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Surface settlement monitoring of the urban canyon - a case study from Brisbane metro

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ABSTRACT: The Adelaide Street tunnel, constructed as part of the Brisbane Metro project, delivered for Brisbane City Council and constructed by ACCIONA, involved shallow, large-diameter tunnelling beneath Adelaide Street, one of Brisbane's busiest corridors. The alignment passed through soft soils, dense underground services, heritage buildings, and mature trees, necessitating high-precision monitoring to mitigate construction risk. Automated Total Station (ATS) used to undertake both surface settlement and 3D structural monitoring. Custom installations were developed to address the challenges of the constrained urban environment, including limited sightlines, complex mounting conditions, and restricted stakeholder access.
The system successfully tracked ground and building movement, enabled early detection of trends, and informed construction decisions throughout excavation. Compared to manual methods, it delivered cost savings, enhanced safety, and more frequent data acquisition. The project highlights the value of tailored instrumentation strategies in complex city settings and provides lessons applicable to future underground infrastructure delivery.

1 INTRODUCTION

The Adelaide Street tunnel, constructed as part of the Brisbane Metro project, delivered for Brisbane City Council and constructed by ACCIONA, involved large-diameter tunnelling at shallow depth beneath Adelaide Street—one of Brisbane's most congested and infrastructure-rich corridors. The alignment passed beneath dense services, heritage buildings, and mature trees, presenting significant geotechnical and structural risks.

Land Surveys, was engaged to design and implement a high-resolution, real-time monitoring system to track both surface and 3D structural movement throughout the excavation. Automated Total Stations (ATS) were selected as the primary technology, providing the accuracy, frequency, and remote accessibility required to manage risk in this constrained city environment.

This paper outlines the design and deployment of the monitoring system, with emphasis on:

- The use of ATS to measure ground and structural movement during excavation;
- The challenges of implementing monitoring in a narrow, high-traffic CBD corridor;
- The role of remote planning tools and high-frequency data in maintaining system performance;
- Lessons learned related to sensor design, data filtering, stakeholder coordination, and system reliability.

These insights offer guidance for future tunnelling projects in similarly complex urban environments.

2 GEOTECHNICAL AND TUNNEL BACKGROUND

While a detailed discussion of the geotechnical conditions and tunnelling methodology is beyond the scope of this paper, a brief summary is essential, as these factors directly influenced the design and execution of the monitoring system.

The ground conditions beneath Adelaide Street are primarily composed of the Neranleigh-Fernvale Beds, overlain by variable layers of fill, alluvium, and residual soft soils. These alluvial deposits typically reached depths of up to 15 metres at the western end of the alignment, with thickness varying due to historical service installations and ground disturbance.

Groundwater levels were generally below the tunnel invert but rose locally—particularly near the sump—requiring active groundwater management during construction.

The tunnel was excavated using the New Austrian Tunnelling Method (NATM), with shallow cover in some locations less than 3.5 m. A split-face, four-stage excavation sequence was adopted: right and left oculars, followed by crown and bench. Temporary support was provided by canopy tubes and spile bars, with a reinforced shotcrete lining applied at 1-metre intervals to stabilise the advancing face.

3 MONITORING SYSTEM DESIGN AND IMPLEMENTATION

3.1 *ATS installation & deployment:*

Automated Total Stations (ATS) are widely recognised as a reliable and precise monitoring solution for tunnel and infrastructure projects, particularly in environments requiring high-frequency displacement tracking (Hoult & Soga, 2018). For the Brisbane Metro project, the installation of ATS was shaped by the complex spatial, structural, and stakeholder constraints of Adelaide Street's urban canyon. Unlike more uniform environments—such as open rail corridors or greenfield tunnels—this dense CBD setting presented challenges including obstructed sightlines, limited mounting surfaces, heritage-listed structures, and varied stakeholder cooperation.

ATS locations were selected through a staged process beginning at the dive structure and progressing toward City Hall. Prism arrays were mapped and the expected zone of influence (ZOI) for ground movement was modelled. Instruments were positioned outside the ZOI where feasible, with clear lines of sight to targets and stable reference points. Design iterations accounted for site constraints, excavation sequencing, and stakeholder feedback and were finalised through registered professional engineer of Queensland (REPQ) review.

A key challenge was balancing system redundancy, spatial coverage, and approval timelines. While more ATS units could reduce cycle times and improve redundancy, each added cost and complexity. Dense vegetation, narrow footpaths, and limited access often required compromises in geometry and instrument positioning.

Fixed infrastructure such as rooftops, balconies, and structural canopies were preferred due to their stability and elevation. However, elevated locations often placed instruments within or above the tree canopy, creating new obstructions. Heritage restrictions, access limitations, and mixed stakeholder responses further complicated mounting choices. Where building-mounted options were unavailable, street furniture such as bus port structures and light poles was used. These required custom brackets and careful consideration of vibration, movement, and vandalism risk.

Power and communications design was similarly constrained. In many locations, dense tree cover prevented effective solar charging. Mains power was preferred but not always available; in one case, a property owner refused access to supply, requiring a large solar panel installation despite shading risks. Temporary power disruptions during construction were mitigated using portable batteries or alternate feeds.

Despite these challenges, all five ATS units, each with bespoke mounting designs, were successfully installed without requiring post-installation relocation. The project highlighted the importance of early visibility modelling, flexible infrastructure design, and strong stakeholder engagement when deploying monitoring systems in constrained urban environments.

3.2 *Surface settlement monitoring:*

Monitoring surface settlement along Adelaide Street was a critical component of the instrumentation and monitoring strategy. Given the tunnel's shallow alignment, variable ground conditions, and constrained construction staging, accurate, high-frequency monitoring was essential to track settlement behaviour and protect overlying infrastructure. This was particularly important for validating observed movement against Gaussian-type settlement profiles, as described by Peck (1969).

The system was designed to achieve ±1 mm accuracy and repeatability. The original scope included 65 settlement markers, arranged in arrays of 5 to 10 points positioned over the tunnel crown. However, during detailed design and early construction, the need for greater spatial coverage became apparent. The final layout comprised three 17-point arrays, fourteen 13-point arrays (expanded from the original 11-point design to reach the building boundary line), and five arrays positioned directly over the tunnel headings—totalling 236 markers. This represented a 366% increase over the initial scope. A typical array cross-section is shown in Figure 1.

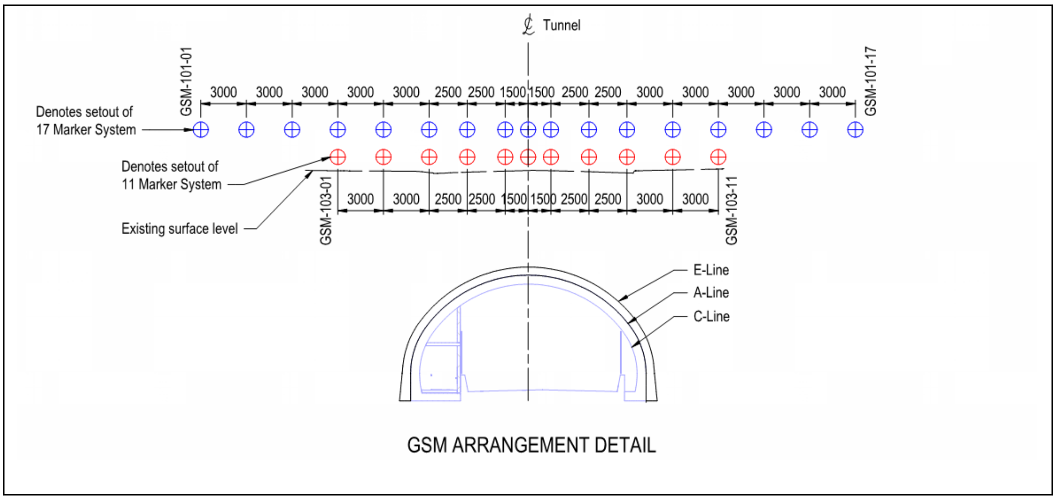


Figure 1. Typical GSM settlement array layout (from I&M Plan).

Three monitoring technologies were considered: cat's eye prisms, patch scanning, and reflectorless measurement. Each was evaluated for suitability in the live, trafficable corridor.

- Cat's eye prisms, designed for in-pavement use, offered a low-profile, durable optical target suitable for vehicle and pedestrian environments. These were installed near kerbs, bollards, and other street furniture to minimise disruption. While generally robust, they were susceptible to water ingress, vehicle wear, debris, and high-pressure street cleaning.
- Patch scanning using Leica MS60 instruments provided high-resolution surface data without fixed targets. However, the high cost and slower acquisition times (2–5 minutes per scan vs. 45 seconds per prism) made this method impractical for the required monitoring frequency and density.
- Reflectorless measurements using TM60 instruments offered quicker, contactless readings and were used as a backup when cat's eyes were damaged. However, accuracy was highly sensitive to incidence angle and surface condition. As movement occurred, the laser contact point could shift, leading to inconsistent data—particularly on cambered or irregular road surfaces.

Cat's eye prisms were selected as the preferred solution due to their accuracy, efficiency, and reliability in urban road conditions. Low traffic speeds along Adelaide Street further reduced the risk of dislodgement.

Initial installations using screw-in anchors experienced post-installation movement under traffic loads. These were replaced with embedded rods and thermal adhesive pads, a technique adapted from highway marker installation, significantly improving durability.

Other field issues included prism displacement due to road degradation near gutters, debris accumulation after rain, and water ingress. A collaborative redesign with the supplier added drainage holes and gasket seals to the prisms, improving resistance to environmental conditions. Once these improvements were implemented, performance stabilised.

In cases where prisms were temporarily unavailable, reflectorless measurements provided interim coverage. A limited number of manual levelling points were also installed along the corridor to support verification checks and confirm anomalies.

3.3 *Building movement monitoring:*

Monitoring building movement along Adelaide Street presented unique challenges, particularly due to stakeholder restrictions that prohibited the installation of physical prisms on some heritage structures. To address this, a reflectorless monitoring methodology was developed and successfully implemented.

The approach relied on capturing three independent reflectorless observations on orthogonal surfaces of each building façade. These corresponded to transverse (left/right), longitudinal (along chainage), and vertical (up/down) displacements. Suitable features—such as window ledges, sills, or frames—were selected based on their orientation relative to the Adelaide Street alignment. By isolating movement in a single plane per observation, displacement in all three directions could be derived with high repeatability.

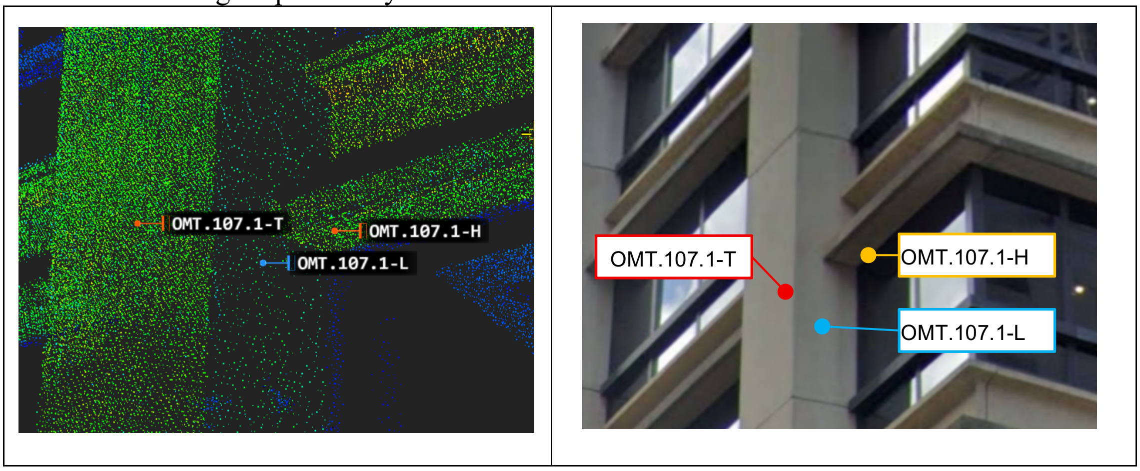


Figure 2. TLH points identified on building façade using point cloud data.

Each group of three readings was configured as a virtual monitoring point within the Leica GeoMoS platform, allowing automated monitoring without the need for physical prism installation. This method eliminated the need for patch scanning or manual measurement while maintaining consistent coverage on restricted-access buildings. Figure *2* illustrates the Transverse, Longitudinal and Height TLH points that were selected using point cloud data, monitoring points were defined in GeoMoS,

The system was validated through internal trials before field deployment, confirming its reliability for detecting structural displacement. Where unexpected readings were observed, measurement points could be quickly reviewed and adjusted in the field, preserving long-term trend integrity.

This approach enabled continuous, high-quality monitoring in locations where physical access was not possible. It provided effective risk management while respecting heritage constraints and formed a key component of the overall monitoring strategy and stakeholder engagement process.

3.4 *Use of point cloud data for planning & maintenance:*

The Brisbane Metro monitoring program commenced during the tail end of the COVID-19 pandemic, when travel and access restrictions posed challenges to traditional on-site planning. These limitations highlighted the need for remote tools to support the design, installation, and adjustment of monitoring infrastructure along the constrained Adelaide Street corridor.

Initial planning relied on publicly available tools, topographic surveys, and site inspections. However, a terrestrial laser scan (TLS) of the corridor—captured by the client's survey team during early project stages—became an invaluable resource once integrated into the monitoring workflow. Although originally acquired for general design purposes, the TLS data proved highly useful for spatial planning and coordination.

To interact with the scan, the subcontractor employed Pointerra, a browser-based 3D point cloud platform. Its intuitive interface and cloud-based delivery enabled rapid review of site conditions, visibility modelling, and clash detection from any device. Other tools, such as SketchUp and CloudCompare, were trialled but saw limited use due to workflow and accessibility constraints.

The point cloud supported several key functions throughout the monitoring lifecycle:

- ATS placement: Simulated visibility modelling from proposed instrument locations.
- Clash detection: Identification of temporary structures or vegetation affecting sight lines.
- Reflectorless targeting: Selection of viable measurement surfaces where prisms were not feasible.
- Maintenance coordination: Extraction of updated coordinates for upload to GeoMoS, enabling remote target adjustment.

Although the monitoring program could have proceeded without the point cloud, its inclusion significantly reduced the need for repeat site visits and removed ambiguity during layout and planning. It became a trusted spatial reference for both field crews and office-based stakeholders.

Looking ahead, the team recommends exploring SLAM-based mobile scanning for future projects. These solutions offer sufficient relative accuracy for monitoring applications, enable faster data acquisition, and could serve as a valuable visual archive of changes if captured at regular intervals throughout the project lifecycle.

3.5 *Data averaging and filtering strategy*

As the Brisbane Metro monitoring system matured, so too did the approach to managing high-frequency surface settlement data. Initially scoped for daily readings, the fully deployed ATS network enabled more frequent observations—progressing to 4-hourly and eventually hourly cycles during the low-traffic overnight period (12:00 am–6:00 am). This window offered optimal conditions with reduced obstruction and grazing, ensuring consistent prism acquisition.

To streamline alerts and reporting, overnight readings were averaged into a single daily value, which became the primary input for alarm logic. Both raw and averaged data were retained to support interpretation and distinguish genuine movement from environmental noise or temporary occlusions. The availability of high-frequency data also offered clearer insights into the performance of problematic prisms.

As data volumes increased, occasional outliers emerged—often linked to grazing or weather-related interference.

Two statistical smoothing options were considered:

- Option 1: 24-hour average (no filtering) – simple to implement using existing SQL logic.
- Option 2: 24-hour average with outlier filtering – excluded values outside ±3 mm of a rolling 48-hour average, but required additional logic and verification.

While Option 2 removed slightly more outliers, it did not significantly alter the interpreted movement. Given the marginal improvement and added complexity, Option 1 was adopted.

To evaluate both approaches, a representative monitoring point (GSM-103.07) was analysed, as shown in Figure *3*:

- Raw data exhibited isolated spikes caused by temporary obstructions (Figure *3* a).
- The 24-hour average reduced major noise (Figure *3* b).
- Option 1 provided a clean, stable trend suitable for alarm thresholds.

Option 1 offered a practical balance between responsiveness and simplicity. Alarms were based on this daily average, with raw data retained for engineering review.

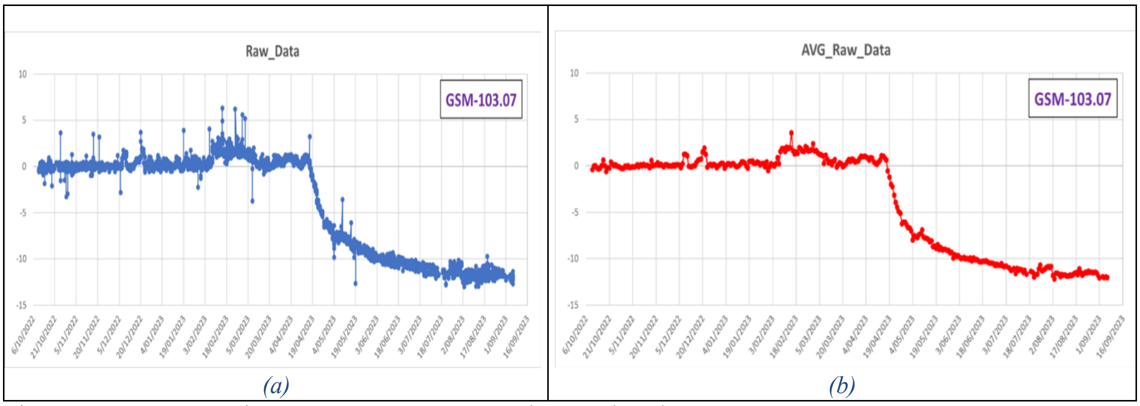


Figure 3. Data comparison at GSM-103.07: raw data, and 24-hour average.

This post-processing strategy worked alongside the built-in ATS filtering, which automatically discarded measurements considered incomplete or unreliable. While the ATS ensured data quality at a basic level, the daily averaging process helped clarify longer-term trends and reduced false alarms, particularly those triggered by weather conditions, temporary obstructions, or other short-term issues.

Clear, stable data was essential for keeping stakeholders confident, especially when unexpected ground movements occurred. By smoothing out short-term fluctuations while accurately representing genuine settlement trends, the monitoring system provided better insight and more reliable information for making construction decisions.

The success of this method also depended heavily on regular communication with site teams. Field personnel regularly checked measurements, responded quickly to unexpected data spikes, and performed targeted prism maintenance where necessary. This hands-on approach kept the monitoring system accurate and dependable over the project's duration.

In short, although more advanced filtering methods might be explored on future projects, combining built-in ATS filtering, simple averaging, and proactive field checks provided a robust, practical, and effective solution for Brisbane Metro.

3.6 *Measurement challenges in the urban canyon.*

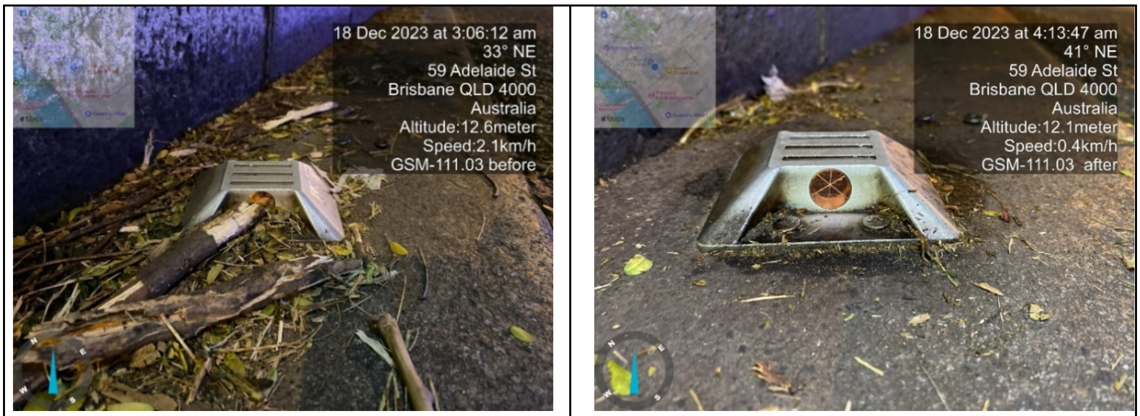
Monitoring ground and structural movement in Brisbane's dense CBD corridor presented unique environmental and operational challenges that affected data acquisition quality and consistency. As noted by Hoult & Soga (2018), sensor accuracy and reliability are highly influenced by mounting position and surrounding environmental conditions—an issue particularly evident in constrained urban settings such as Adelaide Street. While the ATS system incorporated robust filtering and quality checks, a range of persistent urban factors required active management.

Prisms located near street gutters were particularly susceptible to visual obstructions and signal anomalies. These areas were frequently impacted by debris, mud, leaves (notably from mature leopard trees), and splashes from passing vehicles. Seasonal vegetation growth and litter buildup also contributed to temporary visibility loss and degraded signal return, especially following rainfall or during peak construction activity.

Although the ATS software performed automated quality checks—including tilt compensator validation, signal return strength analysis, and dual-face readings—subtle grazing effects could still produce measurements that mimicked true displacement. These errors were most commonly observed with cat's eye prisms mounted at pavement level. This aligns with findings by Lackner & Lienhart (2017), who demonstrated that prism orientation and non-standard geometries—such as cat's eyes—can significantly affect measurement accuracy, particularly under grazing incidence. The importance of systematic quality controls—especially dual-face observations, tilt correction, and signal strength validation—has also been widely acknowledged as critical for reliable automated monitoring (Lienhart, 2017).

When unexplained data spikes were identified, cleaning frequency was increased beyond the standard weekly or fortnightly schedule. An example of the debris as a result of rain is shown in

Figure *4*. Anomalies were reviewed alongside environmental data (e.g., rainfall or wind) and compared to adjacent monitoring points to distinguish genuine movement from noise.



(b) *(b)*

Figure 4. (a) Debris found on cats eye prism in the gutter post rain. (b) Cleaned following maintenance

Sensor placement was a key factor in measurement reliability. While low-profile prisms were chosen to reduce trip hazards, their positioning near gutters made them more vulnerable to damage and obstruction. Although smaller-diameter alternatives were considered, they posed a risk of compromised signal return due to reduced reflective surface area. Further testing would be required to evaluate their suitability in similar environments.

In contrast, cat's eye prisms installed on footpaths required minimal maintenance, while 3D monitoring prisms mounted on building façades required no maintenance at all throughout the monitoring period. Their elevated and sheltered locations protected them from environmental and mechanical effects, highlighting the advantage of locating sensors away from high-traffic, exposed zones wherever feasible.

De Rubertis (2017) notes that even well-designed monitoring systems require site-specific maintenance and validation to remain reliable - particularly in environments subject to mechanical disturbance or environmental exposure. This was especially true for Brisbane Metro, where surface-mounted sensors proved more vulnerable than elevated alternatives.

Overall, consistent field feedback, proactive maintenance, and thoughtful system design were essential to managing the challenges posed by the urban canyon environment.

4 RESULTS AND FINDINGS

The surface settlement monitoring program achieved excellent results, thanks to careful planning, accurate fieldwork, and strong collaboration between monitoring specialists and the construction team.

From the beginning, the monitoring network was tailored specifically to address the complexities along Adelaide Street. Instruments were precisely installed and regularly checked, ensuring consistently high-quality data. Field teams quickly addressed issues like prism obstructions or environmental interference, maintaining data reliability throughout the project.

Communication was a key strength of the project. Regular updates between site personnel and monitoring staff allowed rapid responses to unexpected situations, building trust in the monitoring system.

Automated monitoring also delivered practical advantages compared to traditional manual surveys. It reduced labour requirements, provided quicker access to data, and significantly improved site safety by minimising surveyors' exposure to traffic and construction hazards. These benefits align well with established monitoring practices (Dunnicliff, 1993).

Overall, the monitoring program reliably provided clear, actionable information that supported safe and efficient tunnelling operations in a challenging urban environment.

5 CONCLUSION AND IMPACT

The Brisbane Metro surface settlement monitoring program demonstrated the critical role of advanced instrumentation in managing geotechnical risk within a highly constrained urban environment. Despite spatial limitations, environmental exposure, and stakeholder-related challenges along the Adelaide Street corridor, the use of Automated Total Stations (ATS) enabled consistent, high-precision monitoring throughout the excavation period.

The integration of remote planning tools, particularly point cloud data, with automated measurement systems created a flexible and resilient monitoring framework. This enabled early trend detection, efficient maintenance scheduling, and timely construction feedback. While cat's eye prisms required occasional maintenance, the overall monitoring infrastructure proved robust and well suited to the challenges of the site.

Importantly, the system enabled safe, uninterrupted operation of one of Brisbane's busiest commuter corridors. Monitoring activities were conducted with minimal disruption to public access, and the data generated directly supported construction decision-making, stakeholder communication, and risk mitigation.

The lessons learned—particularly around early planning, stakeholder coordination, sensor placement, and adaptive maintenance—provide valuable guidance for future underground infrastructure projects in similarly complex urban settings. The success of the Brisbane Metro monitoring program highlights the importance of tailored system design, proactive planning, and close collaboration in delivering reliable, real-time instrumentation outcomes.

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