GREEN SQUARE – ENABLING URBAN RENEWAL THROUGH SMART RETAINING WALL DESIGN AND TRENCHLESS CONSTRUCTION

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ABSTRACT

Green Square is one of the City of Sydney's key urban renewal precincts, which is being transformed from old industrial land into a major new residential, retail and cultural hub. The Green Square Stormwater Drain (GSSD) is the culmination of a strategic alignment between City of Sydney and Sydney Water to provide flood protection in the Green Square area. Through a process of optioneering and hydraulic analysis, a new 2.5 km long underground drain consisting of multiple 1800 mm diameter pipes was installed by microtunnelling, and an open trench box culvert was replaced with channel widening via an anchored retaining wall in the final 300 m from Maddox St to Alexandra Canal. The new drain augments the existing trunk drain system and reduces flood hazard, allowing Australia's largest urban renewal project to proceed.

The channel widening section of the GSSD was originally intended to be constructed into the bank of the existing open channel. A constructability assessment for installation of the box culvert within the narrow corridor between the existing open channel and adjacent buildings indicated that open trench box culvert construction would not be cost effective. This paper describes an innovative solution, where the existing channel was widened using an anchored retaining wall, replacing the proposed box culverts.

The trenchless (microtunnel) solution offered an alternative, value for money approach with significantly reduced environmental impact and achieved comparatively minimal community disruptions.

This paper also describes the ground engineering challenges and solutions employed on the site which included difficult ground conditions, landfill and addressing impacts of wall construction on adjacent infrastructure such as roads, bridges and buildings. Ground engineering risks were successfully managed through detailed scoping of investigations, numerical modelling of designs and adoption of observational methods during construction. The specification requirements, design, installation, monitoring and performance of the successful microtunnel drain and anchored wall system are discussed.

1. PROJECT OVERVIEW

Located about 3.5 km south of the Sydney CBD, the Green Square urban renewal area is Australia's largest urban renewal project, delivering significant economic benefits, including 31,500 residential dwellings housing 60,000 new residents and catering for a permanent workforce of 22,000 by 2030. The population density in Green Square will be 50% higher than Pyrmont/Ultimo in inner Sydney, which has the highest current population density in Australia. Total urban renewal development costs are forecast to exceed $13 billion.

The Green Square Town Centre (GSTC) is located at the heart of this urban renewal area. Prior to development, this area was part of a series of ponds, swamps and creeks that drained through to Botany Bay via the Botany Aquifer and the Cooks River. Urbanisation changed the hydraulic character of the area, from a natural water reservoir and waterway corridor to an area of hazardous, flash flooding. As old industrial land gives way to modern high-density development, these existing flood hazards needed to be resolved to protect a growing community.

Sydney Water and City of Sydney share stormwater management responsibilities in the Green Square area under a complex ownership arrangement. Sydney Water is the owner and manager of the "trunk" drainage system, while City of Sydney owns and manages the "local" drainage system. Effective flood risk management required close collaboration and strategic alignment to arrive at a trunk drainage solution that meets the key project objectives of ensuring community safety during floods and enabling urban renewal. The preferred solution involved the installation of 2.5 km of new conduits with the specific aim of reducing high hazard flooding to low hazard in the 1% annual exceedance probability (AEP) flood.

With flow capacity of almost 30 cumecs and a capital value of $100 million, the GSSD is the largest brown-field urban drainage project in Sydney for 30 years. The City of Sydney, Sydney Water and NSW and Australian Governments are jointly funding the project.

The project presented many technical, logistical and community related challenges from solving complex hydraulic and geotechnical issues to installing large conduits in heavily built-up areas with extensive existing utility clashes and potential major traffic disruption. To meet the construction challenge, minimise the social impact and minimise cost the Drying Green Alliance (consisting of City of Sydney, Sydney Water, WSP, Seymour Whyte, UGL and RPS Manidis Roberts) adopted a design and construction method that uses tunnel boring machines to install 1800mm diameter pipes using microtunnelling.

Design and construction of the GSSD was awarded to the Drying Green Alliance following a competitive alliance process. Two alliance consortia were short-listed, on their respective concept designs and total out-turn costs based on the provided reference design and hydraulic models prepared. The Drying Green team developed an alternative design that used microtunnelling of twin and triple reinforced concrete jacking class pipes in parallel instead of open trenched box culverts.

Figure 1: GSSD plan showing retaining wall (left end) and microtunnel sections

2. PROJECT CHALLENGES

The area immediately south of Sydney CBD was originally low-lying swamps and sand hills and following development, has become naturally flood prone. The ground consists of sands interspersed with peat and clay with high groundwater and bedrock about 10 m below the surface. This required extensive dewatering and groundwater management in the microtunnelling up to 10 m deep for the GSSD and construction of local drain inlet structures. The ground is typically contaminated with unregulated fills, affecting microtunnelling progress. The microtunnel GSSD passed under a number of arterial roads with major utility crossings. The trenchless construction methodology ensured minimal impact on these critical roads and utilities including crossing under a 120-year old trunk sewer constructed of bricks.

The retaining wall between Maddox St and Huntley St is four to six metres away from existing warehouses and was constructed in sands interspersed with peat and contaminated fills with high groundwater, requiring a special design to provide a robust and durable solution. Due to the proximity of the buildings, tight design criteria were placed on horizontal deflection and inclinometer and survey monitoring of the wall and adjacent buildings was undertaken during excavation to ensure no damage to the buildings.

2.1 DESIGN CRITERIA ON THE RETAINING SYSTEM

The design criteria on overall stability and ground movements for the retaining wall included:

1) The Factor of Safety (FOS) against slope failure:
    - In the short term (during construction): 1.2.
    - In the long term (permanent state): 1.5.
2) Maximum horizontal wall deflection: 30 mm.

The horizontal deflection limit of 30mm was set to limit vertical ground settlement under the warehouse buildings to an acceptable level so that the integrity of the building structure was protected.

The design of the proposed retaining wall system is in accordance with following design references/standards:

- CIRIA C760 Embedded retaining walls – guidance for economic design.
- AS5100.3 Bridge design—Foundations and soil supporting structures.
- Roads and Maritime Services (RMS) QA Specification R56 Ground Anchors.
- The Standards in the Structural Design Criteria Report 100-2262014B-WAT-REP008.

2.2 THE GROUND CONDITIONS

Subsurface conditions were interpreted based on the available geotechnical information from previous investigation work and additional geotechnical investigation carried out, which involved cone penetrometer testing (CPTu) and Marchetti Dilatometer Testing (DMT) comprising CPT/DMT-01 to CPT/DMT-08. CPT and DMT test locations were located side-by-side at each CPT/DMT location. No additional geotechnical testing was undertaken south of Huntley St (the last 100m of the GSSD) due to access restrictions.

Based on the available geotechnical information, a geotechnical model was developed as shown in the geotechnical long section in Figure 2. Between chainages of approximately CH100 to CH380 (from just south of Huntley Street to Maddox Street) the subsurface conditions were broadly described as comprising fill (very loose to loose sand) overlying a layer of alluvial soil comprising peat and clay. This layer is then underlain by a layer of medium dense to dense sand followed by a second alluvial clay layer. Between chainages 40 and 100 no geotechnical information was available and the profile just south of Huntley Street was assumed to extend to CH 40. The assumptions were later verified through exposure of the ground during construction.

The ground profile for each section analysed considered the nearest borehole or CPT/DMT test location as appropriate. The adopted geotechnical design parameters are summarised in Table 1 below.

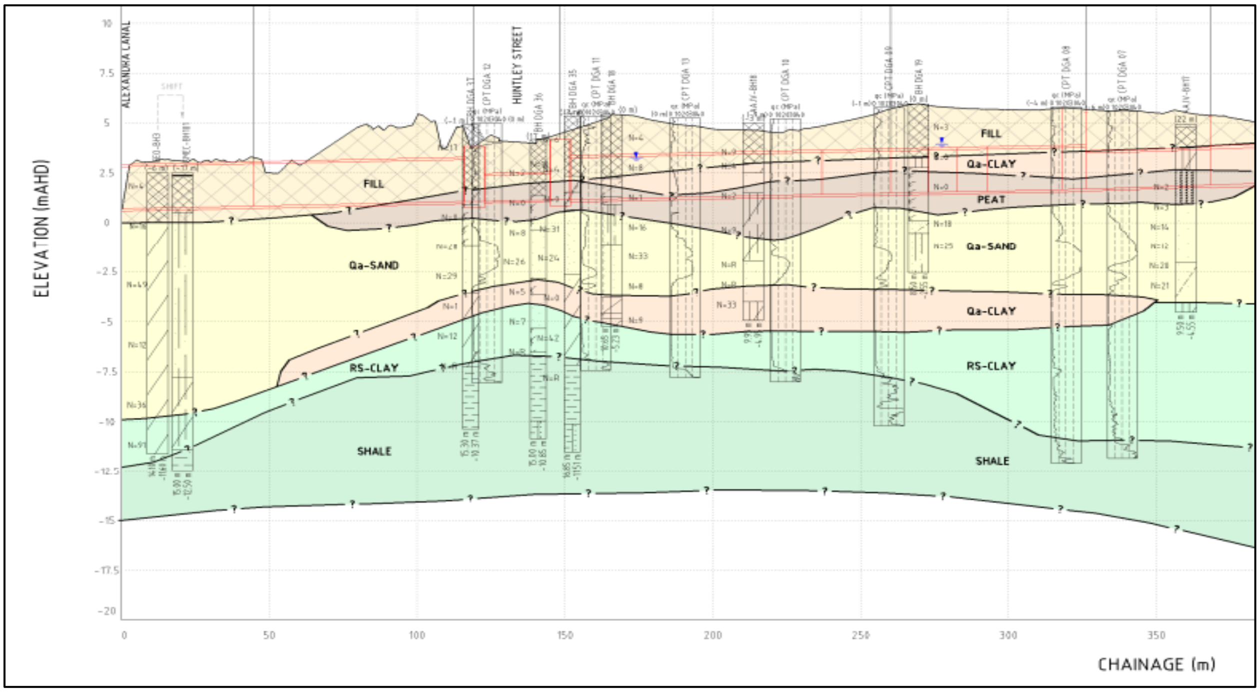

Figure 2: Interpreted geological profile at channel widening area

Table 1: Geotechnical design parameters

Material type	Unit weight (kN/m3)	Undrained shear strength (kPa)	Effective cohesion, c' (kPa)	Effective friction angle, ϕ' (°)	Young's modulus, E (kPa)
Top fill	17.0	-	0	30	7,500
Very loose to loose sand	16-18	-	0	30	7,500-30,000
Peat	16	15-20	0	25	3,000-6,000
Medium dense to dense	19	-	0	35	35,000-60,000
Alluvial clay	19	30 to 60	5	27	40,000-60,000
Residual Clay	20	100-200	10	27	50,000

3. CHANNEL WIDENING

3.1 OPTIONS ASSESSMENT

During the early design stage, the following options for the retaining wall were considered:

1) 600 mm diameter contiguous bored pile (CBP) wall at building side and 300mm CBP wall at existing channel side and temporary struts for construction of the box culvert.

2) 1000 to 1200 mm diameter cantilever CBP wall at the building side only for construction of the box culvert.
3) 2 to 3 rows of 400 mm slope stabilizing piles supporting a widened channel.
4) channel widening involving 600 mm diameter CBP wall with or without one layer anchor at wall top or reaction piles where an inclined anchor could not be installed due to proximity of the neighbouring property boundary.

Option 1 was ruled out due to constructability and time concerns. Option 2 was also ruled out because the site constraints and poor ground condition prevented using a larger piling rig for diameter of 1.0m and greater. Option 3 was not preferred due to the requirement to construct a shared path in the space between the cannel and buildings.

Option 4 was finally adopted with three scenarios on the retaining system:

- A Contiguous Bored Pile (CBP) Wall with one layer of permanent ground anchors. Where there was no room for anchorage, reaction piles (outside the active wedge) are proposed to provide the passive resistance to the CBP wall. At CH0-20 a cantilever wall was adopted due to the shallower excavation and relatively good ground conditions.
- A temporary sheet pile wall with ground anchors adjacent the existing buildings was required to enable the construction of capping beam for the CBP wall as the difference in levels did not allow a stable temporary slope.
- A cantilever temporary sheet pile wall in front of CBP wall at south of Huntley Street to form a temporary piling platform for installation of CBP wall.

Due to space restrictions between CH200 and CH310 inclined ground anchors could not be installed within the property boundary. A row of widely spaced reaction piles was adopted. The reaction piles were connected to the CBP pile wall by the longitudinal capping beam and transverse tie beams at 4m spacing. In selection of the retaining wall system, the consideration was given to site constraints, e.g. steep batter and proximity to the existing buildings. The objective of the design analyses was to determine the required size, spacing, embedment depths and anchor angle, length of the various elements of the system to meet the performance criteria outlined in Section 2.

3.2 THE FINAL DESIGN

The analysis of the excavation and lateral support system was based on the recommendations in CIRIA C760. The design comprised the following items:

- Serviceability Limit State (SLS) analysis to estimate deflection, forces and bending moments on the retaining wall using PLAXIS/WALLAP.
- Overall stability check using PLAXIS/WALLAP.
- Structural design on the structural elements of proposed retaining wall system based on the SLS analysis results from the PLAXIS/WALLAP analysis to determine the sizes of elements for retaining wall system, such as CBP piles, capping beam, sheet pile wall and ground anchors.

Above design procedure was iterated to confirm the stability of retaining system and that it could control the horizontal deflection at the existing structures within the design limits using the construction sequence below. PLAXIS program was frequently used to analyse deep excavations and embedded retaining walls, e.g. Zhang & Donohue (2014). PLAXIS 2-D was used on this project to assess the deep excavation effects on the adjacent buildings and structures and to calculate the wall forces for structural design.

The predicted deflections were the result of analysing the key construction stages at critical sections and determining the cumulative horizontal ground deflection adjacent the building at the completion of construction. A typical predicted deflection of the CBP wall from a 2-D FEM is shown in Figure 3 below.

3.3 PLAXIS MODEL/OUTPUT

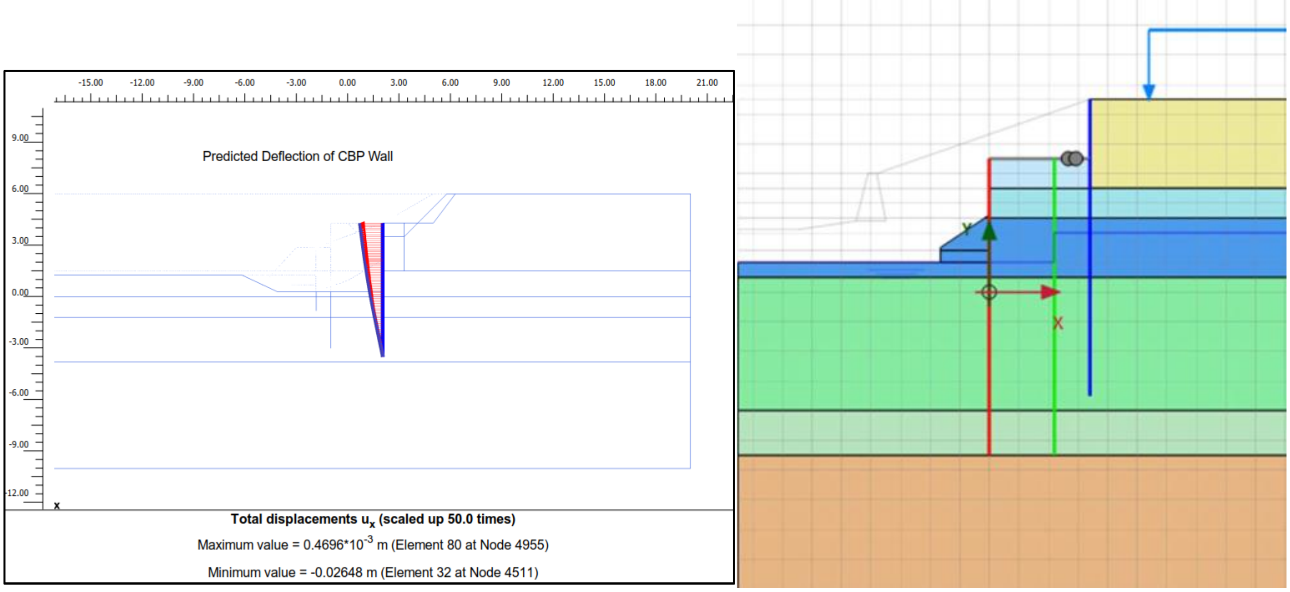

Figure 3: Left: Predicted CBP wall deflection at final excavation level; right: a typical Plaxis 2D model

3.4 ANCHOR TESTING

Anchor pull-out testing was conducted in accordance with RMS Specification R56 Ground Anchors to verify the pull-out resistance of the anchors before final design. Ultimate bond strength of 85 to 155 kPa was estimated from 6 anchor pull-out tests in soil. A lower bound resistance 85kPa was adopted for final design of the anchors.

3.5 INSTRUMENTATION AND MONITORING

An instrumentation and monitoring program was implemented during construction of the channel widening to manage construction risk during excavation in this high risk environment. Instruments included inclinometers, piezometers, building settlement survey markers and 3D survey prisms. The Alert Level of 18 mm and Work Suspension Level of 25 mm were adopted to the inclinometers behind the CBP wall; The sheet pile wall deflection Alert and Work Suspension Levels respectively were 11 mm and 15 mm respectively. All these instruments were installed with a base line reading taken prior to excavation works. The instruments were protected from damage from construction activities and monitored at a frequency of minimum twice per week during construction (from excavation to backfilling to final surface level). The frequency was adjusted during construction with review of the monitoring results. The monitoring frequency was reduced to weekly/fortnightly after backfilling to final surface level was completed.

The monitoring program showed wall deflections (max recorded ~ 15 mm) well within the predicted values and validated the design as robust and durable. Figure 4 shows a typical inclinometer deflection profile taken during construction and movements of prisms on the temporary sheet piles. The finished section of the retaining wall and a photo during construction are shown in Figure 5.

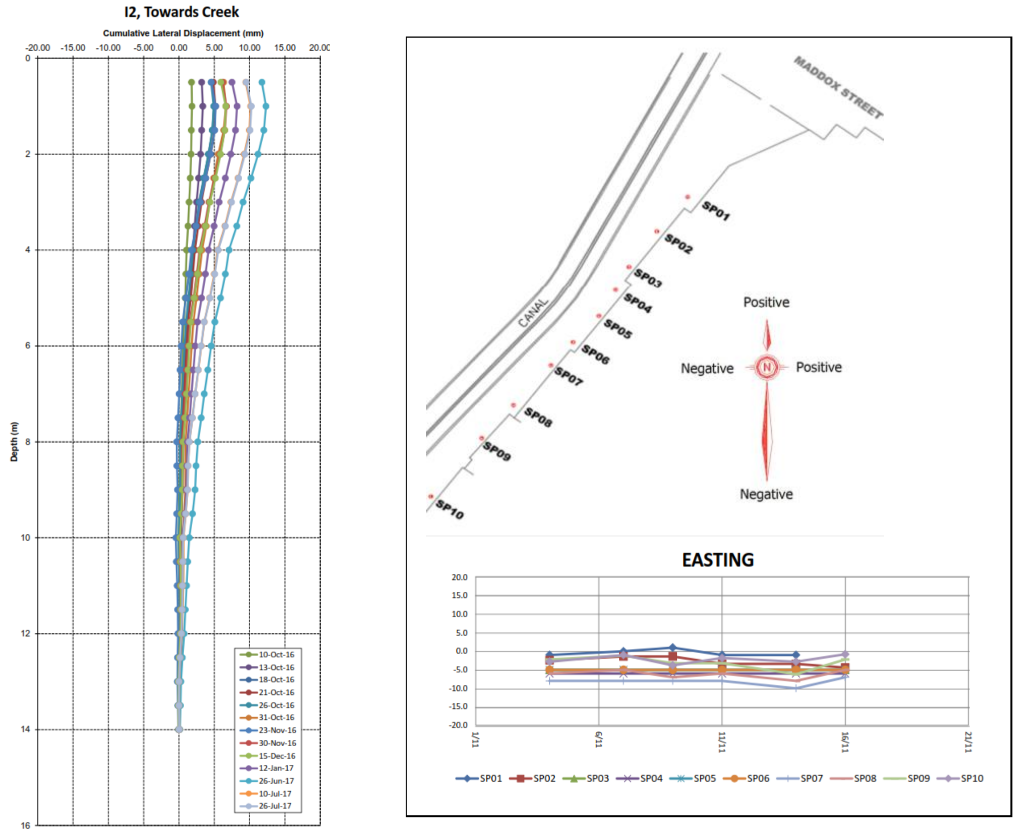

Figure 4: Left: a typical inclinometer plot; right – survey point showing lateral movements at wall top

Figure 5: Left: channel widening near Alexandra Canal outfall (artist's impression); right: photo during construction

4. MICROTUNNELLING

4.1 GROUND CONDITIONS

Ground conditions along the microtunnel drives for the GSSD comprised uncontrolled fill materials, overlying Quaternary deposits, residual soils and rock, as shown in Figure 6. The depositional nature of marine materials, and the uncontrolled nature of fill materials meant the variable ground profile presented significant geotechnical engineering challenges. These risks were managed by adequately scoping investigations, numerically modelling designs and adopting observational methods during construction.

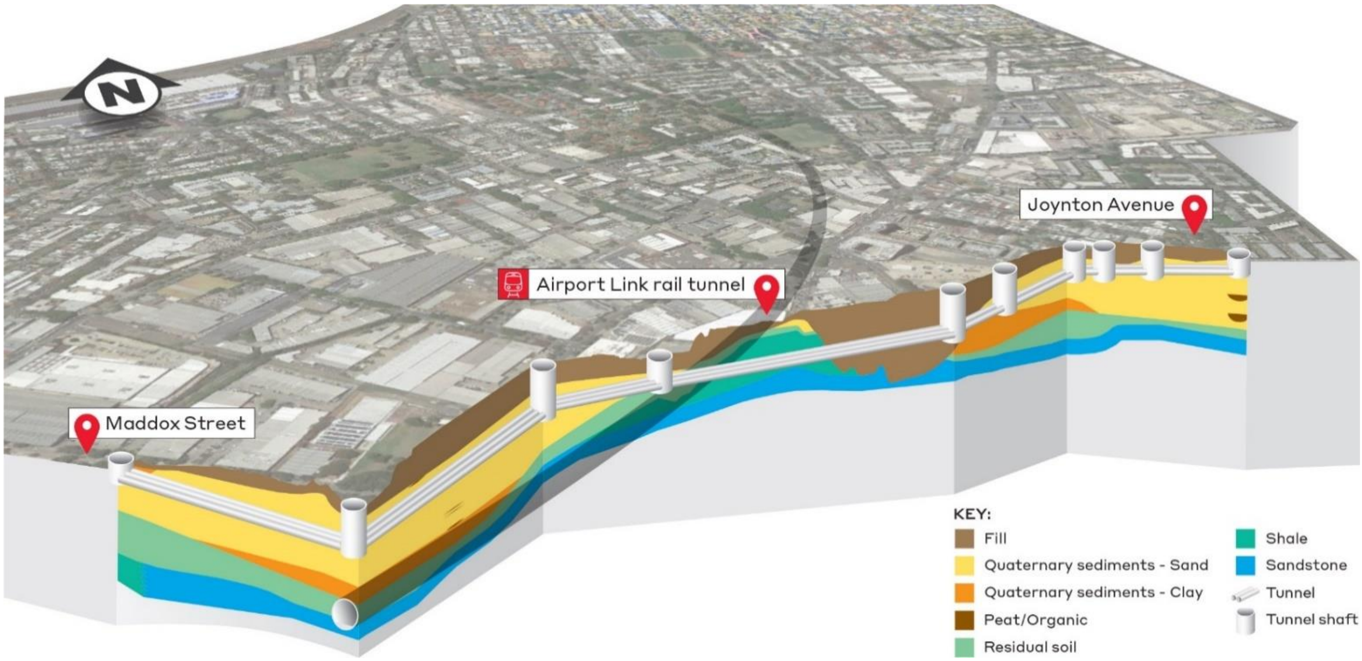

Figure 6: Schematic view of microtunnel drives showing route alignment and stratigraphy

4.2 TRENCHLESS SOLUTION

Conventional “dig and replace” solutions using box culverts were evaluated, however the pipeline geometry and poor ground conditions, difficult construction, impact on utilities and structures, spoil and dewatering disposal, as well as impact on the community and traffic made it undesirable. Subsequently, the Alliance developed its bid-winning proposition to change the stormwater drain’s reference construction methodology from open trenching to a trenchless solution.

For the microtunnelling a boring machine (MTBM) was pushed through the ground by advancing multiple 1800mm diameter pipes from jacking shafts (caissons). Ground behaviour at the face of excavation depended on the composition of the ground. The project adopted a slurry MTBM which provides constant face pressure to counterbalance earth and groundwater pressures by pumping engineered drilling fluid into the MTBM face. The fluid pressure should be kept greater than the earth and groundwater pressures to avoid over excavation, settlement and sinkholes (Figure 7).

Iseki Microtunnel Boring Machine (MTBM) used the ‘closed-face slurry shield’ with no tail void grouting and bentonite to help the drilling process. The slurry spoil transport system provides earth pressure balance, which is controlled by adjusting the flow rate from the control room. Consequently, the rate of spoil removal from the drilling head’s cutting face, directly relates to the pace the drilling head advances. Varying the slurry cycle according to specific ground conditions, allows microtunnelling to continue in soils without reducing performance.

Figure 7: Microtunnel installation in caisson

4.3 CAISSON CONSTRUCTION

Using cast in-situ techniques, construction started on five caissons at ground level, and worked downwards, which was faster, quieter, and safer than traditional construction methods such as secant pile walls. Concrete segments were cast on-site to form rings (one on top of the other), which were then pushed below ground level to form the wall of the shafts 10–12-metres deep (Figure 6). The circular shape allowed the caisson was self-supporting by mobilising hoop stress without struts or ground anchors. To ensure this worked, the overall excavation sequence was given detailed attention to avoid asymmetry/unbalanced forces.

Given how close many of the construction sites were to buildings, roads, and trees, it was important to create as little disruption as possible for those living, working and commuting nearby. In-situ caisson construction proved well-suited for the project and required a significantly smaller site footprint than many traditional methods.

4.4 SETTLEMENT AND GROUND MOVEMENT ASSESSMENT

Microtunnel works had the potential to impact multiple third-party assets comprising over-ground structures, buildings, underground structures and utilities within tight space constraints. Each asset had to be assessed for the impact from predicted ground movement to manage impacts within acceptable limits. Where needed, mitigation measures were developed and implemented to ensure all third-party assets were not impacted throughout construction. As an additional complication, tunnelling was carried out close to the Airport Line rail tunnel, which extends from Sydney CBD to Sydney Airport (Figure 8). Predicting ground movement and assessing impacts followed the well-tested and understood Gaussian curve empirical methods for bored tunnels, which was 1 to 5 mm with a similar volume loss. Finite-element analysis was used next to critical locations to create a combined ground displacement model, which could be used to assess the level of impact on adjacent assets.

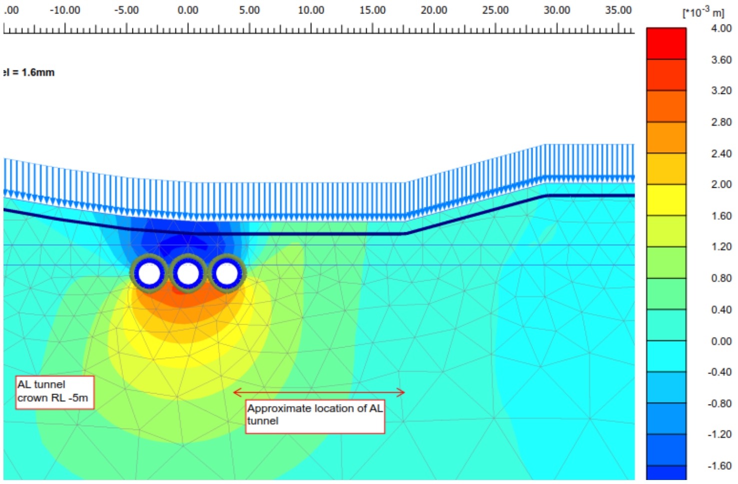

Figure 8: Typical microtunnel section showing estimated displacement (U_y)on Airport Line rail tunnel using Plaxis 2D

4.5 MICROTUNNELLING BENEFITS

Pipe jacking and microtunnelling systems reduce the social and environmental disturbance when installing services in urban areas. Benefits are summarised in Table 2 and included:

- Minimum impact on more than 120 underground utilities crossing the GSSD alignment.
- Minimum impact on existing roads and developments (no open cut).
- Minimum environmental impact (spoil and dewatering).
- Minimum community impact (no open cut).
- Cost-effective hydraulic solution.

Table 2: Comparison with conventional trenching at depth, between Maddox Street and Joynton Avenue

Item	Microtunnelling	Typical Trench
Spoil volume	10,000 m^3	80,000 m^3
Groundwater volume removed	40kL/day	1,000 kL/day
Footprint disturbed	~8,000 m^2	~25,000 m^2
Services (diverted or supported)	5	86
Greenhouse gas	Saved 28% CO_2 emissions	

4.5 LESSONS LEARNED

The microtunnelling section of this project was particularly difficult in the poor ground conditions, with tight logistical constraints, contamination and numerous obstructions. In review of the chain of events, the authors offer the following reflections:

- Address risk of obstructions in landfill prior to route selection.
- Confirm every known utility, existing foundation, or abandoned structure is clear of the alignment, prior to tunnelling.
- Install instrumentation points at appropriate depths along the alignment for feedback regarding MTBM performance. When alarm values are reached, take appropriate action.
- Slurry composition and slurry management are critical to reducing ground loss in mixed face conditions.

5. CONCLUSIONS AND RECOMMENDATIONS

The GSSD is a complex project that was essential to eliminate the high-hazard flooding from the area to deliver a livable urban renewal of this inner-city area. It was delivered through the cooperation of local and state government, construction contractors and designers in an alliance framework.

This paper discusses the major challenges and innovative engineering solutions of the design and construction of the 300 m long earth retaining system to meet the tight design criteria in order to protect existing warehouse buildings, underground services and to accommodate the tight site constraints, e.g. steep batters, weak ground conditions, a very narrow corridor between existing buildings and the proposed retaining wall which limits the use of ground anchors.

The Alliance developed a robust design which involved the following:

- Suitable in-situ testing (CPT and DMT) to better understand the ground profile and to estimate realistic design parameters.
- Innovative retention solutions including cantilever, CBP wall with anchor and CBP wall with reaction pile.
- Advanced numerical modelling to assess ground and structural deformations in staged construction, construction testing and verification.
- Comprehensive instrumentation and monitoring system for construction control.

The monitoring data indicated that the retaining wall deflection, building lateral displacement and settlement were well within the allowable limits, which proved that the design was robust and durable.

Changing the construction methodology of the stormwater drain from open trenching to a trenchless solution achieved close to $A100 million in project cost savings when compared with the original design solution, and significantly reduced environmental impacts and community disruption. The adopted microtunnelling methods successfully addressed the site ground engineering challenges including difficult ground conditions and landfill, while also addressing construction impacts on adjacent infrastructure.

6. ACKNOWLEDGEMENTS

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