Design of an instrumented monitoring system for the Inner Northern Busway Project, Brisbane

Chris Bridges, Garth Powell, Trevor Smith & Tim Cartledge
Coffey Geotechnics Pty Ltd, Brisbane, Queensland, Australia

ABSTRACT
Major excavations within city centres present enormous challenges to the design and construction teams charged with carrying out the work. An effective instrumentation and monitoring system can reduce the risks of all parties concerned and can reassure stakeholders. This paper presents details of the design of one such system for a project in the Brisbane Central Business District.

RÉSUMÉ
Les travaux d'excavation importants en centre-ville présentent des défis énormes pour les équipes en charge de la conception et de la construction. Une instrumentation effective et un système de surveillance peuvent reduire les risques pour les parties concernées et rassurer les parties prenantes. Cet article présente les détails de la conception d'un tel système pour un projet dans le centre de Brisbane.

1 INTRODUCTION

The Inner Northern Busway (INB), Queen Street to Upper Roma Street Project involved the construction of a dedicated busway between the existing Queen Street Bus Station and the completed section of the INB at Countess Street within the busy Brisbane Central Business District (CBD). The project involved the construction of two bus stations (one within an existing underground car park and the other within an existing railway station complex) as well as 500m of cut-and-cover tunnel.

The Client for the project was Queensland Transport (QT) and the project was undertaken as an Alliance contract with the member companies being QT, Leighton Contractors Pty Ltd, Maunsell Australia Pty Ltd, Coffey Geotechnics Pty Ltd, Bligh Voller Nield Pty Ltd and EDAW Gillespies Australia.

This paper discusses the project, and the philosophy behind the planning and design of the monitoring system developed for the project over the cut-and-cover section of the project.

2 THE SITE

The INB Queen Street to Upper Roma Street Project is located in central Brisbane, and is situated approximately 400m east of the Brisbane River. It is contained within a corridor which joins the existing underground Queen Street Bus Station (QSBS) in the south with the existing INB Section 3 at Countess Street in the west (Figure 1).

The site was divided into four areas:

- Area 10 – QSBS to Ann Street
- Area 20 – Ann Street to Roma Street Transit Centre
- Area 30 – The Roma Street Transit Centre (RSTC) to Countess Street
- Area 40 – Countess Street to Upper Roma Street

The busway was constructed beneath Albert and Adelaide Streets in Area 10, as well as within the existing, below ground, King George Square (KGS) Car Park. In Area 20, a new underground bus station was constructed beneath Ann and Roma Streets with the busway continuing behind the abutment of Turbot Street Bridge before rising to ground level within the Roma Street Forum.

The busway continues at grade behind the Roma Street Transit Centre (Area 30) before connecting into the existing INB at Countess Street. A short stretch of busway was also constructed west from Countess Street to provide a "western connection" with Upper Roma Street (Area 40).

2.1 Site History

The site is located within the heart of Brisbane and is, therefore, surrounded by some of Brisbane's oldest structures and busiest roads. The area to the south of Ann Street was developed early in Brisbane's history.

To the east of the alignment straddling Ann Street are two churches built over 150 years ago. The Presbyterian Church adjoins the northeastern edge of the KGS and it had apparently suffered a reasonable amount of distress during the construction of the car park 40 years ago. On the opposite side of Ann Street is the Uniting Church the grounds of which were within 5m of the deepest excavation on site.

On the southwest face of KGS is the historic City Hall with its sandstone façade, which is considered to have little tolerance to movement.

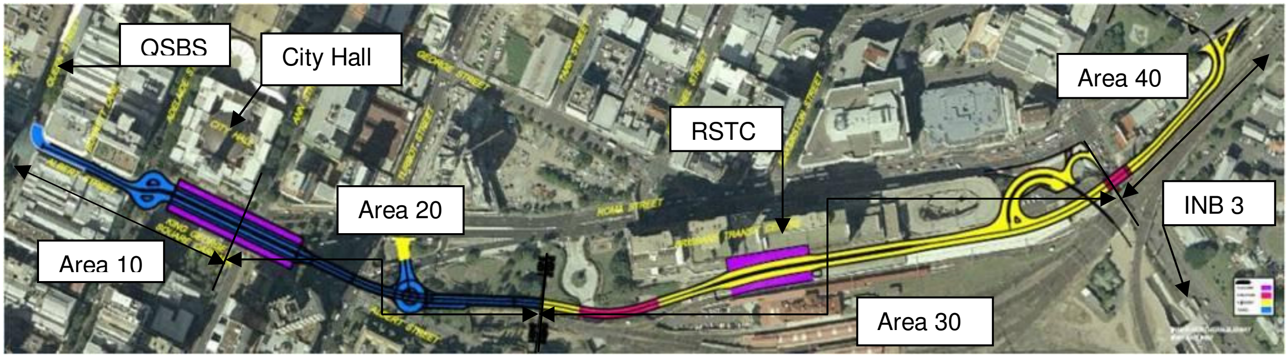

Figure 1. INB Location Plan

2.2 Ground Conditions

The geology along the alignment of the project is the slightly metamorphosed rocks of the 400 million year old Neranleigh- Fernvale Beds, overlain (in places) by young (<2 million years old) alluvium. Fill has also been emplaced in varying locations. The Neranleigh-Fernvale Beds are low grade metamorphic rocks that occur through a large swath of south east Queensland. Along the INB route corridor, the Neranleigh-Fernvale Beds take the form of either fine or medium grained slightly metamorphosed sedimentary rocks.

A notable geological feature along the alignment of the project is a pre-existing creek which generally runs east of the alignment, but cuts across the alignment at Adelaide Street.

In Area 10 the ground conditions comprised fill (to 3m thickness) over alluvial deposits (typically 5m thick but up to 8.5m at Adelaide Street) over residual soil and extremely weathered material (from 11m thick down to 1m at Adelaide Street). The bedrock was typically encountered at approximately 12m below ground level.

In Area 20 the ground conditions were such that the bedrock was typically encountered at approximately 3m below ground level. The residual soil and extremely weathered material above was of the order of 2m thick with the alluvial soils and fill of varying thicknesses making up the upper 1m.

The fill consisted of a matrix of loose clayey gravel with occasional rubble and ash from power stations. The alluvial deposits are typically a sandy clay/ clayey sand with the fine fraction dominating the engineering behaviour, so that it behaved largely in an 'undrained' manner, over the construction period.

The weathering of the surface of the Neranleigh-Fernvale Beds has produced a weathered zone with residual soil and extremely weathered material identified as stiff to hard gravelly clays. The weathering of the bedrock encountered on the projected ranged from highly weathered to fresh. Fresh and slightly weathered rock was typically high or very high strength crystalline material, more weathered rock was typically lower strength. The metamorphic foliation dominated the defect sets, with an additional two sets of joints and some random orientated joints also occuring.

3 PROJECT DESIGN

The INB Queen Street to Upper Roma Street Project was for a 1.25km long busway constructed in the Brisbane CBD. The project included:

- 526m of cut-and-cover tunnel including an underground station
- 4 bridges
- 613m of at-grade busway through the existing Roma Street Rail Station and construction of a new bus station

As discussed above, the project was divided into four areas:

- Area 10 linked QSBS to the new bus station west of Ann Street and was constructed underground. The bus station is partly contained within the existing underground car park at King George Square
- Area 20 is also mainly underground and continues the underground bus station started in Area 10. The busway daylights within Roma Street Forum.
- Area 30 is overland, constructed predominantly on existing railtrack and roads behind the Brisbane Transit Centre. The works required the construction of new or widened bridges.
- Area 40 is overland and joins the busway to Roma Street.

The instrumentation is predominantly in Areas 10 and 20 (Figure 2) and these areas are discussed below.

3.1 Area 10

This length of tunnel connects the existing QSBS to the lowest level of KGS Car Park. The cut-and-cover tunnel was formed from 0.6m to 1.05m contiguous bored pile walls with in situ reinforced concrete roof and base slabs. The tunnel was constructed using the top-down methodology in order to minimize disruption to the shopping area above. Outside the main running tunnel a mined emergency egress was constructed beneath the pedestrian footpath.

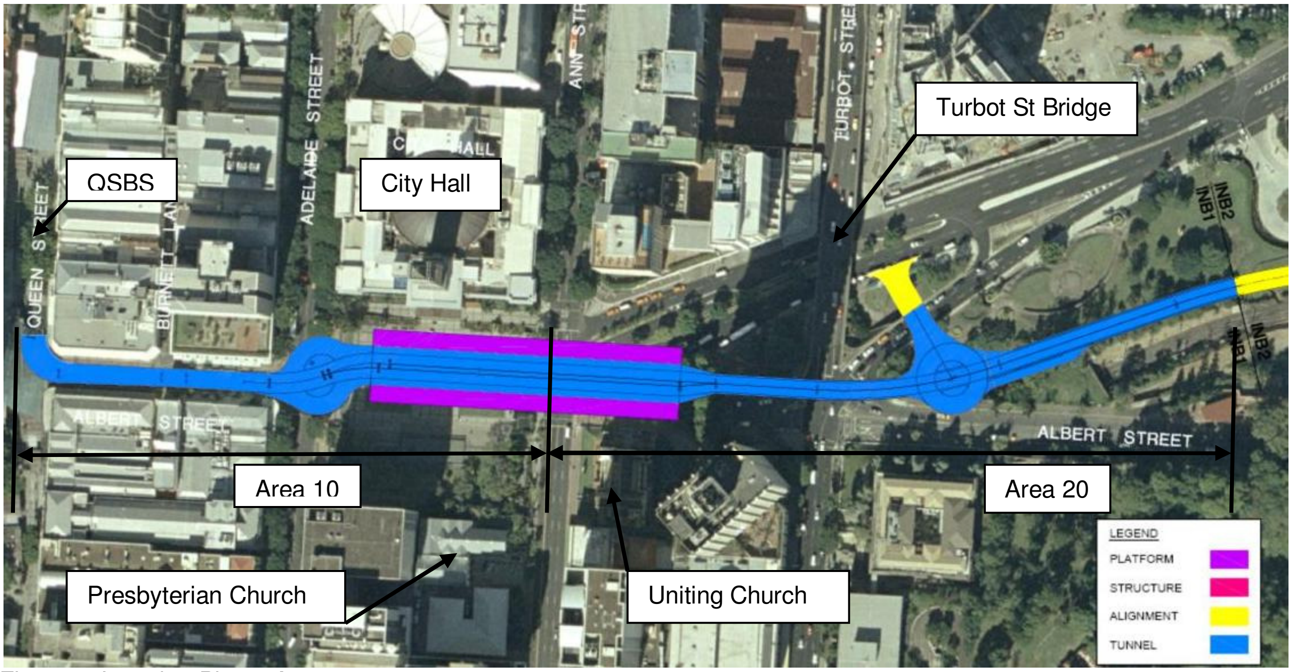

Figure 2. Location Plan – Areas 10 & 20

3.2 Area 20

This section of the works consisted of a cut-and-cover tunnel formed from:

- 0.9m contiguous bored pile walls on the western face of the excavation;
- ground support with 0.6m to 0.9m diameter piles spaced at 4m centres on the eastern face;
- reinforced concrete structure between the two walls forming permanent propping to the walls.

This area has been divided into a number of sections due to the nature of the works. As the tunnel crosses the busy Ann and Turbot Streets, the work was carried out as top-down construction in order to keep the traffic flowing in the city centre with the minimum of disruption. In all other sections of Area 20 the tunnel was constructed using bottom-up techniques.

A majority of the work in Area 20 was for the construction of the new underground KGS Bus Station. The floors and roof were constructed from in situ reinforced concrete with the external walls consisting of bored piles on the western side of the excavation and spaced piles (acting mainly as columns) and ground support on the eastern face. The ground support consisted of rock bolts placed as required following mapping and inspection of the exposed rock face. Internal columns were generally formed from in situ reinforced concrete, but in the top-down section of tunnel under Ann Street 1.2m diameter bored piles were installed from ground level.

In both faces of the excavation temporary rock anchors were installed in areas where additional support was required prior to installation of the permanent structure.

4 INSTRUMENTATION & MONITORING PLAN

4.1 Design of the Instrumentation & Monitoring

Extensive analyses were carried out for the design of the permanent and temporary structures that were required to complete the works. Predictions of ground deformation were obtained using PLAXIS finite element software. The deformation predictions were used to determine the anticipated ground response and effect on structures adjacent to the works (see Section 4.2, below).

The location of instruments and monitoring points were chosen to enable confirmation of design predictions and thus design parameters chosen as well as provide an early warning system to determine if deformation would affect existing infrastructure.

Where possible ground settlement monitoring was carried out through the use of arrays of monitoring points. These were supplemented by instruments, such as inclinometers, placed between critical infrastructure and the works. Finally, instruments (such as tiltmeters and building settlement markers) were placed on key infrastructure to monitor the actual effects on these structures.

4.2 Building Assessment

Prior to construction building condition assessments were carried out of structures generally within 40m of the edges of the excavations (i.e. within 2H of the excavation, where H is the depth of excavation).

A number of critical structures were identified in the review which would have safety and/or political repercussions if damage was done. These included:

- City Hall – built in the 1930s and located adjacent to KGS. This structure was the home of the Lord Mayor and was generally in a poor state of repair. On the centre of City Hall is a large dome and there is a clock tower on the face adjacent to the works.
- Historic churches – as discussed in Section 2.1.
- Turbot Street Bridge – the tunnel would be constructed behind the eastern abutment and close to its supporting piles.
- Dental Hospital – another building in poor repair.
- Albert Street shops – shop facades within 4m of the cut-and-cover tunnel.

A building assessment was prepared for all critical structures which considered the ground conditions, predicted ground deformation and the maximum predicted and limiting tensile strain for the structures. The impact on the building was then determined in accordance with Mair et al (1996).

This assessment led to the determination of instrumentation locations and the corresponding monitoring regime for the structures.

5 INSTRUMENTATION

The instruments were generally supplied by Geotechnical Systems Australia (GSA) and ITM-Soil. They were installed by the Alliance with some assistance from GSA and ITM-Soil. The Alliance geotechnical team monitored reported and maintained the system.

5.1 Structural Monitoring System

The system comprised the following.

- 81 building prisms to monitor 3-D building movements
- 8 vibration monitors capable of monitoring horizontal and vertical vibration
- 70 building movement markers surveyed by precise level and staff

Figure 3 shows the locations of structural monitoring on Albert Street.

Building settlement was monitored using a combination of settlement points as follows:

- BRE type screw-in bolts and marks installed on walls, floors and columns measured by precise levelling; and
- survey prisms installed on walls, columns or facades monitored by an automatic levelling system with the results sent by wireless to a receiving unit at the site office.

The tilt of structures was monitored by a tiltmeter system comprising either:

- bronze tilt plates were mounted in specified locations on the building structure, and these were read by a portable metric tiltmeter (Geokon Model 6201) and readout unit. These were used typically in areas where monitoring was of a temporary nature where the plates could be easily damaged, such as the internal walls of the KGS car park during demolition.
- automatic tiltmeters were installed in critical structures close to the excavation such as the tower of the Uniting Church. The automatic tiltmeters consisted of an in-place EL beam tilt sensor. The adopted units were TLTCF-1s which have an accuracy of better than 1 arc second and have a range of 2.5 degrees. These allowed automatic and continuous measurement of tilt with wireless transmission back to a receiving unit at the site office.

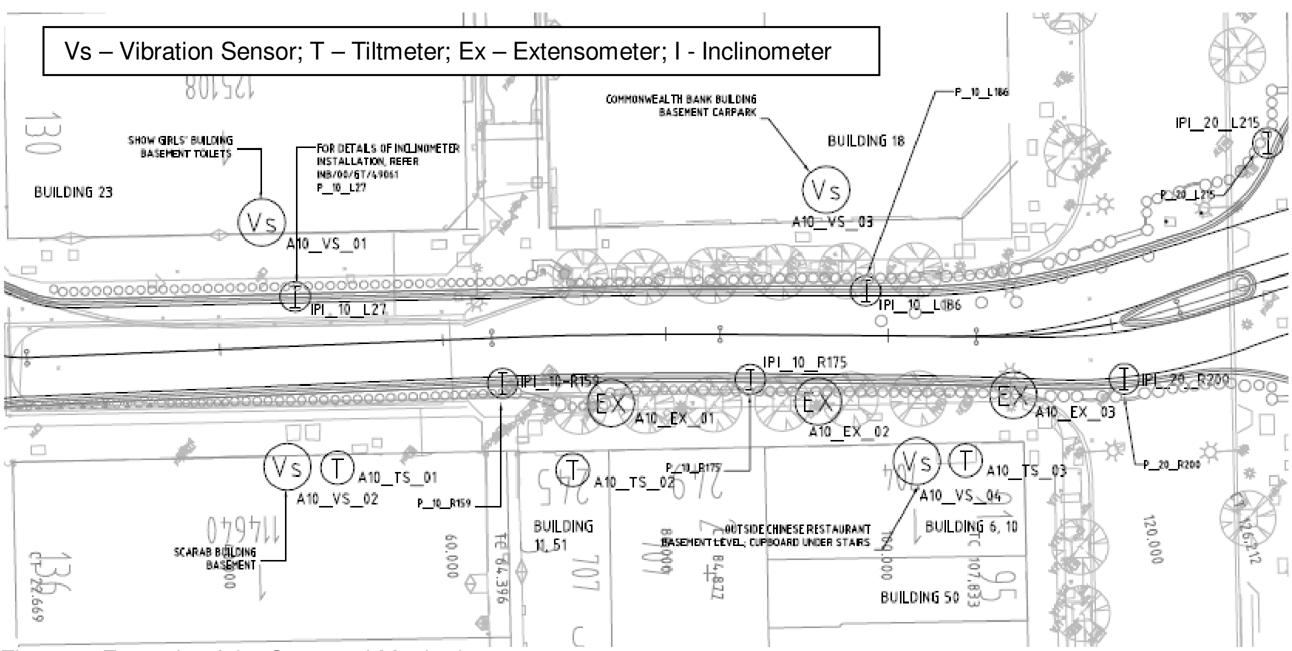

Figure 3. Example of the Structural Monitoring

The vibration monitors were Instantel Minimate Plus. They have a quoted range of 254 mm/s, a resolution of 0.127 mm/s and an accuracy of 5%. Vibration monitoring was carried out on selected buildings adjacent to piling works or where construction activities were likely to result in significant vibrations and where vibration could adversely affect adjacent buildings, structures utilities or equipment. Some buildings structures, utilities or equipment are particularly sensitive to vibration and monitoring of the vibration was particularly important at sensitive buildings such as City Hall, Albert Street Uniting Church and the Dental Hospital.

5.2 Ground Movement Monitoring System

The system comprised the following.

- 5 inclinometers installed by fixing them into the reinforcement cages of the piles, for measuring lateral deflection of the piles.
- 4 inclinometers located outside the excavation.
- 9 standpipes and vibrating wire piezometers for monitoring changes in groundwater level outside the site.
- 130 ground settlement markers located around the excavation surveyed by precise level and staff.

Ground settlement markers were installed to monitor ground settlement due to excavation or other construction activities. They were often placed in arrays leading from the excavation and were monitored by precise levelling. Vibrating wire piezometers and water standpipes were installed to monitor the ground water pressure / levels and changes in pressure / levels due to excavation/construction site activities. These were also used to provide confirmation on the design groundwater levels. The water standpipes were perforated PVC tubing of nominal size 50 to 60mm diameter with slotted holes at about 25mm centres.

The depth of inclinometers extended beyond the zone of influence of tunnels and excavations being monitored. Typically, inclinometers were taken down to at least:

- 2m into hard stratum;
- 3m below the toe level of the retaining wall for excavations;
- full depth of bored pile.

Rod extensometers were used to monitor ground movements above the mined tunnel in Albert Street by measuring the relative movements of both elongation and reduction in the length between the anchor and reference collar. The rod extensometers were Geotechnical Systems Australia Model 4000. These were monitored by an automatic system with the results sent by wireless to a receiving unit at the site office.

6 MONITORING

6.1 Data Collection and Interpretation

The monitoring system combined the elements of the structural and ground monitoring to provide an early warning system during construction. Where possible the instruments transmitted data directly back to a receiving unit at the site office. For the other instruments monitoring data was downloaded directly by geotechnician once or twice a week. Building and ground settlement markers were surveyed and that data was downloaded into the database by the surveyors.

INSITE is a monitoring database which was first used in Australia on this project. This sophisticated monitoring package was originally developed for tunnelling projects and allows realtime assessment of the data, with visual warning provided on its GIS interface. The software provides a standard SMS alert system should trigger levels be exceeded (Figure 4).

Figure 4. Example of INSITE presentation

6.2 Monitoring Review

Monitoring review values were used to evaluate the measured results against expected soil behaviour. Different monitoring review limit values were introduced to categorise measurements in terms of their severity.

The various limit values may be derived with respect to the expected displacements or soil behaviour, based on detailed design calculations or permitted maximum displacement of a particular structure, service, or area, which is critical to the safety, functioning, or maintenance of the structure, service or area.

The review limit values are defined as follows:

"Trigger" level

The "Trigger" level serves as a limit upon which action is to be taken to ensure that the allowable value is not exceeded. It is defined as 70% of the anticipated level of movement likely to occur during construction. This is to advise the site team that the movement is approaching the design level. Additional monitoring may be considered at this time and contingency / remedial measures determined.

"Design" level

This level has been established at the anticipated maximum level of movement. This is to advise the site team that the movement has reached the design level. At this stage remedial measures may be carried out (depending on the stage of construction) and revised "Trigger" and "Design" levels determined.

The “Design” level is defined as best maximum estimate of the anticipated behaviour derived by design calculations. In most occasions, it may be possible to exceed the design value without cause for concern. However, in some cases the design value may be equal to the allowable value and cannot be exceeded.

“Allowable” level

Defined as the permitted maximum displacements of a particular structure or area, which corresponds to a negligible / very slight impact on the existing structure. On achieving this level work will be stopped immediately. The “Allowable” level is a maximum limit not to be exceeded.

6.3 Monitoring Results

The monitoring indicated that none of the “design” levels were exceeded during construction. The real time availability of accurate and reliable data on ground and structural movements, together with site observations, allowed an observational approach to be adopted. This enabled the reduction of temporary support resulting in considerable cost savings during construction.

A full discussion on the predicted vs actual monitoring data will be presented in later papers.

7 CHALLENGES

There were many challenges in installing the instrumentation for this project:

- Many of the downhole instruments were installed during the ground investigation phase of the project. However, given the design development inherent in an Alliance project the alignment of the tunnel changed after the investigation was completed. Therefore, some of these instruments were destroyed before full use could have been made.
- Construction damage was the biggest concern to the monitoring team and particular care had to be made to protect the monitoring points as work proceeded. The close relationship between the construction and design teams developed through the Alliance delivery method ensured that all parties were aware of the importance of the instruments. Very few instruments were damaged during construction as a result.
- In many places there was insufficient space to install instrumentation due to services beneath the ground surface or access constraints.

8 CONCLUSIONS

The monitoring system developed for the INB Queen Street to Upper Roma Street Project was developed based on the knowledge of construction activities, anticipated ground conditions and the location of existing infrastructure in the vicinity of the works.

The data collection and processing by INSITE enabled the geotechnical engineers on site to gain an appreciation of ground and structural responses as the works proceeded and confirmed the assumptions made in design.

Confidence in the monitoring results enabled considerable savings to be achieved in the temporary works

ACKNOWLEDGEMENTS

The writers would like to acknowledge the contribution of all members of the Alliance for establishing and maintaining a positive and cooperative set of behaviours enabling an observational approach to be adopted.

REFERENCES

Mair, R.J., Taylor, R.N. & Burland, J.B. 1996. *Prediction of ground movements and assessments of risk of building damage due to bored tunnelling.* Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (Eds), Balkema, Rotterdam, Holland pp713-718.