Ground Support 2026 - D Cumming-Potvin & J Wesseloo (eds.)
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doi:10.36487/ACG_repo/2625_20

Automated ground support deformation tracking as a rehabilitation planning tool: replacing qualitative with quantitative metrics

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Abstract

One of the regular tasks of geotechnical and mining engineers is the measurement and management of deformation in underground excavations. Although other tools have historically been used to do so, LiDAR (light detection and ranging) has emerged as the most suited technology for this purpose as it caters for quantitative and omission-free rather than merely qualitative and sporadic tracking. Regular scanning has shown to be valuable for mines with squeezing ground conditions, and those exposed to rapid deformation through seismic events.

The authors introduced a novel method to automatically generate meaningful and actionable underground void deformation tracking results and reports from LiDAR data at the previous Ground Support 2023 in Perth. This paper presents progress and significant enhancements made since then to further streamline its methodology for broad adoption by operational geotechnical personnel, and to expand its application as a ground support rehabilitation planning tool. Examples for squeezing ground conditions are provided herein.

Descriptions on further streamlining of automated processing include a series of novel procedures to fully automate scan cloud registration or georeferencing, a step that when done manually as is current state-of-the-art, can often lead to notable spatial error bias in deformation tracking. Any such bias dilutes reliability of the method as a whole but has been overcome with the automated methodology described.

A key priority for geotechnical practitioners is the ability to better plan rehabilitation of ground support so as to ensure continued safety of personnel and access by mobile equipment. Current best practice is reactive rather than preventative, because universally effective and accurate measurements to track capacity degradation of ground support have been lacking. Preventative rehabilitation planning has now become possible and is routinely applied in practice as presented in this paper through fully automated accurate repeat tracking of typically thousands of in situ rockbolt and plate features contained in a single scan. This is achieved by automatically correlating tracked bolt and plate deformation over time with applicable capacity limits, and automatically highlighting areas nearing or having already exceeded these, such that rehabilitation planning is based on sound quantitative metrics.

Keywords: *LiDAR, deformation/convergence monitoring, ground support capacity, instrumentation and monitoring, ground support rehabilitation*

1 Background

Fatalities through rockfalls still occur in underground mining even in industrialised countries with modern best practices, despite ongoing industry-wide efforts in using ground support to prevent them. In situations where risks to personnel or equipment exist, ground support utilisation has been widely accepted by industry as a compulsory means for risk mitigation.

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One well remembered Australian example for a related major incident occurred at Beaconsfield Gold Mine in Tasmania on the 25th of April 2006. It generated global news due to the entrapment and subsequent successful rescue of 2 miners. What has sometimes been overlooked under the circumstances is that the same event led to one fatality through rockfall, all caused by a mining-induced slip along a shear, leading to a seismic event. As summarised by the Special Investigator on behalf of the Coroner in his Investigation Report (Melick 2007), amongst other reasons, the rockfall occurred because "the recommended support system", comprised of a mixture of split sets and what he called threadbars, installed in the area of the fatal fall of ground "was unable to maintain the stability of the excavation".

A major underground mine disaster that reverberated amongst the global geotechnical community more recently occurred on July 31, 2025, at Codelco's El Teniente mine in Chile, in which 6 workers died. The following details about the accident were reported in La Tercera (Vera 2026) by quoting the formally obtained Fatal Accident Investigation Report from the Chilean mining regulator Sernageomin, which does not make its reports publicly available. As stated therein, this event was caused by a rockburst, linked to conditions specific to underground mining and interaction of mining cavities, with the seismic event alone not explaining the magnitude of the accident, "but rather the existence of operational conditions that allowed workers to be exposed to a significant risk scenario" (Vera 2026).

Sernageomin highlights 4 main conditions that led to the accident. Among them is the continued presence of workers in areas with a history of structural damage, particularly related to an event that occurred at the mine in 2023, and the development of work in areas subject to stress interaction typical of deep mining. Aside from failures to adequately consider seismic monitoring data, the investigation maintained that "the installed support systems (bolts, mesh, shotcrete and cables), presented massive detachments, and local collapse, showing limitations in their capacity to contain the projection of material in high magnitude energy release scenarios" (Vera 2026). Following their investigation, the agency tasked Codelco with corrective measures including the implementation of a system to control the exposure of people in areas of geotechnical risks to include verification and renewing of the design criteria of the support system and conducting a technical audit of current approved projects that contrast the design with the actual state executed, among others.

When reviewing United States Department of Labor's Mine Safety and Health Administration Fatality Reports just for more recent years, its database also contains reports on cases where ground support was installed, but fatalities through rockfall occurred regardless. A 33-year-old roof bolter was killed in March 2022 (USDL Mine Safety and Health Administration 2022) despite ground support having been installed, "when he was struck by a roof fall while moving a waterline. The accident occurred because the mine operator did not: 1) conduct a supplemental examination in the #8 entry of the 3 South Mains to identify and correct hazardous conditions prior to miners entering the #8 entry where work was to be performed". In July 2021, a 68-year-old was fatally injured (USDL Mine Safety and Health Administration 2021) when a rock fell and struck him. Once again quoting the report, "The accident occurred because the mine operator did not: 1) promptly initiate appropriate action to correct hazardous conditions in high mine back (roof) and rib areas and maintain ground support where hazardous conditions existed, and in places where miners work or travel, and 2) take down or support the area…" (USDL Mine Safety and Health Administration 2021).

2 Introduction

A common thread between these examples of fatalities through rockfalls provided for 3 major mining regions Australia, Latin America, and North America over the span of the most recent 20 years, is that ground support systems may not be able to contain the ground of an underground mine excavation to prevent fatalities of its workers. In these examples, this was the case even though the underground mining activities or geotechnical conditions that caused them, sometimes through known seismic activity or rockbursts – as described in the thoroughly researched and documented reports by independent authorities – did not appear to be noticeably different to many other typical underground mining operations. No matter where in the world an underground mine is located and managed, or that we have had the benefit of many years to learn from previous failings, the danger of fatalities from rockfall in an underground mine has been and still remains

to this day clear and real. This notion is reinforced by industry experts, including the Australian Centre for Geomechanics (ACG), organiser of the Ground Support Conference series. In its notes for the Ground Support in Underground Mines Course by Wesseloo et al. (2026) – which is held on a regular basis for, and attended by, industry practitioners wanting to improve their expertise on the subject – the ACG explicitly mentions that, in conditions of severe squeezing ground, it is not possible for ground support to prevent failure of ground, it merely provides the means to manage this process. In a fight between rock and ground support, rock will always win.

Each time a fatality report was produced for the examples provided, and as quoted in previous paragraphs, the investigator made a point, or even instructed the operation, to make it a requirement to conduct adequate ground condition; or in other words deformation tracking efforts to provide quantified knowledge on ground support effectiveness over time. Therefore, in the investigators' words rather than the authors, what is needed to prevent such fatalities that ground support by itself cannot, is to "identify and correct hazardous conditions" (USDL Mine Safety and Health Administration 2022), and to "include verification and renewing of the design criteria of the support system" (Melick 2007) in ongoing geotechnical operations. Correcting hazardous conditions involves 2 steps. Firstly, proactively identifying when ground support is deteriorating and nearing its capacity limits to contain host rock. Secondly, to quantify when its capacity will likely be exceeded, such that preventative rehabilitation can be undertaken in a timely fashion to minimise the risk of rockfalls occurring. In order to achieve this, geotechnical practitioners need to make use of the technology available to them to accurately and robustly track the deterioration and remaining capacity of ground support. Simply installing ground support but then leaving its failure to chance because no rigorous monitoring effort is made, is not enough.

There are multiple technologies on offer to track the deformation of underground mining excavations. Some measure the embedded portion of bolts and the surrounding host rock, such as for example tell tales used extensively in coal mining. LiDAR measures the displacement of underground excavation surfaces. Unless such displacements are uniform in their direction and distance, they lead to deformations. Since irregular displacement is the most commonly observed behaviour, we use the term deformation in this context throughout this paper.

Omission-free deformation tracking of an underground drive can only be achieved through detailed tracking of the entirety of all its surfaces. Pointwise measurements with large gaps in-between cannot reliably detect worst deformations that have the highest probability to lead to ground failures, as explained in Figure 1 of Franke & Gonzalez (2026b) for the Latin American Rock Mechanics Symposium (LARMS). What has remained an obstacle in implementing a robust monitoring effort using LiDAR as the most suitable means for omission-free deformation tracking, is that the workflow from data acquisition to final interpretation has not been an automated algorithmic process. It has relied on manual processing methods used by practitioners, leading to many mine sites having a rigorous and robust 3D scanning data regime, but little to show for in terms of actionable reports and output data. A key reason for that is that working with point clouds is tedious to most geotechnical engineers. Point clouds have long been the realm of surveyors, but to fully adopt their use in geomechanics requires upskilling and allocated resources – which could already be stretched. Thus, in the author's experience, there are often insufficient resources to be applied to bringing 3D LiDAR technology into effective use. These findings were originally published in 2022 (Franke & Gonzalez 2022) and further expanded on in 2023, and 2024 (Franke & Gonzalez 2023, 2024), and led the authors to commit to the development of the automated processing, analysis and reporting software VoidMapper (Franke & Gonzalez 2026a), which addresses these shortcomings.

This paper provides an update on new and improved features of the technology. These features are intended to provide better insights into the behaviour of rockbolts – and by extension the entire in situ ground support system – that can now be used to more reliably plan for preventative rehabilitation, and to establish optimised ground support design criteria, as has been identified by fatality investigators as the way forward. New features that have been developed since the authors' 2023 Ground Support conference paper include:

- fully automated alignment of scans within a series designed for deforming point clouds

- fully automated correlation of identical bolts between scan epochs for continuous tracking
- expanded deformation tracking options expressed in a range of graphs to aid decision-making
- automated classification of bolt types for separate tracking.

3 Automated rockbolt extraction from LiDAR data

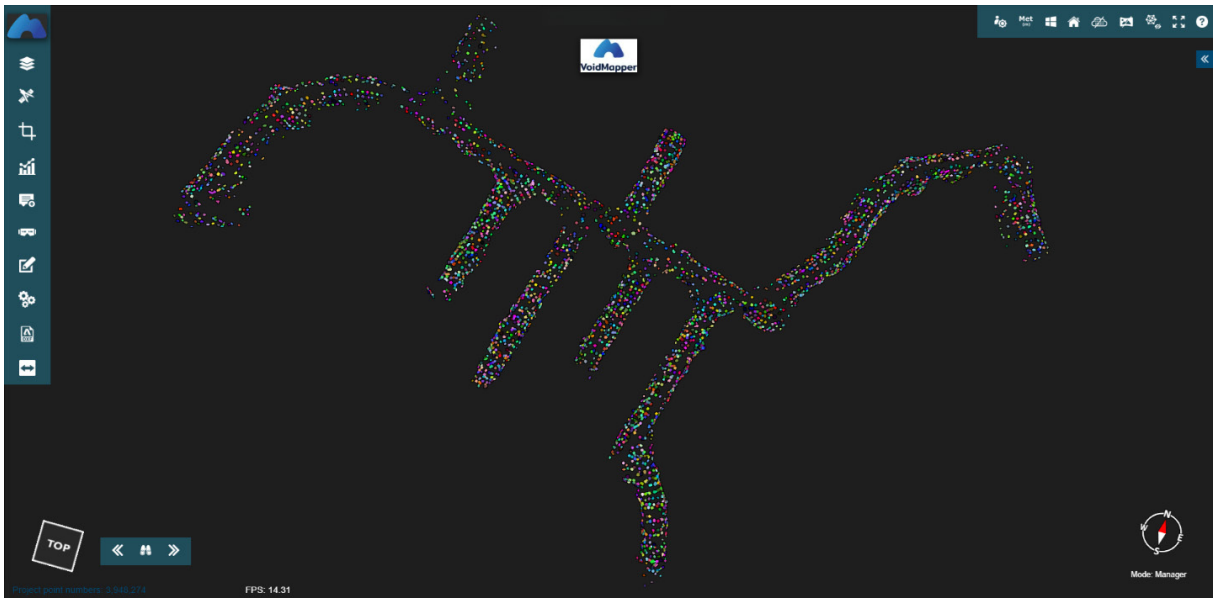
The authors introduced a fully automated system to extract pertinent bolt and plate features from LiDAR data in previous geotechnical conferences, initially at the 2023 ACG Ground Support conference (Franke & Gonzalez 2023). As the system evolved through further development, more refinements were added, as detailed at the 2024 ACG Deep Mining conference (Franke & Gonzalez 2024).

Our contribution to the 2026 LARMS (Franke & Gonzalez 2026b) detailed how the success of rockbolt and plate extraction improves through expansion and diversification of the machine learning (ML) training model. There is a clear and expected correlation between adding more relevant training samples to tell the ML algorithm what portions of the point cloud represent rockbolts and their plates, and how successful it will be in finding these. Even after adding many more thousands of individual bolt and plate training samples for many individual scans from a broad variety of underground mine sites since the publication of our LARMS paper, we still see improvements to the classification results. Success rates as documented therein were already representative of bolt behaviour and are now further improving. Extracting sufficient numbers of rockbolts and plates from LiDAR scan data is important to make statistical tracking of rockbolt behaviour robust and representative. To illustrate the current status of system rockbolt and plate classification and extraction an example is provided for a mine that is subjected to severe squeezing ground conditions in Figure 1. As is evident from the images, the majority of rockbolts and their plates for the entire drive is successfully classified Figure 1a and then extracted Figure 1b.

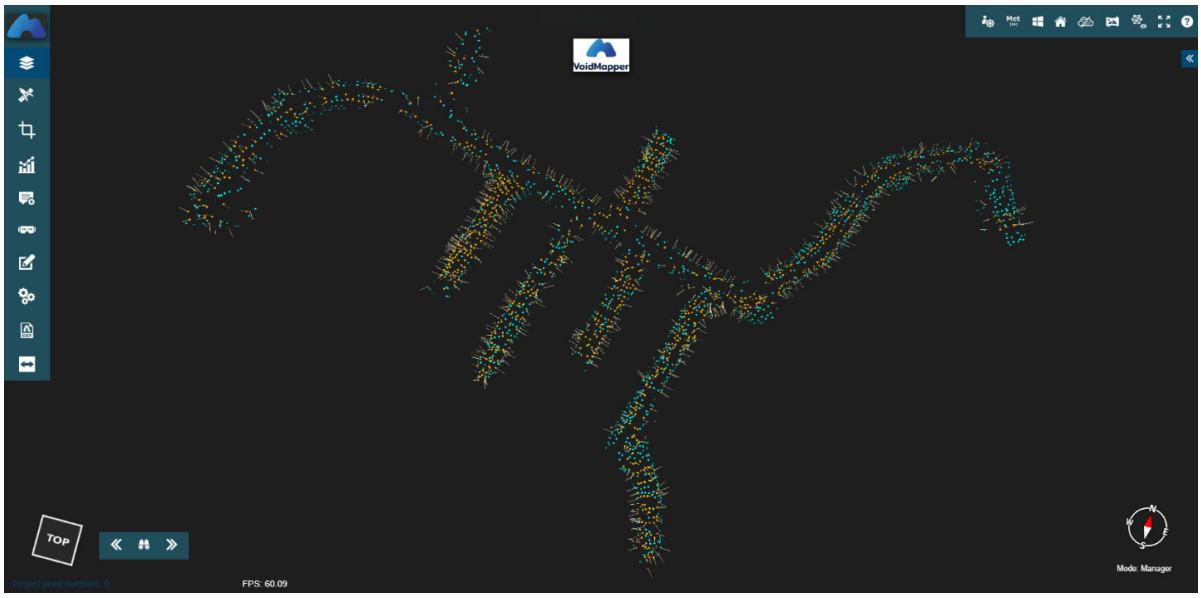
Our expectation is that we will eventually reach a state where adding more samples to the ML training dataset will no longer statistically improve subsequent classification results. In broad terms, what is required to reach the likely theoretical rather than obtainable state of absolute optimum training data, is to include all different permutations of what a bolt and plate, and what a non-bolt area looks like in LiDAR data. What needs to be represented for a universal ML system to be effective is the following:

- A sufficient number of different types and models of bolts and plates currently installed in situ, such that their respective 3D shapes can be recognised to maximise true positives.
- A sufficient variety of different rock shapes and their possible deformation states that could constitute non-bolt areas to avoid false positives.
- Relevant surface appearance disparity of bolt and plate and non-bolt classes, which varies in LiDAR data depending, for example, on whether it is wet or dry, dust covered or clean, covered in other substances leaching out of the rock, or fully or partially covered in shotcrete, to avoid false positives and maximise true positives.
- A sufficient variety of different point cloud structure specifics including point density and point distribution provided by different LiDAR scanners typically used for underground mining deformation tracking, to avoid false positives and maximise true positives.

From the above descriptions it is clear that universally applicable training data needs to be periodically supplemented with new samples to adequately represent new bolt and plate models of new shapes, sizes and materials, and scan clouds coming from new scanner models, as these are introduced to industry. So, whilst there will be a point of best possible training data preparation for optimum automated rockbolt and plate extraction, this will not be a permanent state but rather will need occasional updating to reflect the above changes in scan data appearance.



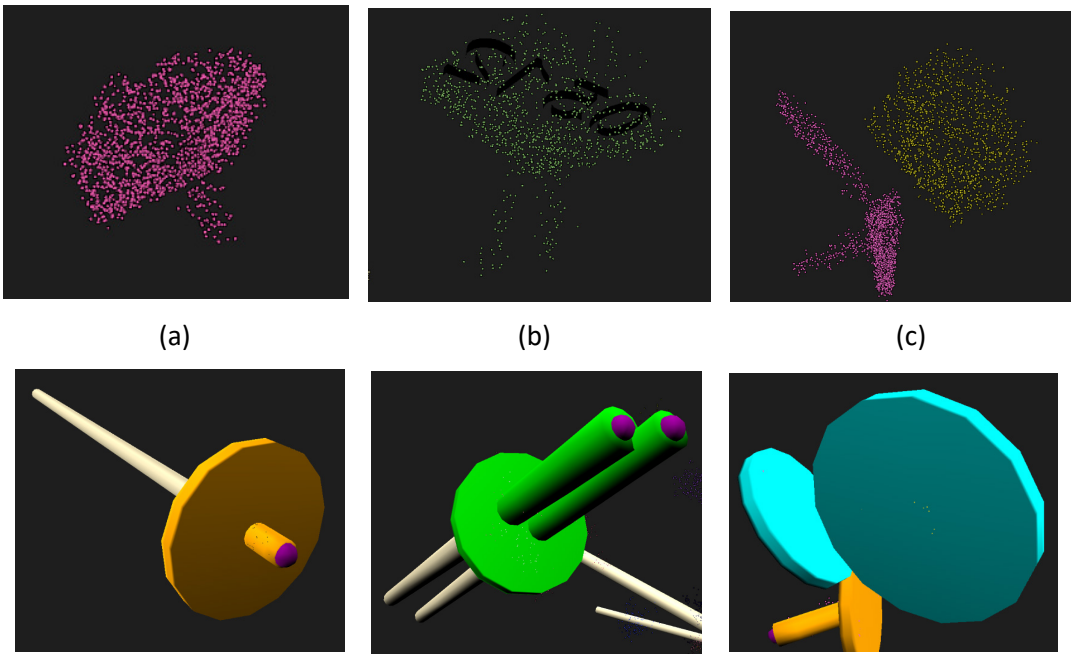
(a)



(b)

Figure 1 (a) Example for ML algorithm classification of scan cloud patches representing bolts and plates and (b) subsequent extraction of their positions represented by bolt and plate shapes showing successful extraction across the entirety of LiDAR scan coverage representing the majority of all bolts and plates installed at all drive locations. This indicates that the algorithm was able to match bolts and plates to its training database regardless of variations in appearance. Unsuccessful classification and extraction would leave large gaps where the ML algorithm cannot identify bolts and plates. Colouring in (a) is per rockbolt and plate instance, colouring in (b) is per bolt type as further explained in Figure 2

Our algorithm exploits distinctive differences between different bolt types captured in the scan point cloud to identify which bolt type any extracted bolt belongs to, as shown in Figure 2.



(a) (b) (c)

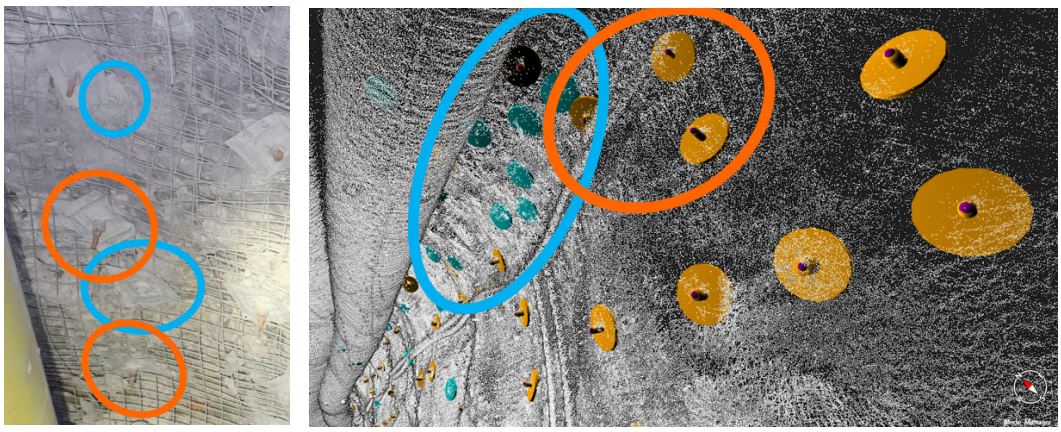
(d) (e) (f)

Figure 2 Typical scan cloud patches classified by the ML algorithm by referring to its training database to learn what constitutes a bolt and plate for (a) a standard steel rockbolt, (b) cable bolt, and (c) a split set. Corresponding extracted positional features are shown in orange for (d) a standard rockbolt, (e) in green for a cable bolt, and (f) in blue for a split set

The algorithm always extracts the plate separate to the bolt. Bolt types that can be identified for separate performance tracking are:

1. standard rebar/solid steel rockbolts
2. split sets
3. cable bolts.

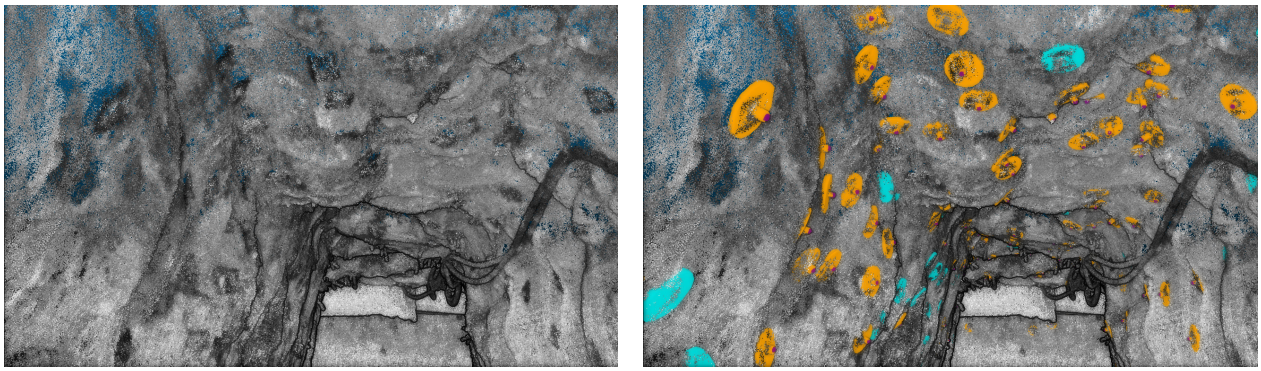
Figure 3 illustrates that the automated system is capable of finding and separating standard rockbolts from split sets even when they have been installed partially overlapping.



(a) (b)

Figure 3 Photograph (a) of standard steel rockbolt installations (circled in orange) and split set installations (circled in blue) illustrating that the algorithm is capable of identifying the majority of bolts and plates for both types, even if they are partially overlapping as shown in (b) the point cloud screenshot featuring extracted bolt and plate overlays

If the data contained in a classified bolt and plate scan cloud patch is of too poor quality to reliably extract a sufficiently accurate position, which is determined through a series of associated quality assurance checks in the algorithm, then such a bolt and plate are classed as Indeterminate and are not used any further. Even with poor quality LiDAR data as input the algorithm typically manages to classify and extract the majority of bolts and plates (as shown in Figure 4), if adequate representation in the ML training data was ensured.



(a) (b)

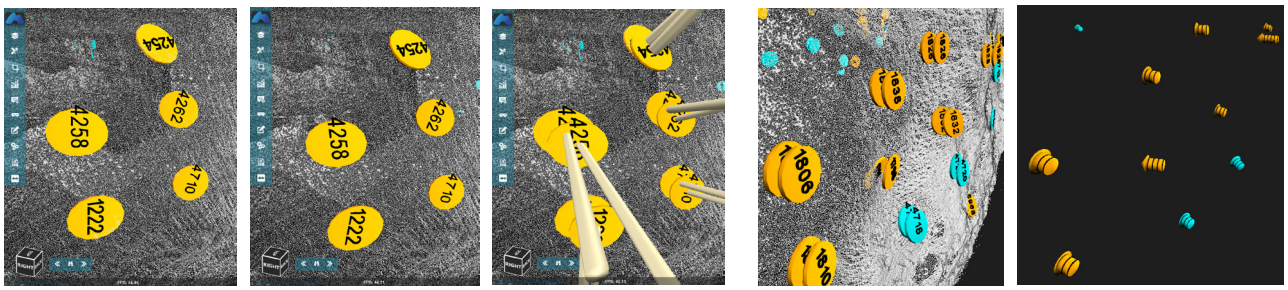
Figure 4 (a) Screenshot of a relatively poor-quality intensity coloured 3D scan cloud (b) overlaid with extracted bolts and plates, showing accurate positional extraction of the majority of them

It is useful to identify poor quality bolts and plates as Indeterminate regardless, rather than not track them at all, because doing so distinguishes them from failed bolts, thereby making the tracking of failed bolts more representative. VoidMapper applies the logic that if a bolt or plate was captured by the scan, but reliable positional characteristics cannot be determined, then it is classed as Indeterminate. Whereas a bolt or plate are only identified as failed if the bolt ID in question had associated data for it in the previous scan collected at an earlier date, but the current scan contains no classified data for this bolt or plate at all. The automated interpretation by the algorithm of such a scenario is that where there was bolt and plate data before but is now completely missing, this bolt and plate has failed.

4 Extracted rockbolt deformation tracking over time

Classifying and then extracting rockbolts from LiDAR data needs to be done for all LiDAR scans of a tracking series for a given repeatedly scanned drive section as a first step. This is only achievable through automated means, as it is not only impossible for a human operator to visually identify as many bolts and plates in a scan cloud as a ML algorithm can – as detailed in Franke & Gonzalez (2024), but no human operator could possibly complete this task for several scans in a timely fashion.

Once this first step has been completed, it becomes necessary to match up identical bolts and plates between extracted bolt and plate data sets for each scan, so that deformation can be calculated. Once again, manual matching of such sets of individual bolts and plates – that may well have a count of up to thousands, depending on the extent of scan coverage – is not feasible. Our system has an automated matching workflow, ensuring that identical bolts are given the same unique bolt ID in each epoch, as illustrated in Figure 5.



(a) (b) (c)

Figure 5 Identification of sidewall identical bolts and correct allocation of identical unique ID numbers for (a) left a first scan date, (a) middle a second scan date, and (a) right overlaid with embedded bolt portions showing. (b) shows a second example of overlaid identical numbers extracted for 2 scans, (c) shows the resultant deformation vectors sized by values as indicated by black rings

5 Rockbolt deformation based rehabilitation planning

As summarised by the ACG in Wesseloo et al. (2026), the approach to deal with squeezing ground conditions is to “not fight the ground, manage the ground”. The ACG supported idea is to:

- slow down convergence to avoid rehabilitation within the life of excavation
- minimise disruption to the operation
- minimise cost of rehabilitation.

Wesseloo et al. (2026) suggests one strategy for avoiding rehabilitation for as long as possible by using yielding ground support and only rehabilitating on an as needed basis. Another suggested strategy is to plan for regular rehabilitation by using inexpensive, rapidly deforming sacrificial temporary support to allow for controlled initial convergence, and for subsequent planned and scheduled rehabilitation cycles. In an example scenario for a service life of up to 2 years, the ACG illustrates that some mines may rehabilitate 50% of the drive, or 30% of the drive twice for example, depending on the strategy applied.

Whichever strategy is used, what is required, is to determine at what point rehabilitation becomes necessary. The way forward is to monitor and quantify the deterioration of ground support and determine at what point it has reached the limit of its capacity to prevent ground failure. In the past, this process has been qualitative, involving laborious and time-consuming visual, and somewhat subjective, inspection regimes. More recently, pointwise quantitative deformation monitoring instruments have been in use, with aforementioned severe limitations to how representative such measurements are. If the worst deformation is most likely to be missed by them, then they are not a reliable way to determine whether ground support capacity has been reached or not. We suggest doing so quantitatively by using LiDAR based automated tracking of rockbolt deformation. This is not only more practical, objective, and omission free, but a representative monitoring method due to its high percentage of tracked bolts at all locations within the drive. Explanations in the following sub-sections provide further detail.

5.1 Correlating rockbolt deformation behaviour with failure

Automatically tracked bolt deformation data can be used as the input starting point for tracking bolt integrity, as first introduced in Franke & Gonzalez (2023) and further expanded on in Franke & Gonzalez (2024). Tracked spatial bolt position deformation is used as a proxy for bolt failure. The assumption is that if a bolt and plate position, as tracked by the system described in this paper, deforms by more than a predetermined failure limit, then its performance and integrity has likely been severely compromised. The underlying root cause for this assumed failure, whether it’s shearing, slipping, debonding, faulty installation, or any others, is unknown. It is equally unknown for other types of monitoring techniques.

If a limit of bolt deformation is to be used as a trigger for rehabilitation, it becomes necessary to predetermine what that limit is. Once this method of using deformation triggers for rehabilitation timing and scheduling is established, aforementioned strategies of as needed or regular rehabilitation can then be implemented by adjusting what the timing should be within a safe yet effective framework.

One possibility is to correlate spatially measured bolt deformation with elongation to failure limits determined through laboratory testing. Most bolt vendors provide elongation to failure limits in their product specification data sheets, as tested through destructive methods in a variety of testing equipment. In situ pull testing of bolts at an underground mine location is also common practice to determine bolt elongation limits. Methods using currently available laboratory equipment, or field deployable pull test rigs, only destructively test for the uniform piston model, which is too simplistic to represent other failure mechanisms actually occurring in situ. There are currently no industry accessible facilities to test for rockbolt dowel action resisting shearing stresses for example (Wesseloo et al. 2026). Aside from emerging systems such as the one described by Hinojosa et al. (2024), standard laboratory tests used by the majority of bolt vendors to quantify their product specifications, currently also do not test efficacy of the entire ground support system in use, only of one particular bolt model in isolation. Importantly, only pull tests account for actual applicable ground conditions and demand. Since pull tests can only practically be completed for a small number of bolts, they constitute an indication rather than a statistically robust representation of capability for all installed bolts.

As a result, correlating elongation to failure values sourced from bolt specification data sheets with in situ spatial deformation is not a like for like assessment, and such elongation to failure limits can only be used as a basic cross-check, not as a definitive limit for measured bolt deformation to trigger rehabilitation.

5.2 Preventative rehabilitation planning

A practical way forward is to empirically determine such deformation limits through ongoing and continuous deformation tracking instead. This by definition is site and location specific, as it should be done for specific areas of comparable ground conditions and geotechnical features such as faults and the like, and for specific areas of identical or at least similar historic ground support designs and types already in use.

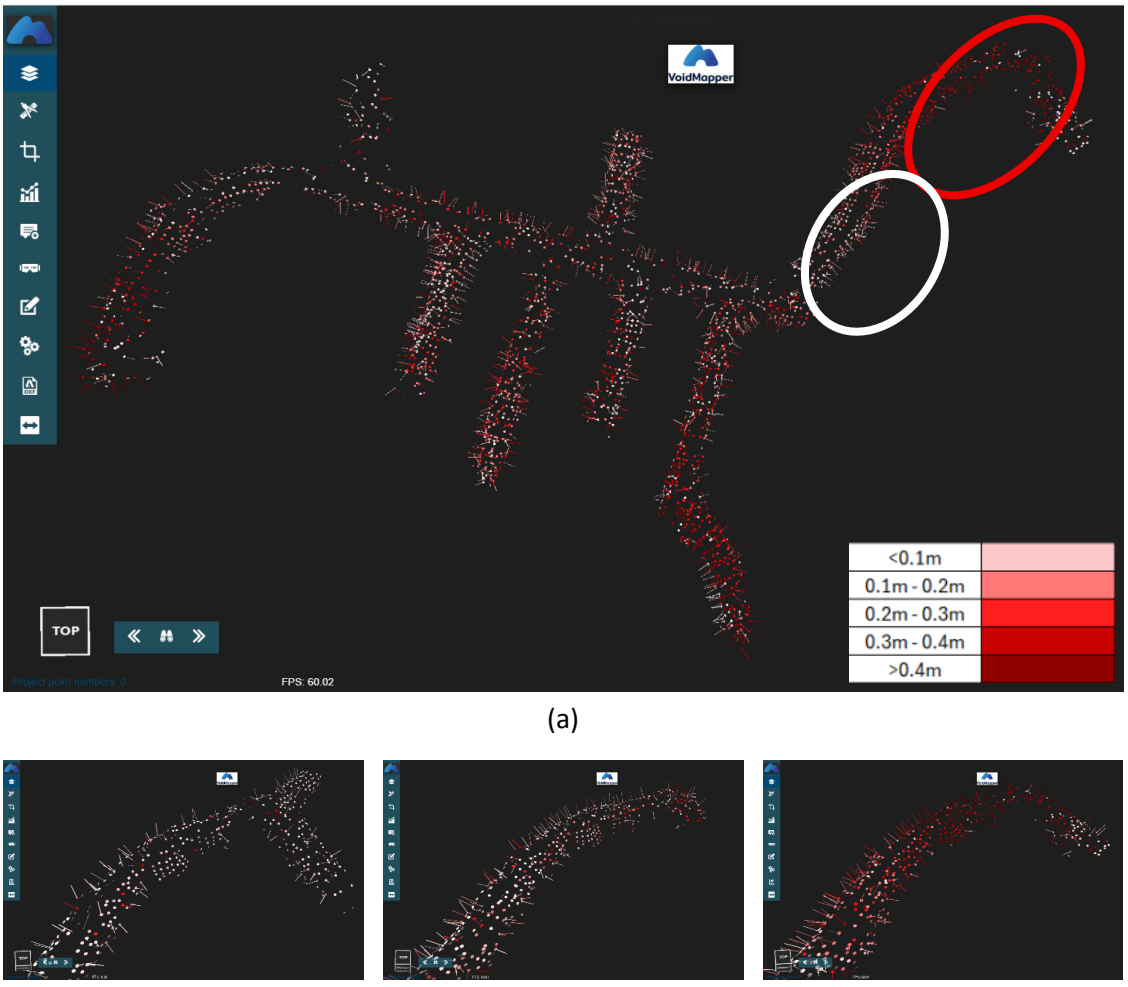
Even though the presented method of tracking rockbolts does not explicitly measure any other contributing ground support features such as straps, mesh, or shotcrete, it does represent the entire system deformation. It represents the combination of all elements and the combination of different installed bolt types and models, because rockbolt deformation as measured is affected or constrained in its spatial movement by all those features.

Such measurements of in situ bolt and plate deformation reflect the efficacy of the entire ground support system interacting with the specific ground conditions and demand of the tracked drive. This is not something that can realistically be tested for in a laboratory, because replicating representative ground conditions and demand in all their unknown variations of embodiment is unachievable. The influence of rock specifics on support system efficacy is significant though. As is experienced by operational practitioners even within their own mine footprint, weaker rock masses lead to less effective performance of an identical ground support system design when compared to its installation in a competent rock mass. In effect, due to the exclusion of ground condition influences, laboratory testing may account for relative support element, or relative support system performance, whereas in situ rockbolt deformation tracking accounts for absolute support system performance including ground condition and change in demand influences. This makes tracking rockbolt deformation a comparably representative means for determining preventative rehabilitation trigger limits.

This empirical method involves observing localised indications of imminent or actual rock mass failure and recording corresponding measured rockbolt deformation values for this intolerable state of ground support. These tracked intolerable deformation values should then be reduced by a Factor of Safety (FoS) to determine the preventative rehabilitation trigger deformation value. What the FoS should be is a decision to be made by site geotechnical personnel responsible for the safety of underground workers on the basis of applicable site conditions and requirements. The tool described in this paper can only provide the underlying data for this decision. The aim is to ensure this data is robust and meaningful.

Applying this trigger to other comparable areas with similar ground conditions and demand featuring similar or identical ground support design mitigates the risk of ground failure when deformation is tracked for them. AngloGold Ashanti has undertaken a case study to implement this process at their Cuiabá mine in Brazil, presented in the 2026 Ground Support Conference (Franke et al. 2026).

VoidMapper outputs rockbolt and plate deformations in a number of ways for different purposes. One of these is a 3D map of bolts and plates coloured by deformation, light pink representing small, dark red large deformations, with intermediate hues and stages in-between. Figure 6a shows an example for the same mine site experiencing highly squeezing ground conditions used in previous descriptions above. The period of deformation for this example is just under 2 months, and there is clear evidence that different sections of this scanned area are deforming at different rates, as indicated by the lighter less deforming and the darker red more deforming colouring. These areas are circled white and red respectively in Figure 6. This spatial information and its visualisation lends itself to identify which region within a drive is nearing or has even passed the defined preventative rehabilitation trigger deformation value. Once such an area has been identified, such visualisations can be used to intuitively communicate to bolting crews where they need to install rehabilitation.



(a)

(b) (c) (d)

Figure 6 (a) Shows rockbolt deformation in a mine with highly squeezing ground conditions automatically tracked over a period of 54 days and coloured by absolute 3D deformation value as per legend provided. Notable differences in behaviour are evident even for neighbouring drive sections as highlighted in the red circle where bolts have deformed significantly, and the white circle where bolts have deformed much less. Images on the lower row show a close-up of the evolution of the severely deforming Northeastern scan region (circled red) over time for (b) the first 11 days (c) 32 days and (d) 54 days of tracking

New drive excavations using the same ground support design with the same or similar ground conditions and demand and geotechnical features can be managed by using the corresponding preventative rehabilitation trigger deformation value previously defined for those. This provides an immediate mechanism for preventative rehabilitation for matching new drive excavations.

6 Opportunities for ground support design optimisation

6.1 Establishing ground support behaviour patterns

Aside from determining preventative rehabilitation schedules and to identify and communicate localised high deformation rehabilitation areas to bolting crews, the 3D map presented in Figure 6 can also be used in additional ways for the purpose of ground support design optimisation. A corresponding method termed deformation based support design (DBSD) for ground support systems was described by Kaiser & Moss (2021). The aim as in our case is to use deformation data for the optimisation of ground support system design. Their workflow includes 4 main steps, beginning with excavation vulnerability assessment, identification of dominant engineering parameters and associated support system selection, then support design analyses, and lastly support system verification through monitoring. Our monitoring tool is intended to provide the robust means to achieve the last step in this type of workflow.

The Kaiser & Moss (2021) DBSD was implemented by PT Freeport Indonesia as described by De Ciolli et al. (2022). The use of our monitoring technique has been utilised by AngloGold Ashanti as described in by Franke et al. (2026).

The sample map shown in Figure 6 for a drive area subject to highly squeezing ground conditions exhibits clear regional variation of deformation as indicated by predominant hue changes, either trending towards lighter, medium, or darker shades of red. Assuming same or at least similar age of installed ground support, this may be caused by a number of characteristics for the respective areas:

- different ground support in use for comparable ground conditions and demand
- identical ground support in use for different ground conditions and demand
- varying proximity to mining activities and/or localised seismic event zones
- installation quality.

Different ages of installed ground support may of course have an influence as indicated by Figures 6b–d, so deformation behaviour would need to be normalised by age after extraction from a single scan area, such as the one shown in the example, for the above Cases 1 to 3 to be directly comparable. Mining operations can identify from supplementary data and information, which of the above reasons for varying ground support behaviour pattern normalised by age applies.

If age normalisation has been accounted for, then the following conclusions can be drawn from the observed deformation behaviour. For Case 1, the ground support system in use in the area exhibiting lighter deformation colours is superior to the one in use in the areas exhibiting darker colours. Operations could therefore adopt the better performing option of the area with lighter colours for any new installations in comparable ground conditions and demand.

For Case 2, the one and only ground support system in use for different ground conditions and demand is less fit for purpose for those areas with conditions exhibiting darker, more deformed red colours. It may be prudent to change the design of ground support in use in these more deformed areas to make it more conservative by increasing capacity or yielding range for example, if service life extension is the desired outcome. Similarly for Case 3, assuming all things are equal for the different areas except the exposure to mining activities or seismic events, it may also be desirable to do the same, if use of a more conservative ground support system design can lead to a more favourable rehabilitation scheme. As indicated in Section 4 by making reference to ACG's best practice documentation, the objective of utilising this deformation data to adjust ground support system design to achieve better service life for it is to either:

- extend its life through more conservative but likely more expensive and onerous ground support so that no rehabilitation is required
- shorten its life through less conservative but likely less expensive and onerous ground support, such that more synchronised rehabilitation cycles can be implemented across all excavations – rehabilitation may be required more frequently but may be less expensive and less demanding on installation, or less disruptive to operations overall.

6.2 Ground support design trialling

Options to track existing ground support installations for the purpose of optimising rehabilitation as described under Section 5.1 are available at any time. It is also possible to conduct dedicated ground support trials if an unverified new ground support design, or new ground support elements such as a particular type or model of bolt or mesh is to be evaluated. In this case a trial drive area with coherent ground conditions and demand could be selected for installation of the new design or support system, ideally complemented by a neighbouring reference support installation of known performance to allow for ground truthing. Deformation tracking of this trial installation, ideally complemented by doing the same for the neighbouring reference, will provide insights into its relative performance. If such performance is superior, then the new design or its components provide a pathway for improved management of ground support for new installations in similar ground conditions and demand.

7 Conclusion

A new approach for establishing quantitative rather than qualitative data that can be used for preventative rehabilitation planning has been introduced. This method has advantages over incumbent techniques as it is considerably more representative. It tracks:

1. the majority of all installed bolts and plates rather than just a select few – this is critical because deformation behaviour is highly variable within even small areas; hence spot check tracking of a low number of bolts can be highly misleading, which poses a significant safety risk
2. absolute ground support performance as measured through bolt deformation, accounting for in situ ground conditions and demand not available through laboratory testing
3. the interaction of the entire ground support system through bolt deformation, rather than testing a single ground support element in isolation
4. the effect of all failure mechanisms on rockbolts and plates, as exhibited through in situ 3D spatial deformation, not just those that can be replicated in laboratory testing environment.

Other point-wise ground support monitoring technologies, or manually processed LiDAR tracking that cannot feasibly provide the kind of feature extraction we have illustrated in the outputs of our automated software, does not provide 1 nor 3. Laboratory performance testing does not measure 1 nor 4, and cannot provide 2 nor 3.

Aside from providing robust representation by combining all of the listed characteristics a) to d), the method presented has other advantages. Its automated processing and reporting aggregates raw data into outputs fit for direct decision-making, without the need for time-consuming and onerous manual intervention. Geotechnical practitioners in operational roles at underground mine sites typically don't have available capacity to produce any such data manually. So full automation of workflows is the best way to make this technology accessible, to increase reliability and efficiency by removing subjective manual processing steps, and to allow geotechnical engineers to focus on their core role of data interpretation and response actions, rather than on data production.

Acknowledgement

The authors would like to acknowledge many fruitful discussions and input from VoidMapper geotechnical end users that have led to system improvements and deliverables. Our particular thanks go to Oceanagold, NSR, Anglogold Ashanti, Westgold, BHP, MMG, Goldfields, and Newmont for their continued support.

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