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# Consumed capacity monitoring of Sandvik MD and MDX bolts using ultrasonic pulse echo

**Osvaldo Vallati [a,*], Jamie Wang [a], Peter Young [a]**

[a] *Sandvik, Australia*

## Abstract

*Rockbolt degradation poses a major challenge in caving operations as dynamic stresses and progressive deformation reduce reinforcement capacity. Recent studies, including MRIWA GSSO2, have identified the lack of low-cost, reliable instrumentation for measuring bolt elongation as a critical gap in effective ground support management.*

*To address this limitation, Sandvik introduces xCell Banshee, an innovative monitoring approach that integrates ultrasonic pulse echo technology into every MD and MDX bolt manufactured by Sandvik, enabling non-destructive, in situ measurement of bolt length, elongation, and consumed capacity. This universal implementation ensures that ground support monitoring becomes a standard feature across MD and MDX bolts, setting a new benchmark for safety and performance in underground mining. Importantly, the system is designed to be largely deployable and truly scalable on site, enabling mine-wide instrumentation without specialised installation procedures or additional hardware.*

*The paper first reviews current practices in caving operations for assessing rockbolt capacity and their limitations. It then introduces xCell Banshee, the new technology, explaining the underlying measurement principles, and details the laboratory testing program undertaken to validate the approach.*

*Laboratory investigations assessed measurement accuracy under varying loading conditions. Tests conducted on 2.4 and 3 m bolts demonstrate robust signal performance and strong agreement between ultrasonic measurements and mechanically measured elongation. Calibration trials identified a systematic length correction factor and quantified temperature effects, leading to the development of compensation algorithms suitable for field application.*

*The xCell Banshee system represents a significant advancement in ground support monitoring by providing real-time, non-destructive assessment of rockbolt integrity and deformation. Integration with digital monitoring platforms enables predictive maintenance strategies and has the potential to significantly enhance safety and performance in caving operations.*

**Keywords:** *MD, MDX, rockbolt, ground support, monitoring, capacity*

## 1 Introduction

Cave mining environments present some of the most demanding geotechnical conditions in the industry, where deep excavations are subjected to high and highly variable stresses that drive deformation, seismicity, and progressive rock mass damage. As mining advances and cave-induced stresses redistribute, extraction level drives frequently experience severe convergence, floor heave, wall bulking, and pillar yielding, particularly in poor ground or faulted zones, often resulting in costly rehabilitation or complete drive closure. These deformation mechanisms are amplified by heterogeneous and brittle lithologies, intrusive contacts, and structural domains that can trigger strainbursting, rockbursting, and violent ground failures (Kamp 2022). In such conditions, excavation stability is critically dependent on the performance of ground support systems,

[*] Corresponding author. Email address: osvaldo.vallati@sandvik.com

which must resist both static and dynamic loading while accommodating ongoing deformation. The ground support systems are therefore subject to progressive capacity loss as deformation accumulates, with damage ranging from plate bending and mesh tearing to bolt yield or rupture. As described by Kaiser & Moss (2022), support elements continuously consume capacity through bulking, ejection loading, and dynamic shaking. Because rockbolt performance degrades as load transfers from the deforming rock mass into the reinforcement, monitoring the consumed capacity of bolts and the broader deterioration of ground support is critical for maintaining excavation stability.

Modern approaches to evaluating the consumed capacity of reinforcement have evolved beyond traditional pull-testing and visual inspections, with a range of instrumented rockbolt technologies designed to measure load, deformation, and anchorage degradation throughout the bolt's service life. Early systems relied on inline load cells placed behind the bolt plate to measure axial force, providing direct but highly localised insight into bolt loading. More sophisticated instrumentation integrates sensors along the bolt length, typically resistance strain gauges or vibrating-wire gauges, to monitor deformation at discrete points, enabling partial reconstruction of the axial load profile. However, these discrete systems often underestimate peak loads due to sensor spacing and averaging effects, a limitation noted in both laboratory and field trials. Despite their technical advantages, embedded-sensor bolts remain costly, installation intensive, and prone to damage during resin mixing or bolt spinning, constraining widespread adoption in production environments.

Alongside instrumented reinforcement, a wide range of non-destructive testing (NDT) methods has been developed to assess the in situ condition of rockbolts, including acoustic emission, electromagnetic time domain reflectometry, impact echo, and piezoelectric impedance methods (Song et al. 2017; Lama & Momayez 2023; Vallati et al. 2020). While these techniques target specific deterioration mechanisms such as corrosion, grout defects, or bolt looseness, ultrasonic methods have become the most widely researched and practically applicable NDT tools because they can be applied directly at the exposed bolt head and interrogate the full embedded length of the bar without disturbing the support system. Ultrasonic NDT has been extended beyond simple integrity testing toward quantifying load transfer, deformation, and remaining bolt capacity. A major development in this area is the rockbolt sensor (RBS) technology, introduced by the National Research Council Canada (Sun et al. 2019), in which a head-mounted ultrasonic module tracks time-off-flight (TOF) variations in longitudinal and shear waves to estimate bolt load, detect plastic deformation, identify distributed strain, and determine the onset of yielding. The RBS system was successfully demonstrated on fully encapsulated reinforcement; however, its measurements represent average deformation over each bolt segment, which limits its ability to capture the highly localised strain and non-uniform loading that commonly develops along grouted bolts. Furthermore, the requirement to install a dedicated sensor at every bolt head, despite the use of low-cost ultrasonic transducers, still introduces nontrivial costs and logistical challenges for large-scale deployment. As the technology remains pre-commercial, these practical constraints continue to restrict widespread operational adoption.

However, as highlighted in the recent MRIWA scoping study on ground support degradation, the industry still lacks a low-cost, widely deployable deformation sensor that can be installed on every rockbolt – or at least on a representative proportion of bolts – for routine assessment of consumed capacity (Potvin et al. 2021). Despite promising developments such as RBS, the report identifies "the most important gap at this stage" (Potvin et al. 2021) as the absence of a simple, robust, and inexpensive bolt mounted device capable of being mass produced and integrated directly into standard reinforcement without significantly increasing installation cost or complexity.

In this context, Sandvik has been advancing 2 complementary approaches for consumed capacity monitoring for rockbolts. The present paper focuses on the xCell Banshee concept, developed for mechanically anchored bolts such as the MD and MDX series, while a companion study addresses the solution for embedded rockbolt known as xCell Hydra.

The xCell Banshee is a method based on pulse echo that can be extended to every improved MD and MDX bolt installed in a mine. The authors realised that ultrasonic pulse echo technology is particularly well suited to mechanically anchored bolts, such as the MD and MDX, because the reflective interfaces and free length allow accurate measurement of bolt elongation. The method does not rely on additional sensors or embedded instrumentation, meaning it introduces no extra hardware cost and requires no change to existing bolt performance or installation processes. Instead, the approach uses manual ultrasonic measurements taken directly at the bolt head, providing a practical and scalable pathway for mine-wide deployment of bolt capacity monitoring while maintaining operational simplicity.

# 2 The technology

## 2.1 Sandvik MD and MDX bolts

The authors developed this ultrasonic testing methodology specifically for the Sandvik MD and MDX bolts (Figures 1 and 2). These bolts are hybrid mechanical–friction reinforcement elements comprising a split tube surrounding a 20 mm rebar that is mechanically anchored at the toe through a wedge assembly and tensioned via a blind nut at the collar. The MDX variant further incorporates a disengaged bar–tube arrangement. Both bolts rely on the long free length of the rebar to stretch uniformly under load and dissipate energy during seismic or deformation induced events.

This geometry makes the MD/MDX family particularly well-suited to ultrasonic pulse echo techniques because the rebar is free along most of its length, and elongation develops globally rather than concentrating into short, highly localised strain zones. The presence of well-defined reflective interfaces at both the collar and the toe wedge enables accurate determination of the total bar length using time-of-flight analysis, which can be directly converted into bolt elongation and consumed capacity.

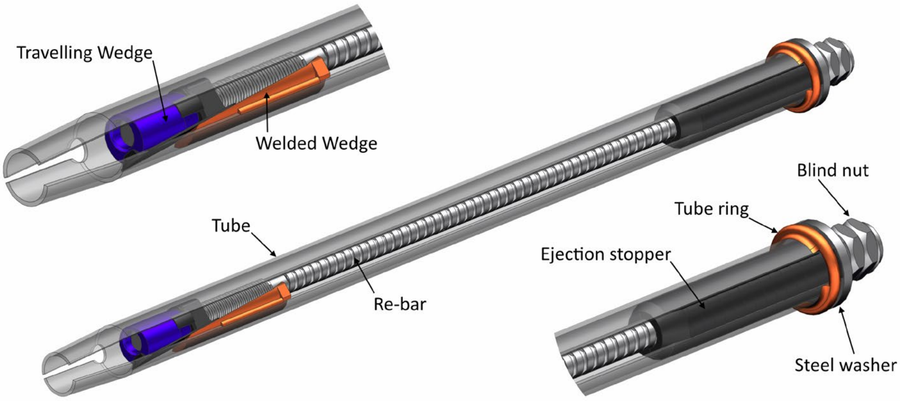


**Figure 1 Anatomy of the MD bolt (Darlington et al. 2024)**

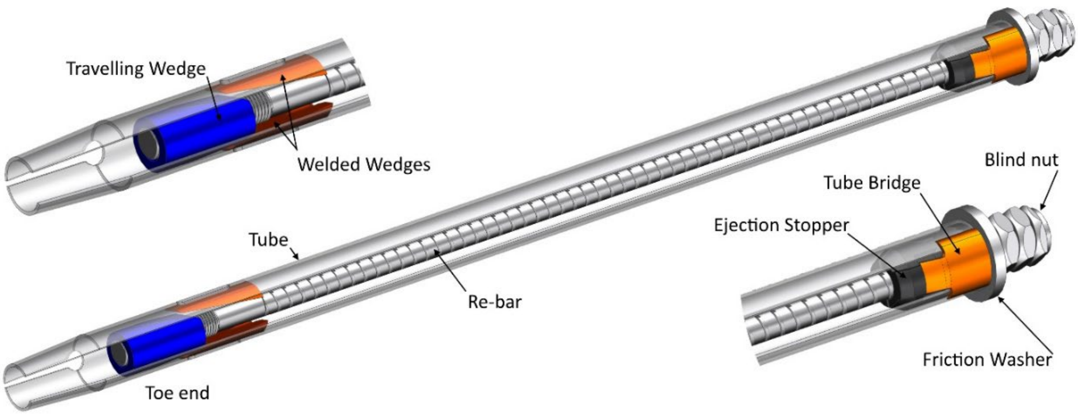


**Figure 2 Anatomy of the MDX bolt (Darlington et al. 2024)**

To further improve measurement reliability, the bolt identification component (bolt ID) has been redesigned as a stiffer, screw-on unit with an integrated O-ring enhancing environmental sealing and protection of the measurement surface without altering the bolt structure or installation process. The new bolt identification is shown in Figure 3. Importantly, this redesign does not alter the bolt cost or the standard MD/MDX installation process, preserving full compatibility with existing equipment and practices.


(a) (b)

**Figure 3 Improved bolt identification. (a) MD; (b) MDX**

## 2.2 Ultrasonic pulse echo technique to measure bolt length

The ultrasonic pulse-echo method is an NDT technique in which a short, high-frequency stress wave is introduced into the bolt from the exposed head and its reflections from internal interfaces are recorded by the same transducer. As a longitudinal or shear pulse travels along the rebar, it is partially reflected at boundaries where acoustic impedance changes, such as the toe wedge, producing a characteristic waveform from which TOF can be determined with high precision. Because the wave travels at a known material velocity, the distance to each reflective interface can be calculated, enabling direct measurement of bolt length.

The pulse echo method is widely used across civil, mechanical, aerospace, and structural engineering as a standard approach for verifying bolt length, bolt load and bolt pretension, owing to its high precision, real-time capability and strong penetration in steel materials. Applications in mining date back to the early work of Tadolini (1990). More broadly, ultrasonic preload and axial stress measurements have been applied for decades in sectors such as bridge anchor rods, turbine fasteners, aircraft assemblies and high-strength structural connections, becoming a recognised method for monitoring axial stress and tightening force variation in bolts during service. ASTM E1685 (2020) provides the formalised test practice governing pulse echo ultrasonic techniques for bolt tension measurement in industrial applications and forms the basis of many commercial bolt gauge instruments and field deployable systems.

The pulse echo ultrasonic method is founded on a simple physical principle: the length of a bolt can be determined from the travel time of an elastic wave produced by a piezoelectric transducer (Figure 4). If an ultrasonic pulse travels through a bolt at wave velocity $v$ and returns after a measured time-of-flight $t$, then the bolt length $L$ is:

$$L = \frac{vt}{2} \quad (1)$$

The factor of ½ accounts for the round-trip travel of the pulse from the bolt head to the reflective interface and back.

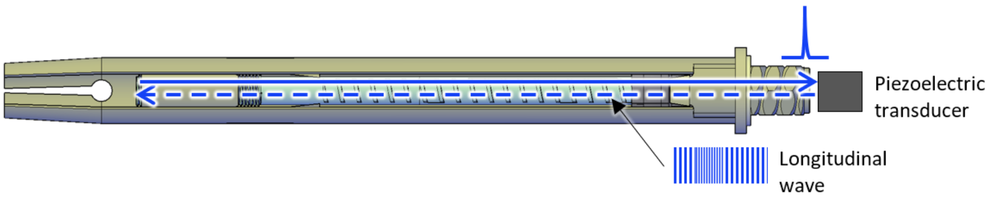


**Figure 4 Representation of the pulse echo technique for length measurement on the MDX bolt**

By comparing successive TOF measurements, changes in bolt length, and therefore bolt elongation, can be determined with high precision.

When a bolt is loaded in tension, 2 physical changes influence the ultrasonic time-of-flight. First, the bar physically elongates, increasing the propagation path. Second, the ultrasonic velocity decreases slightly due to elastic strain, an acoustoelastic effect arising from stress-dependent changes in the material's elastic moduli. Calibration is therefore required to confirm the quantitative relationship between the ultrasonic-measured elongation and the actual physical deformation.

Temperature also affects TOF and must be accounted for in accurate elongation measurements. Temperature influences ultrasonic signals through two mechanisms: thermal expansion, increasing bolt length (small effect, order of $10^{-5}$/°C) and temperature-dependent changes in elastic modulus and density, which reduce ultrasonic velocity (larger effect, order of $10^{-4}$/°C) (Pan et al. 2020). Accordingly, appropriate temperature compensation is required to ensure reliable interpretation of TOF changes in terms of bolt elongation.

# 3 Laboratory testing

The technology was validated and proven through an extensive laboratory testing program. For clarity, this paper presents results from 2 test series that are representative of the broader dataset. Test series 1 focused on validating the ultrasonic elongation measurements under controlled loading applied to the bar component only, while test series 2 involved testing fully assembled bolts, including installation and push loading.

## 3.1 Test series 1: validation test on MD and MDX rebars

Test series 1 involved 6 samples: 2 MDX rebars of 2.3 m length, 2 MDX rebars of 2.9 m length, and 2 MD rebars of 2.3 m length. Each rebar was mounted in a purpose-built configuration on a test frame, where two rigid L-brackets were fixed to the structure and the rebar was passed through the bracket holes. One end of the rebar was restrained, while the opposite end was loaded in tension using a hydraulic cylinder reacting against the bracket assembly (as illustrated in Figure 5).

The instrumentation layout is shown in Figure 5. Elongation was measured using both the ultrasonic probe, via the pulse-echo method, and conventional instrumentation for comparison. In the following sections, these measurements are referred to as ‘ultrasonic elongation’ and ‘mechanical elongation’. A linear variable differential transformers (LVDT_1) was installed at the bolt head to record axial movement relative to the test bench, while a second LVDT_2 monitored the movement of the right-hand bracket. Applied load was recorded through a pressure transducer connected to the hydraulic system.

For ultrasonic measurements, the transducer was magnetically coupled to the end of the rebar to ensure stable and repeatable signal transmission throughout testing.

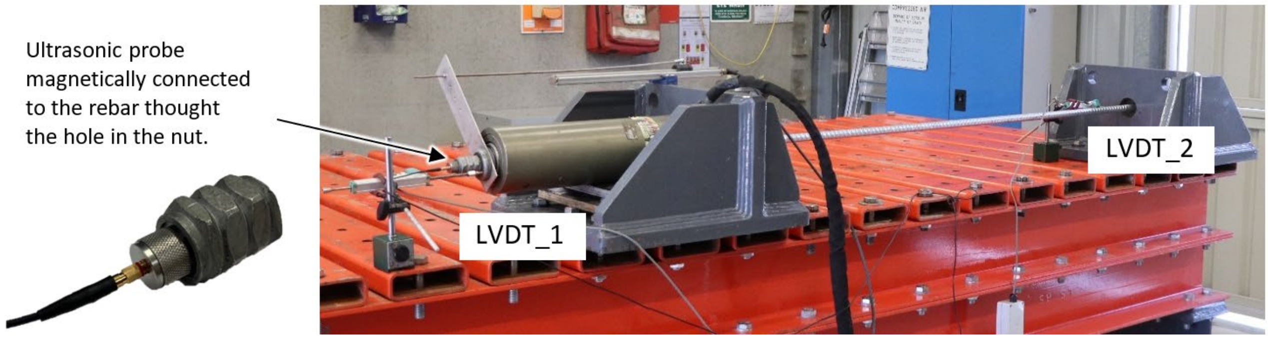


**Figure 5 Overview of the validation testing**

Loading was applied at defined increments to allow manual acquisition of ultrasonic measurements at each step. For safety reasons, tests were terminated once the rebar reached approximately 150 mm of total deformation.

The comparison between the measured ultrasonic elongation and the measured mechanical elongation is presented in Figure 6. For clarity, both elongation measurements are plotted as a function of the measured load, and the difference between the two measurements is shown on the secondary axis.

The validation results demonstrate an excellent agreement between the ultrasonic elongation measurements and the mechanical elongation measured by the LVDTs. Across the full loading range, the 2 curves (red and black curves in Figure 6) follow nearly identical trends, with only minor deviations typically within a few millimetres.

This level of consistency confirms that the pulse-echo ultrasonic method is capable of accurately capturing the true axial deformation of the rebar under tensile loading. The small differences observed, shown by the grey lines in Figure 6, remain well within acceptable engineering tolerances and do not increase systematically with load, indicating stable ultrasonic performance throughout the test. Overall, the results show that ultrasonic elongation measurements reliably replicate mechanical measurements, validating the method for subsequent bolt-level testing.

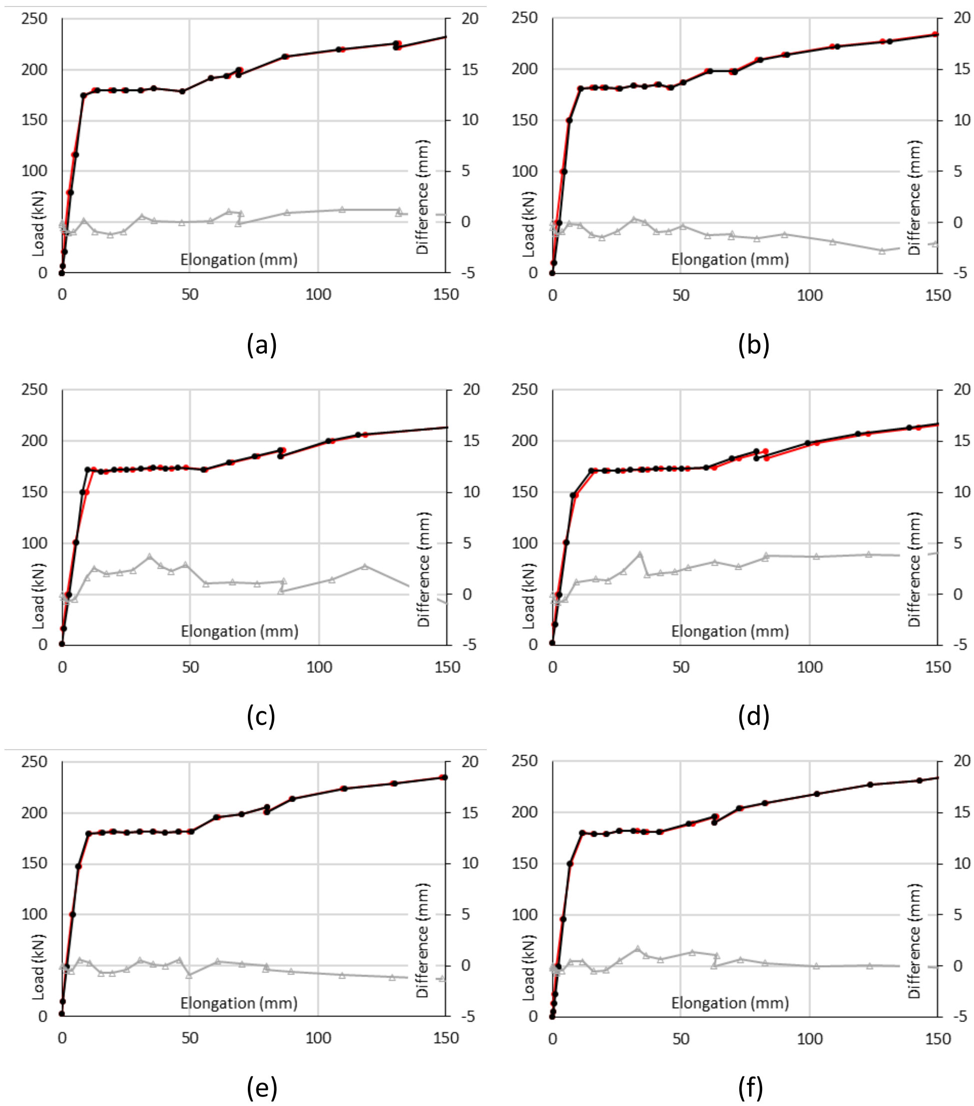


**Figure 6 Validation test results. Red line = rebar elongation measured with ultrasonic technique ‘ultrasonic elongation’; Black line = rebar elongation measured with conventional instrumentation ‘mechanical elongation’; Grey line = difference between the 2 measurements. (a) MDX_2.3 m rebar_ Sample 1; (b) MDX_2.3 m rebar_ Sample 2; (c) MDX_2.9 m rebar_ Sample 1; (d) MDX_2.9 m rebar_ Sample 2; (e) MD_2.3 m rebar_ Sample 1; (f) MD_2.3 m rebar_ Sample 12**

## 3.2 Test series 2: bolt installation and loading test

The second test series was conducted using Sandvik's bolt installation test stand (BIT), originally developed by Darlington et al. (2024) for controlled installation trials, but adapted for this program to enable both installation and post-installation push testing. For these tests, the central concrete block of the BIT was removed and replaced with a steel spacer to accommodate four hydraulic cylinders used for axial loading.

In the first phase, the BIT was configured as shown in Figure 7, with 2 pre-cast and drilled concrete blocks secured to the self-resisting frame. The MDX bolts were installed through these 2 blocks using the BIT's integrated rock drill, feed, and rotation system, replicating the standard underground installation sequence. The bolt was driven into the concrete blocks using the installation driver, with the feed advancing as the rockdrill impact function engaged. Once the bolt reached full insertion, both the hammering and feed advance were stopped, and left-hand rotation was applied to tension the bolt until the target torque of 400 Nm was achieved.

**Figure 7 Sandvik's bolt installation test stand fitted with push test arrangement**

With the bolt fully installed, the rig was re-configured for push testing. Four hydraulic cylinders were installed within the designated spacer and connected to a battery-driven pump through a 4-in-1 manifold, ensuring that hydraulic force was evenly distributed among all cylinders. Prior to loading, the bolts securing the moving block to the frame were loosened so that the block could translate freely during the test. During push testing, extension of the cylinders increased the separation between the 2 concrete blocks, effectively pushing the assembly apart as shown in Figure 8. This imposes axial displacement onto the installed bolt, thereby simulating ground-induced deformation while maintaining realistic confinement and boundary conditions provided by the two remaining concrete blocks.

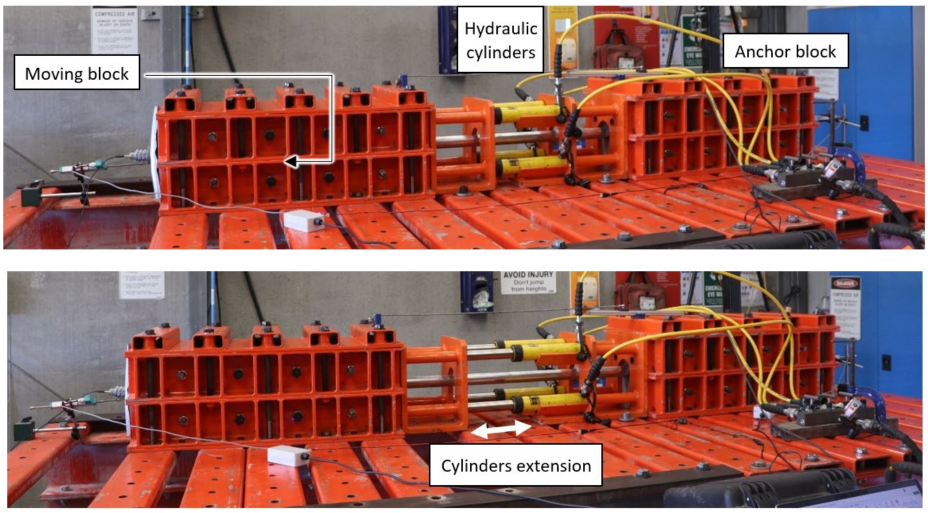


**Figure 8 Hydraulic cylinders during the block separation**

Both ultrasonic elongation and mechanical elongation were recorded and compared. Ultrasonic elongation was measured using the same probe used in the validation tests, magnetically coupled to the end of the MDX rebar. The ultrasonic measurement was zeroed at the beginning of loading to offset the small elongation component associated with bolt torquing (circa 1–2 mm). Mechanical elongation was derived from 2 LVDTs, as shown in Figure 9. One was positioned against the steel washer at the bolt head end to capture axial movement of the rebar, and a second was positioned at the toe to record displacement of the wedge assembly as it expanded under load. The mechanical elongation was calculated as the difference between these 2 measurements. Applied load throughout the test sequence was monitored using a pressure transducer connected to the hydraulic system. Loading was applied incrementally to allow ultrasonic measurements at each step. The tests were concluded once the hydraulic cylinders reached their full stroke capacity. A total of 3 bolts were installed and tested, with results presented in Figure 10.


**Figure 9 Bolt installation test setup for bolt push testing**

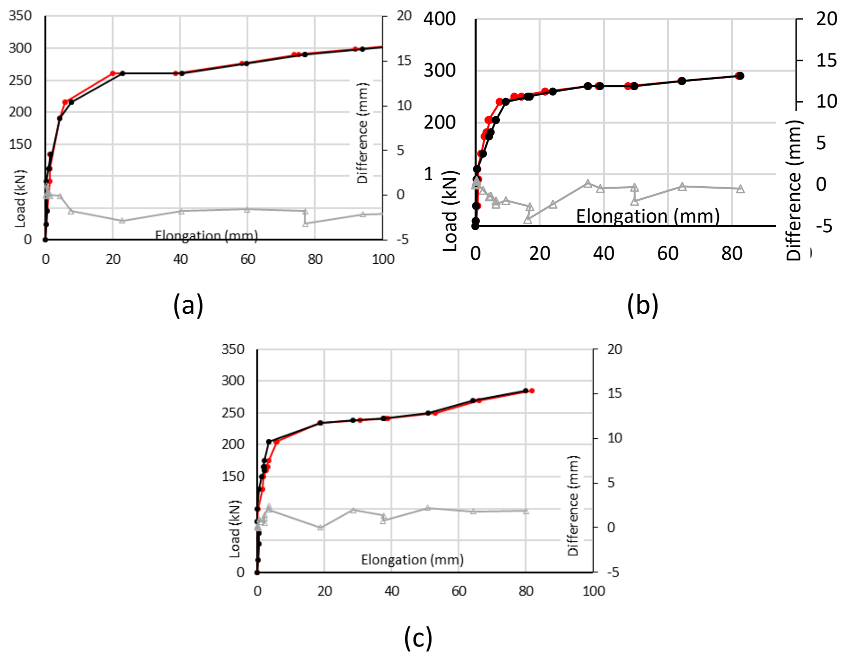


**Figure 10 Push test results. Red line = rebar elongation measured with ultrasonic technique ‘ultrasonic elongation’; Black line = rebar elongation measured with conventional instrumentation ‘mechanical elongation’; Grey line = difference between the two measurements. (a) MDX_2.4 m bolt_ Sample 1; (b) MDX_2.4 m bolt_ Sample 2; (c) MDX_2.4 m bolt_ Sample 3**

The ultrasonic measurement system performed very well throughout the push testing, consistently producing strong signals and stable readings.

The results show that the ultrasonic method closely matches the mechanical measurements, successfully reproducing true bolt elongation with an accuracy of approximately ±3 mm during loading.

Overall, the results confirm that the ultrasonic technique provides a reliable and accurate measure of bolt elongation under installation and load representative conditions.

# 4 Underground deployment model and customer value

To turn the ultrasonic measurement methodology into an operational tool for ground support management, Sandvik has developed a complete deployment and service model tailored for routine use on MD and MDX bolts, all of which are now supplied in an ultrasonic-ready configuration. At the time of the first ultrasonic measurement, the bolt is fitted with a xCell Banshee cap (Figure 11) which shields the bolt head from dust, water, and mechanical damage while ensuring that each bolt can be uniquely identified in the digital system and linked to its measurement history within the xCell Banshee platform.

Measurements are performed manually underground by Sandvik technical service representatives (TSR) using a portable ultrasonic instrument and the dedicated application. The operator collects time-of-flight readings at scheduled intervals, and the data is automatically uploaded to the cloud. This service-based model removes the need for mines to purchase specialised instrumentation or train personnel in ultrasonic acquisition, enabling consistent, high-quality readings while allowing geotechnical engineers to focus on interpretation rather than data collection.

Once uploaded, the measurements appear in the xCell Banshee application, available both as a web interface and an iOS app. The system presents a dashboard designed for geotechnical workflows, with a home overview showing the status of all monitored bolts, location-grouped pie charts summarising the proportion of bolts in elastic, plastic or failed states, trend plots of elongation versus time for individual bolts, event logs capturing significant changes in bolt condition, and a scheduler that recommends which bolts should be measured next. For each bolt, the system provides a dedicated page combining measurements, status classification, comments from TSR operators, configuration data (bolt type, serial number, installation details), and a gallery of collected photos. Automated emails summarise each service visit, highlighting bolts with triggered alarms or overdue measurements, ensuring traceability and auditability for ground support QA/QC.

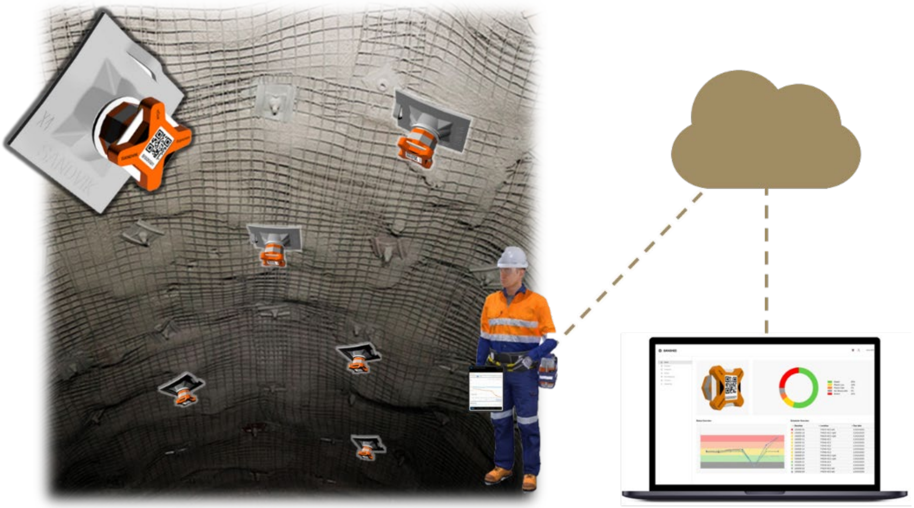

**Figure 11 Overview of the deployment underground**

The resulting system provides a low cost, scalable monitoring solution that can be deployed across large bolt populations without altering bolt design, installation practice, or ground support workflows. Because all

Sandvik MD and MDX bolts are supplied ultrasonic-ready, routine manual pulse echo measurements can be taken on a selected proportion of installed bolts, enabling continuous visibility of reinforcement performance at a fraction of the cost of traditional instrumented bolts. This scalability is central to the value proposition: widespread deployment allows mines to shift from isolated point measurements to a statistically meaningful understanding of reinforcement behaviour across entire levels, stopes, and infrastructure areas.

By providing accurate visibility of consumed bolt capacity, the system supports a range of operational improvements. Real-time insight into bolt elongation and yielding enables geotechnical engineers to refine ground support design based on measured deformation rather than purely empirical assumptions. This leads to optimised bolt patterns, with additional reinforcement installed only where required, and avoidance of unnecessary bolting in areas exhibiting low deformation demand.

Enhanced visibility of reinforcement performance also enables optimised rehabilitation practices. Instead of relying on visual inspections or calendar-based schedules, rehabilitation can be triggered by measured capacity consumption. This allows work to be prioritised in areas showing accelerated deformation, leading to timely interventions, fewer unplanned re-entries, and a reduction in rockfall related downtime. Mines benefit from lower overall rehabilitation expenditure due to better targeting, fewer over-supported areas, and early identification of emerging hazards.

The ability to detect early yielding or overloading of reinforcement provides an additional layer of geotechnical risk management. Early trigger alerts enable prompt action, such as barricading, secondary support, or temporary access control, before conditions deteriorate. This improves safety outcomes and reduces the likelihood of fall of ground events.

Furthermore, the method supports installation quality control by allowing checks on bolt tensioning shortly after installation, providing rapid feedback on operator practice, equipment performance, and compliance with installation procedures.

Ultrasonic measurements can also inform the interpretation of ground failure mechanisms. By monitoring changes in bolt length over time, engineers can better understand the depth and location of failure surfaces, confirm whether deformation is occurring above or below anchorage points, and determine whether additional reinforcement (e.g. cable bolts) is required. This information also improves confidence in design assumptions, such as the rock mass volume used to calculate dynamic demand or seismic support capacity.

At the infrastructure scale, routine measurements create a valuable asset integrity monitoring tool for shafts, ore passes, haulage drives, crusher chambers and other critical excavations. Bolt capacity consumption can be tracked in areas with long service lives, allowing operators to plan maintenance proactively and extend infrastructure longevity.

When paired with continuous monitoring solutions such as the xCell Cyclops system, the ultrasonic bolt capacity measurements provide even greater operational value, enabling mines to combine real-time convergence data with direct reinforcement capacity assessments for a more complete understanding of ground behaviour and support performance.

The xCell Banshee fills this longstanding industry gap and delivers a practical, scalable pathway for mines aiming to adopt data-driven ground support management across their operations.

# 5 Conclusion

This study demonstrates that ultrasonic pulse echo technology can be directly integrated into Sandvik MD and MDX bolts through the xCell Banshee concept. It provides a reliable, accurate, and fully scalable method for quantifying bolt elongation and consumed reinforcement capacity. Laboratory testing confirmed excellent agreement between ultrasonically derived elongation and conventional mechanical measurement. These results validate the robustness of the pulse echo method under realistic loading, installation, and boundary conditions.

By enabling non-destructive, repeatable, in situ measurement of bolt deformation without modifying bolt installation practices or increasing hardware cost, the xCell Banshee system addresses a longstanding industry gap identified in recent ground support research. The deployment model, combining ultrasonic-ready bolts, underground measurement by trained service personnel, and an integrated digital platform, provides a practical pathway for routine monitoring across large bolt populations.

As a result, mines can transition from a reactive, inspection-based ground support management to a data-driven approach that offers meaningful insight into reinforcement performance, emerging hazards, and long-term ground behaviour. The ability to track consumed capacity at scale supports improved design optimisation, targeted rehabilitation, enhanced safety, and more efficient allocation of ground support resources. Overall, xCell Banshee represents a significant advancement in ground support instrumentation, offering a highly deployable solution with substantial operational and geotechnical value for caving environments.

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