without installing pre-cables.
3. Scale and support the intersection area and wall strip to generate the natural overbreak zone through the backs, bleeding the existing mesh if required. Support through the backs commonly occurs with a 3 m bolt rather than a 2.4 m bolt for short-term support.
4. Fire another cut if needed, then place the heading on hold and install all the required intersection cables in a single pass.

This method is generally associated with good to very good ground conditions (Q ≥ 10) in favourable stress environments. An overview of this method is shown in Figure 6.

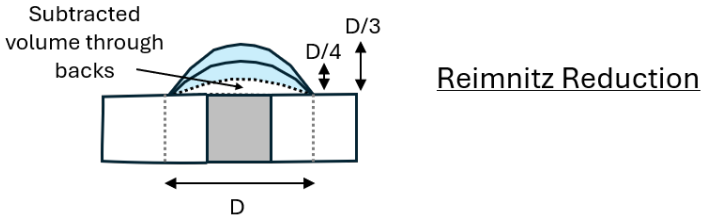


Figure 6 Overview of Reimnitz reduction tension arch dome for intersection support

2.4 Marco Orunesu Preiata's cone

This is an empirical hybrid design method between parabolic arch and kinematic wedge assessments applicable to deep hard rock mines. It considers partial wedge mechanisms based on the back-analysis of the failed rock mass cone above the underground openings as measured in the flat back development faces. This method was developed measuring the angles formed by the failed cone sides and the horizontal width of the drive, where drive width would vary significantly based on the thickness of the orebody. This approach can be varied on a cut-by-cut basis to account for increasing or decreasing mining widths, while still considering kinematic and tensile derived failure modes.

The potential failure volume can be described by:

$$V = \pi \times D^2/4 \times 0.25 + \pi \times D^2/4 \times y/3 \quad (9)$$

$$= (\pi D^2/4 \times 0.25) + ((\pi D^2/4) \times (D/2 \times \tan(\alpha)/3)$$

where:

V = tensile volume (m^3)

D = intersection or drive span diameter (m)

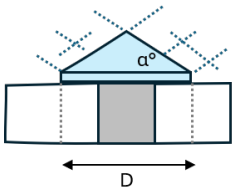
y = height of the cone apex (m) as D/2 x tan(α) with α angle measured in the flatback faces and varying with the rock mass (radians)

0.25 = height of the small cylinder of failed rock and fibrecrete at the base of the cone (m).

Examples of site-specific values for α angle in a deep hard rock Nickel mine in Western Australia include:

- Ore: 25°
- Metasediment: 38°
- Granite: 23°.

An overview of this method is shown in Figure 7.



Marco Orunesu Preiata's cone

Figure 7 Overview of Marco Orunesu Preiata's tension zone cone for intersection support

2.5 Dolinar cylinder

This is an adaptation from Dolinar (2000), where for an underground intersection in sedimentary, laminated or weak layered conditions, a cylinder is used to approximate the failure volume. This is applicable for flexural delamination of a layered rock mass, where shearing of layers along the 'edge' of the cylinder occurs.

$$V = \pi \times D/2 \times D/2 \times D/y \quad (10)$$

$$= \pi D^3/4y$$

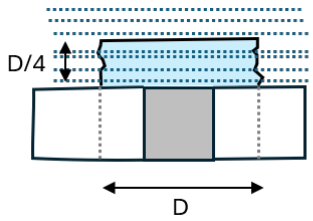
where:

V = tensile volume (m^3)

D = intersection diameter (m)

y = tension depth ratio as a function of D.

An overview of this method is shown in Figure 8.



Dolinar Cylinder

Figure 8 Overview of Dolinar tension derived cylinder for intersection support

2.6 Summary of design methods

All 6 assessment methods have varying advantages and disadvantages as intersection support design methods. It should be noted that each design method is suited to a specific set of geotechnical conditions, and assumptions such as rock mass strength, stress levels and orientations, kinematic conditions, joint properties, excavation sequence and different levels of installed support QA/QC and standards.

To suggest that one design method is better than another would disregard the changes in variables between each mine site. A comparison is offered in Figure 9 and Table 1 between the six different intersection design

methods discussed, considering a typical tensile zone and rock density = 2.8 t/m³. Significant variations in the designed tensile zone weight above an intersection occur between the six different assessment methods.

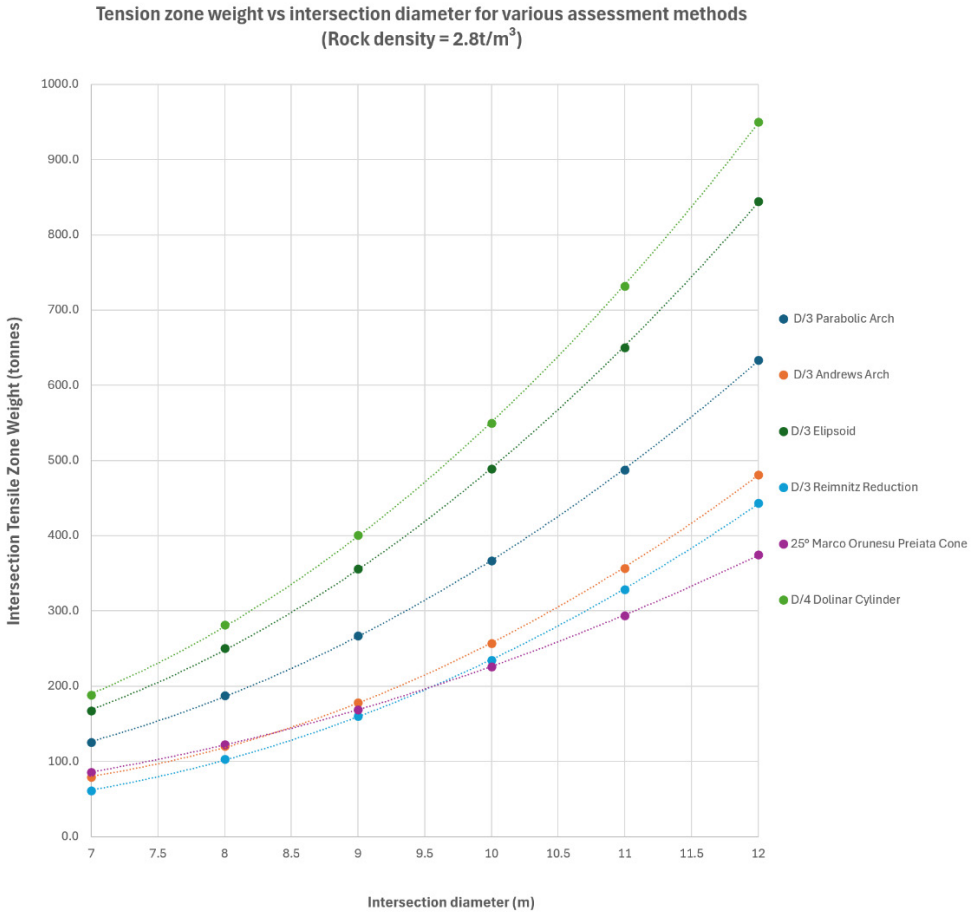


Figure 9 Comparison between intersection assessment methods discussed

Table 1 Summary of intersection design methods and generally applicable scenarios

Intersection assessment method	Generally applicable scenarios	Typical depth to intersection ratio
Dolinar tensile cylinder	Sedimentary, coal or weak layered rock mass	D/5, D/4 and D/3
1/2 ellipsoid tensile dome	Unknown rock mass conditions or poor cable bolting installation standards	D/5, D/4 and D/3
Parabolic arch tensile dome	Most common technique adapted from Rosengren	D/4, D/3 and D/2
Andrews arch tensile dome	Suitable in a wide range of ground conditions, relies on influence of shoulders in intersection and/or primary bolting pattern around the outer ring of intersection span	D/4, D/3 and D/2
Reimnitz reduction tensile dome	Relies on natural overbreak zone being generated though intersection span, before installing cables	D/4, D/3 and D/2
Marco Orunesu Preiata's tensile cone	Applicable to wide spans and intersections where 3 moderate to shallow dipping joint sets are found	23 to 38°

2.7 Intersection development and mining sequence

Intersection support needs to consider the initial excavation sequence and then the anticipated loading conditions that will occur over the life of that intersection. While many mines may operate with a rolling 3–5 year mine life, the reality is that intersection support designs particularly for capital development may need to be serviceable for >20 years. Intersection support design often needs to consider progressive span opening and the associated increasing tensile depth zones. Work completed by Turner et al. (2004) illustrates how progressive span opening affects tensile zone depth in wide spans or intersections, even in relatively small air leg development spans (Figure 10).

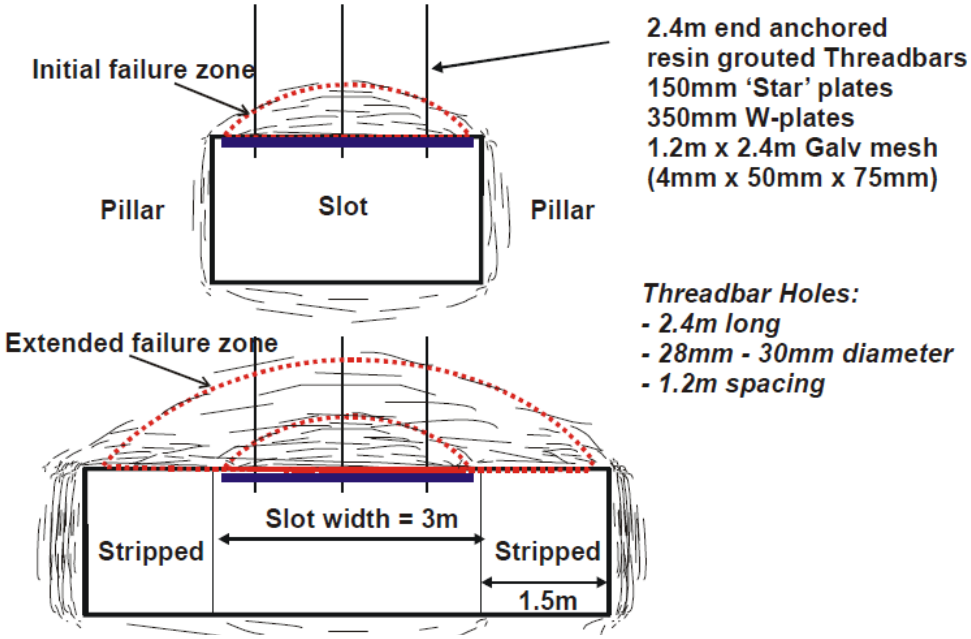


Figure 10 Progressive span and growing tensile zone in airleg development (Turner et al. 2004)

Other factors such as seismicity, nearby stope blasting peak particle velocity, abutment stress concentrations, and sudden de-stressing caused by stress shadowing once a stoping abutment passes the intersection location, are all relevant for the effectiveness of the installed ground support.

Four main methods for intersection development have been observed by the author. These are listed in order of risk tolerance:

1. Pre-cable bolting and post-cable bolting support, with plate and tensioning (generally applicable in almost all rock mass conditions, low risk tolerance).
2. Post cable bolting support: take a strip and cut, hold for cables, then single pass cable bolting support with plate and tensioning (generally applicable in shallow mines, minimal seismicity with good ground conditions).
3. Pre-cable all tendons from a vertical and dumped position prior to taking the drag cut or strip, don't plate and tension anything, fold up the exposed cable strands behind the mesh when bolting (generally applicable in rare circumstances where joint spacings exceed the critical embedment length of a cable bolt grout column, shallow mines, little to no seismicity, very good ground conditions, where the requirement for cable bolting is questionable to begin with).
4. No cable bolting of intersection or increased support: spans are geotechnically mapped under the provision of 'detailed geotechnical assessment' (rarely observed in modern mines, higher risk tolerance).

2.8 Plate and tensioning rationale

Three distinct approaches to 15.2 mm twin-strand bulbed cable bolt plating and tensioning exist in most Australian mines. Like the intersection design methods discussed previously, each tensioning method is applicable to a specific set of circumstances, such as ground conditions, stress regime, typical joint spacing or block size and excavation sequence. While observations from smart cable installation show that tensioning may only generate pre-loading of the cable bolt tendon in the first 0.5–1.0 m, the benefits of having the cable bolt integrated into the wider support system are often significant. The most common three tensioning methods and suggested applications are:

1. No plate and tensioning of cable bolt strands: high reliance on grout bond strength and encapsulation. Generally, only applicable in very good ground conditions and favourable stress environments (where Q ≥ 40). Typical block or wedge sizes often need to be greater than the critical embedment length of the cable bolt grout, allowing an unstable zone to be joined back to a stable zone. The use of bulbed cables is generally more forgiving for this design approach, rather than plain strand. In some instances, cable bolts installed in this method are largely cosmetic, allowing little (if any) load transfer to the surrounding surface support. In Western Australian mines, untensioned cables are more common for short-term stope cable bolting support, rather than long-term personnel exposure for development intersections.
2. Plate and tension single strand: generally applicable in low to medium stress environments, minimal seismicity with fair or better rock mass conditions (where Q > 4). Tensioning of one strand allows partial integration with surface support but still partially relies on the grout bond strength and encapsulation. Under extreme loading conditions the tensioned strand often ruptures, while the un-tensioned strand may be observed dangling from the backs post fall of ground (FoG) cleanup, as shown in Figure 11. In these scenarios the effective ultimate capacity of the cable bolt was 25 t, rather than the designed 50 t.

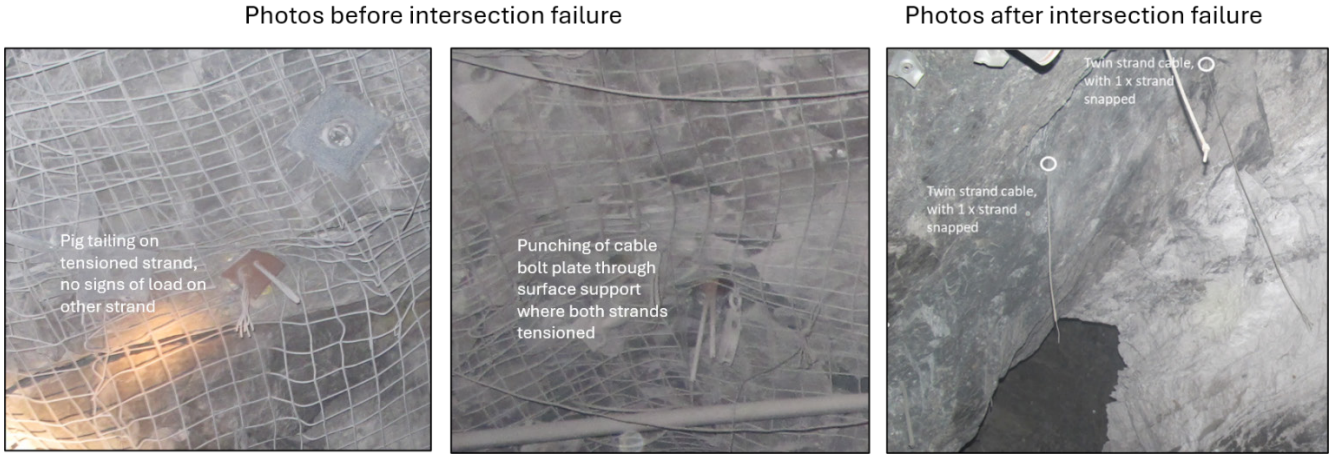


Figure 11 Observations before and after intersection failure at mine site 3

3. Plate and tension both strands: applicable in a wider range of ground conditions and stress environments (Q > 0.1). Tensioning of both strands allows full capacity of the cable bolt to be reliably achieved. Tensioning of cable bolt strands under static conditions often occurs to 5 t across both strands until the plate is pulled firm. Tensioning of cable bolts in dynamic conditions often occurs to 10 t across both strands pulling the plate firm up into the backs. Tensioning to 10 t allows the teeth of the wedge to penetrate the strand, resisting slippage during shock loading. The addition of grease or lanolin oil is often used to protect the barrel and wedge from corrosion and premature failure during shock loading.

3 Intersection rockfall case studies and key learnings

When intersection failures occur, they occur with a very high consequence. This is in part due to the large spans created, leading to large tensile zones or areas of unconfinement. Personnel and machines may be placed in the line of fire when developing or stoping activities occur, should the excavation sequence and support design not consider the failure modes present. The volume of potentially unstable rock can exceed falling object protective structures (FOPS) and roll-over protective structures (ROPS) on heavy underground mining equipment.

3.1 Rockfalls during intersection development cycle

Development of wider drive spans or intersection establishment without adequate cable bolting reinforcement and development hold points can be hazardous. Two recent rockfalls are shown in Figure 12 where in both instances a development jumbo was severely damaged and underground operators were lucky to escape injury or worse. In such cases, failure is generally dominated by kinematic mechanisms and unconfinement, rather than multiple stages of progressive stress fracturing generating a growing tension arch above an intersection span. Given that the development cycle for an intersection or wide span occurs from a supported area into an unsupported area, there is potential for kinematic instabilities to fail and swing (or rotate) towards the development drill.

A common misconception is that all rockfalls fail vertically downwards, without considering the effect of ground support on the boundary for the rockfall and how this may influence the direction of travel. The main consideration here is that operators working behind the last row of fully intact and competent ground support may still be in the line of fire when sub optimal intersection establishment methods are adopted.

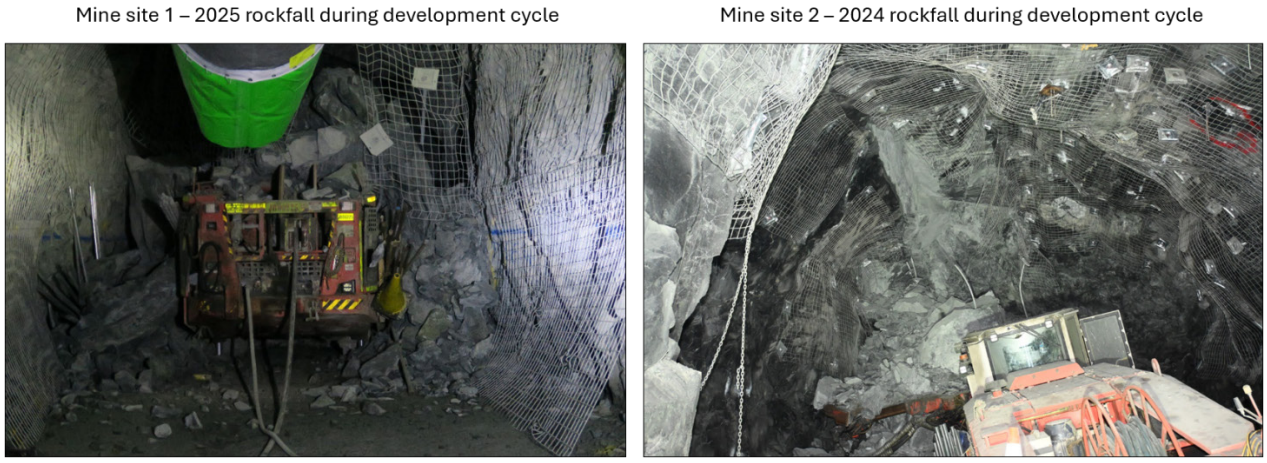


Figure 12 Underground rockfalls during development while forming wide spans or intersections

The key consideration here is that support design and excavation sequence need to be appropriate for the ground conditions encountered when developing an intersection or wide span. In some instances, particularly for rock mass conditions where Q<40, or in blocky or high stress conditions, timing of cable bolt installation within the intersection development sequence is key to maintaining a safe work environment.

3.2 Intersection rockfalls during stoping cycle

In the author's experience, intersection rockfalls during the stoping cycle are slightly more common. This is in large part due to the additional intersection loads that often occur because of poor mining geometries, seismicity, nearby stoping blasts (high PPV), production drilling near or within the intersection span and sudden unconfinement due to stress shadowing. In addition, some of these locations can be >3 years old, with varying levels of water ingress, corrosion and progressive stress fracturing over time. Two examples are

shown where large intersection spans in close proximity to stoping have unexpectedly failed, as shown in Figure 13.

In both cases below, the intersection design method was ultimately inadequate for level of loading observed. In many instances, closure pillars may be more appropriately designed with a greater tensile depth, (e.g. upgrading from D/4 to D/3, or upgrading from D/3 to D/2). This is particularly encouraged as the effects of stress or seismicity are observed in a mine undergoing a stress transition or in poor ground conditions. Back-analysis of previous failure volumes, or cable bolt extensometer installation allow validation of key design assumptions.



Figure 13 Underground rockfalls during stoping cycles

4 Conclusion

Several methods for calculating the zone of potentially unstable rock mass above an intersection are presented. Some have been previously published, and others are more recent adaptations by well-known geotechnical professionals. Each method is outlined, with some considerations offered for application.

All 6 assessment methods have varying pros and cons as intersection support design methods. It should be noted that each design method is suited to a specific set of geotechnical conditions such as rock mass strength, stress levels and orientation, kinematic conditions, joint properties, excavation sequence and different levels of installed support QA/QC and standards. To suggest that one design method is better than another would disregard the changes in variables between each mine site.

Intersection support design often needs to consider progressive span opening, immediate kinematic instability, tensioning standards and the associated increasing tensile depth zones over the life of the excavation. Other factors such as seismicity, nearby stope blasting PPV, abutment stress concentrations, corrosion, progressive stress fracturing, and sudden de-stressing caused by stress shadowing, are all relevant for the effectiveness of the installed ground support.

It is hoped that this paper offers junior engineers a source of reference for intersection design techniques across multiple ground support types and geotechnical conditions.

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