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Advances in estimating the capacity of ground support systems subjected to dynamic loading

Denisha Sewnun [a,*], Yves Potvin [a]

[a] *Australian Centre for Geomechanics, The University of Western Australia, Australia*

Abstract

During the last 2 decades, significant progress has been made by ground support suppliers in developing new dynamically capable ground support components. The mining industry has embraced these new products, many of which are currently implemented in underground mines. Furthermore, the understanding of the dynamic capacity of ground support elements has improved dramatically with the proliferation of laboratory-based dynamic testing rigs (Li et al. 2021), producing a significant body of published test results, as summarised in Potvin & Hadjigeorgiou (2020).

Nevertheless, major gaps in technology exist, and it is still not possible to assess with confidence the capacity of a complete ground support system as it interacts with the dynamic deformation of rock masses.

Due to the practical infeasibility of instrumenting real rockbursts, it is argued that this difficult problem can only be resolved using blasting as a means of generating strong ground motion and measuring parameters associated with the rapid fracturing and bulking of a supported fractured rock mass.

A new displacement-based in situ dynamic testing methodology based on blasting has been developed as part of the third phase of the Ground Support System Optimisation (GSSO 3) research project. This paper presents the new methodology and shares the results obtained from its implementation.

Keywords: *dynamic ground support systems, in situ dynamic testing, rock mass bulking, support capacity*

1 Introduction

Excavation damage associated with the sudden violent release of energy in a rock mass is well known as a rockburst. Rockbursts represent one of the most severe hazards to personnel safety, equipment integrity, and excavation stability in deep underground mines.

Ground support remains essential for mitigating the consequences of rockbursts. Appropriate ground support selection and design is therefore crucial for personnel and asset safety in rockburst prone mines.

Existing design methodologies are typically based on a capacity–demand relationship, where the installed support system must provide sufficient capacity to withstand the expected dynamic demand (load, deformation or energy).

In the last 20 years, numerous new ground support components have become available. These components may be combined in several configurations to create a dynamic ground support system. Testing of individual components in a laboratory is commonly carried out to characterise their energy absorption capacity. While this is valuable for comparing the capacity of different support elements under the same controlled loading conditions, these results are not directly transferable to field conditions (Potvin & Hadjigeorgiou 2020).

To account for the interaction between a rock mass and a complete ground support system, in situ dynamic testing has been carried out by several researchers (Hagan et al. 2001; Heal & Potvin 2007; McCreath et al. 1994; Ortlepp 1969; Shirzadegan et al. 2016; Tannant et al. 1994). While the objectives of these tests varied,

[*] Corresponding author. Email address: denisha.sewnun@uwa.edu.au

each approach used blasting to dynamically load an underground rock mass containing installed ground support systems, providing more representative loading conditions. A summary of these approaches is provided by Hadjigeorgiou & Potvin (2007). Although these studies have provided various insights into blasting and ground support performance, they have had limited success in quantifying the capacity of integrated ground support systems.

A new displacement-based in situ dynamic testing methodology has been developed as part of the third phase of the Ground Support System Optimisation (GSSO 3) research project. This method provides an approach to assess the performance and estimate the displacement capacity of support systems installed in situ. This paper presents the new methodology and the results obtained from its implementation.

2 Laboratory drop testing

Since the late 1990s, understanding of the dynamic capacity of ground support elements has advanced significantly with the development of dynamic testing rigs used to conduct drop tests. Drop tests involve releasing a known mass from a specified height to transfer a controlled amount of kinetic energy to a ground support element through various loading arrangements (Potvin & Hadjigeorgiou 2020).

Dynamic drop testing has been applied to reinforcement elements, surface support, and, in some cases, complete ground support systems. This has produced a substantial body of experimental data on the dynamic performance of ground support, as summarised by Potvin & Hadjigeorgiou (2020).

Drop tests provide useful information on the anticipated dynamic response of ground support elements in that they allow for the determination of the energy transferred from the falling mass as a function of the displacement induced by the element (Knox 2023). Given that the behaviour of the support components are tested under very specific loading conditions on custom made test setups, it must be kept in mind, however, that these tests should be considered as index tests.

While drop tests provide useful information, applying these results to the design of ground support in mining excavations have limitations. Most of the available test data is from the testing of individual support elements. In practice, however, ground support behaves as a system when subjected to dynamic loading during a rockburst. The testing of individual elements alone is therefore not enough to indicate how a support system will perform in situ when subjected to dynamic loading (Heal & Potvin 2007). As pointed out by Heal & Potvin (2007), it is the capacity of, and the interaction between, the individual ground support elements that determines the damage that the ground support will endure during a rockburst.

To address this complexity, various combinations of support elements have been drop tested to represent support systems (Brändle et al. 2022; Villaescusa et al. 2016). While these tests represent the testing of a support system, it is noted that support components are not installed into a rock mass. As there is no interaction between the support elements and a rock mass during the tests, these tests do not reflect the behaviour of a support system as it behaves in situ.

In addition, it is also argued that perhaps the most fundamental constraint of drop testing is the absence of rock mass bulking. Laboratory setups, whether they use the dynamic impact (Knox 2023) or momentum transfer method (Player et al. 2004), do not replicate the fracturing and geometric bulking of a failing rock mass. Consequently, the bond between the reinforcement and tube remain intact during the test, whilst in reality, the rock mass and the bonding agent (resin or cement) shatter around the bolt during dynamic bulking. The results from drop tests are likely to overestimate the energy absorbed by reinforcement during strainburst events.

3 The GSSO 3 research project

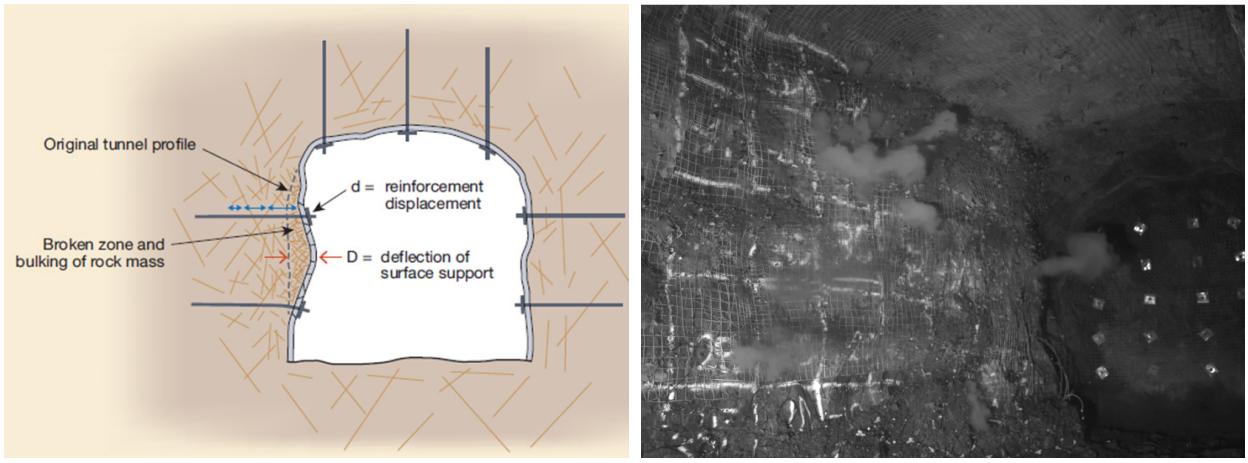
Considering the limitations of current approaches for assessing the performance and the capacity of integrated ground support systems, the GSSO 3 research project developed an in situ dynamic testing program. This methodology involved the use of blasting to load rock masses containing ground support

systems installed underground. This enabled complete ground support systems to be evaluated in situ, capturing the interaction between support components and the rock mass.

The primary objective of the GSSO 3 program was to investigate the overall performance and quantify the energy and displacement capacity of modern dynamic ground support systems. To achieve this, 3 preliminary blasting experiments were carried out to develop and validate the loading methodology. This was followed by 7 fully instrumented ground support tests across 3 underground mine sites.

Blasting carried out in this research does not attempt to replicate a seismic event; instead it was used to provide a repeatable means of fracturing and generating rapid bulking of the fracturing rock mass. Given that dynamic ground support systems should be designed to contain the bulking of a fracturing rock mass (Figure 1a), blasting provided a practical means of assessing support system performance under these conditions. An example of the bulking generated during testing is shown in Figure 1b.

For blasts taken where ground support systems were loaded to failure, the ejected rock mass exhibited fragmentation and failure characteristics that is comparable to that observed from rockbursts. This indicated that the blast methodology applied was able to generate representative rock mass responses for the purpose of the research. The similitude between the fractured rock from blasting and that from rockburst damage is shown in Figures 2 and 3.



(a) (b)

Figure 1 Rock mass bulking. (a) Illustration of support system deformation as a result of rock fracturing and bulking (Potvin & Hadjigeorgiou 2020); (b) Bulking achieved using blasting



(a) (b) (c)

Figure 2 Ground support loaded to failure with blasting. (a) Test 1 blast 2 at Mine 1; (b) Test 5 Blast 2 at Mine 2; c) Test 7 Blast 2 at Mine 3



Figure 3 Rockburst damage. (a) Strainburst triggered by a fault slip seismicity event (Li 2021); (b) Near-field damage from a Mw 2.5 seismic event triggered by a development blast (Yadav 2024)

The methodology used, and the major findings from the tests, are summarised in the subsections that follow.

4 Test methodology

The in situ dynamic testing methodology used in this study was initially based upon in situ tests pioneered by Heal (2010), which provides the only widely published test results interpreted in terms of energy absorbed by support systems with corresponding level of damage.

The approach by Heal (2010) involved the parallel installation of 2 different ground support systems side-by-side on an excavation wall. The wall was divided into 1 × 1 m grid cells used to evaluate energy capacity. The kinetic energy that each square metre was subjected to was calculated using the mass–velocity relationship:

$$E_k = \frac{1}{2}m(v)^2 \approx \frac{1}{2}m(PPV)^2 \quad (1)$$

where:

E_k = kinetic energy

m = mass

v = velocity

PPV = peak particle velocity.

To calculate energy, the depth of fracturing of the rock mass was determined by fracture mapping via internal borehole camera inspections. The velocity was assumed to be equivalent to the PPV recorded by geophones installed on the test wall.

While this methodology provided a critical foundation for the initial in situ testing carried out in the GSSO 3 project, it relied heavily on PPV. As GSSO 3 testing progressed, field observations demonstrated that there was no consistent relationship between measured PPV and the observed extent of excavation wall damage. These findings resulted in a fundamental shift in the testing methodology, away from using PPV and towards directly measuring the continuous bulking displacement of the rock mass as the ground support system reacted and ultimately failed. This revised approach is detailed in Section 8.

4.1 Initial GSSO 3 test setup

Consistent with the methodology developed by Heal (2010), 2 different ground support systems were installed side-by-side on an excavation wall for each ground support test. Each support system covered an area of approximately 5 × 5 m.

For each test wall, up to 3 successive blasts were conducted. To evaluate the response of the rock mass and the support systems for each blast, data was gathered using a comprehensive suite of instrumentation and monitoring equipment. This included the use of 24 geophones that were installed across the test wall to record ground motion. A high-speed camera – supported by lighting, a trigger system and protective bunkers – captured rock mass bulking and support system performance during each blast. Additional video cameras were also used to provide redundant video footage. Borehole cameras were used to assess rock mass damage behind the test wall, and photographic records together with detailed damage mapping were completed after each blast to document the condition of the support systems.

The monitoring equipment was positioned at an oblique angle to the test wall to provide a clear field of view of each blast while minimising the risk of damage from blast-induced fly rock. A typical test wall and monitoring setup is shown in Figure 4a.

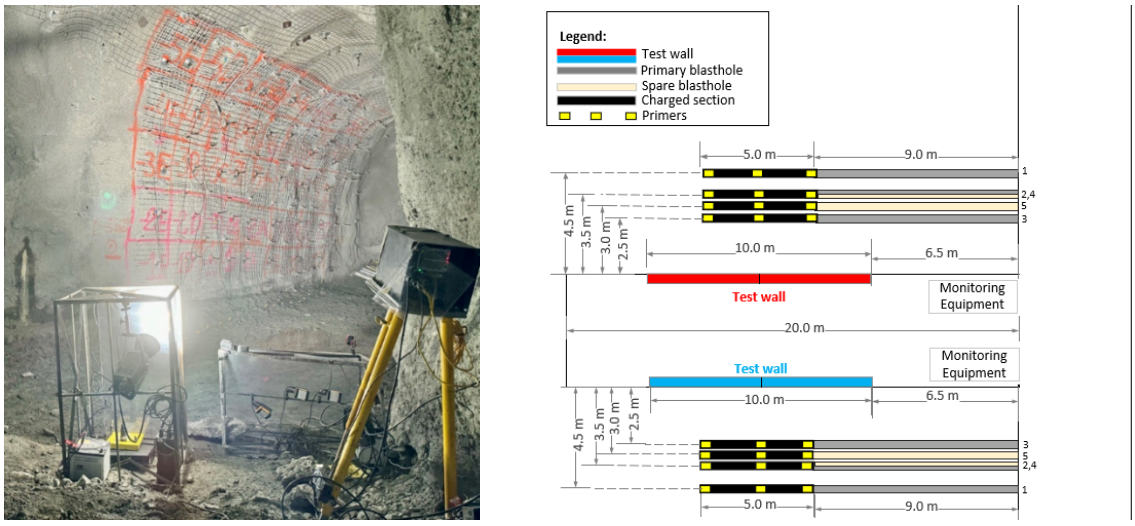
4.2 Blasting

The blasting methodology was designed to subject each test wall to up to 3 successive blasts, with each blast intended to impose increased levels of damage on the rock mass and ground support systems. This was predominantly achieved by varying the burdens behind the test wall and adjusting the explosive densities.

A typical blast design comprised 5 blastholes that were drilled behind each test wall at burdens ranging from 4.5 to 2.5 m. Three blastholes were intended for use as part of the planned blasting sequence, while 2 additional blastholes were drilled as spare holes.

Generally, 76 mm diameter blastholes drilled to a length of 14 m were used. Each blasthole contained a 5 m explosive charge initiated by 3 primers positioned at the start, centre, and end of the charge material. The blasthole collars were typically reamed to facilitate the venting of blast gases.

An example of a typical blast design used is illustrated in Figure 4b.



(a) (b)

Figure 4 Test set up. (a) Monitoring equipment and test wall; (b) Typical blast design, plan view

5 Mine 1

5.1 Test wall 1

Test wall 1 was located in competent ground. The ground support systems installed on the wall comprised 50 mm thick fibre-reinforced shotcrete (FRS), woven mesh, cable straps, resin bolts and cable bolts. The main difference between the ground support systems on either side of the test wall was the cable bolt spacing (1.5 x 1.0 m versus 2.0 x 1.0 m).

The first blast taken for the wall was carried out from an 89 mm borehole located at a 5 m burden. Following the blast, no major deformation was observed on the test wall, with minor shotcrete cracking identified on the bottom central area (Figure 5). The maximum PPV was measured at 4.0 m/s, from sensor 13 located at the centre of the wall (Figure 6).



(a) (b)

Figure 5 Test wall 1 after Blast 1. (a) Location of shotcrete cracking highlighted in yellow; (b) Close-up of shotcrete cracking

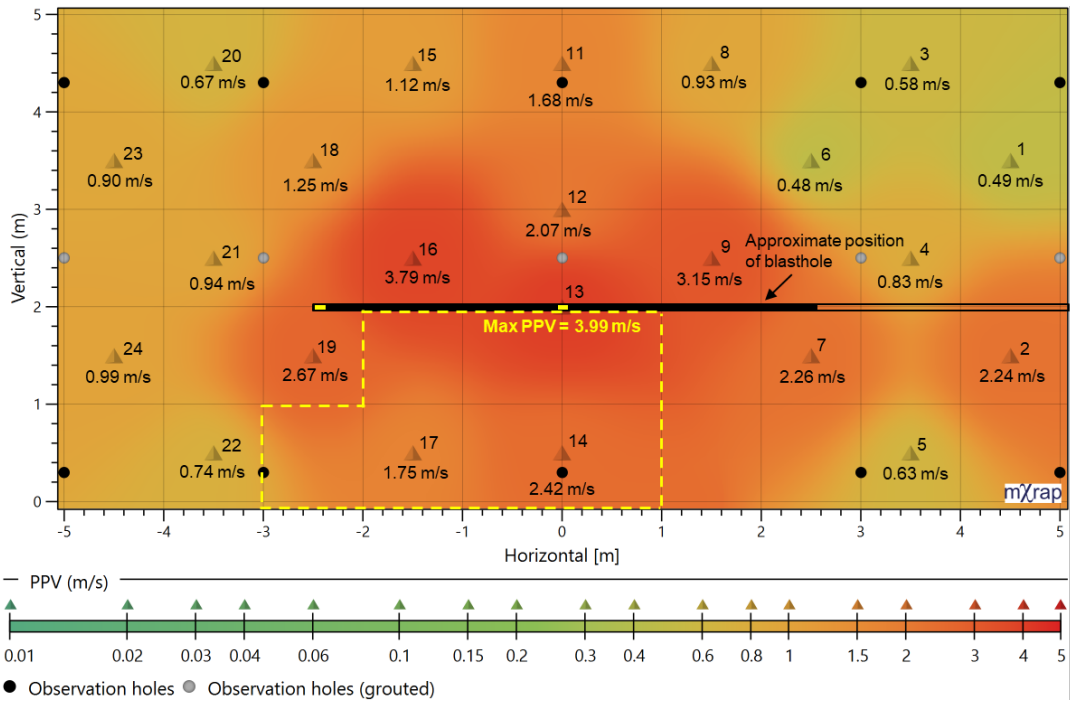


Figure 6 Measured positive PPV on sensors from shock wave for Test 1, Blast 1. Yellow dashed lines represent area where shotcrete damage was observed

The PPV values measured on the test wall were higher than expected given the lack of damage observed following the blast. To verify these measurements, the near-field PPV values recorded on the wall were compared with the far-field PPV measurements obtained from the in-mine seismic monitoring system (Figure 7). Using the site-specific strong ground motion relationship calibrated by the Institute of Mine Seismology, the results indicated a strong correlation between the near-field and far-field measurements. This provided confidence in the reliability of the PPV measurements recorded on the test wall. This was the first indication that PPV may not be appropriate to estimate rock mass damage.

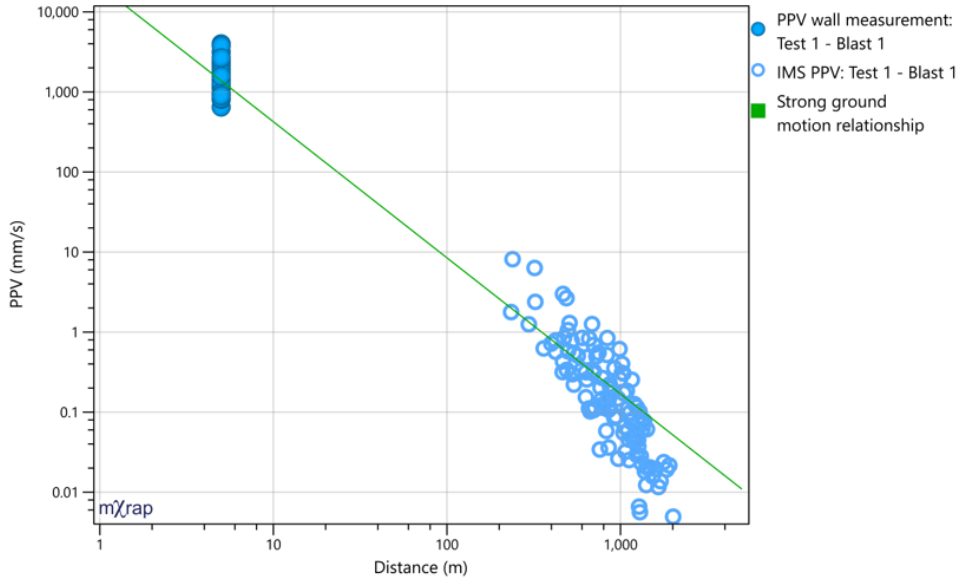


Figure 7 Correlation between near-field measurements on the test wall and the far-field measurements by the in-mine seismic system

Blast 2 at Mine 1 resulted in a major fallout of the test wall. This provided valuable insights into the response of the ground support systems, demonstrating that loading the systems to failure provides the most effective means of assessing ground support systems under dynamic conditions.

5.2 Test walls 2 and 3

Two blasts each were carried out at Test Walls 2 and 3 at Mine 1. Due to safety related constraints, these blasts were conducted at large burdens. As a result, low PPVs were measured and no significant damage was observed on either test wall.

6 Mine 2

Two test walls (Test Walls 4 and 5) were setup in competent ground opposite to each other in an 18 m long excavation at Mine 2.

In addition to testing each systems performance and the failure mechanisms of the support components, the main aim of testing at Mine 2 was to collect additional data to assess the suitability of PPV for use to estimate rock mass and support damage.

Ground support for Test Wall 4 and 5 were developed based on the results from Mine 1. For surface support, gauge 4 (5.8 mm thick) weldmesh was installed on both test walls. Given that Mine 1 incorporated FRS on all walls, it was decided that the walls at Mine 2 would be tested without the inclusion of FRS. This allowed for assessing the effect of excluding FRS on overall support system performance.

For reinforcement elements, Test 4 comprised MD bolts on the left of the test wall and split sets on the right.

Reinforcement elements for Test 5 comprised D-Tech bolts and split sets on the left of the wall, and D-Tech bolts only on the right.

6.1 Test wall 4

Three blasts were taken for Test Wall 4. For blast 1 and blast 2, high PPVs were measured on the test wall with no major damage observed (Table 1). For Blast 3, the maximum PPV recorded on the test wall was 1.8 m/s. However, several geophones had become loose by this stage of the testing, reducing the reliability of the measurements. Based on the established correlation with the far-field data, the maximum PPV for Blast 3 was estimated at approximately 3.0 m/s.

As with Mine 1, the near-field measurements showed good correlation with the far-field PPV data recorded by the Engineering Seismology Group. This is shown in Figure 8.

Table 1 PPV results for Test wall 4

Blast	Burden (m)	PPV (m/s)	Damage on the test wall
1	4.5	3.17	No major damage
2	3.5	3.83	No major damage
3	2.5	3.00*	No major damage

* estimated from correlation with far-field peak particle velocity (PPV) data

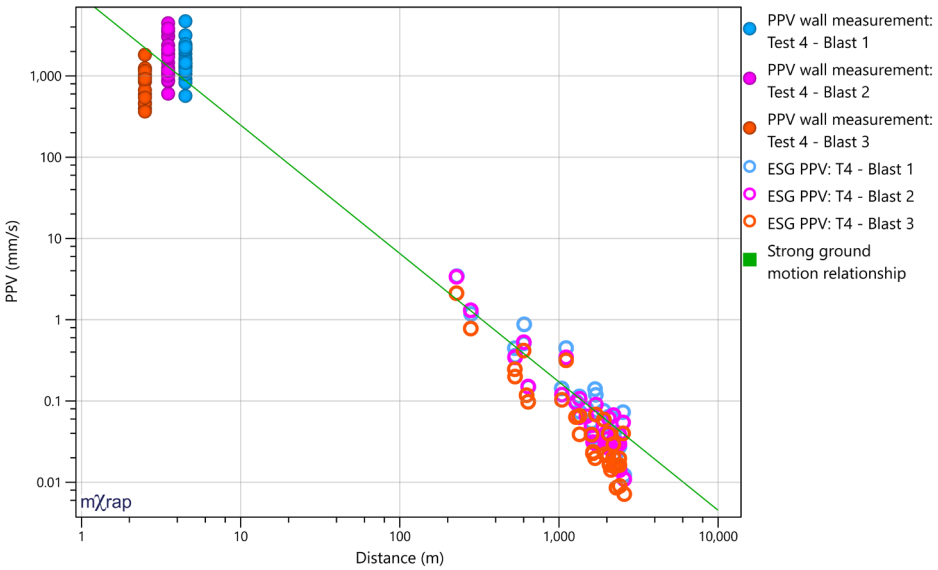


Figure 8 Correlation between near-field measurements on the test wall and the far-field measurements by the in-mine seismic system for Test 4

6.2 Test wall 5

Two blasts were carried out for test wall 5. Blast 1 was taken at a burden of 4.5 m behind the face. Minimal damage occurred on the test wall. The maximum PPV recorded was 3.98 m/s. Blast 2 was fired from at a burden of 2.5 m behind the test wall. Following Blast 2, major fallout of the test wall and total failure of the ground support system occurred (Figure 9).

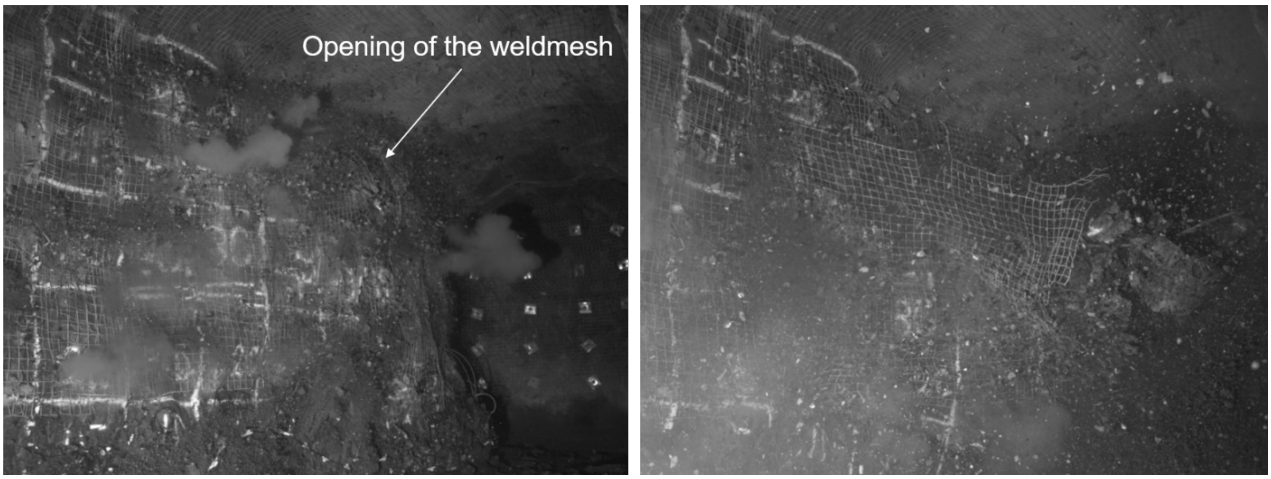


(a) (b)

Figure 9 Test wall 5. (a) Prior to Blast 1; (b) After Blast 2

From the high-speed camera footage, the rock was seen bulking with an initial release of blast gases at a few points across the test wall. This was followed by continued bulking and the continued release of blast gases from multiple points across the test wall. Small rock fragments then began to eject from the wall, along with the opening and tearing of the weldmesh at a vertical overlap located at the top of the wall, corresponding to the area of maximum deformation (Figure 10a). This was followed by the complete opening of the mesh, and ultimately, the total failure of the rock mass and ground support systems (Figure 10b).

The maximum PPV measured on the wall was 3.42 m/s, recorded by a sensor located at the centre of the test wall. The velocity chart in relation to high-speed camera footage and waveforms at the time the maximum PPV was reached is shown in Figure 11. As the maximum PPV was reached, no major observable reaction (bulking) of the ground is evident.



(a) (b)

Figure 10 Blast 2. (a) Opening of the weldmesh at the top of the test wall; (b) Total failure of ground support system

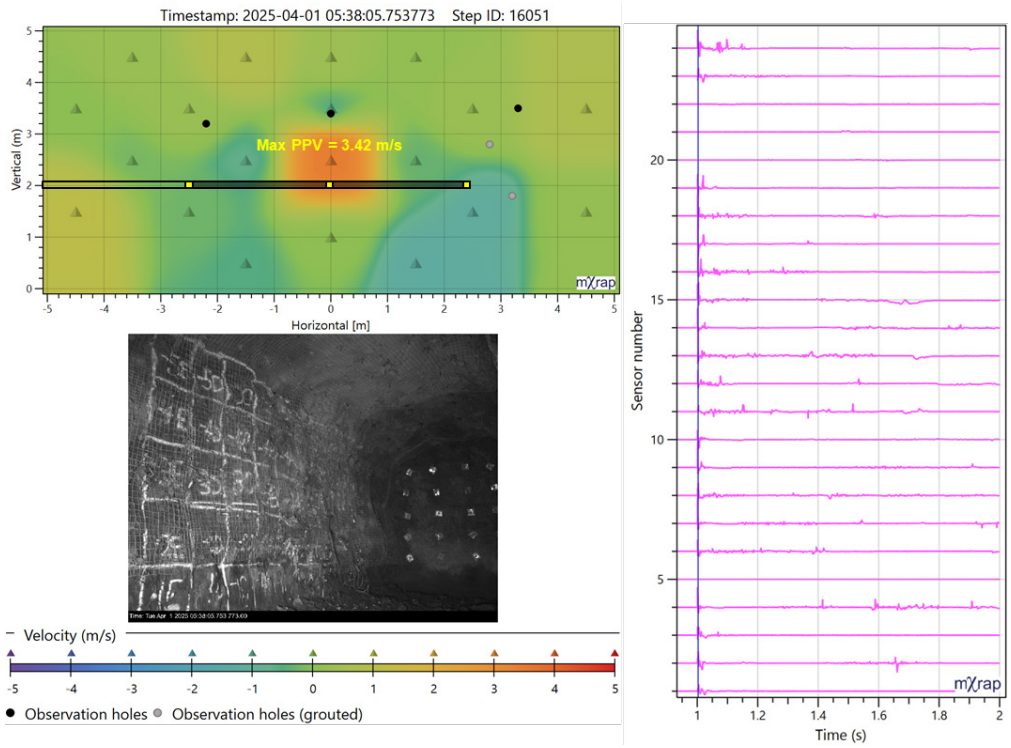


Figure 11 T5B2 velocity chart in relation to high-speed camera footage and waveforms at the time the maximum peak particle velocity (PPV) was reached

6.3 Learnings

Most of the blasts taken at Mine 2 resulted in high PPV measurements with minimal damage to the test walls. This confirmed that PPV does not provide a consistent indicator of rock mass damage.

The analysis of the velocity chart in relation to high-speed camera footage also provided valuable insight in that no significant bulking was observed at the time the maximum PPV was reached. This indicated that the PPV only represented the velocity at the test wall surface prior to any significant damage occurring and does not represent the velocities of the bulking rock mass.

These findings indicate that during testing, PPV may trigger some fracturing of the rock mass; however, it has limited contribution to rock mass bulking, which is entirely driven by gases. For rockbursts, the PPV from remote seismic events may also induce some fracturing and trigger a strainburst, however, the energy driving rock mass bulking likely comes from the stored strain energy near the surface of an excavation.

Observations from the high-speed camera footage showed that the maximum displacement of the support system occurred immediately prior to mesh failure at the vertical overlap (Figure 10a). This observation represented a significant turning point in the development of the testing methodology, as it was then decided that the focus of the research would be shifted away from PPV and towards an approach that could enable the quantification of displacement capacity at the point of support system failure.

7 Update to test methodology

Following the results of the ground support tests at Mine 2, the testing methodology was revised to focus on loading a ground support system to failure. This would allow for continuous wall displacement measurements as the rock mass bulked, with the aim of obtaining a measurement of the ultimate displacement capacity at the point of support system failure.

To facilitate the update in the testing approach, a second high-speed camera was acquired to allow for a stereo camera setup. This enabled continuous three-dimensional displacement of the test wall to be measured throughout the blast. The stereo camera setup prior to a blast in shown in Figure 12a.

8 Mine 3

8.1 Objectives

The main objective of testing at Mine 3 was to implement and evaluate the displacement-based dynamic in situ testing methodology. Two test walls (Test Walls 6 and 7) were set up in competent ground to achieve this. A single blast was conducted at Test Wall 6, resulting in no significant damage to the wall. Two blasts were conducted at Test Wall 7, resulting in complete ground support system failure as intended. The details of the setup and the results for Test Wall 7 are presented in the subsections that follow.

8.2 Ground support

The ground support selected for Test wall 7 comprised debonded Posimix bolts and bulbed cable bolts on the left of the wall and fully bonded resin bolts on the right. For surface support, MINAX 80/4.6 Geobrugg mesh was installed together with FRS (50 mm thick).

8.3 Blast results

Two blasts were carried out for Test wall 7. Blast 1 was fired 4.2 m behind the test wall. The main aim of this blast was to test the monitoring equipment, particularly the stereo high-speed camera setup.

Following the blast, it was confirmed that all instrumentation functioned as intended. It was also observed that there was no damage to the test wall. This was the expected outcome given the large burden of the blast.

Blast 2 was executed as the final blast for the test wall, aimed to ensure failure of the ground support systems. To achieve this, the blast was fired from 2 blastholes, located at burdens of 3.0 and 2.4 m. Following the blast, total failure of the ground support systems was achieved (Figure 12b).



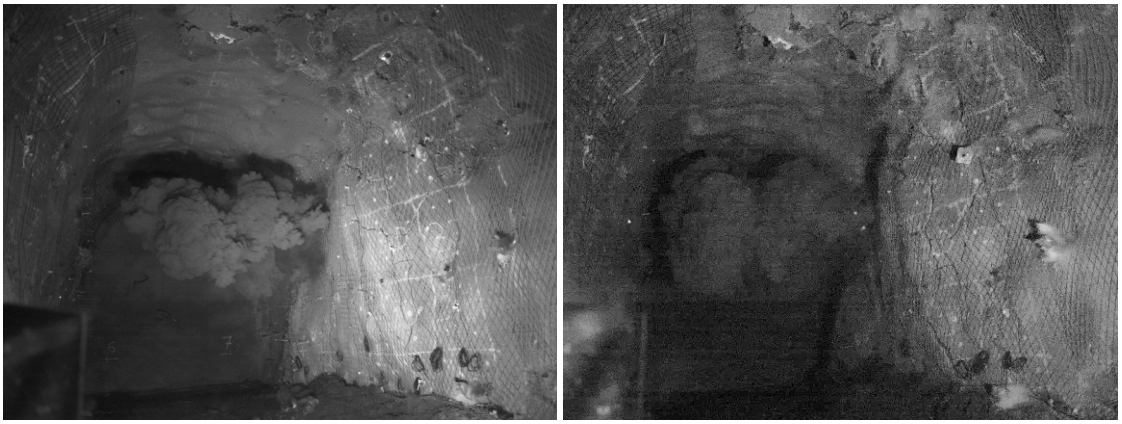
(a) (b)

Figure 12 Test wall 7. (a) Stereo high-speed camera setup prior to Blast 1; (b) Support failure after Blast 2

From the high-speed camera footage, the release of the blast gases from an observational hole was evident following the initiation of the blast (Figure 13a). Shotcrete cracking then became prominent (Figure 13a). This was followed by continued bulking as the ground support worked to retain the rock mass (Figure 13b).

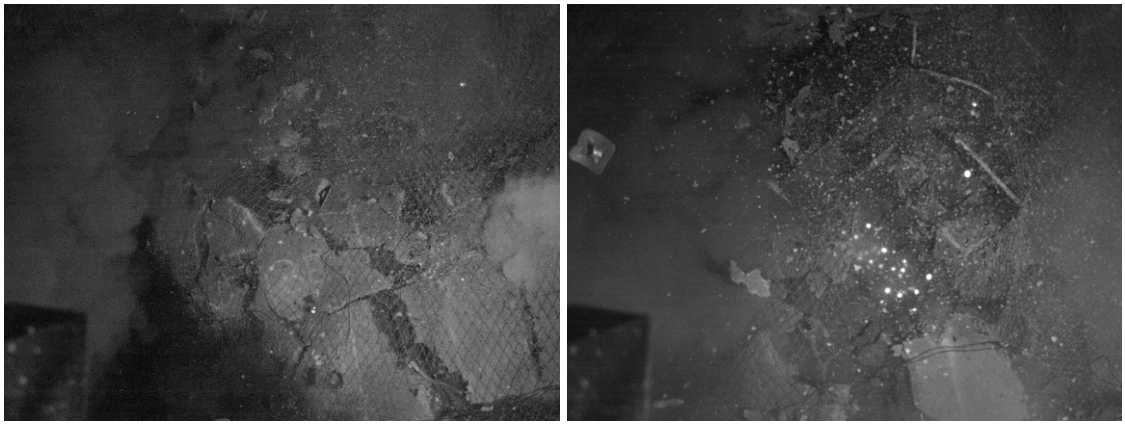
The maximum displacement of the Geobrugg mesh observed before failure is shown in Figure 14a. This was followed by the tearing of the mesh wires, which then continued to tear whilst mesh overlaps began to open.

This eventually led to the ultimate failure of the rock mass and ground support systems (Figure 14b).



(a) (b)

Figure 13 Test 7 Blast 2. (a) blast gases escaping observation hole with shotcrete cracking evident; (b) Bulking of the rock mass while being retained by ground support systems



(a) (b)

Figure 14 Test 7 Blast 2. (a) Maximum displacement prior to failure; (b) Total rock mass and ground support failure

8.4 Displacement during blast

For the displacement analysis, ground support system failure was defined as the maximum local deformation at which the support system could no longer contain the shattered, bulked rock mass.

To allow three-dimensional reconstruction of the test wall geometry as the blast progressed, 30 pairs of synchronised high-speed camera frames were selected from the blast initiation to the point immediately prior to ground support failure.

Three-dimensional photogrammetric reconstruction was then performed on the selected pairs of frames using the 4D processing approach in the Agisoft Metashape computer software. To ensure that the model geometries were of a sufficient quality, all wireframes generated from the reconstruction process were manually cleaned before taking displacement measurements. This cleanup involved removing noise caused by blast gases, flying debris, and any material that was not relevant to the bulking test wall. Low-confidence regions were also removed.

As the blast progressed, it was not possible to attain complete wireframe and point cloud reconstruction of the entire test wall. This was primarily due to the left-hand side of the test wall becoming progressively obscured by the bulking rock mass, and due to lower light intensity in this region. Despite these limitations,

the likely region of maximum bulking remained visible throughout the analysis, enabling displacement measurements to be obtained up to the point immediately before ground support failure.

Following 3D reconstruction, displacement was determined by comparing the initial reconstructed wireframe (reference model) with each subsequent reconstruction by performing cloud-to-mesh (C2M) analyses in the computer software program CloudCompare.

The reconstructed point clouds mapped with the resultant displacement measurements that illustrate the key wall displacements as the blast progressed are presented from Figures 15–20. For visual reference, the corresponding images from the primary high-speed camera are shown alongside each displacement model.

These results demonstrate the capability of the displacement-based methodology to quantify displacement leading up to ground support failure.

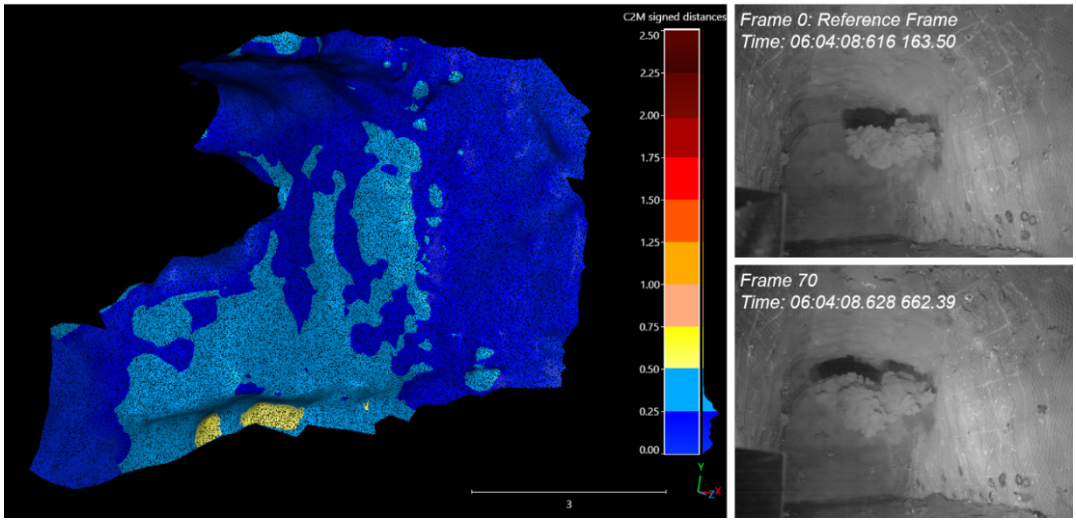


Figure 15 Displacement (m) between the reference model and frame pair 70, 12 ms after reference frame

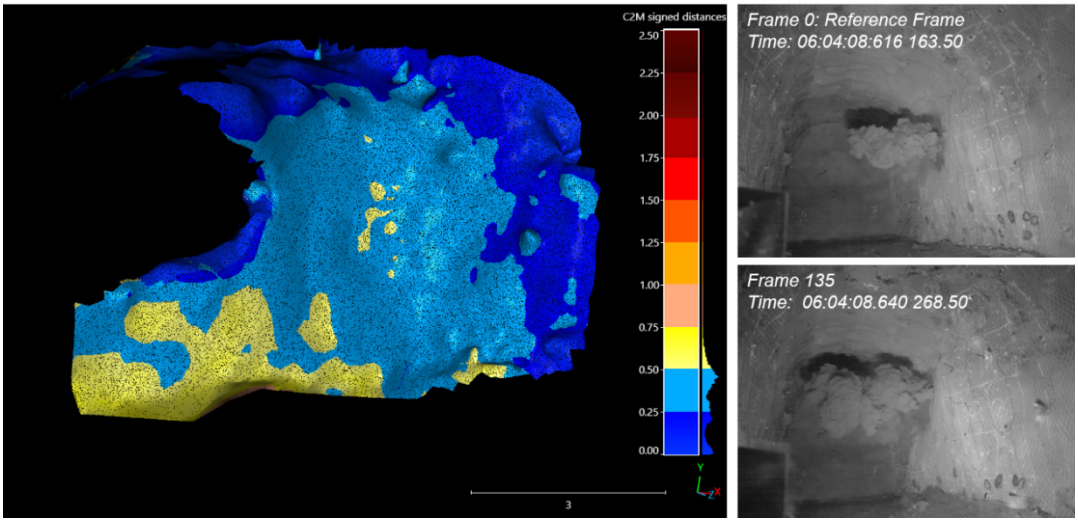


Figure 16 Displacement (m) between the reference model and frame pair 135, 24 ms after reference frame

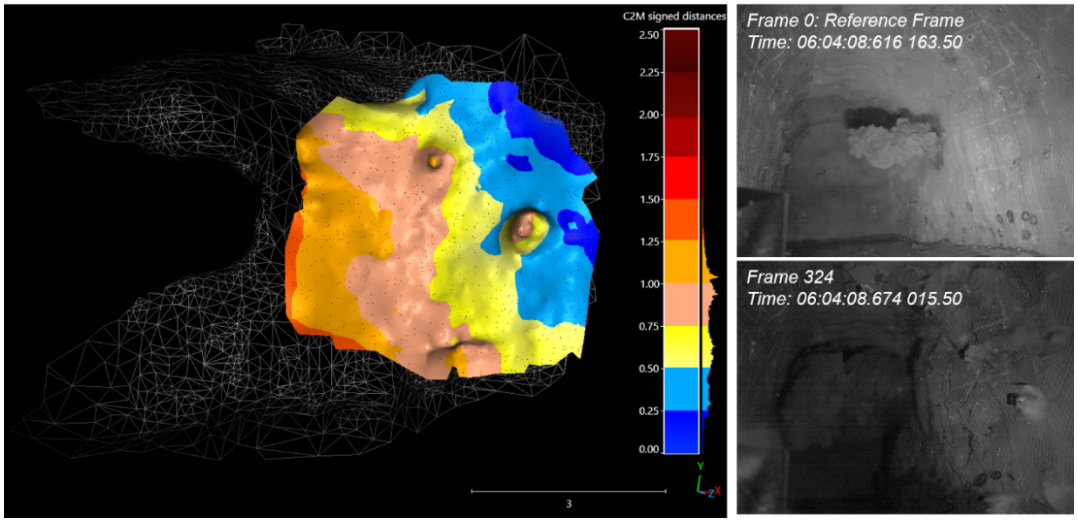


Figure 17 Displacement (m) between the reference model and frame pair 324, 58 ms after reference frame

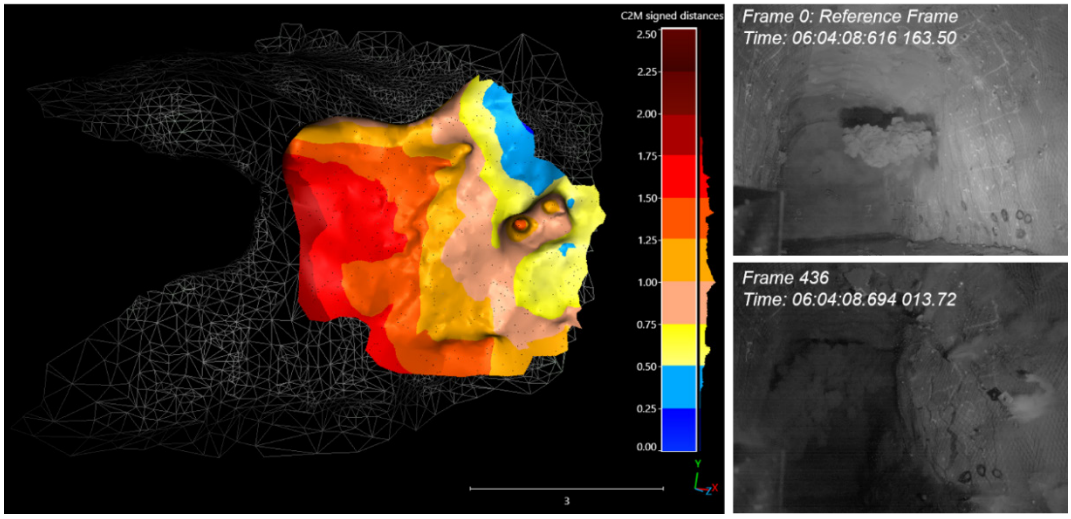


Figure 18 Displacement (m) between the reference model and frame pair 436, 78 ms after reference frame

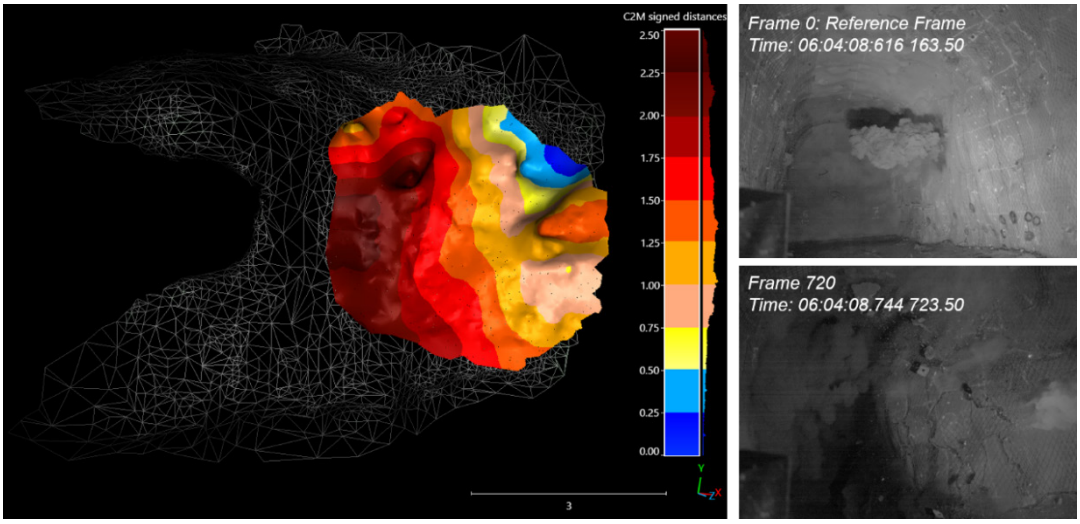


Figure 19 Displacement (m) between the reference model and frame pair 720, 129 ms after reference frame

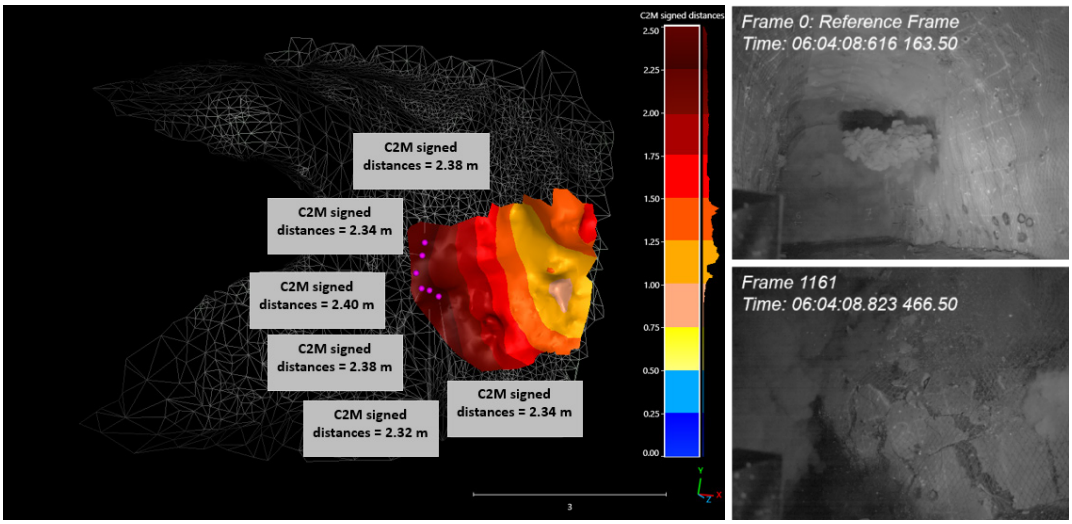


Figure 20 Displacement (m) between the reference model and frame pair 1161, 207 ms after reference frame

Figure 20 represents the maximum ground support system displacement before the mesh tearing (Figure 14a). From the displacements measured, the ultimate displacement capacity of the ground support system that was installed on the right of the wall is estimated at 2.40 m, with measured maximum displacements ranging from 2.30 to 2.50 m, depending on the location at which the measurement was taken on the wall.

Displacement during the blast for positions along a horizontal row at the right of the test wall is presented in Figure 21. These results illustrate the variations and overall increase in displacement of the wall over time as the rock mass bulked and the ground support system responded to retain the rock mass.

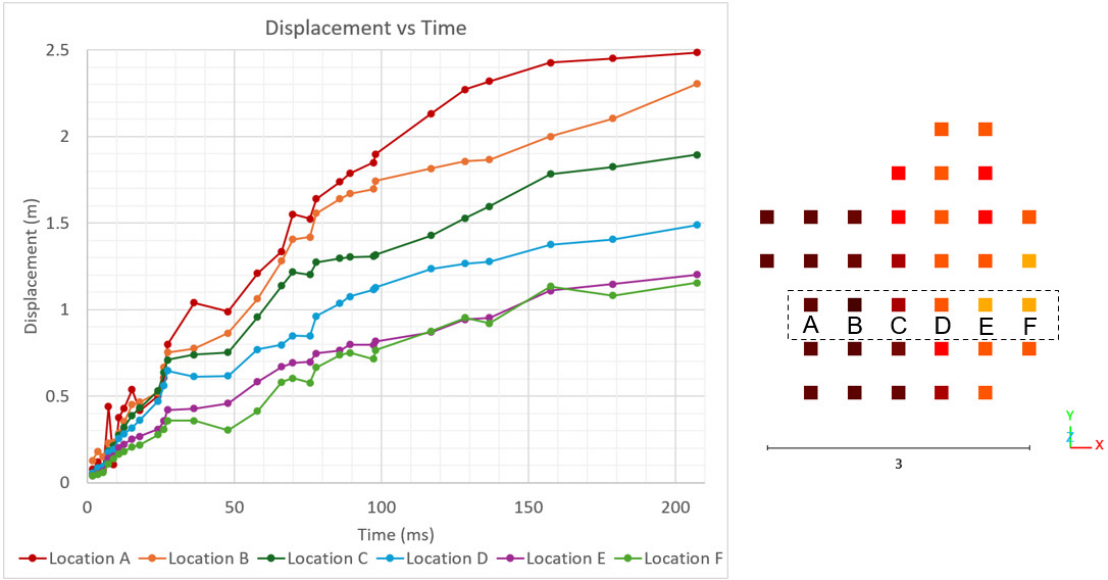


Figure 21 Rock mass displacement with time until point before total ground support failure

9 Practical outcomes

This research provides valuable insight into the response of ground support systems as it works to retain a bulking rock mass. Improved understanding of this interaction may better inform the selection and design of ground support systems.

A major outcome of this research is that it provides a means of estimating continuous displacement measurements with time as a support system is dynamically loaded and works to retain a bulking rock mass.

In particular, the research allows for an estimation of the ultimate displacement capacity at the point of failure of ground support systems, which is considered an important parameter for comparing the true capacity of a support system as it interacts with a rock mass under dynamic loading conditions.

This provides a key variable (d_{ult}) that may be applied to the deformation-based support design methodology developed by Kaiser & Moss (2022).

In addition to the estimation of ultimate displacement capacity for a support system, periodic LiDAR scans are recommended to quantify the remaining displacement capacity of the system. This enables the residual capacity of ground support systems to be assessed throughout the life of an excavation and provides a basis for identifying when rehabilitation is required prior to the ultimate displacement capacity of the support system being reached.

10 Future work

To validate and expand upon the results obtained using the displacement-based dynamic in situ test methodology, the next research phase (GSSO 4) will focus on carrying out up to 10 additional in situ dynamic ground support tests.

These tests will be conducted on existing installed ground support systems across multiple mine sites, with each test aimed at obtaining continuous displacement measurements throughout the dynamic loading process and at estimating the ultimate displacement capacity of the support system.

During this phase, the photogrammetry methodology will also be further refined through the incorporation of additional surveyed control points throughout the test wall. This will improve the accuracy of the photogrammetric reconstruction and provide improved confidence in the displacement measurements.

In addition to this, bulking velocities and the energy demand associated with the dynamic loading of ground support systems will also be investigated. This will provide further insight into support system performance and contribute to deformation-based support design methodologies.

11 Conclusion

To mitigate the impacts of rockbursts, geotechnical engineers rely on ground support as the primary tactical control measure to absorb energy and contain fractured rock masses. Dynamic support design methodologies require a reliable estimation of the dynamic capacity of an integrated ground support system as a direct input for design.

The in situ dynamic tests conducted as part of the GSSO 3 research project demonstrated that peak PPV alone is not a reliable indicator of rock mass damage.

Observations from the high-speed camera footage at Mine 2 showed that the maximum displacement of the support system occurred immediately before mesh failure at the vertical overlap. This observation was critical to the revision of the testing methodology, which was shifted away from PPV and towards an approach focused on quantifying displacement capacity at the point of support system failure.

The displacement-based dynamic in situ testing methodology implemented at Mine 3 demonstrated that high-speed photogrammetry is an effective approach for measuring continuous three-dimensional displacement during dynamic loading events. This enabled estimation of the ultimate displacement capacity of a ground support system, providing a pathway towards defining key parameters required for deformation-based support design.

The analysis of the velocity charts in conjunction with the high-speed camera footage at Mine 2 also provided valuable insight in that no significant bulking had occurred at the time the maximum PPV was recorded. This limitation can also be addressed through high-speed photogrammetry as it enables estimation of the rock mass bulking velocity, providing a more representative measure for the dynamic loading imposed on the support system.

The measurement of bulking velocity represents the way forward towards assessing the energy capacity of support systems. The continued development and application of the displacement-based dynamic in situ testing methodology is required to achieve this.

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References

Brändle, R, Luis Fonseca, R, von Rickenbach, G, Fischer, G, Vallejos, JA, Marambio, E … & Cuello, D 2022, 'Large-scale dynamic testing of ground support systems at the Walenstadt testing facility', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 177–190, https://doi.org/10.36487/ACG_repo/2205_10

Hadjigeorgiou, J & Potvin, Y 2007, 'Overview of dynamic testing of ground support', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 349–371, https://doi.org/10.36487/ACG_repo/711_26

Hagan, TO, Milev, AM, Spottiswoode, SM, Hildyard, MW, Grodner, M, Rorke, AJ … & Grave, DM 2001, 'Simulated rockburst experiment-an overview', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 101, no. 5, pp. 217–222.

Heal, D 2010, *Observations and Analysis of Incidences of Rockburst Damage in Underground Mines*, PhD thesis, The University of Western Australia, Perth.

Heal, D & Potvin, Y 2007, 'In-situ dynamic testing of ground support using simulated rockbursts', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 373–394, https://doi.org/10.36487/ACG_repo/711_27

Kaiser, PK & Moss, A 2022, 'Deformation-based support design for highly stressed ground with a focus on rockburst damage mitigation', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 1, pp. 50–66, https://doi.org/10.1016/j.jrmge.2021.05.007

Knox, G 2023, 'Laboratory-based drop testing of rock reinforcement', in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 23–38, https://doi.org/10.36487/ACG_repo/2325_0.02

Li, CC 2021, 'Principles and methods of rock support for rockburst control', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, no. 1, pp. 46–59.

Li, CC, Hadjigeorgiou, J, Mikula, P, Knox, G, Darlington, B, Royer, R … & Hosp, M 2021, 'Performance of identical rockbolts tested on four dynamic testing rigs employing the direct impact method', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, no. 4, pp. 745–754.

McCreath, DR, Tannant, DD & Langille, CC 1994, 'Survivability of shotcrete near blasts', *1st North American Rock Mechanics Symposium*.

Ortlepp, WD 1969, 'An empirical determination of the effectiveness of rockbolt support under impulse loading', *Proceedings of the International Symposium on Large Permanent Underground Openings*, Universitats-forlaget, Oslo, pp. 197–205.

Player, JR, Villaescusa, E & Thompson, AG 2004, 'Dynamic testing of rock reinforcement using the momentum transfer concept', in E Villaescusa & Y Potvin (eds), *Ground Support in Mining and Underground Construction*, CRC Press, London, pp. 327–340

Potvin, Y & Hadjigeorgiou, J (eds) 2020, *Ground Support for underground mines*, Australian Centre for Geomechanics, Perth.

Shirzadegan, S, Nordlund, E & Zhang, P 2016, 'In-situ dynamic testing of rock support at LKAB Kiirunavaara mine', in E Nordlund, TH Jones & A Eitzenberger (eds), *Proceedings of Ground Support 2016*, Luleå University of Technology, Luleå.

Tannant, D, Brummer, R & Kaiser, P 1994, 'Response of rockbolts to nearby blasts', *International Workshop on Applied Rockburst Research*, pp. 257–264.

Villaescusa, E, De Zoysa, A, Player, J & Thompson, A 2016, 'Dynamic testing of combined rock bolt and mesh schemes', *Seventh International Conference and Exhibition on Mass Mining*, Australasian Institute of Mining and Metallurgy, Melbourne.

Yadav, P 2024, 'Geomechanical evolution of the Nickel Rim South Mine', in P Andrieux & D Cumming-Potvin (eds), *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 61–84, https://doi.org/10.36487/ACG_repo/2465_0.03