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Towards a new understanding of dynamic support performance and its implication for design

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Abstract

Ground support is one of the main means of managing rockburst risks in mines. Its main goal is to contain shattering and dynamic bulking of rock masses. This paper focuses on the behaviour of ground support systems during the dynamic bulking process. It draws from 2 work packages under the umbrella of the Australian Centre for Geomechanics Ground Support System Optimisation Phase 3 (GSSO 3) research project. The data comes from high-speed video footage from in situ dynamic testing of ground support systems and a large empirical database of rockburst damage. The interpretation relies on observations the authors have made over many years in deep mines.

Different situations related to small/medium as well as large seismically triggered strainbursts (rockbursts) are explored. The situations include, rockbursts in hard-solid rock mass and rockbursts in deep mines, where excavations are surrounded by a layer of stressed broken rock mass.

The behaviour of typical yielding ground support systems is analysed in detail. The interaction between support elements and the shattering/bulking rock mass leading to failures is explained. The support systems' weakest link for each situation is also identified.

The paper concludes with the implication of these analyses on the industry approach to dynamic ground support systems design.

Keywords: *dynamic ground support, rockburst, deformation, performance, in situ testing*

1 Introduction

Potvin et al. (2019) described rockburst risk in seismically active mines as extreme because of the possible consequences of multiple fatalities which also often lead to long periods of mine shutdown, loss of ore reserves and in extreme cases, permanent mine closure.

Although these accidents are infrequent, the rockburst risk remains tangible in deep and high-stress mines. A recent major seismic related tragedy occurred on 31 July 2025, at the Codelco's El Teniente mine in Chile, where 6 mine workers were fatally injured by a rockburst related to a 4.2 magnitude seismic event.

Seismic risk is a very complex problem and as such it is intricate to manage. Potvin et al. (2019) proposed the seismic risk management flow chart reproduced in Figure 1.

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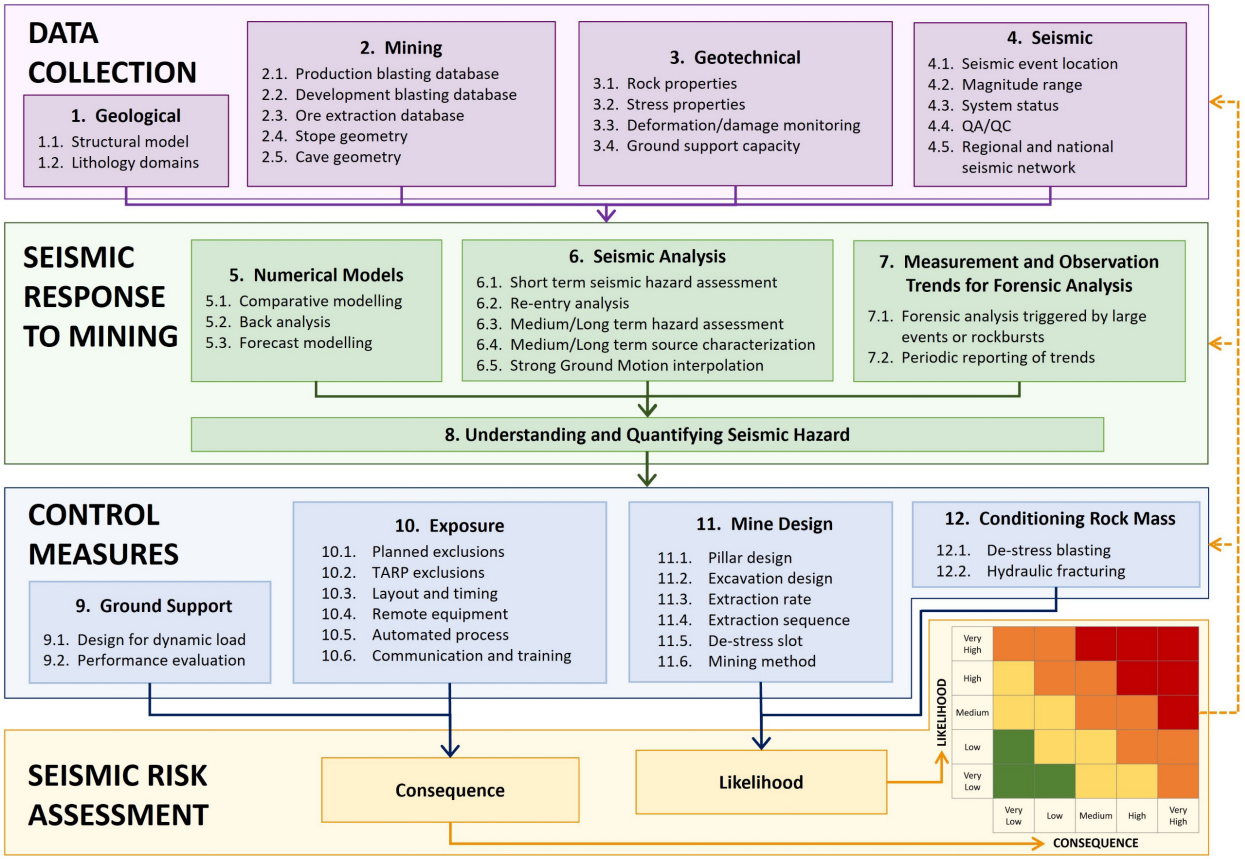


Figure 1 Seismic risk management flow chart (Potvin et al. 2019)

The flow chart shows that the approaches to control the consequences of rockbursts include a combination of ground support practices and restricting people exposure.

Ground support subjected to dynamic loading has been the subject of intense research in the mining industry for several decades (for example, Tannat et al. 1995; Canadian Rockburst Handbook [CRH] 1996; Ortlepp 2005; Simser 2005; Potvin & Wesseloo 2013; Morissette et al. 2014; Louchnikov & Sandy 2017; Mercier-Langevin 2019; Board 2019; Graham et al. 2023; Landry et al. 2024; Cuello et al. 2024).This paper focuses on the behaviour of ground support during the dynamic bulking process. It draws from 2 work packages under the Australian Centre for Geomechanics (ACG) Ground Support System Optimisation Phase 3 (GSSO 3) research project umbrella.

The first work package focused on in situ dynamic testing of ground support systems where blasting is used to impact a supported test wall from behind to produce dynamic bulking of the supported rock mass. This is described Sewnun & Potvin (2026). These tests were well instrumented with 24 geophones installed on the surface of a 5 × 10 m test wall and recorded with one or 2 high-speed cameras.

Traditionally, site personnel and researchers had to use their imagination to ‘reconstruct’ what happened during the dynamic bulking process, by observing the crater carved out of the drive surface and the highly fragmented muck pile with broken ground support elements lying on the muck pile or sticking out of the wall.

The high-speed camera footage enables unique visual observations of the full dynamic bulking process including the ground support system components interacting with the fracturing and bulking rock mass. This enabled us to scrutinise and analyse this process.

This paper also draws from observations of naturally occurring seismically induced rockburst case studies. GSSO 3 has assembled a comprehensive database including 252 rockburst damage case studies from 17 mines (Potvin & Goulet 2026). The interpretation of ground support mechanisms put forward in this paper is

a culmination of 'learnings' from the in situ dynamic tests and rockburst database, as well as observations the authors have made over many years in deep mines.

2 Rockburst damage mechanisms

Thirty years ago, Kaiser and co-workers (CRH 1996) proposed 3 rockburst mechanisms (Figure 2), presumably caused by the radiated stress wave (shock wave) induced by seismic events.

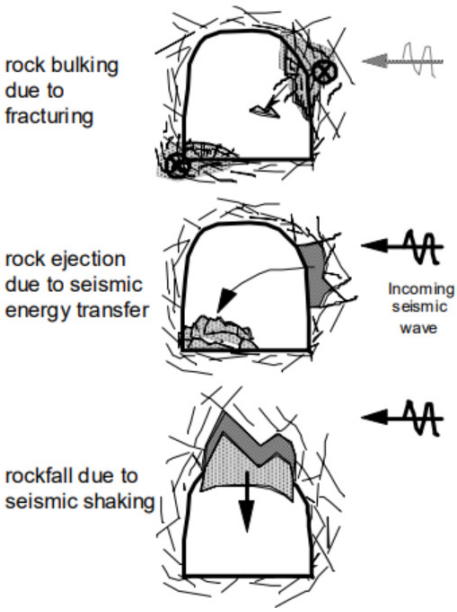


Figure 2 Rockburst damage mechanisms (after CRH 1996)

One decade later Heal et al. (2006) introduced the concept of excavation vulnerability to rockburst damage by empirically quantifying 4 factors:

- stress condition
- ground support capacity
- excavation span
- geological structure

Picking up on the stress condition factor, these rockburst mechanisms were later refined by Kaiser & Cai (2013), highlighting the contribution of the stress being accumulated and stored in stiff rock mass (stored strain energy), to rockburst damage.

> *"In other words, for all three rockburst types, the energy stored in the rock before a rockburst and the local mine stiffness must play a role in the damage process and affect the severity of damage and needs to be considered in support design." (Kaiser & Cai 2013)*

They therefore proposed the following 3 mechanisms:

- self-initiated strainburst: when a remote seismic event has no role in triggering nor creating rockburst damage
- seismically triggered strainburst: when a remote event initiates but does not contribute energy towards rockburst damage
- dynamically loaded strainburst: when a remote seismic event contributes significant energy towards rockburst damage.

Results from the GSSO 3 in situ dynamic tests suggests that the shock wave from remote events may not have a significant contribution to the dynamic bulking of the rock mass (Sewnun & Potvin 2026). More work is required to fully understand the role of remote seismic events to rockburst damage.

Because this paper is concerned with the behaviour and performance of ground support systems subjected to dynamic bulking, the source of energy creating the dynamic bulking will not be further discussed in this paper. For this discussion, we will refer to the damage mechanism simply as strainbursts, with the understanding that in most cases, it will be remotely triggered by a seismic event and driven by stored strain energy.

The shakedown mechanism (bottom drawing in Figure 2) is an issue of insufficient static ground support design capacity or deteriorated ground support capacity and lack of ground support maintenance, rather than dynamic bulking. Therefore, it will not be discussed in this paper.

A fourth damage mechanism is rarely discussed in literature but was recognised by Heal et al. (2006) and addressed with their fourth excavation vulnerability factor (geological structure). This mechanism has been identified and documented in the ACG GSSO 3 database. It is occurring because of fault slip events, and damage occurs at locations where the slipping fault crosses excavations. Empirical data shows that in most cases this mechanism caused very localised damage, a few metres on each side of the fault, with low to moderate depth of failure. This suggests that dynamic bulking is not the primary source of damage. This mechanism will also not be discussed in this paper.

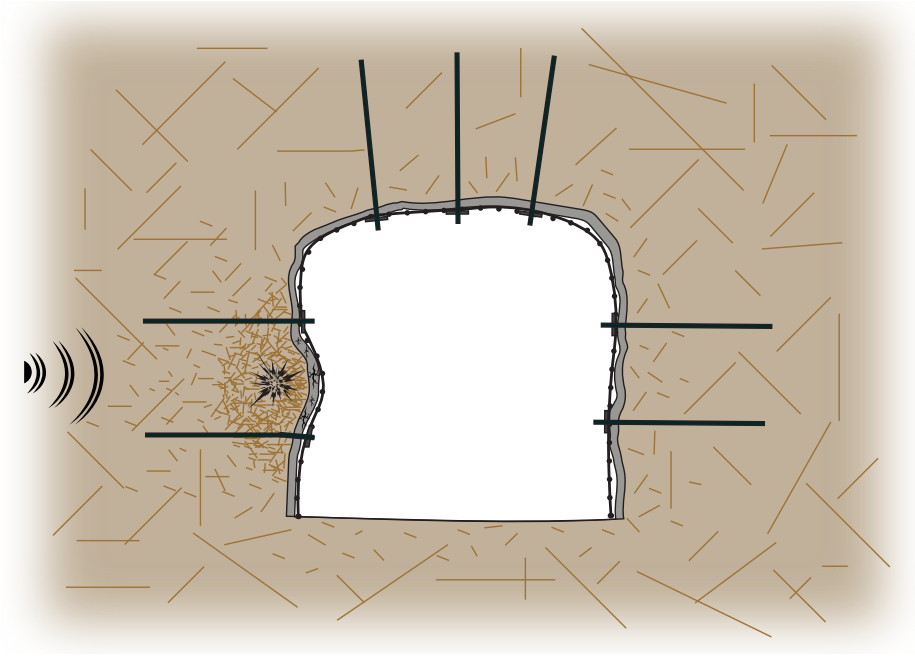
3 Ground support systems containment of dynamic bulking

Ground support systems achieve their purpose if they can contain the shattered bulking rock mass. In this section, we will look at 3 main scenarios of dynamic bulking and scrutinise ground support systems performance. The discussion will emphasise how each of the ground support elements interact with each other as well as with the intense fracturing and bulking of the rock mass.

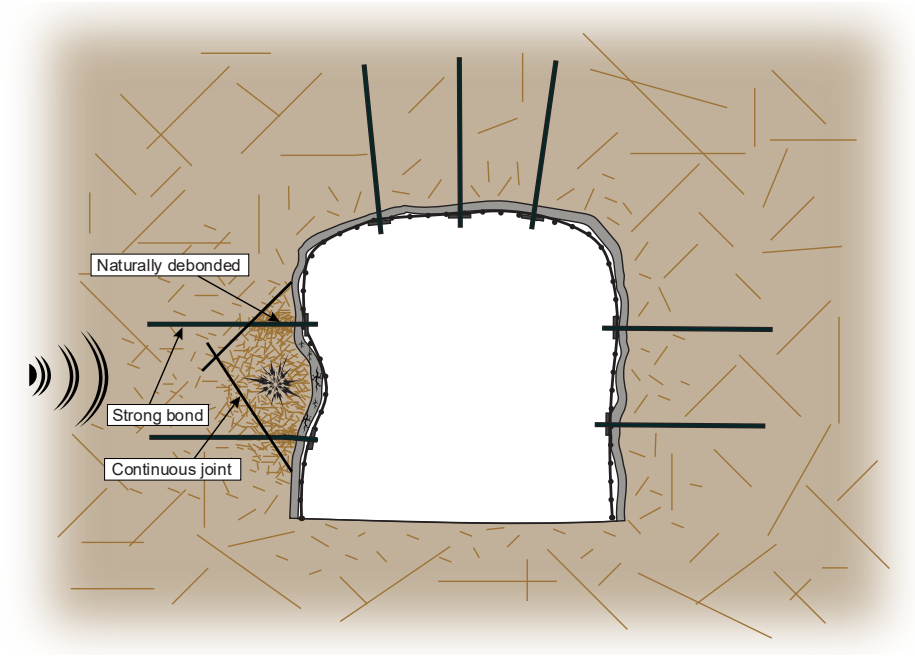
3.1 Small to medium strainburst

Figure 3 illustrates the bulking process and how the ground support system attempts to contain a small to medium strainburst. Once the strainburst is triggered, the shattering of the rock mass propagates almost instantaneously, causing debonding near the head of nearby rockbolts. This is rapidly followed by rock mass bulking which will cause deformation into the excavation, stretching the surface support which transfers the load to rockbolts. The support system will contain the bulking only if:

- The surface support can contain the deformation and provide some resistance against bulking. Whether mesh is used without or over shotcrete, the overlaps between mesh sheets are the critical areas where failure generally occurs. When shotcrete is used without mesh, the total failure of the shotcrete will occur very early in the bulking process.
- The connections between the surface support and the bolts can sustain the load applied to the connection caused by the deformation of the tunnel surface.
- The bolts can accommodate the load and deformation of the bulking rock mass. The reinforcement typically snaps near the collar, but it may also snap deeper in the rock mass, at the interface of the naturally debonded (shattered rock) and intact rock mass. This interface can be a distinct plane along a persistent joint. The failure crater is then well delineated on such joints (Figure 3b).



(a)



(b)

Figure 3 (a) Illustration of the bulking mechanism resulting from a small to medium strainburst; (b) Highlighting the potential effect of continuous joints

3.2 Large strainburst

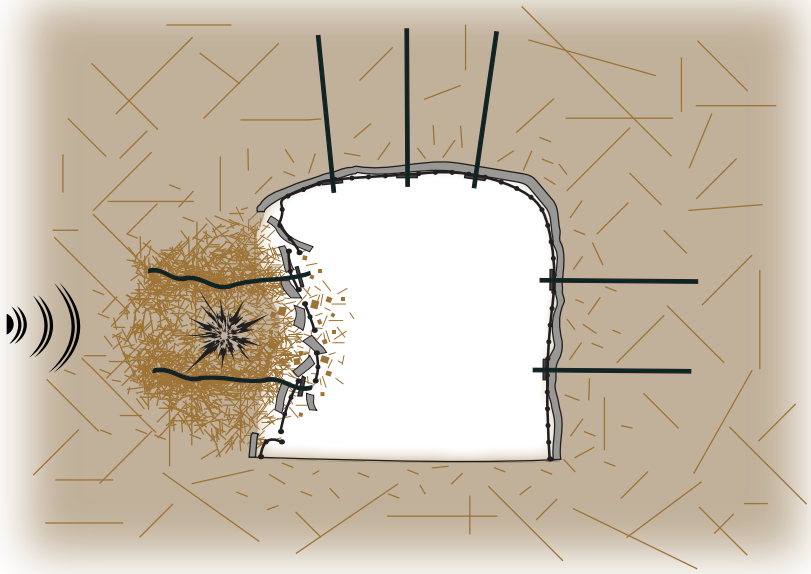
For this scenario, the case of short versus deep reinforcement is described.

3.2.1 Short reinforcement

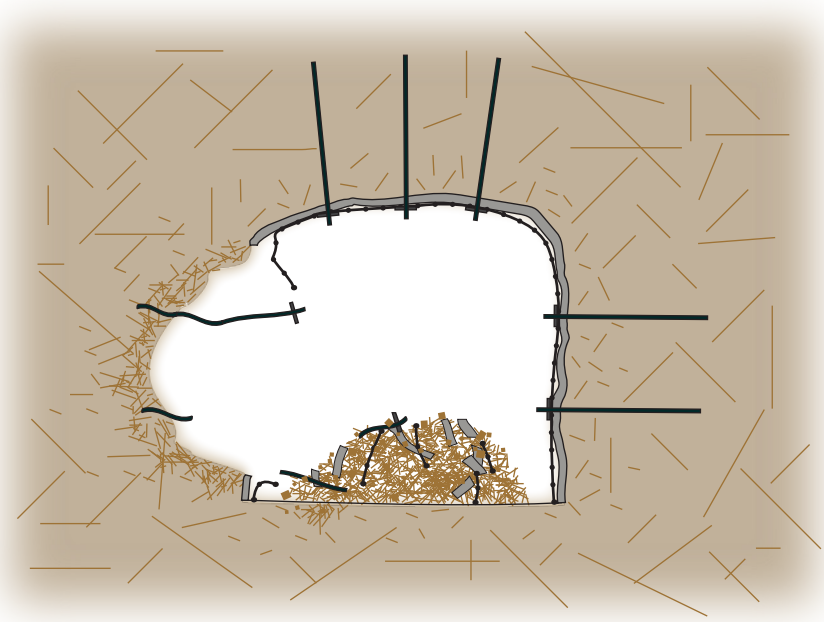
Figure 4a illustrates the bulking process and ground support system with typical 2.1 to 2.4 m long reinforcement trying to contain a large strainburst. In this case, the shattering is intense and propagates further than the previous scenario (Figure 3). If the depth of failure is smaller than the bolt length, then the bolt can provide some resistance to bulking. But if the depth of failure is greater than the bolt length, the rock mass shattering

affects the whole length of the bolts, causing the entire bolt to be debonded and ineffective. No matter the type of bolts (grouted, friction, point anchor or hybrid) or their theoretical capacity, the instantaneous loss of the bond or anchorage to solid rock mass, negates the opportunity of the bolt to engage and be mobilised. Bolts are often found in the muck pile without any sign of tensile loading (Figure 4b).

Without bolt resisting the bulking, the surface support will eventually fail as the deformation will be extreme. When mesh only is involved, the overlap is generally the weakest component of the support system and is therefore where the failure initiates. When shotcrete only is involved, the total failure of the shotcrete will occur very early in the bulking process.



(a)



(b)

Figure 4 (a) Illustration of the bulking mechanism resulting from a large strainburst; (b) Resulting damage from the rockburst

3.2.2 Long reinforcement

Figure 5 illustrates the bulking process and ground support system with long cable bolt reinforcement (5–7 m) intending to contain a large strainburst. The impact of the strainburst on disabling the bond between the bolt and the rock mass is similar to the previous case, but the destruction of the cable bolts bond only extends to the section near the collar (typically 2 to 2.5 m). The length of cable beyond the crater will retain a strong bond.

In this scenario, the only effective reinforcement elements are the cable bolts and to a lesser extent, rockbolts near the edge of the crater, where the failure zone is shallower. The cable bolts will contain the bulking if the connections as well as the surface support survive, and the cables can accommodate the deformation of dynamic bulking.

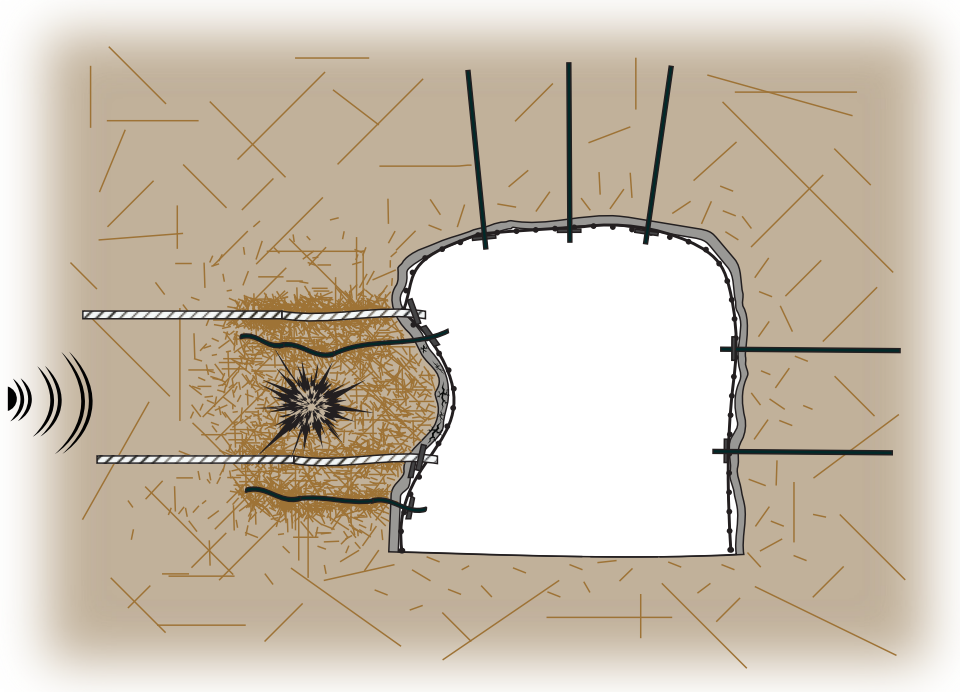


Figure 5 Illustration of the bulking mechanism resulting from a large strainburst, with deep reinforcement (cable bolts)

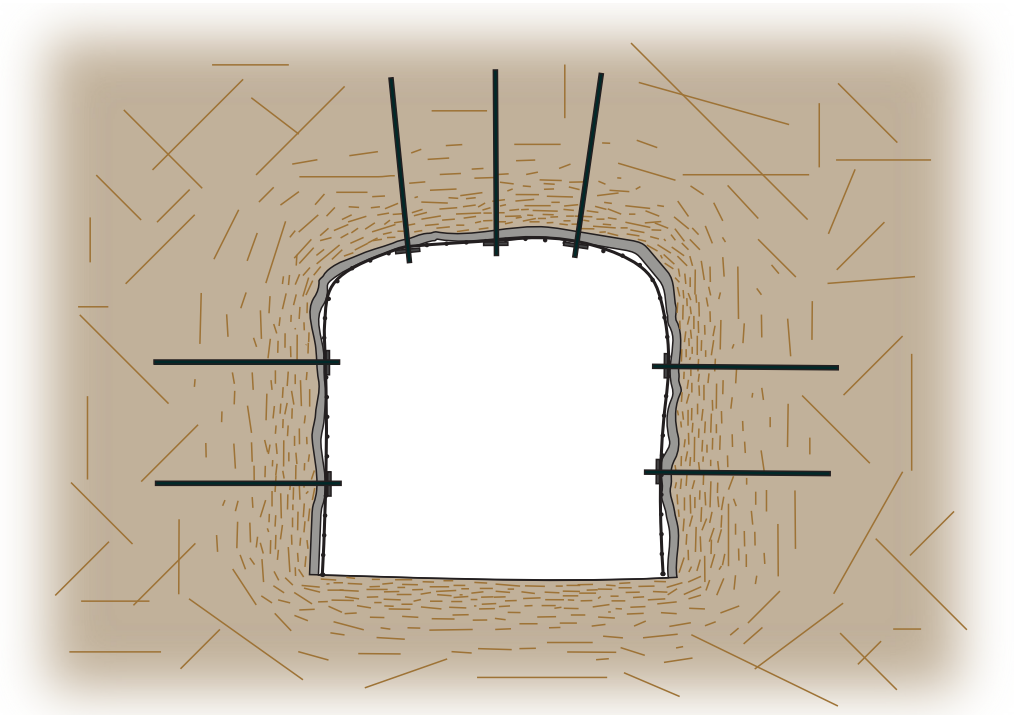
3.3 Strainbursts in stressed fractured rock mass

In very deep mines, it is common that excavations are surrounded by a layer of stress fractured rock as illustrated in Figure 6a. The pseudo-static fracturing process enlarges the thickness of the broken layer until increasing confinement away from the excavation inhibits this process, and equilibrium is reached. The thickness of the broken zone may reach between 1 and 2 metres in very deep mines.

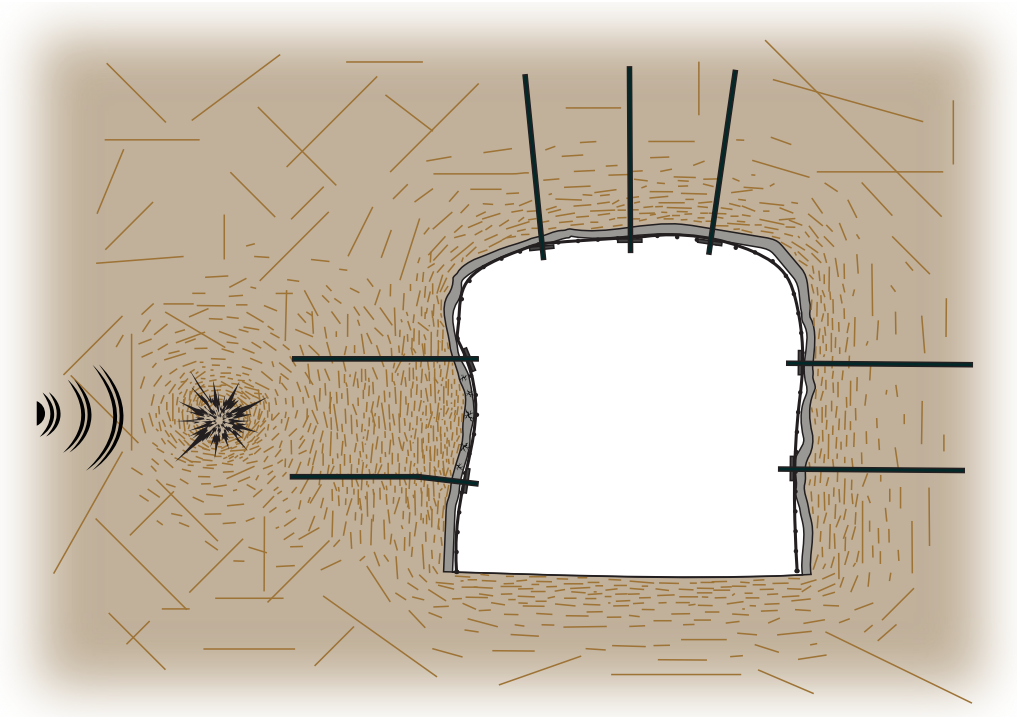
This stress fracturing process will be accompanied by some bulking and may consume some of the capacity of the support system, and therefore some ground support rehabilitation may be required. The rehabilitation should not remove the stress fractured layer, but new support elements can be added. This is because the stress fracturing also present important advantages. The fractured rock mass is in post-failure mode, and as such, it is incapable of storing any significant amount of stress (and energy) and therefore, any potential strainburst can only occur further from the excavation boundary (Figure 6b).

Being away from the excavation, the strainburst is in a more confined location, and this confinement counteracts the bulking forces. The broken rock layer, if properly supported, can also be highly energy absorbent because the energy can be dissipated through multiple small displacements and generation of new fractures within the heavily fractured layer. The key here is to contain the excavation surface from unravelling.

It is the authors observation that deep mines with fractured rock mass around excavations are significantly more resilient to rockburst damage from large seismic events compare to mines where excavations are surrounded with strong intact rock mass. However, when damage occurs, it can cause deep failures and long reinforcement is required to mitigate the rockburst risk.



(a)



(b)

Figure 6 (a) Illustration of the fractured zone surrounding excavations in some deep and high-stress mines; (b) Bulking mechanism resulting from a large strainburst in stress fractured rock mass conditions

3.4 Support system failure mechanisms

As described in the previous section, the anchorage or bond between the reinforcement and the solid rock mass, is critical if the capacity of the reinforcement is to be mobilised during rock mass bulking. The bond is also almost instantaneously partially or entirely shattered, depending on its location with regards to the strainburst as well as the original position of the reinforcement compared to the resulting crater. This section further explores support system failure scenarios as a function of the reinforcement original position compared to the crater.

It is noted that multiple failure scenarios are possible in a single strainburst damage location. Furthermore, for the purpose of this discussion, we have simplified dynamic bulking as being a dynamic expansion of the rock mass creating tension in the reinforcement. The reality is more complex and strainburst involves intense fracturing of the rock mass and shearing along natural discontinuities and fragments that may result in shearing of rockbolts. When we refer to 'bolt snaping', it may be the result of a tensile or a shear failure.

3.4.1 Failure mechanisms near the edge of the crater

The shape of the crater implies that the zone of shattered rock mass near the edge of the crater is shallower than in the middle of the crater. Hence, the integrity of the bond in the deeper part of the bolt at the edge of the crater should remain strong enough to prevent the bolt being pulled out of the hole. However, there will be a section of the bolt near the collar where the bond will be shattered and ineffective (Figure 7).

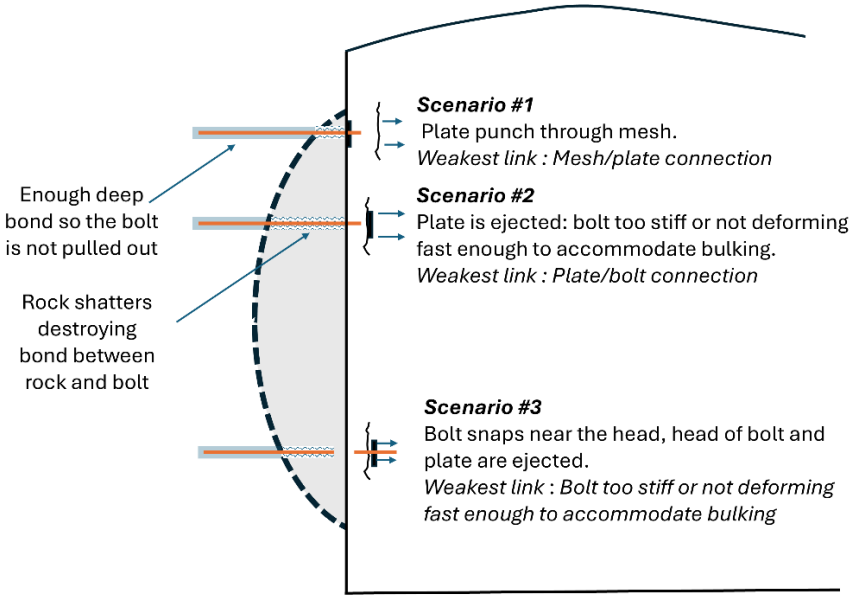


Figure 7 Cross-section of a tunnel showing an idealised strainburst crater describing scenario #1, scenario #2 and scenario #3 of supports system failure

In this situation, 3 failure scenarios can happen.

- **Scenario #1:** the plate punches through the mesh. This can happen for several reasons. For example, plates can punch through mesh because of steel on steel guillotine. Some mines have used larger plates, a second mesh-plate, mesh straps, rubber plate over the steel plate to prevent the punching or guillotine effect.
    - Another common mechanism is when mesh strands slip a bit under the plate and the welds rupture where the wires wrap around the bolt collar.
    - The observation of the plate punching through the mesh will be rockbolts sticking out from and attached to the wall, with the plate still on the bolt. A square shape hole from the plate punching will be visible in the failed mesh (Figure 8) and often, mesh overlaps open as a result.

This is more likely to happen if there is no shotcrete layer behind the mesh. If there is shotcrete, large shotcrete slabs will be formed because of the face bulking and will distribute the load on a large area of the mesh. In that case, the shotcrete slabs instead of the bulking rock fragments will exert the load on the mesh (Figure 9).

- **Scenario #2:** the plate punches through the bolt head. The observation will be rockbolts sticking out and attached to the wall, with no plate. The bolt head/nut will be visible in the part of the bolt sticking out of the wall. This will occur if the connection between the plate and bolt attachment (nuts/ head) is weaker than the load-deformation capacity of the bolt (Figure 8).

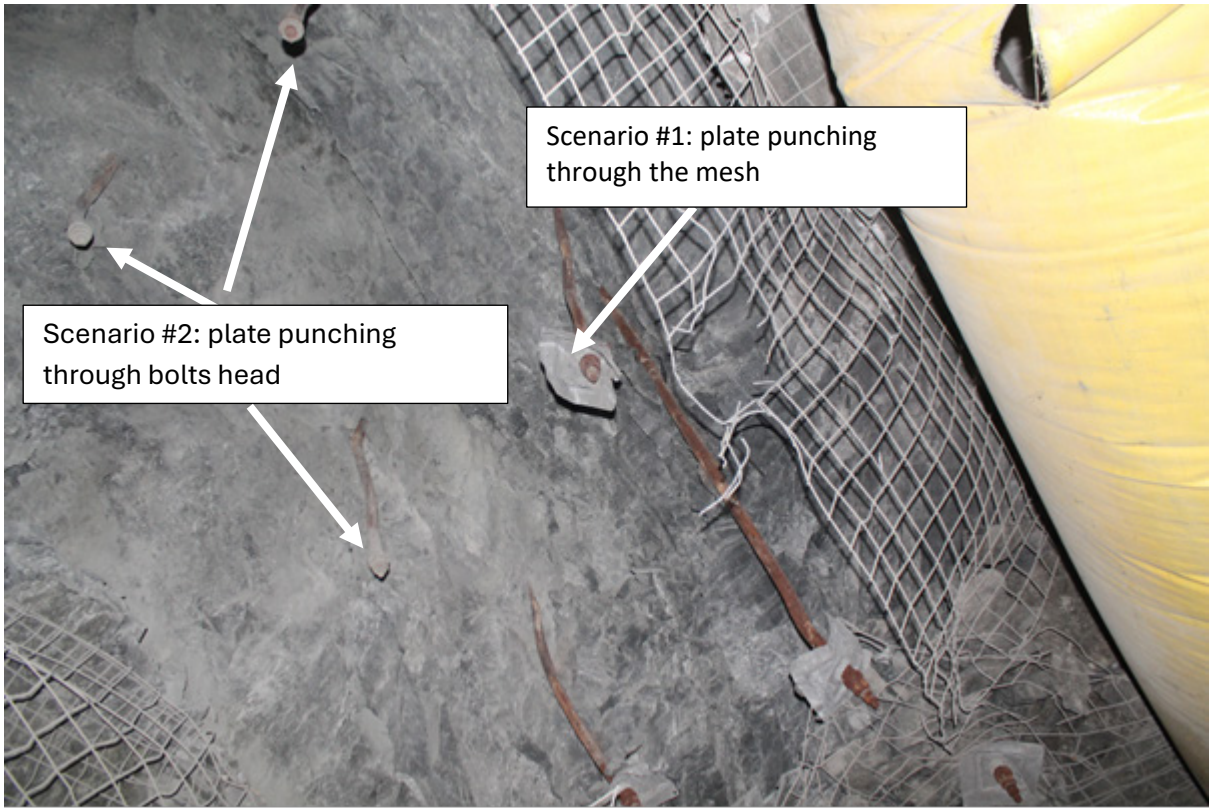


Figure 8 Example of failure scenario #1 plate punching through the mesh and scenario #2 plate punching through the bolt head



Figure 9 Shotcrete failing as large plates distributing the load on large areas of mesh

- **Scenario #3:** the bolt snaps near the head. The observation will be rockbolts sticking out and attached to the wall, with no plate and no bolt head (Figure 10). Short bolt head with plate can be found on the floor. Bolt necking typical of tensile failure can be observed on the bolt sticking out of the crater wall as well as on the ejected bolt head. This will occur if the bolt load-deformation capacity is exceeded, or if the bolt cannot deform fast enough to prevent bolt rupture, because the bolt strain rate is too low to accommodate the rock mass bulking velocity. Gebremedhin et al. (2024) discuss bolt strain rate during dynamic testing.



Figure 10 Example of failure scenario #3 where bolts failed near the collar, heads and plates are ejected

Figure 11 shows a further 2 failure scenarios that can occur at the edge of the crater.

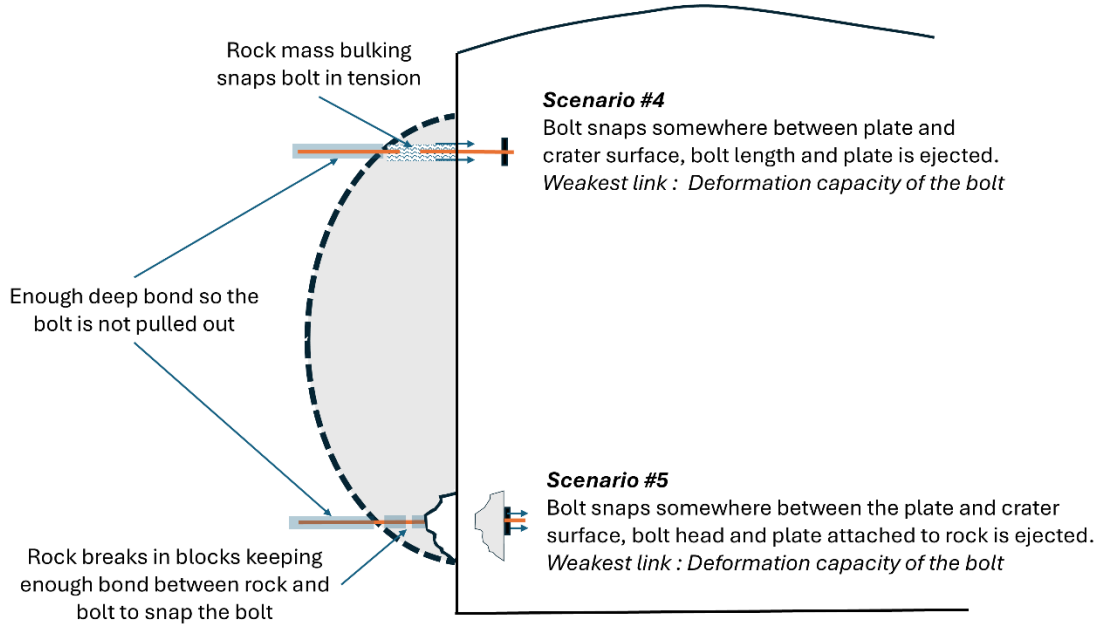


Figure 11 Cross-section of a tunnel showing an idealised strainburst crater describing scenario #4 and scenario #5 of supports system failure

- **Scenario #4:** the bolt snaps at a point between the plate and the crater wall. Beyond that wall, the bond remains functional preventing the bolt pullout, whilst the bond between the crater wall and the plate has been destroyed. The observation will be a section of the bolt showing necking or signs of shearing being ejected with the nut and plate still attached to the bolt (Figure 12).

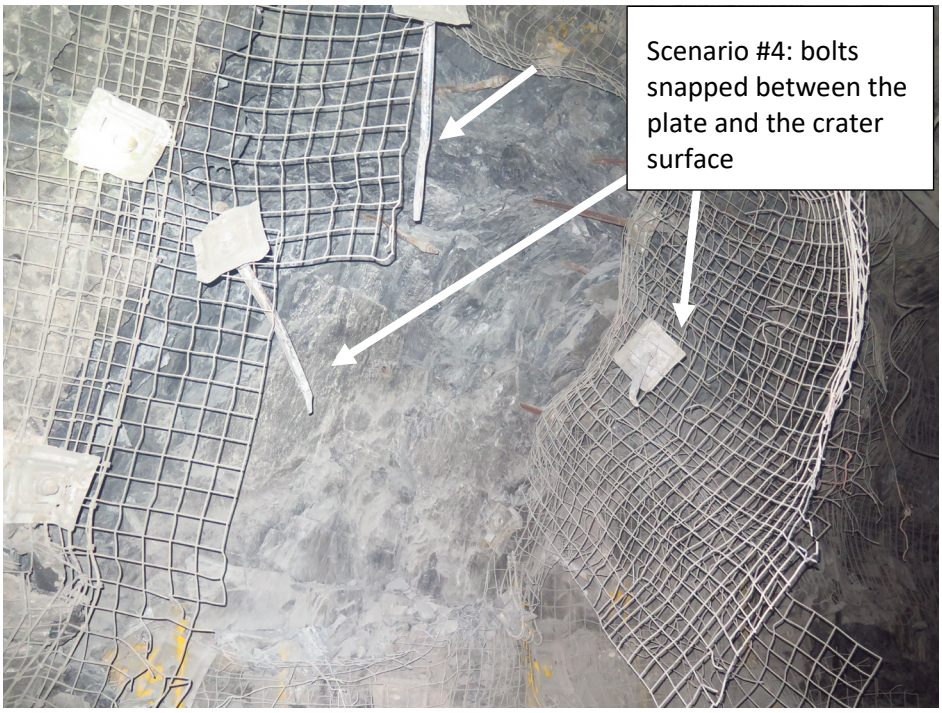


Figure 12 Example of failure scenario #4 where bolts failed near the crater surface, section of bolts and plates are ejected

- **Scenario #5:** the bolt snaps somewhere between the plate and the crater surface. This can happen when the failure near the edge of the crater fractures into larger blocks of rocks maintaining enough bond strength within the ejected piece, to snap the bolt somewhere between the plate and the crater wall. The observation can include; a section of the bolt showing necking or rupture, ejected with the plate still attached to the bolt and found in the muck pile or suspended in failed mesh. Sometimes, a piece of rock may be still attached to the bolt (Figure 13). Also, a 'naked' section of the bolt sticking out of the crater showing necking can be observed.

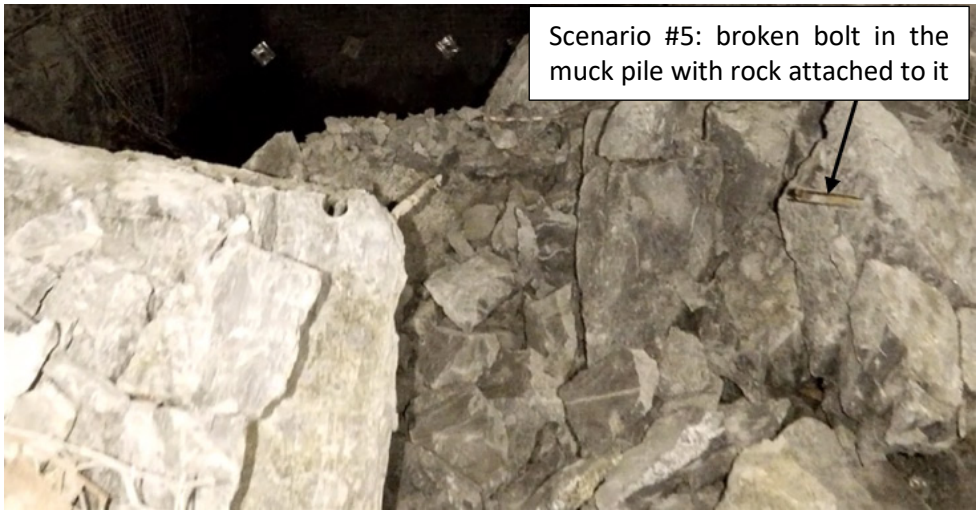


Figure 13 Example of failure scenario #5 where bolts failed somewhere between crater surface and collar, section of bolts and plates still attached to pieces of rocks are ejected

3.4.2 Reinforcement installed in the deep part of the crater

Three failure scenarios were observed for reinforcement installed in the deeper part of the crater (Figure 14).

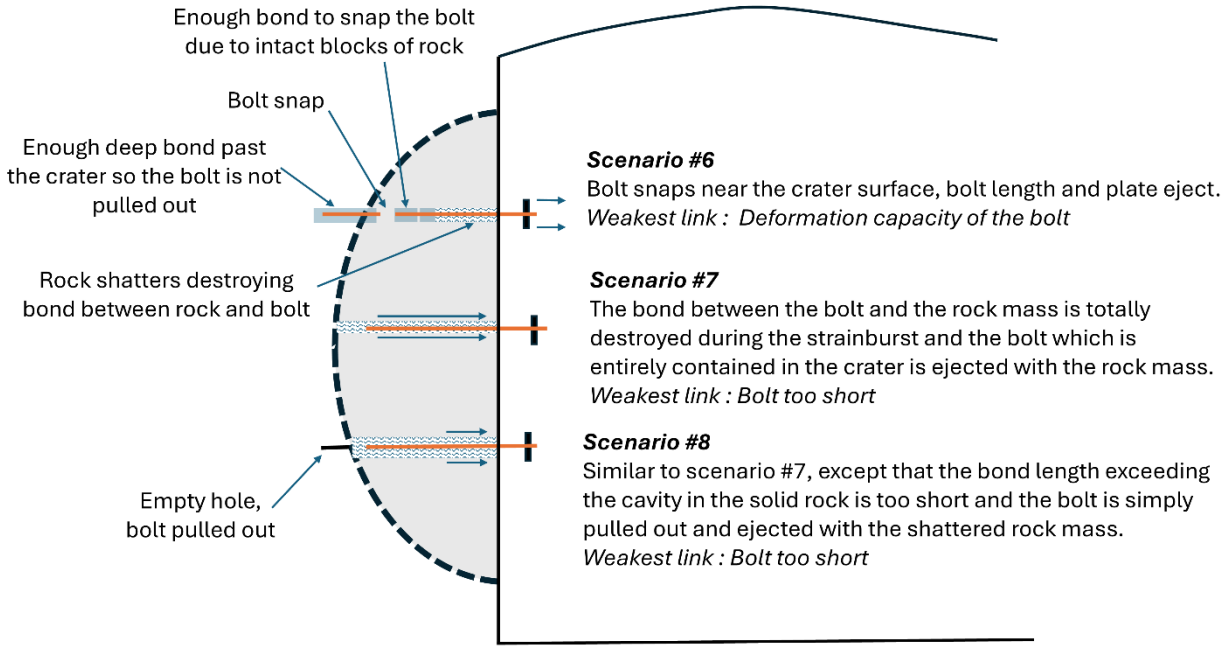


Figure 14 Cross-section of a tunnel showing an idealised strainburst crater describing scenario #6, scenario #7 and scenario #8 of supports system failure

- **Scenario #6:** this scenario is similar to scenario #5, but in this case, it is near the crater boundary deep into the failed zone where the rock mass has broken into larger pieces of rock providing long enough bond on both the tail of the bolt and the section embedded in the broken piece of rock to pull or shear and snap the bolt. The observation will be a long section of the bolt ejected with the plate still attached and inside the crater, a short tail section of the bolt sticking out, with a long section of the bolt and plate in the muck pile (Figure 15).



Figure 15 Example of failure scenario #6 where bolts failed near the crater surface leaving a short tail of the bolts inside the hole

- **Scenario #7:** the bolt is entirely contained into the crater and the bond between the bolt and the rock mass is shattered over the entire length of the bolt before any tension is applied by the bulking process. The entire bolt is released with the plate still in place and it shows no sign of loading (Figure 16).



Figure 16 Example of failure scenario #7 where entire bolts are ejected and found in the muck pile without signs of being loaded

- **Scenario #8:** similar to scenario #7, but in this case, the bond length is slightly exceeding the cavity in the solid rock, but it is too short to prevent the bolt being pulled out and released – with the shattered rock mass. The observation will be like scenario #7, except that the trace of the borehole exceeding the crater will be visible (Figure 17).

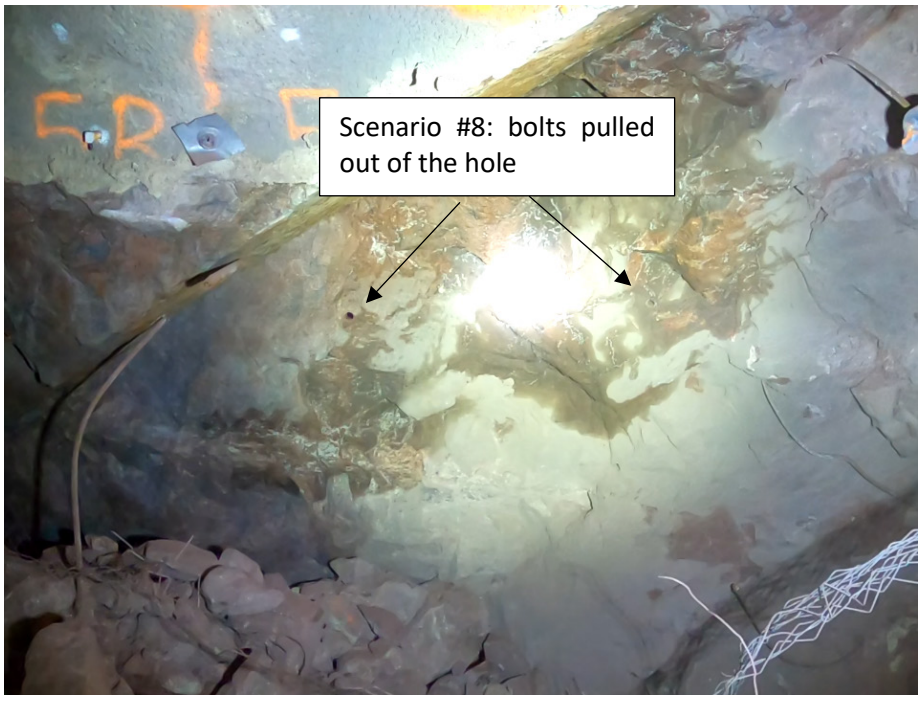


Figure 17 Example of failure scenario #8 where entire bolts are ejected and found in the muck pile without sign of load. Short traces of empty boreholes can be found in the crater surface

3.4.3 Deep reinforcement (cable bolts 5–7 m long)

When deep rockburst failure is anticipated, the installation of long reinforcement increases the capacity of the reinforcement to contain the rock mass bulking (Figure 18). Cable bolts tend to have bigger and thicker plates which also enhance the capacity of the connection. Punching of the barrel and wedge through these cable bolt plates is therefore unlikely. The following 3 failure scenarios have been observed.

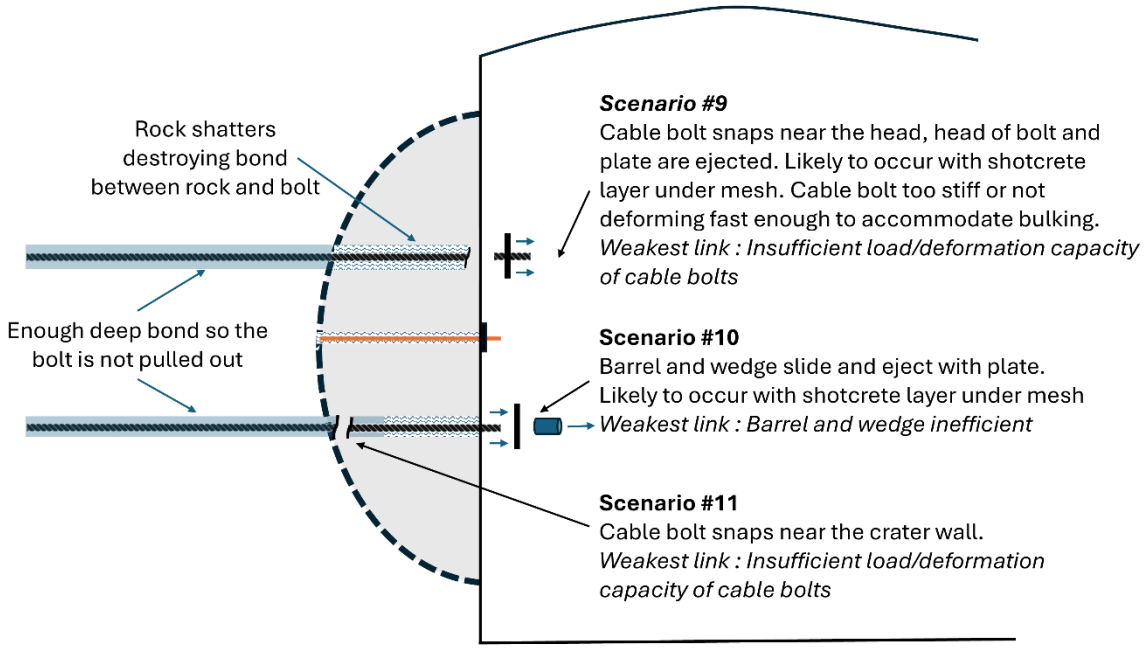


Figure 18 Cross-section of a tunnel showing an idealised strainburst crater describing scenario #9, scenario #10 and scenario #11 of support system failures

- **Scenario #9:** this is similar to scenario #3. The cable snaps near the head. The observation will be a cable bolt sticking out and attached to the wall, with no plate and no bolt head. The cable bolt head with plate can be found on the floor. This will occur if the cable load-deformation capacity is exceeded, or if the cable cannot deform fast enough to accommodate the strain rate imposed by the rock mass bulking velocity (Figure 19).



Figure 19 Example of failure scenario #9 where the cable bolts broke near the head ejecting the plate (not visible on the photo), barrel and wedge and the cable bolt tail

- **Scenario #10:** barrel and wedge systems are known to occasionally suffer slippage problems due to corrosion or miss-match between the cable diameter and barrel and wedge. A common practice is to apply light grease to the inside of the barrels at installation to prevent corrosion to affect the wedge mechanism. If slippage occurs, the observation may involve ‘pig-tailed’ sticking out of the crater wall. Barell and wedge and plates will be ejected and can be found separately in the muck pile or on the floor (Figure 20)



Figure 20 Example of failure scenario #10 where the barrel and wedge slid and the cable bolt tail de-stranded (pig-tailed)

- **Scenario #11:** this is similar to scenario #5. The cable bolt snaps somewhere between the plate and the crater surface. This can happen when the failure near the edge of the crater breaks into larger blocks of rocks maintaining enough bond strength within the ejected piece, to snap the bolt at a point between the plate and the crater wall. The observation can include; a section of the cable bolt ejected with the barrel and wedge and plate still attached to the bolt and found in the muck pile or suspended in failed mesh. Sometime a block of rock can still be attached to the bolt. Also, a 'naked' section of the cable bolt can be sticking out of the crater (Figure 21).



Figure 21 Example of failure scenario #11 where the cable bolt failed somewhere between the plate and the crater surface

Plain strand cable bolts need approximately 2 m bond length assuming good grout, to mobilise the full strength of the steel and break the cable bolt. If the failure crater is very deep (4 m plus), it is possible for the cable bolt to be pulled from the end of the hole. This would become scenario #12.

4 Forensic analysis of ground support capacity from in situ dynamic tests

The different scenarios of how ground support systems fail as a result of strainbursts are now applied to the forensic analysis on how ground support systems have performed during 2 in situ dynamic tests using blasting to induce rock mass bulking (Sewnun & Potvin 2026).

The first case involved 2.4 m long dynamic bolts with weldmesh (no shotcrete), where on the left half of the test wall, split sets were added to form a dice-five pattern to increase the bolt density (Figure 22). The red dash line is the contour of the crater, and the depth of failure is shown as a heat map with the maximum depth reaching 2.6 m.

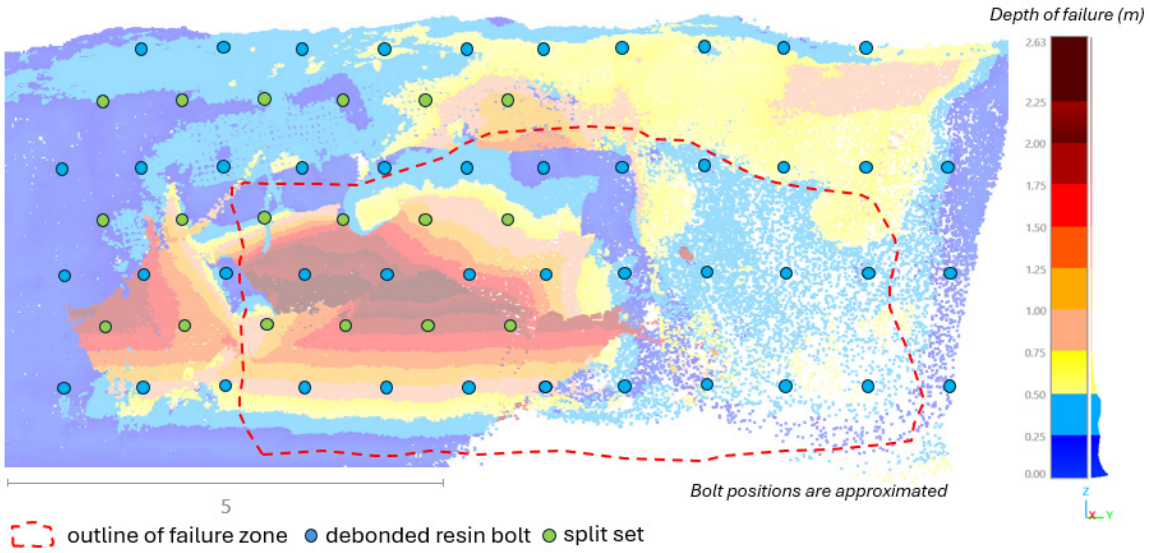


Figure 22 In situ dynamic test first site showing the delineation of the failure zone (red dashed line), the depth of failure (heat map) and the type and location of reinforcement (small circles)

Figure 23 summarises the performance of the reinforcement. A total of 28 bolts were included in the crater and the 19 bolts in the central part coloured in red were entirely contained within the shattered rock mass. These bolts failed without taking any significant load, as in scenario #7. Along the periphery at the top of the crater, the rockbolt plates punched through the mesh as described in scenario #1, and the mesh overlap opens at the location where the maximum bulking occur. This is discussed in more detail in Sewnun & Potvin (2026).

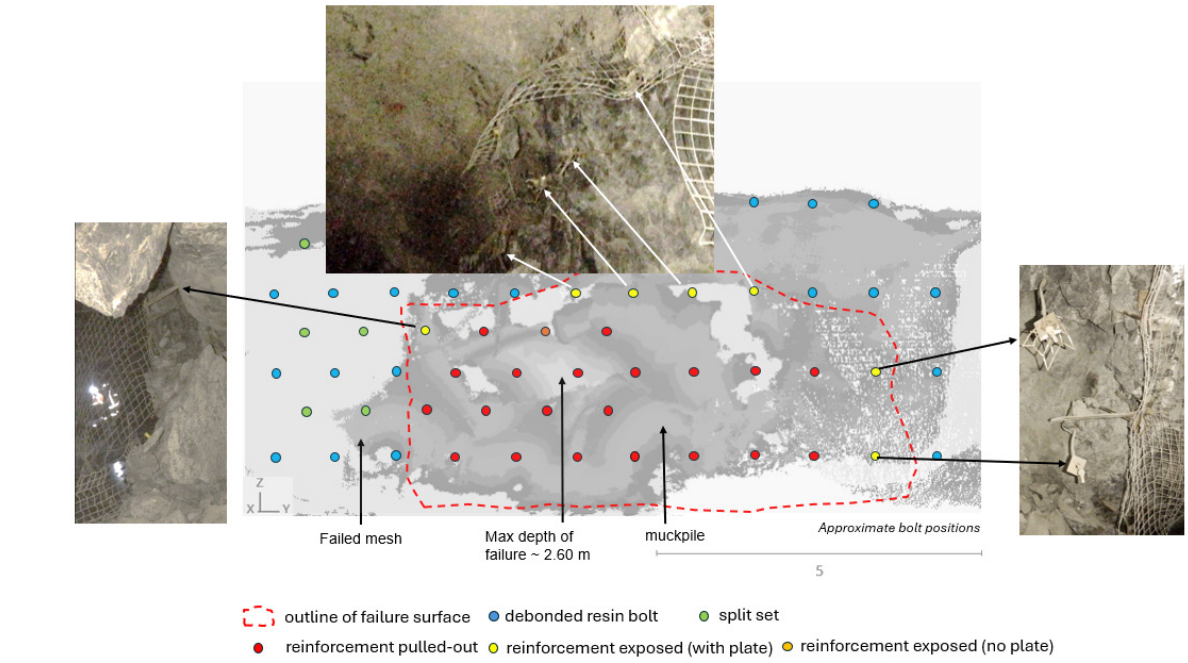


Figure 23 Failure mechanism of the ground support system showing scenario #7 failure of 19 bolts (in red) entirely ejected from the central part of the crater, and scenario # 1, plate punching through mesh for the six bolts (in yellow) in the periphery of the crater

In the second test, the reinforcement involved debonded resin bolts and cable bolts on the left side of the test wall and fully bonded resin bolts (without cable bolts) on the right-side (Figure 24). The surface support for both sides included 50 mm fibre-reinforced shotcrete overlaid with high-tensile strength Minax 80/4.6 chain-link mesh.

The red dash line delineates the contour of the crater, and the depth of failure is shown as a heat map, with the maximum depth of failure reaching 2.6 m. The cable bolts were 6 m long.

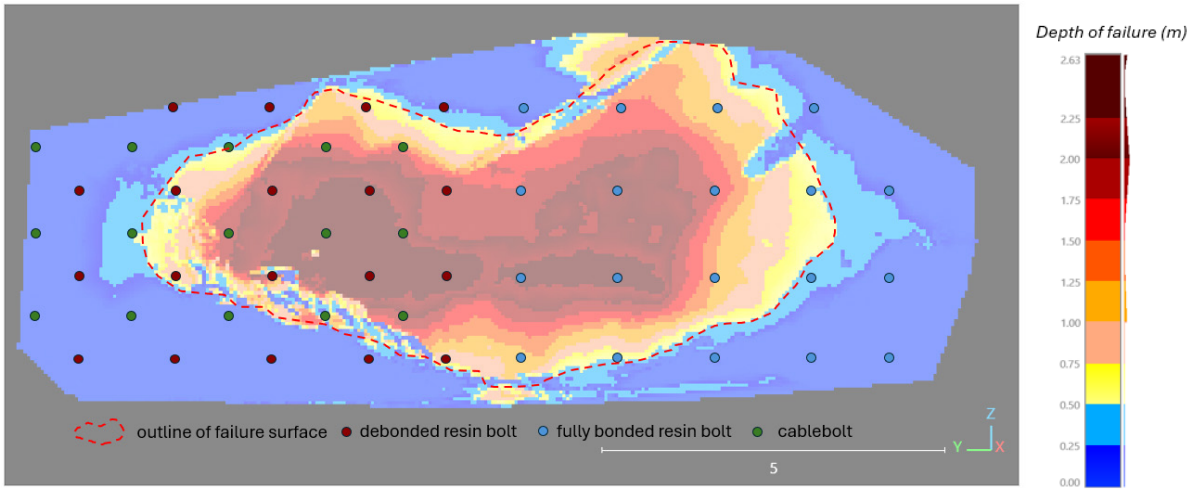


Figure 24 In situ dynamic test second site showing the delineation of the failure zone (red dashed line), the depth of failure (heat map) and the type and location of reinforcement (small circles)

Figure 25 indicates how the reinforcement failed, relating to the failure scenarios described in Section 3.4.1. The same trends as with the previous test were observed. In the central part of the crater, the ten bolts coloured in red were completely contained within the shattered rock mass and failed without taking any significant load (as in scenario #7). In the periphery of the crater most bolts (coloured in orange) were sticking out of the crater wall and have snapped near the collar (scenario #3) but at least one had the bolt head intact without plate (scenario #2).

In comparison with the previous case, the peripheral bolt plates could not punch through the mesh because of the shotcrete. The load transfer from the shotcrete to the plate is so effective that it either snapped the bolt heads, or the plate punched through the bolt head. This suggests that the deformation capacity of the reinforcement has been exceeded, or the bolt could not yield fast enough to accommodate the bulking velocity of the rock mass (scenario #3).

It is also observed that 3 cable bolts failed (circled in blue, Figure 25) inside the central deep crater area. The failure mechanisms of these cable bolts could not be observed because the quality of the drone mounted camera video was insufficient to detect any remnants of these bolts deep in the crater. There are 2 possible mechanisms, the first would involve cables being pulled out of the hole. This is unlikely, because the embedment length beyond the crater wall was approximately 3.5 m, which is more than enough to prevent slippage of the cable. The most likely mechanism is that these cable bolts snapped near the crater wall, scenario #11.

The failure of the surface support occurred at between 2.1 to 2.4 m displacement. The mesh tore vertically at the location of maximum displacement on the right side of the test wall, where there was no cable bolts. It is noted that this initial tearing of the mesh was not at an overlap location.

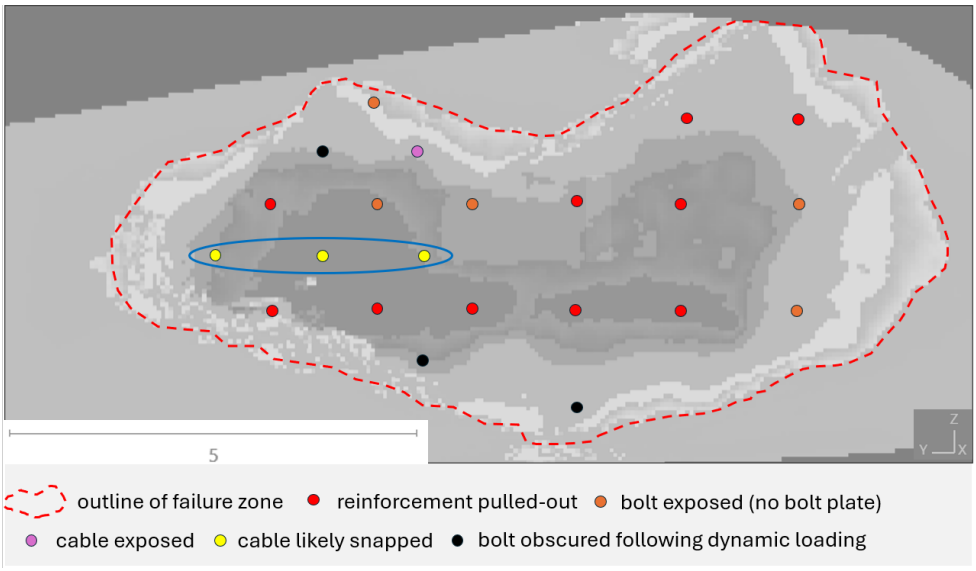
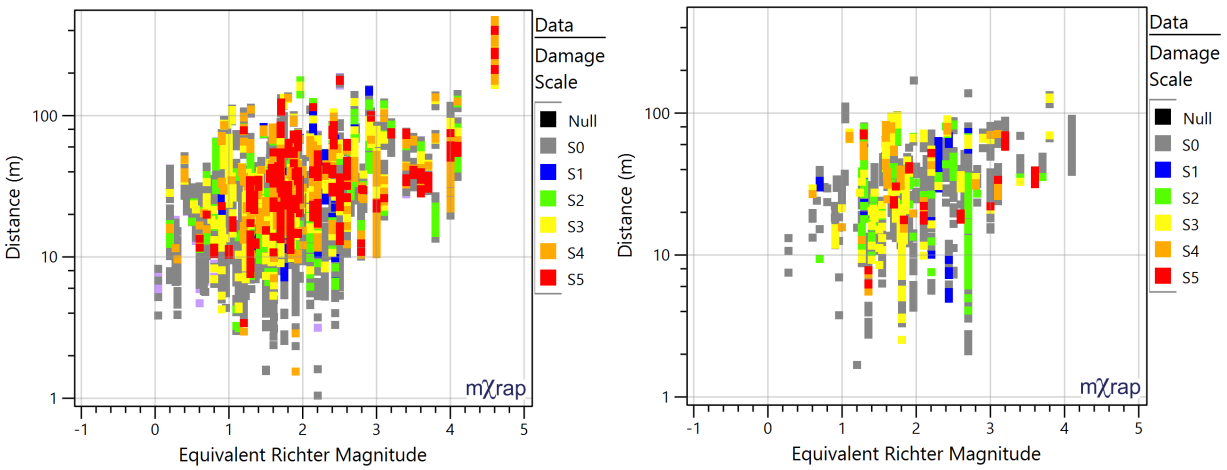


Figure 25 Failure mechanism of the ground support system showing scenario #7 failure of 10 bolts (in red) entirely ejected from the central part of the crater, and 5 bolts (in orange) sticking out of the crater surface failing as scenario #2 and #3 in the periphery if the crater. The 3 failed cable bolts circled in blue are believed to have snapped but the video footage quality did not allow to confirm this

Looking at the total failure area, the left side of the crater where cable bolts were installed is only marginally smaller than the failure on the right side. Although this may suggest that the addition of the cable bolts only had a marginal benefit, the high-speed video footage clearly shows that the bulking velocity is higher on the right side, where there are no cable bolts. As the right-side bulking progresses, it deconfines the cable bolts reinforcing the left side, encouraging the failure to progress from the weaker reinforced side to the stronger side.

As noted in the Introduction, the GSSO 3 project assembled an empirical database of seismic failures. The benefits of adding cable bolts was also clearly demonstrated from the empirical database (Figure 26), where each point represents damage around tunnels, and the hot colours (orange and red are severe damage with rockfalls). The density of hot colour points is much lower on the right graph where cable bolts were used.



(a) Without cable (18,965 pts), coloured by damage scale (b) With cables (2,819 pts), coloured by damage scale

Figure 26 Scatter plots of rockburst damage points coloured according to damage scale (orange and red have highest damage). The graph on the left had no cable bolts and show a higher proportion of severe damage compared to the graph on the right which had cable bolts

Similar observations are made for the first in situ test, where the bulking velocity on the higher bolt density (left side, Figure 23) is significantly slower than on the lower bolt density (right side, Figure 23). In this case, the positive impact of the higher bolt density is significant as the damage on the right side extend substantially further.

The benefit of higher bolt density is also empirically confirmed from Australian Centre for Geomechanics (ACG) GSSO 3 rockburst database (Figure 27), where the proportion of cases with bolt density of 0.75 bolt/m^2 or lower experienced more severe damage than cases with higher bolt density.

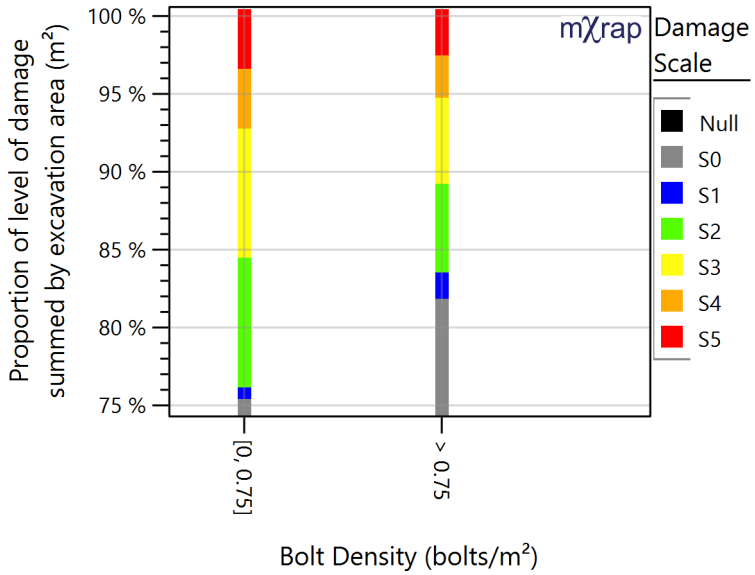


Figure 27 Bar charts showing the proportion of levels of damage (S0 to S5), where S4 and S5 have the most severe damage with fall of ground. The lower density of bolting experienced a higher proportion of severe damage

5 Implication for dynamic ground support design:

Some of the results from the ACG GSSO 3 research project are seriously challenging some aspects of the current approaches to dynamic support design and practices

The majority of the reinforcement designed to contain the dynamic bulking in the in situ dynamic tests was completely ineffective (red points in Figure 24 and 26). The 2 main reasons for this are:

1. The bond or anchorage between the rockbolt and the rock mass is completely destroyed by the strainburst at the very early stage of bulking (naturally debonding the reinforcement). Therefore, these bolts never contributed to containing rock mass bulking. This is evidenced with entire bolts being ejected and showing little or no tensile deformation.
2. The length of the reinforcement was too short considering the failure volume and shape. When designing dynamic ground support systems, not considering the unstable rock mass failure volume and shape (as is done in static support design) is a critical gap in current approaches.

If the bolts in the central part of the crater are ineffective, the bulking containment must then be entirely assumed by the reinforcement located in the periphery of the crater, in combination with the surface support. Without mesh plates, straps or shotcrete underlying the mesh, the bolts plate will tear through the mesh. If shotcrete is used, the bolt will snap (in most situations), near the collar. Even if the peripheral reinforcement survives, without the central bolts effectively containing the bulking in the central part, the deformation of the surface support will become excessive. This was demonstrated in the second dynamic test previously discussed, where the chain-link mesh tore beyond 2.4 m displacement (Figure 28).

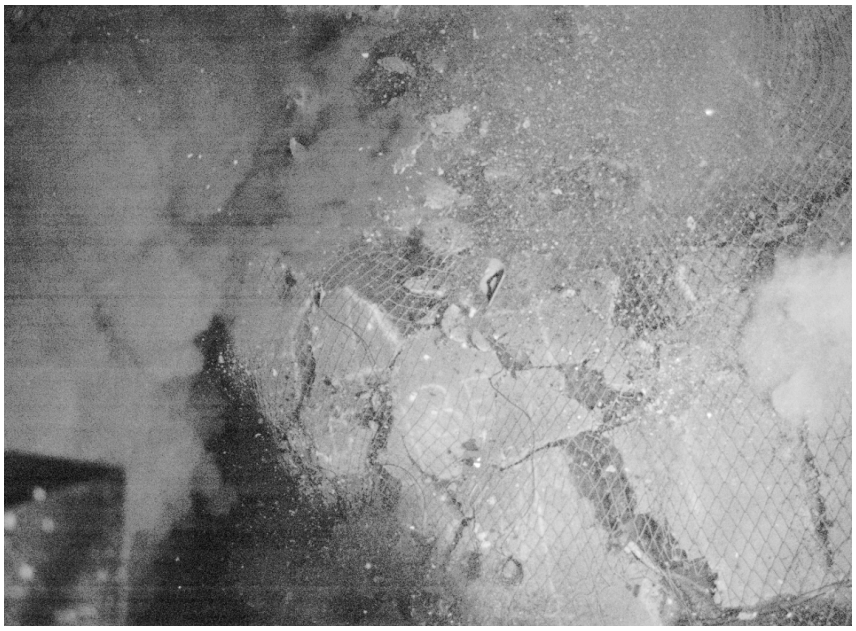


Figure 28 Extreme deformation of the chain-link mesh during the second in situ dynamic test

The volume and shape to be contained should be defined at the design stage, to ensure installation of longer reinforcement where required, so that most reinforcement elements will have enough bond-length inside solid rock mass (beyond the crater surface) to activate whatever yielding mechanism they have been designed for, to contain bulking. However, the reinforcement effectiveness depends on its ability to yield fast enough to match the bulking velocity. This area needs further research to quantify strain rates of yielding bolts and typical velocity from blasting tests.

Regarding bulking velocity and yielding reinforcement reaction time, the technique familiarly called 'drop testing' is widely used to study the dynamic response of reinforcement (for example Ortlepp & Stacey 1998; Gaudreau 2004; Falmagne et al. 2005; Hadjigeorgiou & Potvin 2007; Player et al. 2008, 2009, 2013; Doucet & Voyzelle 2012; Villaescusa et al. 2016; Brandle & Fonseca 2019; Evans 2024; Knox & Hadjigeorgiou 2026). It is interesting to note that drop tests generally provide a yielding response duration around 20 to 100 milli-seconds from first displacement to failure, depending on the weight and height of the drop. This is roughly in line with the bulking velocity measured during these in situ dynamic tests. However, in the drop tests, the reinforcement is encased in a steel pipe (single or split-pipe). The bonding agent (grout or resin) is minimally impacted during drop-tests, which is not a good representation of what happens in the field. It only has similarity to scenarios #5, #6 and #10 described in Section 3.3 of this paper. Therefore, drop test results will often lead to an over-estimation of the energy absorption capacity (as well as strain rate) compared to what is achievable during a strainburst. Bolt or cable yielding properties will also be affected by the natural debonding caused by strainburst.

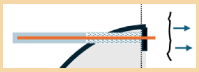
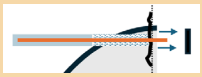
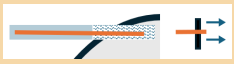
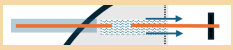
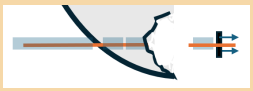
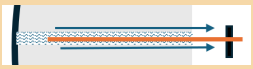
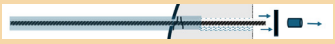
Drop tests only provide a basis to compare the dynamic capacity of different ground support elements. These energy capacity values should not be used for design, however, they are commonly seen in design calculations.

6 Conclusion

The GSSO 3 research project examined the behaviour and performance of ground support systems subjected to dynamic loading using in situ dynamic testing and empirical rockburst data.

This paper presented an interpretation of the mechanisms underpinning the ground support system containment of dynamic bulking of rock masses, with a detailed description of how different components of the system fails. The failure scenarios are summarised in Table 1.

Table 1 Summary of ground support failure mechanisms

Failure scenario	Failure mechanism	Illustration	Weakest link
Scenario #1 crater periphery	Plate punches through mesh. Steel on steel guillotine		Mesh plate connection
Scenario #2 crater periphery	Plate ejected. Bolt too stiff		Plate/bolt connection
Scenario #3 crater periphery	Bolt snaps near head. Bolt head and plate ejected		Bolt too stiff, or not deforming fast enough
Scenario #4 crater periphery	Bolt snaps between plate and crater wall		Insufficient deformation capacity
Scenario #5 crater periphery	Bolt snaps between plate and crater wall		Insufficient deformation capacity of the bolt
Scenario #6 deep part of crater	Bolt snaps near crater surface		Insufficient deformation capacity of the bolt
Scenario #7 deep part of crater	Entire bolt ejected. Bolt entirely contained inside failure area		Bolt too short
Scenario # 8 deep part of crater	Entire bolt ejected. Bond length beyond crater too short		Bolt too short
Scenario #9 deep part of crater	Cable bolt snaps near the head		Insufficient load/deformation capacity of the cable
Scenario #10 deep part of crater	Barrel and wedge slide and ejects with plate		Barrel and wedge inefficient
Scenario #11 deep part of crater	Cable bolt snaps near crater wall		Insufficient load/ deformation capacity of the cable

The following mechanisms have significant implications on the design of dynamic ground support systems:

- Surface support:
  - The most common weakest link of support systems is the mesh overlap.
  - Without shotcrete or effective plate attachment (like mesh plates, mesh straps, conveyor plates) reinforcement plates will puncture the mesh and the connection between reinforcement and surface support will be lost long before the reinforcement capacity is consumed. Notwithstanding the laboratory capacity of the reinforcement, without shotcrete, the surface support is likely to fail at a much lower energy absorption value.
  - As the rock mass bulks, the shotcrete will break into large plates distributing the load over large areas of the mesh leading to better containment of surface deformation.

    - Shotcrete provides a very efficient load transfer between surface support and reinforcement. The reinforcement will survive only if the connection (nuts and plate arrangement) is strong and it can contain the deformation and velocity of rock mass bulking.
- Reinforcement:
    - The destruction of the bond between reinforcement and rock mass caused by the strainburst early in the bulking process will change the yielding characteristics of reinforcement during rock mass bulking and often compromise its capacity.
    - Defining the volume and shape of the bulking rock mass is important to ensure that enough bond length in solid rock (beyond the crater) is available to mobilise the capacity of bolts.
    - The mode of failure of reinforcement elements is a function of their location with regards to the crater shape (central area versus periphery).
    - Reinforcement deformation velocity (strain rate capacity) must match the rock mass bulking velocity.
    - Cable bolts require large and thick plates to prevent the barrel and wedges to punch through plates, because the surface bulking will transfer intense loading via plates on the cable bolts.

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