



# INSPECTING THE FOUNDATIONS

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Non-Destructive Testing

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Revolutionizing Rebar  
Inspection with AI



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# Looking NDT 2026

A new year always brings a moment to pause.

Before projects pick up pace and calendars fill up, it's a time to reflect — on what has stood the test of time, what is aging quietly, and what now deserves closer attention. For those working in inspection and evaluation, this feeling is all too familiar.

Across the world, infrastructure and civil structures are being asked to do more than ever. Bridges, dams, & concrete assets built decades ago continue to support modern demands, often under conditions they were never originally designed for. What's visible on the surface rarely tells the full story — and that's where non-destructive testing plays a critical role.

As we step into 2026, NDT is no longer just about identifying defects. It's about understanding structures more deeply, reducing uncertainty, and enabling smarter decisions around safety, maintenance, and long-term performance. The focus is shifting from inspection as a requirement to inspection as insight.

This January edition of NDT Trends reflects that shift. It explores how experience, emerging technologies, and data-driven approaches are shaping the way infrastructure and civil assets are inspected and managed today.

As always, our goal is not to provide final answers, but to spark conversations — the kind that continue on sites, in offices, and among professionals who carry the responsibility of keeping critical structures safe.

As we begin the new year, thank you for being part of the NDT Trends community.

Santosh Gavankar  
Editor-in-chief



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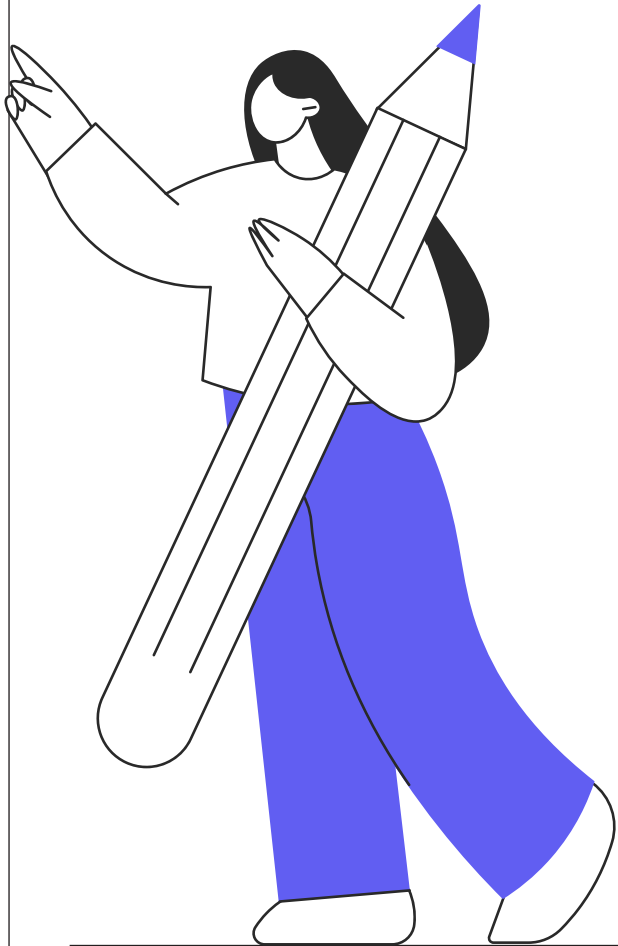
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# SOME THINGS IN NDT CAN'T BE ~~Googled.~~

That's why we created **NDT Talks** — a monthly panel where real experts share insights you won't find online.





*Top Stories*



# *Insights in Focus*

*Top Stories Shaping  
the NDT Industry*





# Bechtel Awards NDT Contract to MISTRAS for Louisiana LNG



Image Source - @Offshore\_Energy

**M**ISTRAS Group, Inc. has been selected by Bechtel to deliver non-destructive testing (NDT) services for the Woodside Louisiana LNG terminal, a multibillion-dollar liquefied natural gas production and export facility currently under construction in Sulphur, Louisiana.

The Woodside Louisiana LNG project, permitted for up to 27.6 million tonnes per annum of LNG production, stands among the most significant energy infrastructure developments globally and represents a major expansion of U.S. Gulf Coast LNG capacity. The facility is expected to play a critical role in meeting long-term global energy demand while reinforcing the United States' position as a leading LNG exporter.

Under the scope of work, MISTRAS will provide a comprehensive suite of NDT services essential to ensuring construction quality, safety, and regulatory compliance. These services include Radiographic Testing (RT), Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), Positive

Material Identification (PMI), Ultrasonic Thickness Testing (UT), and Leak Testing. Collectively, these methods will support the integrity verification of welds, materials, and critical components across the LNG terminal.

All inspection activities will be executed by certified MISTRAS technicians in accordance with applicable industry codes, standards, and regulatory requirements. The deployment of advanced NDT techniques is expected to support Bechtel's construction execution by enabling early detection of defects, reducing rework, and maintaining high standards of asset integrity throughout the project lifecycle.

The selection of MISTRAS underscores the growing reliance on specialised non-destructive testing expertise in large-scale LNG developments, where quality assurance and structural reliability are paramount.

# Voliro Reshapes Leadership with Timo Müller as New CEO & Florian Gutzwiller Transitions to Board of Directors



**V**oliro AG, a global leader in advanced aerial robotics for industrial non-destructive testing (NDT) and inspection, has appointed Timo Müller as Chief Executive Officer with immediate effect. Florian Gutzwiller, who has served as CEO, will transition to a strategic role as a member of the Board of Directors, remaining actively involved in shaping the company's long-term vision and growth.

The leadership transition marks a strategic inflection point for Voliro as it advances from commercial deployment toward the next generation of autonomous, physically intelligent aerial robots designed for contact-based industrial inspection at height. The shift underscores the company's ambition to expand the role of aerial robotics beyond visual surveys into high-value, data-rich NDT applications across critical infrastructure.

Timo Müller brings deep product leadership and hands-on field experience to the CEO role. As a key architect of the

Voliro T platform, he has worked closely with customers since the company's founding, gaining first-hand insight into the operational realities and constraints of industrial inspections. This end-to-end understanding of aerial robotics, inspection physics, and real-world NDT requirements positions him to lead Voliro through its next phase of growth.

"Voliro's future depends on leaders who understand not only how to build advanced robots, but how those robots must physically interact with the world," said Florian Gutzwiller. "Timo has that understanding at every level. I am proud to see him take on the role of CEO, and I have full confidence in his ability to lead Voliro into its next phase. Transitioning to the Board allows me to focus on long-term strategy while continuing to support the team and the vision we have built together, as Voliro moves beyond 'fly and see' toward autonomous, contact-based industrial work at height."

Under Müller's leadership, Voliro will focus on advancing its aerial NDT platforms, strengthening partnerships with



asset owners and inspection service providers, and scaling global operations. The company’s technology enables stable, contact-based inspection using interchangeable payloads, supporting ultrasonic testing and other sensor-driven NDT techniques in environments that are traditionally difficult, costly, or hazardous to access.

“Becoming CEO is first and foremost a commitment to the team and customers who have shaped Voliro since 2019,” said Timo Müller. “I am excited to take on the leadership of this next era. Together with an exceptional team at Voliro, we have set the benchmark in aerial robotics for contact-based inspections at height. Now we are building on that foundation to deliver the next generation of autonomous aerial manipulation capabilities, addressing the built world’s inspection, repair, and maintenance challenges.”

As part of the transition, Florian Gutzwiller will continue to support Voliro as a Board member, alongside a leadership

team with deep expertise in robotics and industrial systems. The Board is chaired by Prof. Dr. Roland Siegwart, Professor for Autonomous Systems and Director of Wyss Zurich at ETH Zurich, a globally recognised authority in autonomous robotics. Board member Dr. Matthias Bichsel contributes decades of executive experience in global energy and industrial operations, providing strategic guidance as Voliro scales its NDT technology across real-world industrial environments.

With this leadership structure, Voliro reinforces its commitment to technological excellence, customer-driven innovation, and long-term value creation in the industrial inspection and non-destructive testing market, as autonomous aerial robotics play an increasingly critical role in maintaining the world’s built infrastructure.



# FARO and Creaform Combine to Restructure Into Two New Units



Image Source - @FARO

**F**ARO Technologies and Creaform, both businesses of AMETEK, Inc., have announced a major organisational realignment that reshapes their approach to metrology, non-destructive testing (NDT), and reality capture. Effective immediately, FARO’s 3D Measurement business segment has been combined with Creaform to form FARO CREAFORM, while FARO’s reality capture business segment has been reconstituted as FARO INSIGHT.

The reorganisation marks a strategic milestone aimed at delivering greater customer value, accelerating innovation, and strengthening long-term growth across industrial measurement, inspection, and digital-twin workflows. By aligning complementary capabilities under two focused business units, the companies seek to simplify engagement, enhance solution coherence, and address increasingly complex inspection and measurement challenges across

manufacturing, maintenance, and infrastructure sectors.

FARO CREAFORM brings together two established leaders in portable and handheld metrology to deliver rigorous dimensional measurement solutions designed to provide practical certainty in critical decision-making. The business unit will focus on enabling manufacturers and maintenance teams to act decisively through highly accurate, mobile, and user-centric NDT and metrology solutions. The unified structure also offers customers a single point of contact across a comprehensive portfolio spanning hardware, software, and services.

Under the leadership of Fanny Truchon, FARO CREAFORM is positioned to advance the role of portable metrology in quality control, inspection, and lifecycle management. “FARO CREAFORM is more than a consolidation. By combining the strength of two leaders, we’re opening possibilities that will



empower industries to move from hindsight to foresight. FARO CREAFORM aims to become the undisputed leader in portable metrology”, explained Fanny Truchon, Business Unit Manager of FARO CREAFORM.

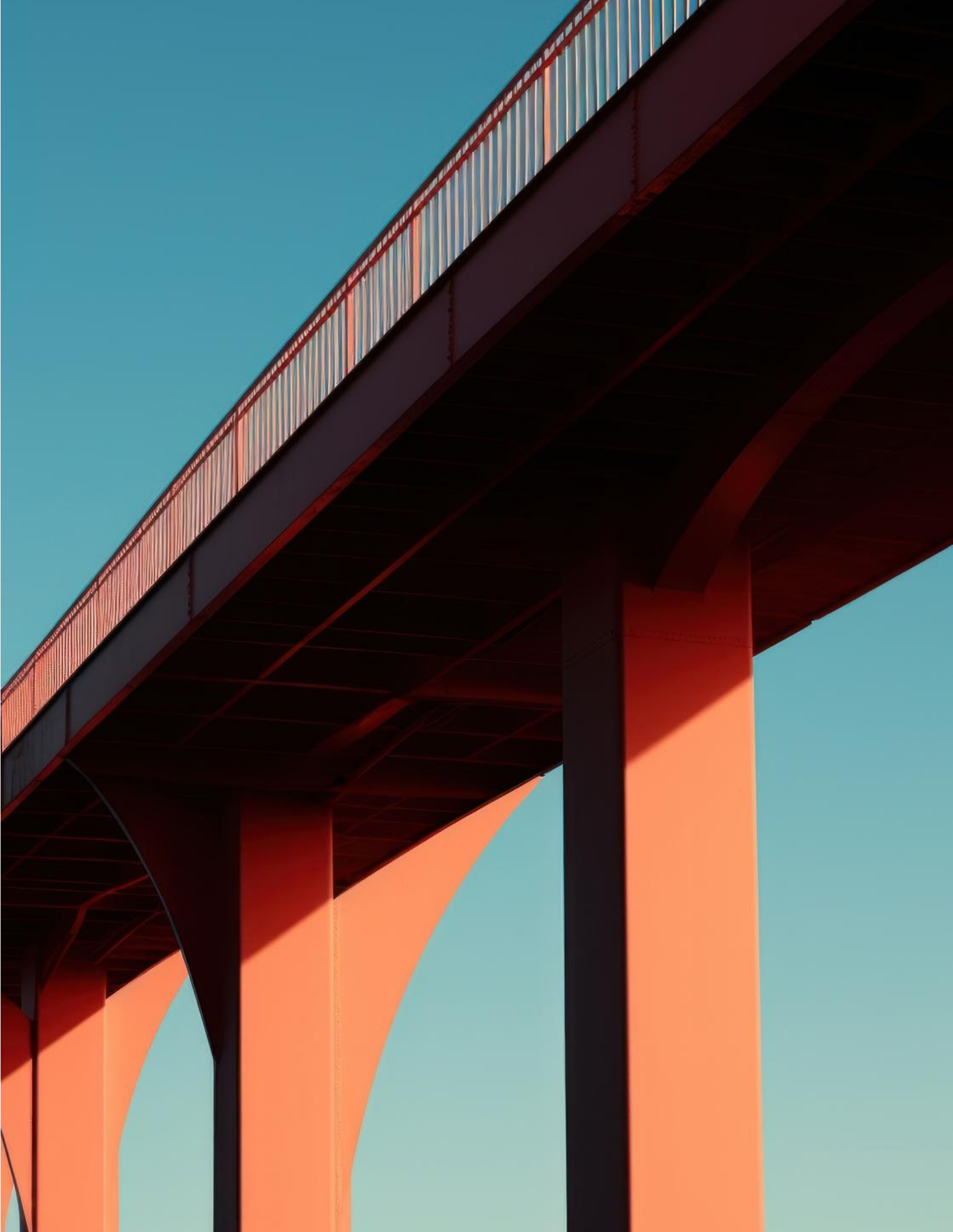
In parallel, FARO INSIGHT has been established to focus exclusively on reality capture technologies that convert physical environments into trusted digital data. Led by Dietmar Wennemer alongside Virtek Vision, the business unit will deliver an integrated reality capture ecosystem enabling seamless data acquisition, point-cloud processing, and information sharing across digital-twin workflows. These capabilities support inspection, documentation, and analysis across AEC&O, public safety, and geospatial applications, where accurate, non-contact measurement and traceable data are critical.

“FARO INSIGHT’s approach is simple: we want to digitize the world. Our hardware and software solutions reduce ambiguity to help track building progress, document changes, digitize crime scenes, structures, mines, forests,

and landscapes to provide insights customers can build on”, added Dietmar Wennemer, Business Unit Manager at FARO INSIGHT and Virtek Vision.

The new structure builds on FARO’s more than four decades of leadership in 3D measurement and reality capture, alongside Creaform’s long-standing innovation in handheld metrology since 2002. Together, these foundations support a unified operating model designed to ensure continuity for customers and partners while delivering clearer communication, faster innovation cycles, and enhanced solution integration.

With FARO CREAFORM strengthening dimensional metrology and NDT capabilities, and FARO INSIGHT advancing large-scale reality capture and digital representation of physical assets, the reorganisation underscores AMETEK’s strategic commitment to precision measurement, inspection confidence, and data-driven industrial decision-making across global markets.







*Insights*

# How Cosmic Muons and AI are Redefining Deep Non-Destructive Testing

A new wave of deep inspection technology is helping engineers better understand risk, plan smarter repairs, and safely extend the life of aging infrastructure.

**GSCAN**



The world's most critical infrastructure is currently entering a new era of infrastructure management. Asset owners and engineers face the immense challenge of managing assets that are approaching or exceeding their original design lifespan.

In Europe and the US, 4 million bridges are now over 50 years old. In the UK alone, over 3,500 bridges have surpassed their anticipated service life, creating an escalating need for highly reliable inspection data to guide maintenance and capital expenditure.

The core obstacle has long been the inability to obtain clear measurements of a structure's deep internal condition. While established NDT methods are indispensable for routine inspection, they often share a practical limitation: they cannot effectively penetrate and deeply image the core of massive structures, particularly those reinforced with layers of steel, leaving integrity assessments reliant on extrapolated surface data.

The current situation often leads to a 4x investment overspend, 2x deficient maintenance, and 5x excessive CO2 emissions due to suboptimal planning and reactive repairs. This leaves owners facing tough choices: either accept unknown risk, commit to possible costly over-remediation based on limited information, or embrace advanced technologies to pinpoint exactly where repairs are needed.

GScan is directly addressing this challenge by developing and deploying muon tomography (MT). This non-invasive technology harnesses natural cosmic muons and advanced Artificial Intelligence (AI) to provide high-resolution 3D imaging and accurate condition data on hidden critical elements buried deep within our infrastructure. This approach is not a replacement for traditional NDT methods; it is a vital, necessary extension, offering the

missing volumetric data required for informed, predictive life-cycle management. With muon tomography, it's possible to start putting more trust into the data of existing structures. Volumetric inspection enables:

- Spatially known locations
- More accurate deterioration models
- Reduced safety risks

Cosmic insights for aging infrastructure management While muon tomography is not a new technology, with its first ever application taking place in 1955 by Eric George, it has only been in the past decade where it has been applied to structures, and the results have been transformational for the industry. Key recent milestones for the technology include the successful deployment in a trial to detect wire breaks in suspension bridge cables, the first deployment of MT on an operational post tension bridge in the UK, and the first half joint inspected with MT, all taking place in 2025.

Muons are subatomic particles that are born when cosmic rays hit the Earth's atmosphere. They move at nearly the speed of light, penetrate everything and are completely harmless to humans (and animals). Unlike artificially generated X-rays or gamma rays, muons possess the energy and mass required to traverse great depths.



### How it works

Gscan's system involves the deployment of specialized Muon Flux scanners placed at strategic points on the structure. The scanners precisely measure the incoming and outgoing paths (trajectories) of millions of muons over time. By mathematically reconstructing the scattering patterns, the system generates a high-resolution imaging of the structure's internal components. The technology is able to:

- » Penetrate deep into reinforced structures, providing detailed 3D images of hidden elements.
- » Detect structural issues such as voids, section loss and breaks in the tendons
- » Establish reinforcement and post-tension details when original records have been lost - a frequent and critical problem with aging assets.

## Actionable Intelligence for Critical Infrastructure Management

An important question for asset owners is, "What's hidden inside our structures?" Critical defects can progress largely undetected, while a structure that appears deteriorated on the outside can sometimes be in pristine condition inside.

Muon Flux Technology directly answers this important question with its unique ability to resolve structural issues previously deemed un-inspectable, effectively making the invisible visible. The technology's utility extends beyond reinforced concrete assessment; it is also a powerful tool for evaluating the technical condition and internal geometry of steel structures.

## Detecting Tendon Breaks and Section Loss

Corrosion remains the primary concern for reinforced concrete. Crucially, conventional methods often fail to accurately assess the extent of corrosion-induced steel loss deep within the cross-section.

MFT can detect damage to internal structures and changes in chemical composition induced by carbonation, chloride ingress, and corrosion. The system provides an empirical measure of the remaining steel cross-sectional area with 3mm accuracy.

## Assuring Grout and Void Integrity in Vulnerable Areas

Integrity assessment of post-tensioning ducts, anchors, and deep foundations is paramount. Voids within grouted tendons can compromise load transfer and invite accelerated corrosion. With millions of bridges now over 50 years old, areas like half joints present a significant risk. These vulnerable components have historically been challenging to inspect.

As the only technology that is capable of "seeing" inside complex areas like half joints, MFT is proving to be a crucial step forward. The system accurately locates and quantifies the precise coordinates and volume of voids or poor consolidation. This delivers the accurate measurement-based information on the condition of the half joint re-entrant corner, reinforcement, and anchor points necessary to:

- » Avoid unnecessary demolition
- » Safely reduce repair budgets
- » Preserve vital infrastructure

This enables surgical repair strategies: identifying the exact location and geometry of the void allows maintenance teams to perform precise, targeted repairs, drastically reducing the cost and



invasiveness associated with exploratory drilling or mass repairs.

## Monitoring Long-Term Material Changes

For long-life, sustainable assets, the ability to track structural health over time is essential. By establishing a diagnostic baseline, repeated muon scans allow engineers to track the progression of density variations over time. This provides quantitative data necessary for forward-looking asset management, allowing assets to be managed based on their actual rate of deterioration rather than generic service life estimates.

## AI-Powered Analysis and 3D Reconstruction of Data

The sheer volume of data generated by millions of muons necessitates advanced computational processing. This is where the integration of Artificial Intelligence (AI) and Machine Learning (ML) help to bring a new level of analysis.

MFT, which was developed in 2018 with the dedication of the GScan founders and development team in Estonia, combines state-of-the-art scanners with AI-enabled software.

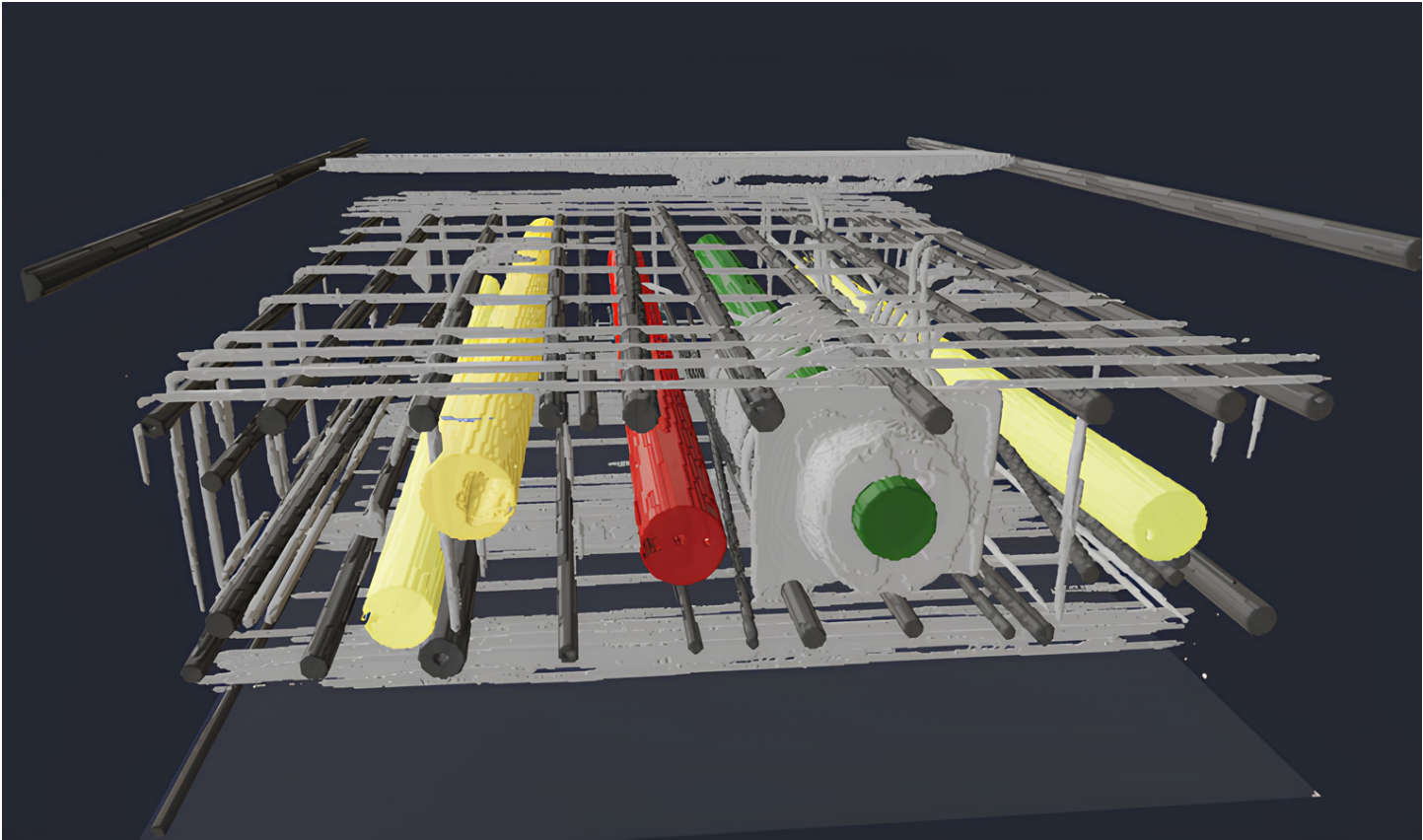
- The AI/ML components perform several critical functions:
- » AI enables the capability to analyse and classify many different materials with machine learning-based 3D modelling tools for advanced reconstruction.
  - » For analysis of object detection results, GScan developed ML algorithms that detect different materials based on the scattering histogram pattern and this layer is mainly used to point out the desired elements and their location.
  - » To detect anomalies inside the duct, the system uses scattering-based algorithms that clearly reveal the location of missing grouting.

The unified reconstruction and AI-assisted classification deliver faster turnaround from acquisition to interpretable 3D outputs and actionable decision-making.

Together with the explicitly planned multi-view tomography, the technology provides true volumetric (3D) models tied to site coordinates, with deliverables formatted for CAD/BIM/GIS integration.

## Operational Benefits and Future Applications

For asset managers, MFT offers distinct operational advantages:



- » Safety profile: By utilising natural cosmic rays, the system eliminates the need for exclusion zones, specialised radiation permits, or safety officers required for artificial radiation sources, enhancing site safety and streamlining deployment.
- » Environmental Impact: Having focused on the scalability, reliability and a small carbon footprint throughout the development, GScan's MFT systems are energy-efficient and produce no hazardous waste throughout their lifespan, nor after it - ensuring steps towards a cleaner, safer and more sustainable future.
- » Deployment: GScan's MFT System is built for smooth fieldwork. Measurements are immune to external factors like moisture, material thickness, or inspector skill. It also requires minimal operational training.

Gscan's technology has been strategically deployed in several ground-breaking projects, including the National Highways Structures Moonshot programme, which helped to develop the technology.

MFT was specified by Gwynedd Consultancy (YGC) on an in-service Post Tensioned Bridge on the Welsh Trunk Road Network. Significant NDT and intrusive work had already been carried out on the bridge, but this had not been able to find deeply buried tendons. GPR techniques had been unsuccessful, as the shallow steel reinforcement in the deck soffit masked the location of the deeply placed PT ducts and a foil backed waterproofing layer on the top of the bridge deck was impenetrable to GPR.

Principal Engineer for YGC, Bob Humphreys, said "We are very pleased with the results GScan have provided; the MFT successfully located all PT apparatus and steel reinforcement in the area scanned. We are now in a much better position to manage the structure."

The technology is rapidly gaining demand all over the globe with scheduled works in the UK, Japan, Germany, Netherlands, France, Switzerland and Estonia. By providing accurate, volumetric, and non-invasive data on the internal condition of massive structures, GScan is enabling a new standard of infrastructure management.

Organisations that embrace this data-driven asset management are achieving substantial reductions in maintenance costs while improving asset reliability. The technology is leading directly to reduced operational risk, optimised maintenance budgets, and the maximum safe extension of critical asset life.

Want to know more about Muon Flux Technology?

Learn More





# Non-invasive structural monitoring of the Chetwynd Bridge

Preserving a nationally significant heritage structure through collaborative, non-invasive monitoring



**C**hetwynd Bridge is a Grade II\* listed three-arch cast-iron bridge in Staffordshire, UK, and the largest surviving pre-1830 cast-iron arch bridge in England, (second largest in the world). Built in the early nineteenth century, it represents one of the most significant surviving examples of cast-iron arch bridge construction worldwide. Following a comprehensive programme of restoration to its ironwork and protective coating, [Staffordshire County Council](#), (SCC), with Amey acting as asset manager. [Amey](#) consulting undertook a comprehensive structural assessment of the bridge involving load testing and a vision-based sensing to monitor movement. Based on recorded results mirrored by finite element modelling Amey showed the cast iron arches were being loaded beyond available capacity which resulted in the bridge being restricted to 7.5 Tonnes.

## Case Study



Amey reached out to trusted specialist supply chain partner [Terra Measurement](#) on behalf of SCC. This led to a structural monitoring scheme being commissioned to better understand the bridge's behaviour under operational traffic loading while fully preserving the historic and architectural significance of the structure.

Terra Measurement, a UK-based geospatial surveying and consultancy practice specialising in monitoring and measurement of complex structures, was appointed to design and deliver the monitoring solution. A central requirement of the commission was that the system should be entirely non-invasive, reversible, and visually unobtrusive, providing reliable long-term data without introducing any permanent alteration or risk to the historic fabric.

To meet these requirements, Terra Measurement adopted a technology-led but consultant-defined approach, selecting wireless structural health monitoring equipment supplied by Move Solutions. Move Solutions develops wireless monitoring systems for civil infrastructure and built assets, with a focus on non-invasive installation, long-term autonomy, and cabling-free deployment, supported by remote data management through its MyMove

cloud-based platform. As part of the monitoring programme, [Move Solutions](#) carried out the modal frequency analysis based on vibration data acquired from the accelerometer network, while Terra Measurement reviewed and interpreted the results for the client.

This collaborative approach brought together Terra Measurement's responsibility for monitoring strategy, installation methodology, and client-facing interpretation with Move Solutions' sensor technology, data platform, and specialist analytical capability.

## Monitoring strategy and heritage constraints

Before defining the monitoring layout, Terra Measurement undertook a detailed engineering and site assessment to establish the most relevant structural parameters to observe and to identify the constraints imposed by the bridge's heritage designation, environment, and operational use. Particular attention was given to the dynamic response of the cast-iron arches under traffic loading, alongside environmental influences such as temperature variation and river-related flood risk.

Based on this assessment, Terra Measurement defined the monitoring objectives, sensor locations, acquisition strategy, and installation methodology in consultation with SCC and Amey. The monitoring strategy focused on capturing meaningful, high-quality structural behaviour data while fully complying with heritage and environmental constraints, including the prohibition of drilling, bonding, or permanent attachments, and the requirement that the bridge's visual appearance remain unchanged.





## Technology partnership and system configuration

The monitoring system was designed to observe the dynamic response of one arch of the bridge under operational traffic and environmental actions. The focus was on vibration, displacement, and tilt measurements, complemented by video monitoring to correlate structural response with vehicle passages.

The system comprises a network of fully wireless sensors, eliminating the need for cabling and minimising installation complexity.

**The deployed instrumentation includes:**

- 36 wireless triaxial accelerometers for vibration measurement and modal analysis
- 9 dynamic displacement sensors for real-time displacement monitoring

- 15 wireless tiltmeters for angular variation measurement
- 2 gateways for local data collection and cloud transmission
- 3 complementary video cameras for synchronised visual monitoring

Move Solutions supplied the monitoring instrumentation and MyMove platform, enabling continuous data acquisition, remote access, and long-term data storage. Modal frequency analysis was led by Move Solutions using vibration data collected from the accelerometer network and delivered through the MyMove platform, establishing a baseline dataset for future comparison, with Terra Measurement responsible for the technical review and client-facing interpretation.

## Installation methodology

Strict heritage constraints governed

the installation process. No drilling, bonding, or permanent attachment was permitted, and all equipment had to be fully reversible. In addition, the bridge spans a river subject to flooding, requiring all devices to be installed above historical flood levels.

Installation was carried out by Terra Measurement using non-invasive magnetic mounting for all sensors. Magnetic mounting provides stable mechanical coupling to the cast-iron elements while remaining fully reversible, ensuring reliable vibration transmission without introducing stiffness discontinuities or permanent damage. Each mounting arrangement was tested to confirm resistance to vibration, temperature variation, and weather exposure prior to final deployment.

Maintaining the bridge's visual integrity was critical. All sensors were painted to match the surrounding painted cast-iron surfaces, ensuring that they

remain unobtrusive to bridge users and fully compliant with heritage authority requirements. This allows the system to operate continuously without drawing attention.

The installation was completed without the need for traffic management, scaffolding, or structural modification. Magnetic mounting allowed rapid placement and immediate verification of signal quality, while remote wireless calibration further reduced on-site intervention.

## Power supply and data management

Powering monitoring systems on heritage structures presents particular challenges. Solar panels were not permitted for aesthetic reasons, and the installation of new power infrastructure was prohibited. To address this, the system was connected to an existing 24-volt street-lighting circuit, which charges a dedicated backup battery to ensure continuous operation during temporary power interruptions. This battery-powered, cabling-free setup minimizes physical impact and maintenance requirements while guaranteeing reliable, uninterrupted monitoring.

All monitoring data is transmitted wirelessly to the MyMove cloud platform via cellular gateways, providing real-time access to measurements, automated alerts when predefined thresholds are exceeded, and secure long-term storage for trend analysis.

Acceleration, displacement, and tilt data are synchronised with video recordings, allowing structural responses to be directly correlated with individual vehicle crossings. This integrated dataset enables objective, evidence-based engineering assessment without the need for frequent on-site inspections.

## Outcomes and engineering value

Since installation in September 2023, the monitoring system has continuously recorded the dynamic behaviour of one arch of the bridge. Key outcomes include the successful identification of every vehicle crossing, including overweight vehicles that pose particular risks to cast-iron structures. The modal frequency analysis outputs established baseline dynamic characteristics for the monitored arch, enabling future changes in behaviour to be detected and assessed objectively. Terra Measurement reviewed these outputs and, over time, identified subtle variations in structural response that would not be apparent through visual inspection alone.

These insights provide SCC and Amey with a robust evidence base to support asset management decisions, maintenance planning, and long-term preservation strategy. In particular, the monitoring data contributes to informed decision-making regarding future intervention, strengthening the technical justification for strategic options even where visible deterioration is limited.

## Engineering significance

The Chetwynd Bridge project demonstrates the practical value of continuous, non-invasive structural monitoring for sensitive heritage infrastructure. When combined with a carefully defined monitoring strategy and close collaboration between client, consultant, and technology provider, advanced monitoring technology can deliver high-quality engineering data without compromising historic fabric or appearance.

**The project highlights several transferable lessons:**

- Magnetic mounting is effective for reliable vibration measurement on metallic heritage structures
- Visual integration is essential in protected environments
- Leveraging existing power infrastructure enables autonomous operation
- Wireless networks reduce installation complexity and long-term maintenance requirements
- The digital platform trigger levels notified SCC and Amey of potential damage due to overloading events.
- Continuous monitoring provides insights unavailable through periodic inspection alone
- Historical digital data captured could potentially be used to model bridge deterioration.

These lessons provide a framework for similar applications on historic bridges and protected structures worldwide.

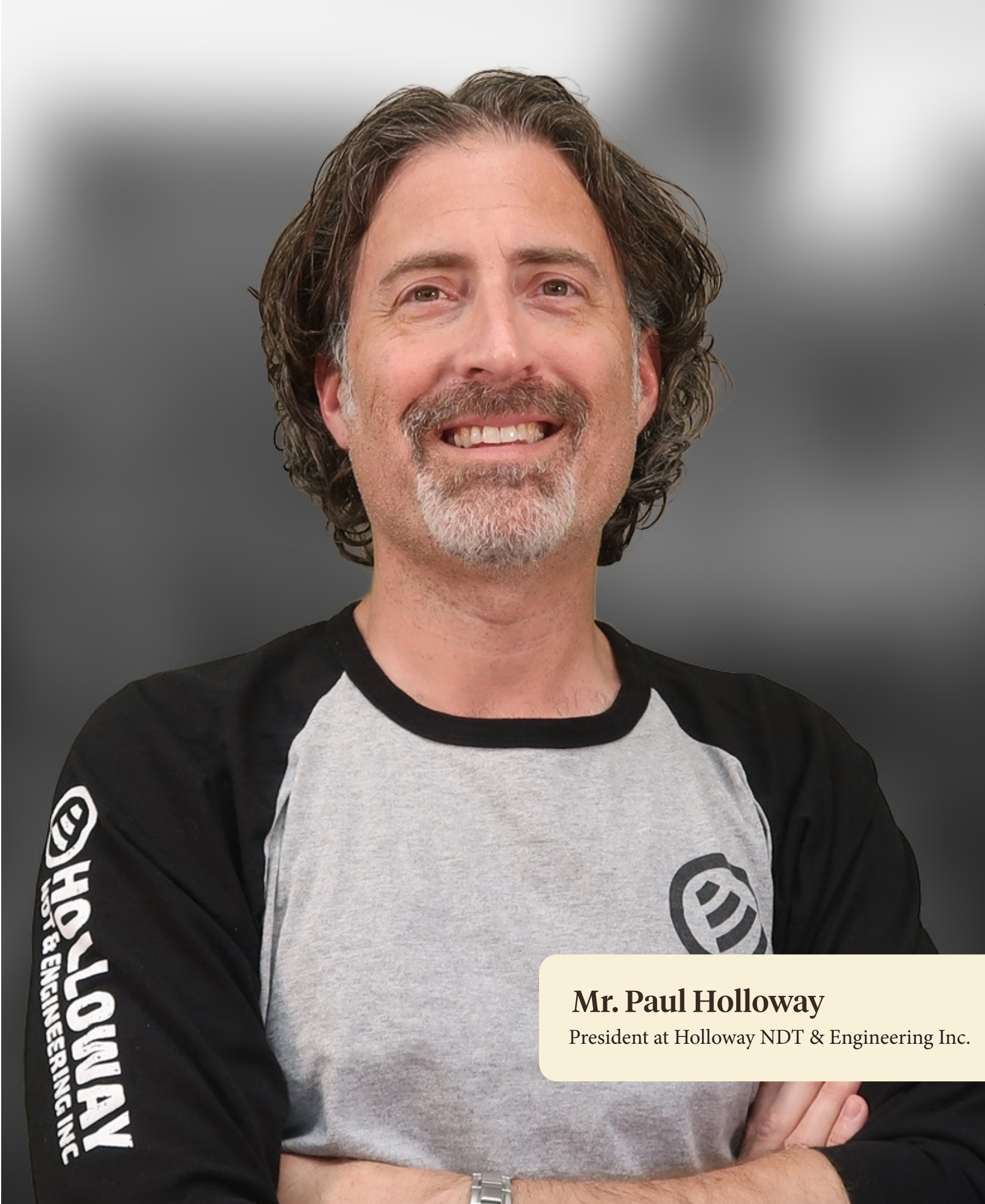
## Conclusion

The structural monitoring of Chetwynd Bridge illustrates how a consultant-led, technology-enabled approach can successfully safeguard a nationally significant historic structure. Terra Measurement's monitoring strategy and delivery, supported by Move Solutions' wireless instrumentation and collaborative support, MyMove platform, and modal analysis capability, has resulted in a robust, non-invasive monitoring system aligned with heritage, operational, and engineering requirements. The technical partnership and collaboration between the two teams has been as successful on many other infrastructure projects.

The project provides a reference model for the monitoring of historic bridges and protected structures worldwide, demonstrating that preservation objectives and high-quality structural monitoring can be achieved together.







**Mr. Paul Holloway**

President at Holloway NDT & Engineering Inc.



*Expert Talk*

# Crafting a Legacy in NDT

## A Practical Playbook for NDT Digital Transformation

*In the intricate world of NDT, where precision meets innovation, Mr. Paul Holloway stands as a seasoned veteran. With over two decades of experience, his journey from a Project Engineer to the helm of Holloway NDT & Engineering Inc. epitomizes resilience, adaptability, and an unyielding passion for excellence.*

*Originally from a small town in Western Canada, Mr. Holloway's foray into NDT was not a planned one; rather, it was a fortuitous detour that led him to discover a place where science intersects with practical application in profound ways.*

*In this exclusive interview with OnestopNDT, Mr. Holloway delves into the nuances of his professional odyssey, reflecting on both the triumphs and tribulations that have shaped his trajectory. From navigating challenging projects to advocating for greater awareness of NDT's potential, his insights illuminate not only the technical intricacies of the field but also its profound human dimension.*

*Beyond the daily confines of his corporate role, Mr. Holloway's multifaceted interests, from music composition to his foray into YouTube, underscore a holistic approach to life and learning. Let's get started with the engaging, insightful conversation underway without any further do.*



**Hello Mr. Paul, greetings of the day. Let's begin, shall we? Could you introduce yourself to our amazing audience?**

Sure, thank you for the opportunity to speak with you! I am a UT Level 3 and Professional Engineer located just outside Toronto Canada. I grew up in Western Canada, and have a Masters Degree in Applied Science (Mechanical Engineering) from the University of Waterloo.

**... let's briefly chat about your journey into the NDT world. You started as a Project Engineer and currently, you are the President of Holloway NDT & Engineering Inc. So how has the entire journey been for you?**

I think many people get into NDT completely by accident, and I am no exception. I was laid off from my job in hydraulics, which is how I went back

to school to pursue my Masters and ended up, somehow, in this crazy world of NDT. My current work is about 50% field and 50% office and looks nothing like what I envisioned for myself when I was 25. But I wouldn't have it any other way.

**... you might have had so many amazing experiences in your professional life. Could you share one positive and one negative experience with our audience?**

I've had many positives and negatives. Usually, the negatives are short-lived and come with a lesson that leads to more positive experiences. That being said, in a former position I once got an underwater robot stuck in a tank in the middle of winter. We deployed the robot to the interior of the shell through a hole in the roof. The water was slowly circulating (presumably to keep it from freezing), and was cloudy so we had very little visual from the camera, but the UT signal on the immersion probe was fantastic. Deploying the system took all morning so we decided to break for 30 minutes for lunch. While we were gone, the circulating water slowly pulled in some of the umbilical cable, which wrapped around some internal piping. Trying to drive the robot back out, with no visuals, eventually caused it to basically "tie knots" around everything.

After 3 weeks, the robot was recovered by a very expensive diving team, which

they accomplished in all of about 7 minutes. I learned that stretching capabilities and growing doesn't come without risks, and I should have anticipated more and planned better. We closed that job with my tail between my legs, but they did give us a pretty sweet DVD of the underwater rescue mission, so there's that.

As far as positive experiences, there are far more of those! It's always really satisfying to come into a situation as a tiebreaker, whether it's crack-sizing or simply rescanning a weld to see which of the previous three inspection companies found what they were supposed to. It really gives you an appreciation for doing things right. In these situations, the client is very concerned about inspection quality, so all eyes are on you! I enjoy supplementing results with imaging techniques like encoded scans and TFM to make it easy for any non-UT people reviewing the reports to appreciate the capabilities of the technology. The clients appreciate this, as it helps alleviate some of the mystery behind ultrasonic testing.

**... you have been active in the NDT industry for well over 20 years, what is one most challenging projects you worked on? And how did you navigate through the challenges in the project?**

One of the most challenging was a pipe inspection job that I was involved in a few years ago out in Western Canada. It involved new construction at

an old plant, and some of the pipe they used was thermo-mechanically controlled process, or TMCP, steel. This is a type of material which has improved properties but the way it's made results in a degree of anisotropy. The term anisotropic means "different depending on the direction", which can complicate things as far as the refracted angle is concerned. In regular shear waves, we enter one value for a velocity of around 3250 m/s at room temperature. And this value is supposed to be the same for all angles. But TMCP steels tend to exhibit increasing velocity as the refracted angle increases. This can result in major plotting errors when it comes to discriminating between geometric and flaw indications. I noticed the "melting S-scan" effect, as the upper angles seemed to plot far too deep in the material. I then attempted a basic pitch-catch with a 60-degree probe pair and noticed the surface distance spacing was far too great. We were gifted a section of pipe from the excellent welding crew, with which myself and Ed Ginzel wrote three papers about and published them on NDT.net. Anisotropic steels, and ultrasonic inspection thereof, were not new, but it was new to me. And I like to think the papers we publish will eventually help lead to improved inspection techniques.

**... well, Mr. Paul, what is that one thing that you think needs to be changed in the NDT industry?**

NDT is an industry in need of good people, and it also pays very well. But for many, it remains an unknown industry. You can probably go to any high school in Canada and talk about trades like carpentry, plumbing, or electrical that students will recognize, but very few know about NDT. We need to shine a light on the opportunities in the industry because it's a fascinating and valuable occupation that is very closely knit and can take you to very interesting places.



**“  
The best NDT technicians are always  
eager to learn... and that never ends.**”





**Let’s talk a bit about your organization. Can you briefly describe what your org does?**

Holloway NDT & Engineering Inc. is primarily a niche NDT service company focused on ultrasonic testing. We have Level 2 and Level 3 technicians and our goal is to provide expert services in advanced testing and consulting. On the engineering side, we have several R&D projects in development and completed related to ultrasonic testing. Some of the completed ones include the intermodal total focus method (TFMi) with Sonatest, & the Extended Range Variable Wall (ERVW) calibration blocks with PH Tool.

**... how does your organization measure success, and what metrics do you use to evaluate your performance?**

Reputation is our measure of success. We base this on our relationships with existing clients and our introductions to new clients. It’s important for us, with an engineering backbone, to be inventive and practical... balancing the inspiration that comes from creativity with tangible usefulness in the field.

**After working so many years in the industry, what keeps you motivated?**

The industry is incredibly rewarding because there is such a strong human connection. I give, and get a lot of thank-yous. These are the sorts of things that can really fill up your batteries and make you feel appreciated and encouraged to keep going.

**... you have been the President of Holloway NDT & Engineering Inc. for the past 10 years, do you have any mantras for people who are new to the management role?**

To be honest, I am not keen on building an empire. I enjoy the freedom being in a small company provides, and I am lucky I have very little technical managing to do. Being a manager means balancing a lot of details all at once, and I’m fortunate to have an excellent employee to hand some technical things to, and my wife who takes care of absolutely everything under 20kHz.

**Too many questions about work. Let’s take a break. So, how does life look for you outside of work, Mr. Paul?**

I have a wonderful family at home, good neighbours, and in my spare time (if I can find any), I write music with a friend in Brazil. We used to play in a band in Edmonton many years ago, and now we have a prog-adjacent project called Skeptosphere.

**... your YouTube channel is quite popular among the masses. What made you start with a YouTube channel? Also, any tips for any NDT aspirant who wants to begin with YouTube?**

I’m probably not the best to solicit advice about beginning on YouTube. There are plenty of 8-year-olds doing toy reviews that are much more popular than me! I wanted to start with YouTube because I thought there was a lack of explanation out there for technical things related to NDT. And with my short attention span (“squirrel!”), I gravitate towards shorter bits of information. Making a video 4-6 minutes long and being able to describe something in that time is good practice for me as a Level 3, and if I’m able to help someone else out along the way, even better.

**... got any advice for the newbies who are going to enter the NDT industry? Any specific skill that you think every NDT aspirant should possess before entering the industry?**

I mentioned that the industry needs people, but not just warm bodies. The best NDT technicians are always eager to learn... and that never ends. You can

be next to retirement and still have to change gears to get things right. As well, much of the time we work in teams. So being agreeable and approachable really helps.

**And finally, how do you plan to scale your org to newer heights?**

I don’t! Holloway NDT, is designed to

remain “lean and mean”. Growing in numbers means more management time for me and less time on tools. That doesn’t sound like fun. And life is supposed to be fun.







*Product Spotlight*

# Revolutionizing Rebar Inspection with AI

**In** the construction and infrastructure industries, ground penetrating radar (GPR) is a key tool for NDT and condition assessments. When inspecting concrete structures - from bridge decks and tunnels to slabs and walls - GPR provides essential insights into internal composition, helping to locate and map critical components like rebar, post-tension ducts and conduits.

Objects such as rebar appear as characteristic, arch-shaped signals called hyperbolas in the GPR scans. To find out important data such as the number of rebar in the scanned area, the spacing, depth and other information, you would need to go through the scan data and manually identify and tag each hyperbola. Imagine how much time that would take on massive datasets! It would be simply unrealistic.







- **Enhanced Accuracy and Objectivity:** The AI auto-tagging serves as a powerful assistant, performing the bulk of the identification work. This allows you to transition from time-consuming primary identification to an efficient review process - only needing to perform a quick review of the tags.
- **Deeper Data Analysis:** The AI recognizes most hyperbolas based on their shape. This objective tagging enables NDT professional to then apply their own expertise in pattern recognition and environmental context to definitively determine the reflecting object. This streamlined process makes it exceptionally easy to immediately visualize and share the reinforcement information for thorough structural analysis.
- **Faster Reporting and Export:** The solution dramatically cuts your overall reporting time. Data can be exported in a few clicks with several fast options including Excel, DocX, SEGY, HTML, and a shareable URL, among others. With the Excel export option, the system automatically separates the AI tags into individual cells, displaying the most useful information for each one, including distance, depth, spacing, and more.

The time for manual hyperbola tagging is over.

We introduce the industry's first AI-Powered In-Field Auto Tagging for all handheld Proceq GPRs, available with the release of version 6.0 of the GP app. This marks the beginning of the AI era for GPR technology, transforming how NDT professionals process and share concrete scan data.

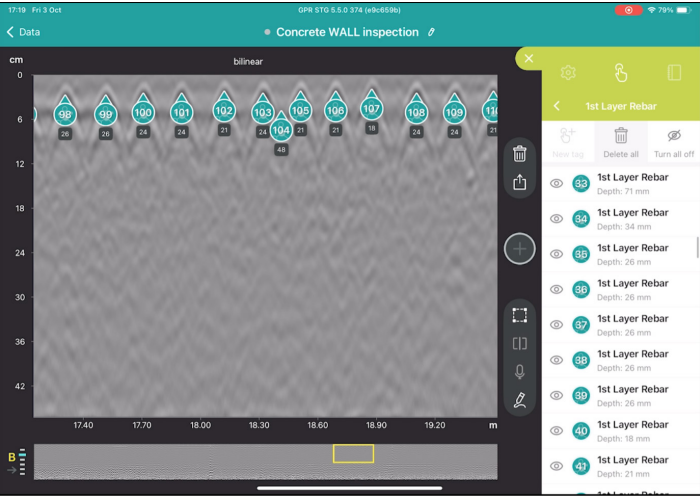
### The future of concrete scanning with in-field AI auto tagging

The advanced AI algorithms are now able to accurately detect and tag most of the hyperbolas from your GPR data in a matter of seconds. It works by automatically scanning through datasets, identifying hyperbola shapes, locating the corresponding peak in the A-scan, and marking with a numbered tag.

This is the exact procedure you would do yourself, except it can accurately identify and tag hundreds of hyperbolas in just a few seconds rather than hours.

### Unlocking deeper insights, faster

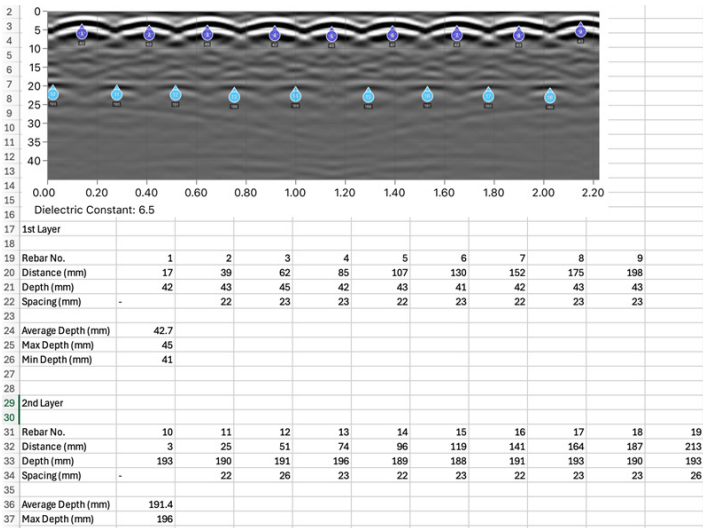
The rapid, precise identification, tagging and counting capability of the AI tool directly enables on-the-spot decisions to be made with confidence, dramatically reducing overall analysis and reporting time with:



By automating the most time-consuming part of in-field data analysis, concrete scanning professionals can now complete projects faster and gain even more actionable insights from their Proceq GPR scans.

A science professional at Element Construction Testing facility in Singapore served as a Beta tester for the new AI Auto Tagging feature, commenting:

“This tool help us to save a lot of time, reduce human error with precise AI analysis. I think it is quite beneficial in the future of the testing industry.”

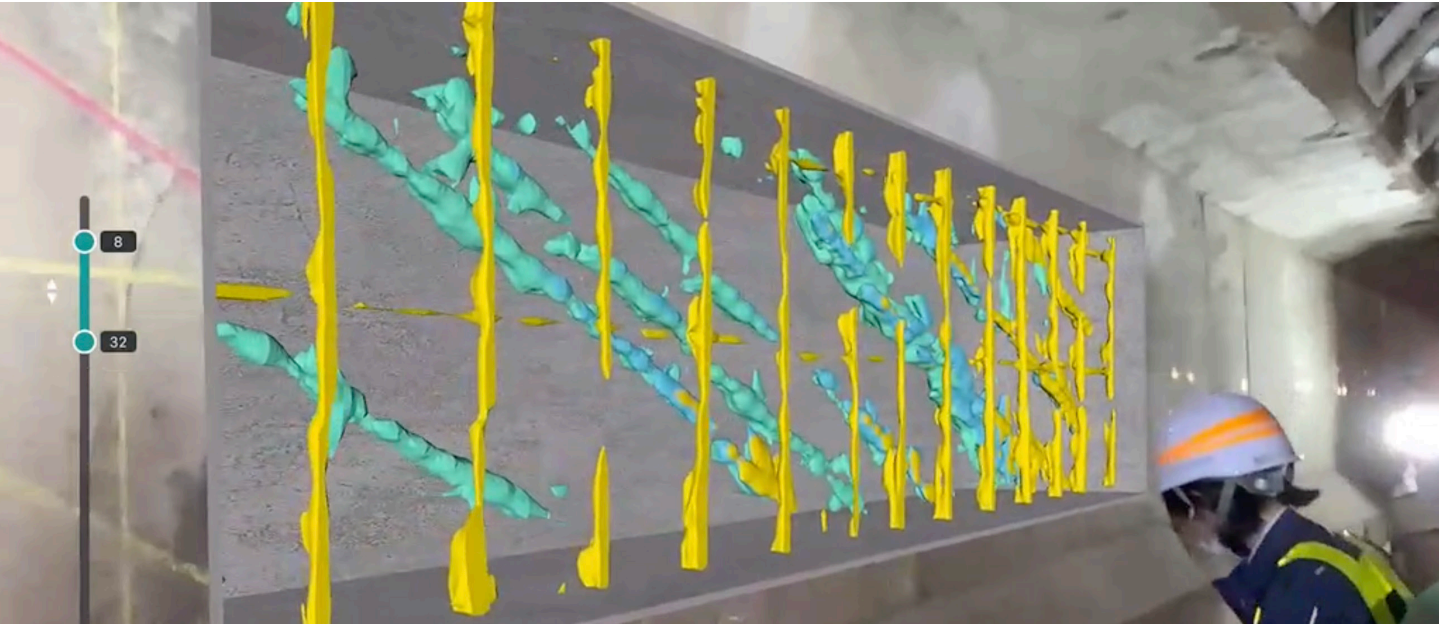


Example of AI-tagged data exported to Excel spreadsheet showing tagged rebar layer information.

### The AI journey has only just begun

This is truly just the beginning of AI integration. With a commitment to a constantly evolving software model, the release of AI Auto Tagging opens a new chapter of advanced analysis that Proceq looks forward to exploring and expanding upon with our users in the future.

- Proceq redefined the NDT industry by shifting the focus from complex, bulky “hardware” to “intelligent software.” They became the industry standard by pioneering three specific innovations:
- **SFCW Technology:** Stepped Frequency Continuous Wave (SFCW) technology to deliver high resolution imaging



- for both shallow and depths up to 150cm with only one antenna, replacing the need for multiple traditional antennas.
- **The iPad Ecosystem:** Replacing grainy screens with high-definition, touch-screen tablets, ever-evolving software delivering features like this AI Auto Tagging, and seamless cloud sharing.
  - **Augmented Reality (AR):** Overlaying 3D scan data onto the real-world project surfaces to help stakeholders see what's hidden.

AI is the natural evolution. While Proceq's AR and 3D views gave us the “eyes” to see through concrete, AI Auto Tagging now provides the “brain” to interpret and process the results faster.

The software has evolved from simply showing you where objects like rebar are, to automatically quantifying them. This closes the gap in the in-field workflow and opens up new possibilities for concrete scanning and reporting.

The AI Auto Tagging is available now with all handheld Proceq GPRs (GP8800, GP8000 & GP8100) and the GP app version 6.0 at no extra cost to both existing and new users.

Don't have a Proceq GPR yet? Contact us to discover how you can bring this industry-first, time-saving technology into your NDT workflow.

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## Research Paper

# Structural health assessment of existing dams based on NDT, physics-based models and machine learning tools

Gabriella Bolzon, Antonella Frigerio, Mohammad Hajar, Caterina Nogara, Emanuele Zappa

## Abstract

The safe operation of dams is ensured by monitoring systems that collect periodic information on environmental conditions (for example, temperature and water level) and on the structural response to external actions. In newly built or retrofitted facilities, large networks of sensors can take daily measurements that are automatically transferred to servers. In other cases, additional information can be acquired, occasionally or systematically, through emerging drone-based non-contact full-field techniques.

The measurements are processed by various analytical and machine learning tools trained on historical data sets, capable of highlighting any anomalous recordings. Monitoring data can also support the accurate calibration of a physics-based model of the structure, usually built in the finite element framework. The analyses carried out by the digital twin allow the experimental database to be expanded with the displacements evaluated in the event of extreme environmental conditions, damage or collapse mechanisms never occurred before.

This contribution illustrates an integrated approach to the safety assessment of existing dams that combines experimental, computational and data processing methodologies. Attention is particularly focused on model calibration procedures and on the uncertainties that influence the characteristics of the joints. The presented results of the validation studies performed by the Authors on benchmark and real-scale problems highlight the merits and limitations of alternative approaches to data exploitation and remote measurement.

## 1. Introduction

Dams constitute an important asset for many countries. Concrete dams located in the Alpine region, built until

the 1970s, provide clean energy and supply drinking and irrigation water. They also contribute to controlling floods that are expected to increase in frequency and intensity due to climate change. In addition, hydropower plants contribute to providing balancing services that stabilize the electricity grid, fostering the exploitation of non-programmable renewable energy sources (like solar and wind) to achieve the European decarbonization targets. Therefore, despite their aging, existing dams are becoming increasingly important as they comply with the energy and environmental policies implemented in recent years to address the present concern about climate change.

Dam monitoring systems obtain information on the environmental conditions (air and water temperatures, water level in the reservoir, precipitation) and the deformation of the dam as loads change [1–4]. The number and location of the measurements and the recording frequency vary depending on the facility. The collected data are transmitted, stored, and then processed by various analysis tools.

Traditionally, in this context, monitoring data are managed by the so-called statistical, or Hydrostatic Seasonal-Time (HST) model developed by EDF (Électricité De France) in the late 1950s and subsequently improved to reliably support structural health evaluations [5–10]. HST approach approximates the structural response by the combination of pre-defined functions that consider the effect of water level, temperature and aging separately. Parameter values are calibrated for each dam based on available measurements.

Monitoring data can be interpreted alternatively by Machine Learning (ML) approaches based on more flexible algorithms [11,12]. Neural Networks (NN) [13–16], Extreme Learning Machines (ELM) [17], Support Vector Machines [18–20], Gaussian Process Regression [21], hybrid Deep Learning models [22] and Boosted Regression Trees (BRT) [23–25] have proven to be effective prediction tools for dam monitoring when properly optimized and validated. Comparison studies have also demonstrated that no ML approach outperforms the others in all situations [26].

However, accurate predictions alone do not constitute a complete surveillance system. Establishing the limits within which measured observations are considered reliable is essential, allowing anomalous behavior to be detected. Currently, the definition of thresholds is mainly based on a multiplicative factor in combination with the standard deviation of the residuals of the predictions. In this context, Salazar et al.[27] propose updating the limits each year, introducing a weighted average of them. This analytical approach allows the identification of individual outliers

but neglects the multidimensional context. To overcome this limitation, Mata et al. [28] have recently introduced a methodology that complements the traditional approach through the consideration of moving averages and moving standard deviations of residuals. In addition, they proposed a second approach that operates in a multidimensional framework and employs a clustering technique to identify anomalies [29]. Alternatively, Chen et al. [30] formulate a multi-target forecasting method that exploits the internal relationships between target variables.

The source of any anomalous reading should also be identified. Outliers may be associated with minor events (for example, the malfunction or need for recalibration of some instruments) or load combinations that have never occurred before and, therefore, are not included in model training. Anomalies could otherwise indicate ongoing degradation processes [9,31–33]. ML tools alone cannot solve these problems, especially since measurements in damaged conditions are generally not available. Dam failures are rare, and information concerning any past event is difficult to transfer from one situation to another. Unlike other infrastructures [34,35], practically all dams represent single prototypes due to their peculiar geometry, geomorphological and ambient conditions.

This issue can be addressed by constructing prediction models of the structural response to simulate the most likely critical scenarios [36,37]. Finite Element (FE) approaches are mainly used for this purpose, due to their generality and flexibility [38–42]. Potentially, the models can also account for uncertainties, introducing probabilistic distribution of the material properties and environmental conditions. However, stochastic methodologies have been mainly applied to simplified models due to their high computational costs, only partly mitigated by the consideration of analytical surrogates trained on the results of a limited number of finite element simulations [37,43–45]. Reduced models are also used for sensitivity studies and parameter identification procedures [46–55].

The presence of artificial (construction and contraction) and natural (i.e., cracks) joints constitutes the main non-linearity and uncertainty source of operated dams [9,42,56–63]. Joints represent surfaces of potential displacement discontinuity, often introduced on purpose to limit the stresses produced by thermal action and other expansion mechanisms [31–33,42,57], and by the interaction with the foundation [62].

Calibrating the mechanical characteristics (friction, roughness, cohesion, fracture energy) of dam joints can be challenging. The most direct methodology is based on the consideration of



core samples extracted through the considered interfaces and subjected to large-scale tests under cycling loading. In fact, it is necessary to take into account both the characteristic dimension of the inherent heterogeneity of the dam concrete and contact surfaces, and their variability over time due to the external (ambient) action [61–65].

Non-destructive approaches have been proposed to detect cracks and determine interface parameters using the information collected on site during operation [66–70]. Generally, strain-gauges monitor joints opening and sliding, while other equipment (such as sonic and ultrasonic tomography and georadar) is used for surveys, mapping and control of the propagation of existing cracks. However, existing dams are not always equipped with sensors that provide detailed (in space and time) information about the relative displacements at joints. Data can be extracted from full-field measurements [71–78], e.g. performed by Digital Image Correlation (DIC), photogrammetry and Time-of-Flight (ToF) techniques capable of providing adequate precision. DIC application to an experiment similar to that described in Ref. [61] allowed for measuring crack opening displacements with 0.1 mm tolerance [79].

Digital images and photogrammetry data can be collected by mounting optical sensors on drones, or Unmanned Aerial Vehicles (UAVs), that approach the target locations from different directions [80–92]. Several studies have investigated the accuracy and limitations of these methodologies. Both laboratory and on site applications have been considered, estimating the motion of the UAV based on information from background stationary features [88,89]. The effect on image quality of ambient actions, such as wind and its fluctuations, has been analyzed in Ref. [90]. UAV photogrammetry, used to reconstruct the geometry of dams [84–87], showed that the accuracy of the measurements depends on the optimal distribution of Ground Control Points (GCPs). In Ref. [84], the vertical contraction joints could not be observed on the horizontal sections of the 3-Dimensional (3D) scene. However, they could be identified in the Red-Green-Blue (RGB) information scale of the point cloud, being darker than the surrounding region. Three-dimensional DIC was also applied to images acquired with two cameras mounted on a UAV, achieving an absolute error smaller than 0.34 mm [91]. In Ref. [92], it was shown that rapid changes in illumination brightness and shadow on the target area can produce blurry images. However, the quality of the acquired data can often be enhanced by correction algorithms, possibly based on ML tools implemented in parallel units to improve computing efficiency [93–97].

This contribution aims to provide an overview of the structural health assessment of dams, lighting the interplay

between different competences and methodologies involved in this complex topic. In particular, Section 2 focuses on the definition of suitable interpretation models and on the calibration of their main parameters based on historical data series, while Section 3 is devoted to the non-destructive characterization of dam properties by full-field measurements per formed on site. Finally, closing remarks are reported in Section 4.

## 2. Structural health monitoring of existing dams

Periodic inspections are standard practice in the monitoring of existing dams [98,99]. Piezometers, thermometers, plumb line trans ducers and optical coordinometers are the main instruments used to quantify external actions and structural response. Collected data are processed in almost real time to promptly identify any abnormal behavior. For this purpose, the measurements are compared with models, which can be statistical, deterministic, or hybrid. The use and merits of these alternatives are compared in this section through the analysis of the results of some relevant applications

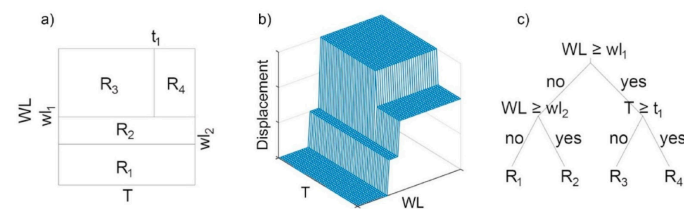


Fig. 1. (a) Partition of a two-dimensional space (T, WL) by recursive binary splitting; (b) perspective plot of the prediction surface; (c) partition tree.

### 2.1. Data-driven models

Traditionally, dam monitoring data are managed by the HST model. This approach approximates the structural response by the combination of pre-defined functions, with coefficients calibrated on the measurements. The contribution to the overall displacements generated by the water depth in the reservoir is usually defined by polynomials, while the effect of temperature and aging is accounted for by harmonic and log-arithmetic (or linear) functions, respectively [6–11].

Alternative ML approaches like NN and ELM [13–17] rely on more flexible functions, and weights determined from the available monitoring data. BRT do not consider any interpolation [23–27], but these models produce accurate predictions with good generalizations capabilities. This methodology was therefore adopted in the present

demonstrative study as a valid alternative to HST. BRT combine regression trees, which are part of the decision tree methods, with boosting, a technique that sequentially builds and merges a series of models. Modern decision trees are described in detail in Refs. [23,24]. They subdivide the observations into a certain number of regions according to the values of the input variables, assuming that the system response can be considered constant within each subdomain. For example, Fig. 1(a) visualizes one possible partition of the domain defined by the variables WL (water level) and T (temperature). Fig. 1(b) displays the piecewise constant approximation of a displacement component that represents the structural response. The partitions are defined during the training phase based on a heuristic greedy approach, i.e. the BRT algorithm selects the best option available at the moment to identify the splitting variable and the splitting point that define the regions. The difference between the actual output values and the mean values associated with each region defines an error-index, which is minimized to define the node of the regression tree shown in Fig. 1(c). The recursive binary partitioning process is repeatedly applied to each new region until some stopping criterion is satisfied.

Typical input and output data are for instance represented in Figs. 2 and 3. The measurements refer to the concrete arch dam recently proposed as benchmark problem by the International Committee on Large Dams (ICOLD) [100].

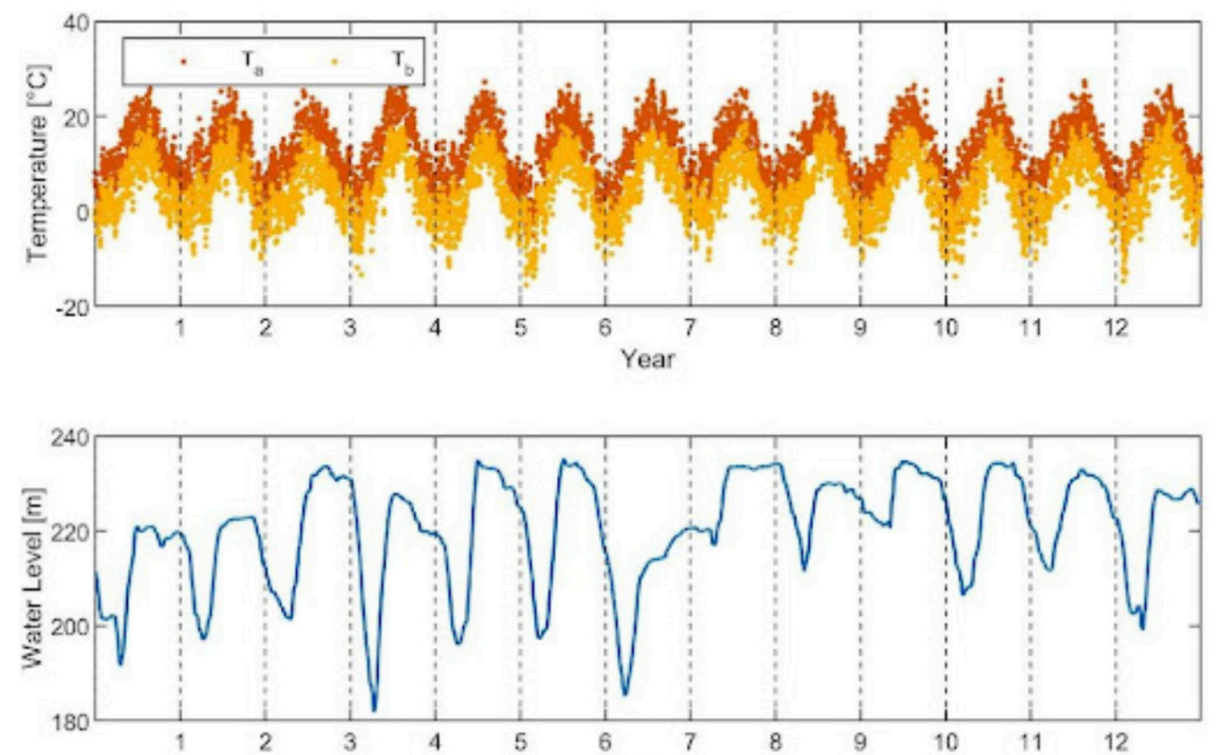


Fig. 2. Air temperatures (acquired by 2 sensors) and water level of the concrete arch dam proposed as ICOLD benchmark problem [100]: daily measurements.

The predictions shown in Fig. 3 are produced by BRT trained first on an initial monitoring period of 5 years [101]. The training is then extended from year to year as new data becomes available to obtain the next one-year predictions.

Fig. 4 visualizes the difference between measured and predicted values of the training and test sets. The latter starts from the sixth year. The red dashed lines indicate the warning thresholds. The limits are updated annually by assuming that the density function of the residuals of each year follows a normal distribution with mean value  $\mu$  and standard deviation  $sd$ . The interval  $\mu \pm 2.5sd$  is considered in this application. Monitoring readings that fall within the predefined range are classified as regular. Otherwise, they represent anomalies.

In particular, for each of the three years before the one for which the limits have to be defined, the mean  $\mu_i$  and standard deviation  $sd_i$  are computed on the residuals between the predictions calculated when the year is part of the test-set and the measurements. Finally, the estimated  $\mu$  and  $sd$  values are obtained as a weighted average of the three  $\mu_i$  and  $sd_i$ , to which weights are applied according to the reference year, equal to 1, 1/2 and 1/3 from the most to the least recent one respectively. This average is considered because the residuals of only one year could be biased if they correspond, for example, to extreme temperature conditions or water levels not previously considered in the training. Increasing



the amount of training data leads to progressively more accurate predictions. The reduction in residuals, in turn, leads to narrower alert levels.

The alert system is verified by introducing outliers into the data and checking whether the disturbances can be detected. In this application, 20 % of the displacements relevant to the last (13th) year were randomly selected. The data were modified to simulate outliers by randomly adding or subtracting 8 mm from the original measurements. All anomalies were correctly identified by the system. In fact, they correspond to the residuals beyond the limits visible in Fig. 4. Among the remaining normal data, just two false outliers were identified in the 10th year. Overall, the method proves to be effective in identifying the disturbances although the origin of the anomalies often remains unclear unless only

the recordings of a specific device are affected. This problem can be solved by supplementing data-driven investigations with physics-based interpretation models. Their definition and calibration based on monitoring data is introduced next.

## 2.2. Physics-based predictive models

Physics-based models of the structure are key tools to reliably interpret the measurements and identify the source of any anomalies. To be effective, the models must be accurately calibrated to reproduce the real system response. These predictive tools can then be used to simulate the most likely critical scenarios and produce synthetic pseudo-experimental data to improve the surveillance procedures. The FE approach is mainly used in the context of dam engineering. This methodology is also applied to the present case study, which refers to a real arch-gravity dam,

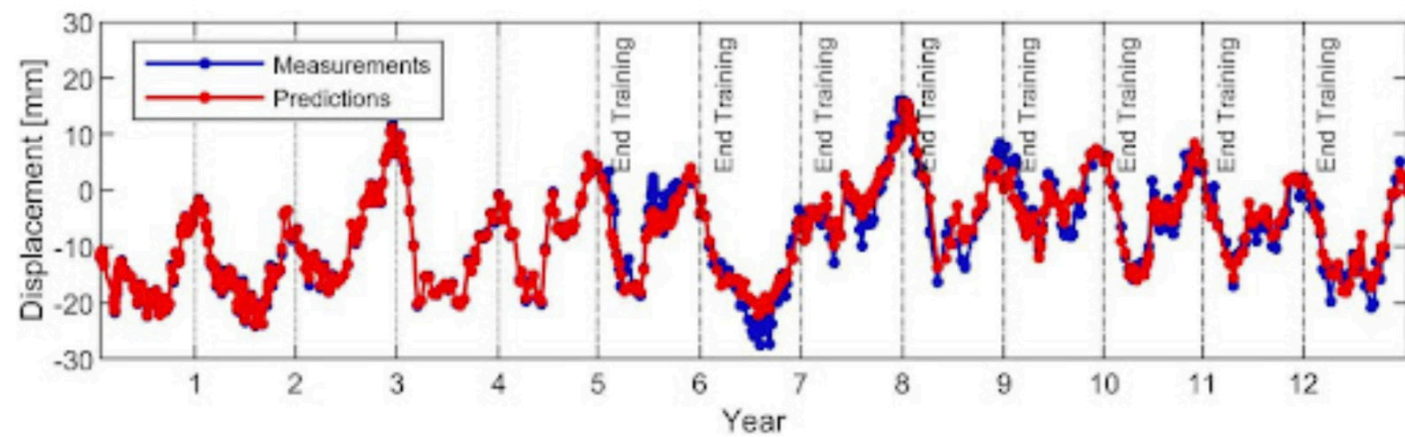


Fig. 3. Measured and predicted displacement near the crest of the concrete arch dam proposed as the ICOLD benchmark problem [100].

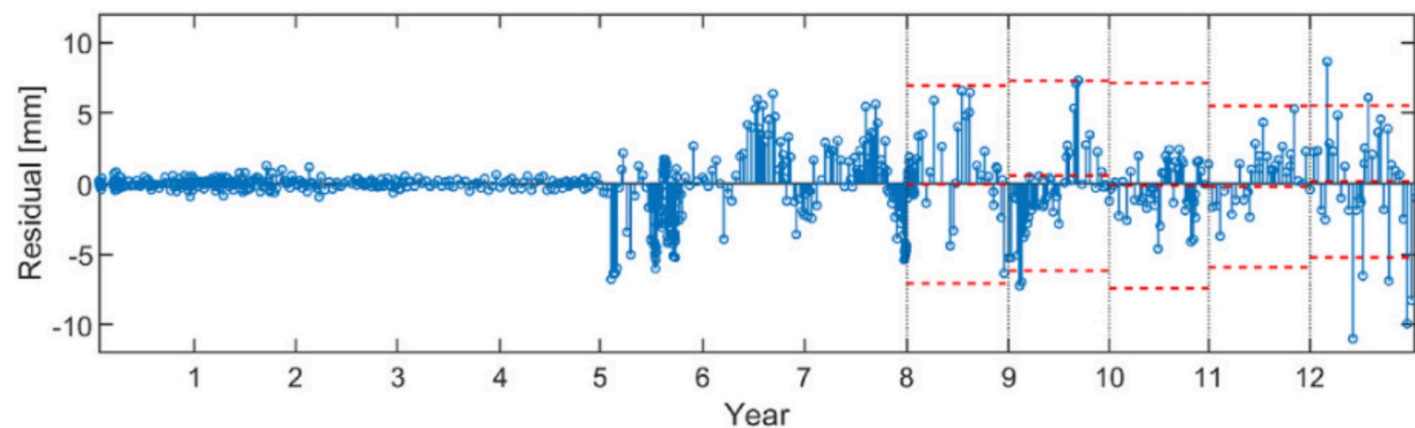


Fig. 4. Difference between measured and predicted values in Fig. 3, and the corresponding warning levels (red lines) updated year by year. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

schematized in Fig. 5. Notably, the 3D discretization includes a large portion of the foundation in order to correctly reproduce the system response to external actions. The geometry of the dam body is based on the original design drawings, while the rock portion is approximated starting from the available topographic data.

The mechanical and thermal properties of concrete and rock are initially defined on the basis of geomechanical investigations and laboratory tests carried out on specimens produced on the construction site.

However, a range of variation needs to be considered due to initial uncertainties and potential changes over time. Therefore, parameter values may be optimized considering the data recorded during the lifetime of the structure, derived from seasonal variations of the external actions.

Daily time series of the reservoir level and air and water temperatures are available. These data are used as input to the FE analyses. The thermal and mechanical problems defined on the discretized domain are then solved separately, following the operational procedures proposed in Ref. [41]. However, unlike the simplifying assumptions introduced therein, actual time series data were used in the present study rather than approximated functions.

The thermal problem is approached by a transient analysis carried out over the entire monitoring period, solving the discretized (in space and time) version of the heat diffusion equation:

$$k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho c \frac{\partial T}{\partial t} = 0 \quad (1)$$

In relation (1):  $T(x, y, z, t)$  represents the temperature field;  $t$  is time;  $x, y, z$  are the spatial coordinates;  $k$  (thermal conductivity),  $\rho$  (density) and  $c$  (specific heat) are material parameters, usually assumed constant. Temperature values are imposed on both dam faces, with different values for the wet and dry areas. If surface thermometers are installed, the recorded temperatures are interpolated linearly and assigned to the relevant mesh nodes. Otherwise, as in the present case, the average daily air temperature is imposed to the dry faces while a single value is assigned to the wetted boundary, equal to the water temperature recorded at a certain depth (e.g., 5 m). The temperature distribution inside the dam body at a given time is represented in Fig. 6. The computational results presented here are obtained by a widely used commercial code [102].

Transient results can be strongly influenced by the initial conditions. Therefore, a preliminary analysis is performed for an initial period of 5–6 years until a steady state is achieved. In this phase, the daily air and water temperatures correspond to the annual regression of the average temperature recorded on each day of the year, obtained from the entire historical series. The water level that defines the wetted surface (to which water temperatures are applied as boundary conditions) is also calculated from the annual regression of the data series at the basin level. Subsequently, the daily average of the measured air and water temperatures is assumed as input data. When possible, the temporal series are validated by the comparison with the temperature values recorded by thermometers placed on the structure.

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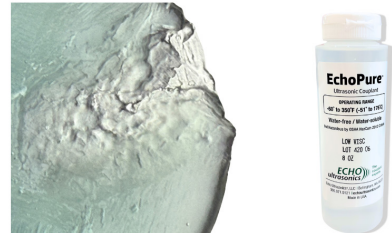
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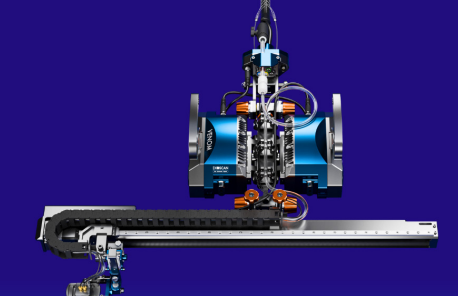


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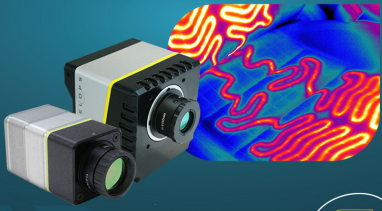
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The background of the entire page is a complex, layered illustration. It features a central figure of a person in profile, wearing a teal hard hat and a dark jacket, looking towards the right. The background is a collage of architectural and industrial elements, including scaffolding, structural beams, and large circular forms, all rendered in a palette of orange, teal, and white. The overall style is modern and technical.

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