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Geotechnical challenges in the design and construction of Sydney Metro works at Central Station

Défis géotechniques dans la conception et la construction de la gare centrale du métro de Sydney

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ABSTRACT: The existing Central Station in Sydney is the busiest railway station in Australia housing 25 platforms. The Sydney Metro works at Central Station (CSM) involved the excavation of a 27-metre deep station box below former Intercity Platforms 13, 14 and 15 (immediately adjacent to existing live tracks 12 and 16), and the construction of a pedestrian concourse, Central Walk (CW), which has been mined 1.5-metres below the suburban tracks and platforms 16 to 23 (connecting to Chalmers Street in the east). The requirement to protect the live tracks, pedestrian movements, existing heritage and movement of sensitive structures resulted in very carefully considered design and construction methods. This paper firstly presents the geological context of the project including the design and construction challenges due to the presence of several geological features through the site and the historic developments. Critical geotechnical design issues are discussed in conjunction with a description of the construction solutions adopted for the excavation of the station box and Central Walk. The unprecedented underpinning schemes implemented across various parts of the project are also presented in the paper. The paper also discusses the geotechnical monitoring scheme, and the monitored impacts to adjacent rail and structures.

RÉSUMÉ : La gare centrale existante de Sydney est la gare ferroviaire la plus fréquentée d'Australie, abritant 25 plates-formes. Les nouveaux travaux principaux de la station centrale du métro de Sydney (CSM) impliquaient l'excavation d'une station de métro de 27 m de profondeur sous les plates-formes interurbaines existantes 13, 14 et 15, immédiatement adjacentes aux rails sous tension existants 12 et 16, et la construction d'un tunnel piétonnier appelé la promenade centrale (CW) qui a été minée à 1,5 m sous les chemins de fer de banlieue et les quais 16 à 23 reliant la rue Chalmers à l'est. L'obligation de protéger les rails vivants, les mouvements des piétons et les structures existantes sensibles au patrimoine et aux mouvements a abouti à des méthodes de conception et de construction très soigneusement étudiées. Cet article présente tout d'abord le contexte géologique du projet, y compris les défis de conception et de construction dus à la présence de plusieurs caractéristiques géologiques à travers le site et les développements historiques. Les problèmes de conception géotechnique critiques sont discutés en conjonction avec une description des solutions de construction adoptées pour l'excavation de la Metro Box et de la promenade centrale. Les schémas sous-jacents sans précédent mis en œuvre dans les différentes parties du projet sont également présentés dans le document. Le document examine en outre le programme de surveillance géotechnique et les impacts surveillés sur les rails et les structures adjacentes.

KEYWORDS: metro, excavation, underpinning, mining.

1 SYDNEY METRO, CENTRAL STATION

1.1 *Introduction*

In 2024, Sydney will have 31 metro railway stations and a 66km standalone metro railway system, revolutionising the way Australia's biggest city travels. A significant underground station along the alignment is the Sydney Metro's Central Station, constructed under the existing Central Station, which is Australia's busiest railway station with an average of 233,970 passengers daily (UTS, 2019).

The Sydney Metro works at Central Station (CSM) involves the excavation of a 27-metre deep station box below the former intercity platforms 13, 14 and 15, immediately adjacent to existing live tracks, and the construction of a pedestrian concourse, Central Walk (CW), which has been mined 1.5-metres below the existing suburban tracks and Platforms 16 to 23, connecting to Chalmers Street in the east.

Figure 1 shows the project works within the existing station and Figure 2 presents a cross section along the east-west concourse showing the key elements of the CSM works including the station box, the Central Walk, the breakthroughs at both ends of the existing Eastern Suburbs Railway (ESR) box and the Eastern Entry (EE).

This paper discusses the geotechnical challenges associated with the key underground construction elements at both the station box and Central Walk during the design and construction.

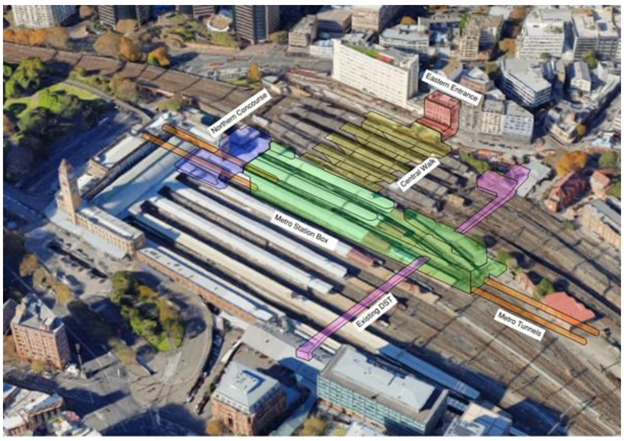

Figure 1. Central Station Metro works overlaid with existing station

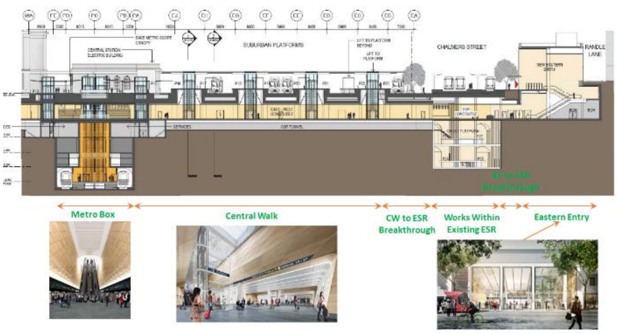

Figure 2. Section through the East-West direction

1.2 *CSM main components*

A brief description of the main CSM components which required significant geotechnical inputs is provided below.

1.2.1 *Station box*

Figure 3 below illustrates a general section through the station box. A combination of 750mm, 900mm and 1200mm diameter cast in-situ bored piles form the upper part of the permanent station box structures and have been designed to retain lateral pressures transmitted through the soils as well as to carry the vertical loads induced by the suspended structures in and above the station box. Top-down construction of the station box was then carried out to a 27-metre depth involving 5 levels of basements adjacent to the existing Platform 12 and 16 tracks located 2.1-metres away. The station box works also included the underpinning of the existing Devonshire Street Tunnel through the station box.

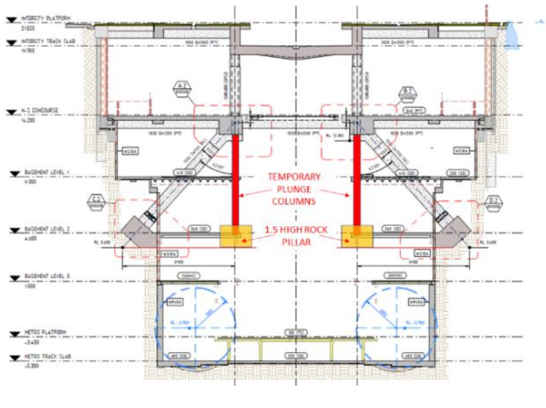

Figure 3. General cross section through the station box

The general construction sequence for the station box was as follows:

1. Construct perimeter piling and plunge columns
2. Excavation and construct the intercity platform slabs
3. Excavation and construct the concourse level slab
4. Excavate to level RL 3.655 (key interface level with the Sydney Metro Tunnel and Station Excavation contractor)
5. Load transfer from the temporary plunge columns to the permanent raking columns
6. Construct levels B2 and B1
7. Excavate to metro track soffit once tunneling work completed
8. Construct level B3 and remaining structural works.

2.2 *Central Walk and the Breakthroughs*

The Central Walk pedestrian concourse links together the EE/ESR Concourse, station box concourse and the suburban platforms. The structural width of the concourse is 22.2-metres, a structural height of approximately 4.7-metres (from top of structural slab) and total length of approximate 80-metres. The Central Walk concourse includes a service tunnel which was excavated as a temporary advance construction tunnel ("adit") for construction access. Central Walk has been constructed by mining method under the suburban tracks and Platforms 16 to 23. The works included provision of escalators and lifts from the new concourse to Platforms 16/17, 18/19, 20/21 and 22/23, and the demolition of the existing baggage tunnel running along the length of Platform 18/19.

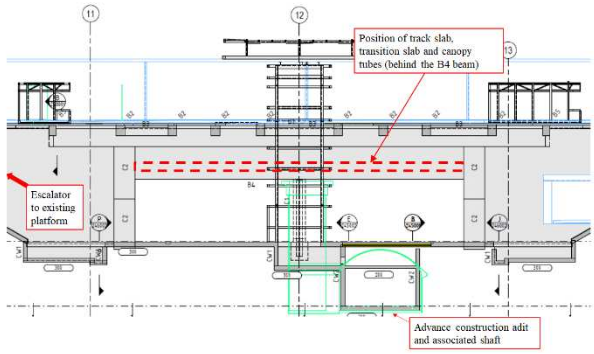

Figure 4. Cross section of Central Walk

A combination of track slab and transition slab scheme was adopted for Central Walk as the temporary / primary support to the roof and the overlying rail tracks and platforms.

There were two connections between the new Eastern Entry through to the new Central Walk under Platform 23, through the existing ESR box, namely the EE-ESR and the EE-CW breakthroughs which were supported using a pipe roof (called 'canopy tubes') drilled from the shafts at the Eastern Entry and Platform 23 respectively to the existing underground station box of the ESR underneath Chalmers Street. The canopy tubes for the CW to ESR Breakthrough involved 610mm diameter x 12.7mm thickness tubes pretensioned with 2x50mm diameter Freyssibar. While for the EE to ESR breakthrough, 508mm diameter x 12.7mm thickness tubes were utilized.

A typical cross section through Central Walk is shown in Figure 4. The general construction sequence for Central Walk was as follows:

1. Construct temporary construction adit and stubs at each Platforms for connection to the spoil shaft;
2. Construct platform grillage beams including the B1, B2, B3 and B5 beams and roof canopy foundations;
3. Excavate B4 shafts at platforms install C2 stubs;
4. Install track slab and transition slab, or canopy tubes;
5. Mine Central Walk from the station box in a sequential manner, install temporary steel sets and ground support, and excavate lift and escalator shafts to platforms.

3 SITE CONDITIONS AND GEOLOGY

3.1 *History*

There is a long development history associated with the existing Central Station site, starting from the mid-19th Century. The various developments in the past have significant impact on the current CSM works due to the presence of deep fill zones and buried brick walls, in particular on the method of excavation support and piling works.

The original Sydney train terminus was opened in 1855, located between Cleveland Street and Devonshire Street. The building that occupies the current Central Station site was officially opened in 1906, with a total of 11 platforms, which was expanded to 19 platforms by 1913. As part of the station construction, the former Devonshire Street was closed and the present day pedestrian tunnel constructed during this period, partially below natural ground level, using open cut methods.

During the 1920s, the station further expanded to the east, with the addition of the present day Platforms 16 to 23. At this time, the Devonshire Street Tunnel and existing baggage tunnels were extended and upgraded, and a series of tunnels were constructed linking a new northern concourse and southern concourse to these platforms.

The next major change to the station occurred in the early 1950s with the excavation of the ESR box, below Chalmers Street, housing the current platforms 24 and 25 and two “ghost” platforms. The excavation of the ESR box involved mainly open cut techniques, with shoring of soil and weathered bedrock performed through a combination of brick retaining walls, sheet piling and shotcrete which presented significant challenges to the current CW to ESR and ESR to EE breakthrough works.

3.2 *Geology*

The CSM site is situated within the geological area known as the Sydney Basin. The Sydney Basin is generally characterized by a sub-horizontally Permo-Triassic age sedimentary sequence of rocks including Ashfield Shale, Mittagong Formation and Hawkesbury Sandstone Formation

Due to the site history, and major redevelopments throughout the last 150 years, the presence of fill materials were found to be ubiquitous across the site. Due to the many different episodes of excavation and filling associated with various subways, drainage trenches and old platforms, the material is significantly heterogeneous.

Central Station is built on the former ‘Sandhills Cemetery’, and is located to the north of the mapped extent of the Botany Basin sediments. Hence transported soils were also encountered, including those potentially associated with the wind blown sediments of the upper Botany Basin sediment.

Residual soil derived from both Ashfield Shale and Hawkesbury Sandstone, and the inter-boundary Mittagong Formation, was encountered during excavations at the site. Typically, residual soils and extremely-weathered rock are around 0.5 to 5-metres in thickness. The residual soils associated with shale bedrock areas are generally described as medium to high plasticity silty clay, of very stiff to hard consistency.

The volcanic dyke passing through the CSM site has been numbered as the Pittman LIX Dyke, commonly known as the Ultimo dyke. The dyke was encountered during construction of the station box, and was measured as 3 to 6-metres wide. Figure 5 shows the 3-D geological model with rock head and the dyke.

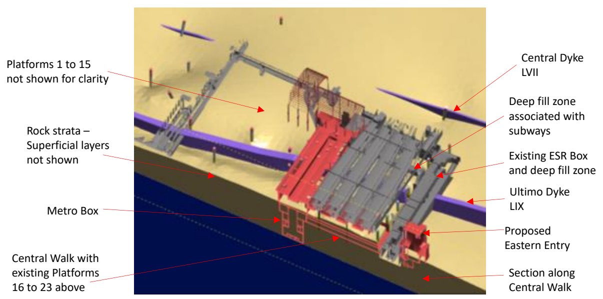

Figure 5. 3-D Geological Model for Central Station

The high locked-in horizontal stresses at magnitudes well beyond the corresponding overburden pressure, and the associated ground movement during excavation had significant impact on the CSM design and construction due to the top down construction method adopted. The in-situ stress testing using overcoring for the CSM site indicated general agreement with the published stress relationships as presented in Pells (2004) and Bertuzzi (2014).

The available geotechnical data indicates two broad groundwater regimes including a perched water body within the fill, surficial soils and weathered shale between RL 17 to 19m AHD, and a lower water body within the Hawkesbury Sandstone, with a water level of about RL 3.5 to 4.2m AHD.

The geological interpretation indicated that the excavation of the station box will encounter up to 9 metres of soil material including fill, alluvium and residual clay, overlying Ashfield Shale and Hawkesbury Sandstone. The excavation of Central Walk also involves a similar however with the absence of alluvial material.

4 DESIGN INNOVATIONS AND GEOTECHNICAL CHALLENGES

4.1 *Design innovations*

Alternative design schemes were developed in the competitive bidding, detailed design and construction stages, to de-risk potential impact to rail operation of the existing station, and to accelerate construction program. Some of the design schemes that were changed from the reference design, and involved significant geotechnical challenges are listed below and discussed in this section:

- An advance adit tunnel is added in the design for removal of excavation spoil and transporting construction material to reduce the required rail possessions;
- An alternative track slab scheme for Central Walk was adopted for ground support prior to mining under to avoid construction delay due to unforeseen obstructions during canopy tubing and eliminate possible construction disruption to live rail traffic;
- A top-down construction method with raked struts for the station box for space and structural efficiency, reduce extent of temporary works and enable early completion of critical parts of the station box;
- A full underpinning scheme for Devonshire Street Tunnel to eliminate any closure to the popular pedestrian tunnel hence less disruption to passengers, and
- A widened undercut providing space for the back of house to keep mechanical and electrical equipment.

4.1 *The advance adit alternative*

4.1.1 *The adopted scheme*

The original reference design that was put to tender included a permanent service void below Central Walk, as shown on Figures 2 and 4. After the contract award, consensus was reached that a temporary advance adit along this service void should be seriously considered. The adit was then built to facilitate the transport of spoil and materials to and from the suburban platforms during the construction of Central Walk, hence reducing the need for hi-rail track access. As construction of Central Walk proceeded, the roof of the adit was demolished, and the adit space was converted into the permanent services void below Central Walk. The construction adit connected the station box in the west and to the ESR box at the east, passing beneath the existing and disused baggage tunnel at Platform 18/19. A long section along the adit is shown in Figure 6 below.

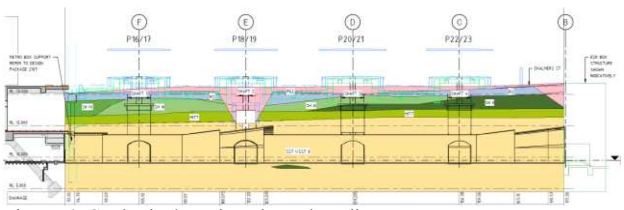

Figure 6. Geological section along the adit

4.1.2 *Geotechnical challenges*

The majority alignment of the adit tunnel was excavated in Class III or better sandstone, approximately 6 metres below the suburban live rail. An arched roof and vertical sidewalls were generally adopted, and the ground support comprised steel fibre reinforced shotcrete and temporary Glass Reinforced Polymer (GRP) rockbolts at 1.2 metres transverse and 1.5 metres longitudinal spacing.

The key geotechnical challenges for the construction of this tunnel included the interfaces with the station box, the interface with the Platform 18/19 baggage tunnel and the interface with the ESR box.

At the station box interface, canopy tube pre-support was adopted to prevent any wedges releasing during the adit initial excavation. A reinforced concrete header beam was adopted also at this interface to provide initial restraint to the canopy tubes prior to the first advance. Final support was provided by steel fibre shotcrete reinforced with lattice girders in this interface.

The construction of the adit involved tunnelling below the existing baggage tunnel and the associated drainage trench, as well as construction of a shaft through the center of the baggage tunnel. As there was limited rock cover between the baggage tunnel and the temporary adit, the adopted design solution comprises pre-support of ground ahead of the tunnelling face using 114mm diameter canopy tubes, with final ground support comprising a thickened shotcrete lining with lattice girders and steel reinforcement, as shown in Figure 7.

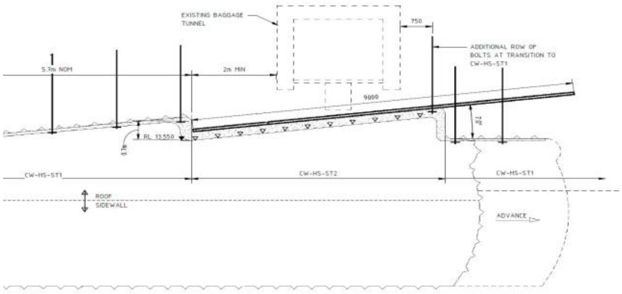

Figure 7. Adit ground support below the existing baggage tunnel

At the ESR interface, ground support comprised pre-support with canopy tubes, steel fibre shotcrete and lattice girders. GRP rockbolts have also been included to address the future Central Walk to ESR breakthrough, the excavation of which would induce additional stresses on the adit tunnel lining.

During the adit construction, a maximum tunnel convergence movement of 5.6mm was recorded against a predicted value of 6mm.

4.2 *Central Walk mined excavations*

4.2.1 *Adopted tunnel support scheme*

The reference design for Central Walk excavation that was put to tender involved smaller diameter canopy tubes of 408mm diameter for roof support and then excavation and steel frame support at every 1.5-metres advance. The tender design adopted 910mm diameter canopy tube with the removal the need for all temporary steel frame. This could have provided significant advantage on the construction program. However during the site investigation stage of the detailed design, it became clear that the 910mm canopy tubes would have a high probability of encountering obstructions during their installation. As a result of this risk assessment, a “track slab” scheme was constructed on Track 16 to Track 22 in lieu of the 910mm canopy tube solution. The track slab structure consisted of a series of steel beams with a reinforced concrete deck on top and reinforced concrete slabs connecting the ends of the track slab to the B4 beam (canopy support beam portals) or B6 beam (station box header beam). It was installed in a full weekend possession using open cut. The track slab provided initial structural support during the mined excavation and construction of the final structure, following which time it performs as a component of the permanent way. Typical track slab module using 400 SHS is shown in Figure 8 below.

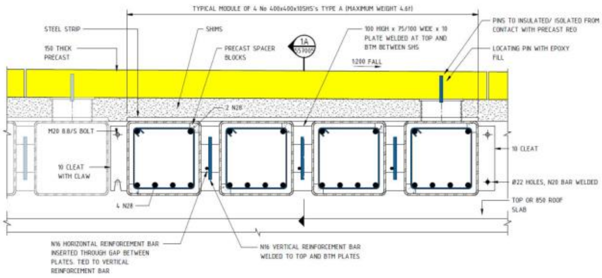

Figure 8. Central Walk track slab module detail

4.2.2 *Geotechnical challenges*

The key geotechnical challenge for the track slab scheme at Central Walk was to design an appropriate temporary support, underpinning and excavation sequence to enable the safe construction of the works, and to minimize the impact on the live tracks and platforms merely 1.5 metres above. Over 80 excavation and temporary support/underpinning stages were stipulated in the design over the excavation length of 60 metres, which was then substantially optimized during construction based on the observed ground conditions, and monitoring results.

Numerical methods have been used to assess the overall ground-structure interaction, associated ground movements and impact to live rails and platforms. This included 2-dimensional longitudinal and transverse FE models (using RS2), and 3-dimensional FE model (using Plaxis) which explicitly modeled the temporary and permanent structural elements associated with the track slab and the supports in Central Walk, as well as the 3-dimensional excavation sequence as shown below in Figure 9.

During the design, a surface platform settlement of up to 22mm and a rail movement of up to 18mm were predicted. Monitoring of the ground, rail and structure response was carried via a comprehensive instrumentation scheme enabling the validation of the predicted system response against design criteria for serviceability and associated ultimate performance predictions and effects on adjacent infrastructure (including live rail operations). Track and rail infrastructure monitoring for differential movements have been undertaken in accordance with requirements outlined within SPC207 Track Monitoring Requirements for Undertrack Excavation. During construction, a maximum platform coping beam movement of 17mm and a track movement of 16mm were recorded, at Platform 16 and Rail 17 respectively.

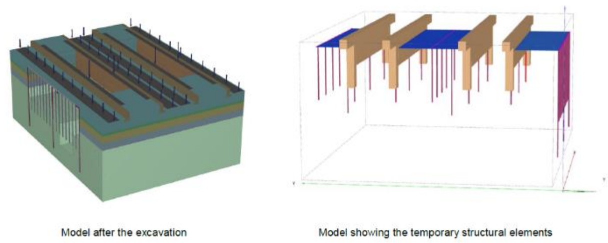

Figure 9. Plaxis model for assessing Central walk excavation staging

4.3 *Station Box top down construction with raked struts*

4.3.1 *The adopted scheme*

The perimeter pile wall for the station box, spanning from ground level to approximately basement level 1 at a depth of 12.5 metres, was designed to facilitate the top-own construction of the CSM works underneath the existing Central Station heavy-rail platforms with the minimal temporary works against the lateral earth pressure and water ingress. Plunge in steel columns, located along the central part of the station box, were designed to support the suspended basement structures during the top-down construction. After excavation to RL3.655, a load transfer was required from the temporary plunge columns to the permanent raking struts in order to progress the excavation beyond the RL 3.655 level, after the TSE contractor handed over the zone below RL 3.655. The permanent loads from the intercity track level and the concourse level, as well as the hanging loads from B1 to B3, were then supported from inclined struts which are founded above RL 3.655, as shown in Figure 2.

4.3.2 *Design to accommodate rock stress relief*

One of the critical geotechnical issues for the station box excavation involved the assessment of ground movements induced by release of locked-in stress in sandstone, and the design to accommodate a top-down sequence to minimize the impact to the permanent structures that have already been constructed above. Geotechnical and structural engineers interacted closely to derive an optimal solution. Firstly, a geotechnical movement analysis of the structure was carried out due to the excavation, using Rocscience software RS2 via both continuum and discontinuum analyses, as shown in Figure 10 below. The numerical model included consideration of the previous Eastern Suburbs Railway (ESR) station box excavations and the associated stress relief.

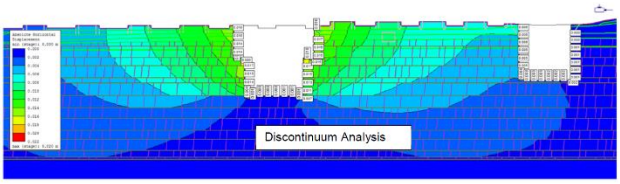

Figure 10. Results of the ground movement assessment

The analysis results show that the stress relief induced displacements were to be substantially horizontal. The estimated maximum horizontal/lateral displacement for the base (characteristic) stress field was about 20 mm for discontinuum analysis. This equates to approximately 0.8 mm per meter depth of excavation which is consistent with previous empirical data (particularly considering favorable orientation relative to the major and minor horizontal principal stress field). During construction, a maximum wall movement of 18.7mm was recorded at Pile 261, located at the western wall near Grid 14.

To avoid the expected movement in the rock crushing the permanent structure, the solutions adopted for the metro concourse structure (at RL 14.2) included hydraulic jacks that controlled the effects of inwards lateral movement and also in the meantime maintained the contacts between the rock and the beams so as to provide lateral restraint to plunge columns in a controlled manner.

4.3.3 *Raking column footing assessment*

The raking column (also called "raked struts") footings were designed to support the imposed dead and live loads from both the intercity and concourse slabs. They were expected to be heavily loaded with an estimated footing load of over 36MN each. As the footings were to be located adjacent to the station box cutting face, it is prudent that the footing is sized and located such that the induced stress at the excavation boundary does not exceed the rock mass strength at the same location to avoid a progressive failure of the rock mass. The foundation behavior including the assessment of ultimate bearing capacity and the induced stress was undertaken via a PLAXIS Model (see Figure 11 below). The assessed stress along the excavation boundary was less than 1.6MPa, with a safety factor of 2.5 against the typical rock mass strength.

During construction, the founding strata for these heavily loaded footings were closely mapped and the associated movements were monitored. Further strengthening works were carried out during construction adjacent to the Ultimo Dyke. The monitored footing movement was typically less than 4mm.

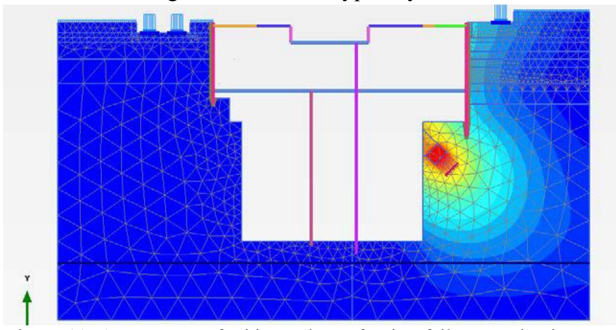

Figure 11. Assessment of raking column footing failure mechanism

4.3.4 *Interfacing with the TSE tunnel*

During the station box top-down construction, dead and live loads from the intercity and concourse slab were transferred via end bearing plunge columns founded on RL 3.655, 3m above the crown of tunnels passing through the base of the proposed excavation profile, as shown in Figure 2. Prior to full excavation of the station box, the tunnels were required to be operational to service the tunnel boring machine (TBM) operations during the remainder of the tunnel construction.

This important interface was carefully assessed during design and closely monitored during construction due to the potential safety concerns. A strong dependency on the in situ stresses of the rock was evident. As shown in Figure 2, a 1.5-metre-high and 3.4-metre-wide rock pillar was left in place around the plunge columns. Both design assessment and monitoring indicated the heavily loaded plunge columns had no significant adverse impact on the integrity of the TBM tunnel lining.

4.4 *Devonshire Street Underpinning*

4.4.1 *Devonshire Street Underpinning scheme*

The reference design scheme for Devonshire Street Tunnel (DST) involved excavation from the DST to divert the utilities under and an open excavation with a strengthened ground slab. This would have required the closure of the DST. The adopted scheme involved a full underpinning structure and included: 1) 1050 mm thick deep beam to retain the temporary and permanent earth pressures and the loads from the DST structure on either side of DST, and 2) 900-diameter horizontal pipe piles spaced 1.35 m c/c connected to deep beam/wall at RL. 10.00 m (centerline) to form the effective underpinning structure. As shown in Figure 12 below.

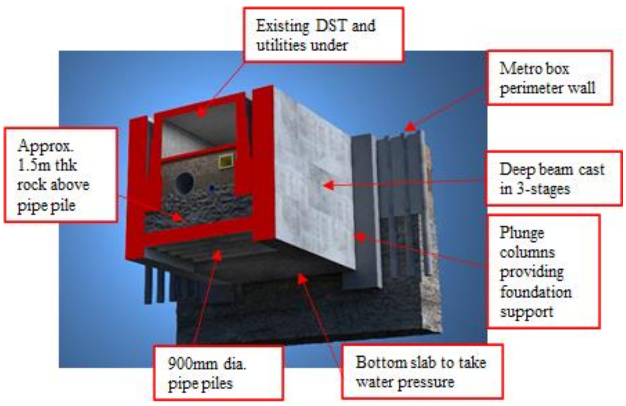

Figure 12. Project model DST tunnel underpinning structure

4.4.2 *Geotechnical challenges*

The DST was recorded to be backfilled with sand around the tunnel, of unknown origin (but possibly locally sourced). The recent inclined boreholes encountered shallow obstructions, potentially related to former stanchion footings. Deep sand fill to a depth of 6.7 metres to the south of DST was also encountered. Further the ground adjacent to the DST has been assessed to have been disturbed due to the presence and upgrade of sewer and stormwater drains adjacent to the DST. To mitigate this ground condition risk, a secant pile wall consisting of 600mm diameter piles was installed between the deep beam and the DST to retain the soil around and below the DST during the adjacent excavation of the station box and underpinning.

The potential DST movements during the staged excavation and underpinning were assessed in a sophisticated Plaxis 3D model. A DST movement of 17mm was predicted. Survey monitoring was undertaken of the DST to assess the magnitude of strains induced within the tunnel structure, and the underlying utilities. Further, horizontal inclinometers with in-place sensors were proposed in three of the horizontal pipe piles enabling real time communication of monitoring data. A 27mm maximum movement was detected during the DST construction however location was outside the station box. Within the station box the movement of the DST was recorded to be less than 8mm.

4.5 *Undercut*

4.5.1 *The Undercut Scheme*

The station box geometry was limited by the existing intercity and suburban rail lines that are required to remain in their current alignments. At the southern end of the station box this provided a limiting width for the box that is less than that required by the metro train at the base of the station box. This was resolved by creating an undercut that begins at Basement level 1 sloping to Basement level 2. This wall effectively undercuts the base of the piles along the eastern edge between grids 20 and 22.5 for a total length of 34 metres and a maximum width of 4.5 metres. A cross section of the undercut and when it was under construction is shown in Figure 13.

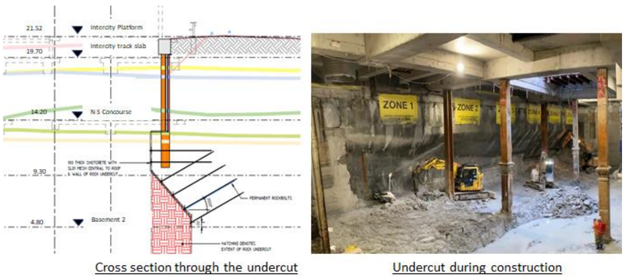

Figure 13. the Undercut (34m long and 4.5m wide)

4.5.2 *Geotechnical challenges*

The critical issues involved in the geotechnical design of the undercut included 1) the design and sequencing of a suitable ground support system to enable the support of the undercut to the soil loads, the dead and live loads imposed by the two floors at the intercity rail/platform and the concourse levels, and the concentrated pile loads with the pile toe 200mm above the undercut; and 2) to minimize the deformation so that the overlying permanent structures and adjacent Track 16 are not adversely affected. To address these issues, the design included six layers of ground support involving DSI DEWI double corrosion protection bolts and conventional DSI CT bolts. The excavation was carried out in 6 zones and a total of 14 stages. The design assessments included global and wedge limit equilibrium analyses, and deformation analysis using RS2 and Plaxis. During construction, initial probing was carried out to confirm design assumptions. Geotechnical mapping and close monitoring of the ground and structural movements were carried out. During construction, further bolting was implemented in Zones 3 and 4 due to unexpected movement pattern. 36mm undercut movement was predicted in the design assessment however up to 11mm was monitored during construction due to additional ground support adopted to minimize risk.

5 GEOTECHNICAL MONITORING

The instrumentation and monitoring for the works was required to meet design and specific contractual requirements. The monitoring involved the use of automatic survey prisms, in-place inclinometers, tilt beams, rail monitoring points at 2.4-metre centers, Shape Accelerator Arrays, groundwater monitoring wells, tilt beams, tiltmeters and vibrating wire strain gauges. In addition, Alarm 1, Alarm 2 and Alarm 3A Response levels (AAA) for movement of rail tracks, building and structures including existing subway tunnels and utilities were developed. During construction, all monitoring data involving a total of 6169 monitoring points was uploaded directly to an online instrumentation database system which was shared by the design and construction teams. There were a few cases of rail and the DST movements exceeding the action levels however none of them have resulted in disruption to the existing station operation and the construction.

6 CONCLUSIONS

The CSM works have been carried out in Australia's busiest operating railway station with complexity rarely seen. The history of the site, geological context and the requirements of maintaining the rail operations as normal in all existing platforms presented significant geotechnical challenges. Design innovations involving significant geotechnical input were added in the detailed design and construction stages to minimize impact and disruption to the existing station and speed up construction program. The good collaboration between design and construction has resulted a successful and on-schedule delivery of the complex underground works.

7 ACKNOWLEDGEMENTS

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