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The Great Wall of St Peters – design and construction of a two-tiered trapezoidal reinforced soil wall in a former shale quarry in Sydney City

La Grande Muraille de St Peters - Conception et construction d'un mur de sol renforcé trapézoïdal à deux niveaux dans une ancienne carrière de schiste à Sydney City

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ABSTRACT: A 350 m long retaining wall was built over the former municipal waste landfill at St Peters as part of a multi-billion dollars road tunnel project in Sydney. The retaining wall is located at the tunnel portal that retains the old rock escarpment and provides precious leisure space above the wall. The wall comprises a 21 m high two-tiered trapezoidal reinforced soil wall (RSW) partially supported by a semi-rigid foundation system that provides fill storage behind the wall while meeting tight construction budget and program. An innovative design approach was adopted in the foundation and wall design to maximise backfill storage behind the wall and to overcome space restriction. The constructed two-tiered trapezoidal RSW successfully provided an additional 2,700 m^2 of parkland and retained an additional 8,000 m^3 of fill materials upon completion. The benefit of retaining the additional fill materials behind the wall was substantial and outweighed the cost of the wall and its foundation. More importantly, the fill materials were kept onsite hence eliminating the transfer of an environmental problem elsewhere.

RÉSUMÉ: Un mur de soutènement de 350 m de long a été construit sur l'ancienne décharge municipale de déchets à St Peters dans le cadre d'un projet de tunnel routier de plusieurs milliards de dollars à Sydney. Le mur de soutènement est situé au niveau du portail du tunnel qui conserve l'ancien escarpement rocheux et offre un espace de loisirs au-dessus du mur. Le mur comprend un mur de sol renforcé par deux tirants trapézoïdaux (RSW) de 21 m de haut, partiellement soutenu par un système de fondation semi-rigide qui fournit un stockage en décharge derrière le mur tout en respectant le budget et le programme de construction serrés. Une approche de conception innovante a été adoptée pour les fondations et les murs afin de maximiser le stockage des décharges derrière le mur et de surmonter les restrictions d'espace sur le site. Le RSW construit avec succès a fourni 2, 700 m^2 supplémentaires de parc et conservé environ 8, 000 m^3 de décharges. Les économies réalisées sur le maintien des décharges derrière le mur étaient substantielles, permettant de couvrir le coût du mur et de ses fondations. Plus important encore, les décharges ont été conservées sur place, éliminant ainsi le transfert d'un problème environnemental vers un autre site.

KEYWORDS: Reinforced soil wall, pile foundation, fill materials

1 INTRODUCTION

The WestConnex M8 is part of multi-billion dollars road tunnel project in Sydney that was recently opened to traffic in July 2020. The project comprises 9 km of twin tunnels that connect Kingsgrove in the southwest and the St Peters Interchange (SPI) adjacent to Sydney Airport. Figure 1 shows the location of the project in relation to other WestConnex projects.

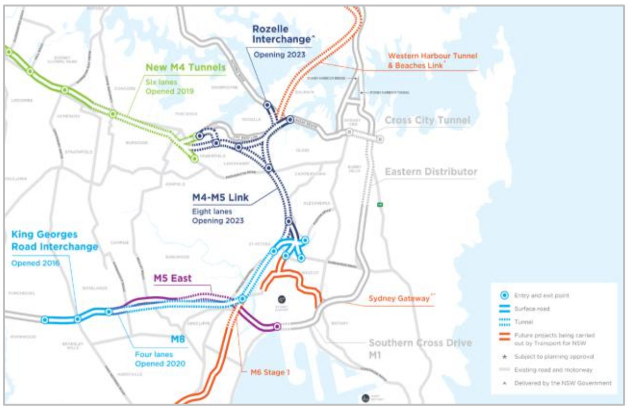

Figure 1. Schematic view of the WestConnex M8 in relation to other WestConnex projects in Sydney.

A two-tiered trapezoidal reinforced soil wall (RSW) was constructed over landfills along the northern boundary of SPI. The wall is about 350 m long and has a maximum retention height of 21 m. The wall provided an additional 2, 700 m^2 of parkland above and accommodated an additional 8, 000 m^3 of fill materials when completed.

The construction of the project was awarded to CPB Dragados Samsung Joint Venture (CDSJV) with Aurecon Jacobs Joint Venture (AJJV) as their design partner.

This paper describes the challenges faced by the project team during the design and construction of the RSW at SPI, and the innovative design approaches adopted to overcome these challenges.

2 ST PETER INTERCHANGE (SPI) BACKGROUND

SPI was constructed over the former municipal waste landfill known as the St Peters tip that covers an area of approximately 15.7 hectares. The St Peters tip had previously been used as a shale quarry between the early 1900s and 1960s. It became a major municipal waste depot in Sydney to the late 1980s (City of Sydney, 2018). Figure 2 shows an aerial photo of the St Peters tip in 1943.

The surface survey of the former brick pit and borehole data acquired indicated that the base of the shale quarry was at around RL-33m AHD, some 40m below the existing ground level. The shale quarry was excavated mainly in good quality Class I and Class II (Pells et al., 1998) Ashfield Shale.

Following the closure of the brickworks and quarry, the site was converted into a landfill and later to include a waste recycling operation known as Alexandria Landfill (Ellmoos and Whitaker, 2016). The original shale quarry escarpment along the northern boundary underwent a series of cuttings and backfills. Sections of the batter were left exposed for prolong period at an angle between 50 degrees and near vertical.

Figure 2. Aerial photo of St Peters Tip in 1943

In 2014, the Alexandria Landfill was acquired for the construction of SPI as part of the WestConnex M8 project. The SPI is bound by the Princess Highway in the north and Canal Road in the west.

SPI comprises the eastern tunnel portals of the WestConnex M8, ten bridges of four different heights, leachate treatment plants and associated infrastructure that includes a 350 m long and 21 m high retaining wall located immediately adjacent to the tunnel portal that runs along the northern boundary of SPI.

3 DESIGN DEVELOPMENT

3.1 *Early development of the retaining wall*

A two-tiered reinforced soil slope (RSS) with batter angles between 60 and 70 degrees was initially proposed to retain the old shale quarry escarpment at the eastern tunnel portal. However, this option was no longer considered due to the increase in area needed for further urban development at SPI and also the technical criteria related to height and batter of a slope (i.e. 7 m maximum height for each tier and 4 m wide maintenance bench between two consecutive tiers of RSS).

A two-tiered retaining structure with near vertical facing, slope of 1H:12V, and a maximum permissible height of 10 m per tier was considered in the design to provide an additional 2,700 m^2 of parkland directly above the wall.

Various types of wall were considered during the early design stage; including, cast in-situ concrete counterfort wall, precast concrete gravity wall and reinforced soil wall (RSW). RSW was finally adopted as it requires the least construction space and has the fastest construction rate when compared to the other two options, which proved to be critical as the project approached to completion.

3.2 *Design Development of RSW*

The RSW known as RW01B consists of two main sections. The first 50 m of the wall is a single tier trapezoidal RSW located north of the tunnel portal cut and cover structure, with most of the wall founded in bedrock. The remaining section of the wall is a two-tiered trapezoidal RSW built over landfill. The upper and lower tier run parallel to each other until the last 30 m where the two walls start to split. A general layout of the RSW is shown in Figure 3.

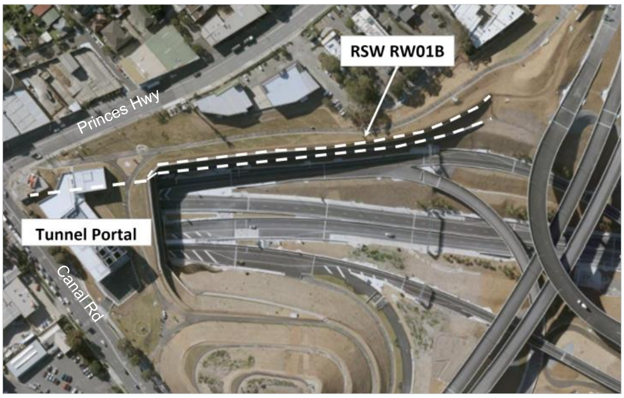

Figure 3. Aerial photo of St Peters Interchange tunnel portal and RW01B at completion in July 2020.

Construction at SPI began in mid-2016 and the construction of the RSW was scheduled in early 2019. The design of the RSW met with many challenges due to additional site constraints and design changes that occurred at SPI. The landform at SPI in particular, had changed significantly since the construction started in mid-2016 with the civil works and bridge construction well underway.

3.3 *Challenges and constraints*

Construction of the new bridges and road pavements at SPI involved significant amount of excavation. Although the excavated fill materials could be transported to a landfill site in outer Sydney, the cost of removal from SPI was expensive and would have an enormous carbon footprint associated with the number of truck movements involved. Therefore, the project's team determined to retain the excavated fill materials at SPI as much as practicable.

The RSW was used to retain some of the fill materials between the back of the reinforced soil block and the rock escarpment. The design focused on the control of short- term and long-term deformation of the wall, given that the fill materials were highly variable and further consolidation of the fill materials might occur upon placement behind the retaining wall.

The footprint of the RSW was occupied by a 12 m wide construction access to the temporary tunnels under Princess Highway between 2016 and 2018. The access road provided haulage of the tunnel spoils and electricity for tunneling. To make way for the access road, some sections of the shale quarry fill and rock batter were excavated temporarily secured with shotcrete and rock bolts. However, most of the brick pit batters were left in place, creating challenges when designing the RSW as the fill and rock batters would clash with the wall.

A 200 m long sheet pile wall was also installed to retain the lower part of the access road from fill and rock batter of lower strength. The sheet piles were to be left in place to maintain stability of the existing batter to ensure safe construction of the RSW. This led to an alternate method to allow the RSW to be constructed in front of the shale quarry batter and with the sheet pile wall left in place as shown in Figure 4.

The RSW was also required to accommodate utilities that connect the main line tunnel to the leachate treatment plant and the Fire Water Complex No.1 (FWC1) east of SPI. These include two pressurised fire hydrant pipes, two pressurised leachate pipes, and a combination of 14 communication and low voltage electrical conduits. While the construction of the RSW was not on the critical path, the commissioning of these utilities was. The timely delivery of the wall design and construction were crucial to ensure the RSW would not delay the commissioning of both the leachate treatment plant and the FWC1.

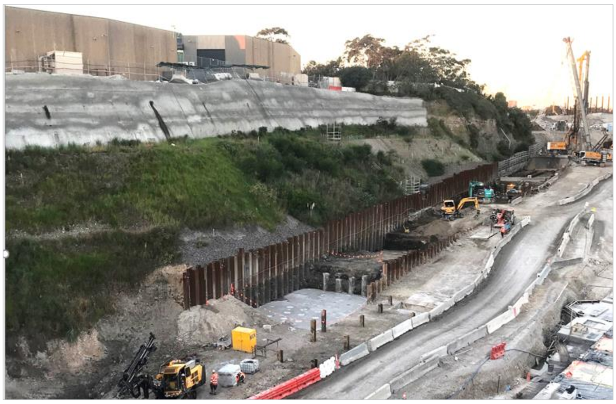

Figure 4. Shale quarry fill and rock batter and sheet pile wall installed along the back of RSW. Photo was taken during construction of the pile-slab foundation that supports the RSW.

Finally, there was a near zero tolerance on the change in wall geometry and position. At the time the wall design re-continued, majority of the structures adjacent to the RSW had completed. The final wall position and geometry needed to accommodate the completed structures. Moreover, the Portal Veil, an architecture masterpiece located at the tunnel portal, had moved significantly towards the RSW. Any changes to the wall geometry would risk clashing the wall panels with the utilities and the Portal Veil at the tunnel portal. The Portal Veil was also on the critical path in the construction program.

3.4 *Stiffness of the fill materials*

A Multichannel Analysis of Surface Wave (MASW) survey was undertaken at the beginning of the project to assess the stiffness of the existing fill at surface within the SPI. A secant modulus at 50% of failure strain (E_{50}) was back calculated based on the shear wave velocity and an assumed ratio of E_0/E_{50} of 10. The estimated E_{50} ranged from 15 to 22 MPa.

Prior to the compaction of the fill materials behind the RSW, plate load tests were carried out on existing and newly compacted fills to assess the range of stiffness may be achieved when compacting the fill materials behind the RSW. The tests were carried out using a 358mm diameter plate with the underlying soil loaded to between 150 kPa and 1.6 MPa. Results from the test indicated the stiffness of the compacted fills was between 12 to 40 MPa within the stress range of 200 to 400 kPa (Figure 5).

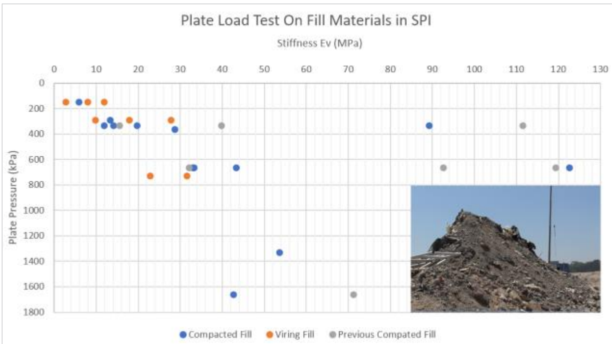

Figure 5. Results from plate load test performed in fill materials at SPI

4 DETAILED DESIGN

4.1 *Detailed design of the two-tiered trapezoidal RSW*

The initial wall design comprised a two-tiered RSW with traditional rectangular reinforced soil block. The upper and lower tiers RSW were approximately 10 m high that required reinforced soil blocks of at least 9 and 13 m wide respectively, i.e. soil reinforcement steel straps 9 m long for upper and 13 m long for lower wall. The RSW would retain a 50-degree active wedge consisting rock fills and fill materials behind the active wedge. However, the presence of the sheet pile wall discussed in Section 3.3 limited the space available to construct the lower tier RSW. Removal of the sheet pile wall was not an option as the need to temporarily stabilise the material behind the sheet piles and the batter immediately above with soil nails and shotcrete would significantly delay the construction program.

A new concept of a partially supported two-tiered trapezoidal RSW to resolve the above issues and maximise the backfill storage behind the RSW was then proposed. The objectives of the new concept were to avoid clashing with the sheet pile wall and to bring the start of the 50-degree active wedge closer to the wall face to maximise the fill storage behind the wedge as shown in Figure 6. The new RSW design shows no clash with sheet pile wall, no cutting into the former shale quarry rock batter and increased the fill storage volume by bringing the line of active wedge closer to the wall face.

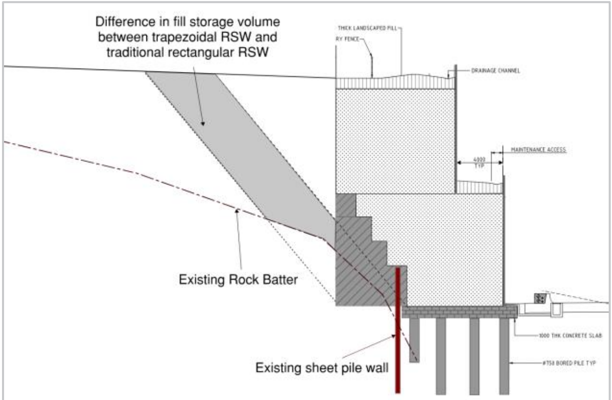

Figure 6. Size comparison between the two tiered trapezoidal RSW design and the initial rectangular RSW design in the background with diagonal hatch. The light grey area represents the increase in backfill storage by adopting the trapezoidal RSW design.

The proposed concept was first introduced to the project team and later presented to Transport of New South Wales (TfNSW) for technical consultation. The proposal was unique as it was specifically developed to resolve an onsite issue and the design had never been constructed in a similar fashion for an infrastructure project in New South Wales (NSW). Collaboration with TfNSW was crucial in developing a new technical direction for this two-tiered trapezoidal RSW design.

The upper tier wall was modelled as an equivalent sill beam load applied to the lower tier wall in accordance with TfNSW R57 Reinforced Soil Wall Specification (TfNSW, 2020). The equivalent sill beam model adopted for the design is applicable to a single tier RSW as the sill beam is usually limited in width and located near the front section of the RSW. For a two-tiered RSW, the upper tier wall is located on the rear half of the lower tier wall and extends beyond the back of the lower tier wall. The center of maximum tension therefore is located further back from the wall face when compared against a traditional single tiered RSW supporting a sill beam.

The mechanical height of the two-tiered RSW and the center of the maximum tension behind the lower tier RSW were evaluated in accordance with the FHWA GE011 (FHWA, 2009) ``to compare against the equivalent sill beam model. The resulting loads applied due to the combined effects from the equivalent sill beam model and the FHWA GE011 model were significantly greater than if the wall were modelled based on FHWA guideline alone. This design approach was considered necessary to comply with the design basis of R57 Specification and to ensure the wall has adequate strength to counter wall movements given that the wall is to be partially supported, and the lower tier wall is subjected to high lateral and vertical loads.

4.2 *Semi-rigid foundation support*

As the two-tiered trapezoidal RSW is located within the former St Peters tip with soil waste of up to 30 m thick, reinforced concrete piles were required to support the bottom tier of the wall to control vertical wall movement. The piles were designed as ground improvement piles. Pile and load transfer platform (LTP) arrangement that has been widely adopted in supporting RSW and road embankments over ground improvement (e.g. Huang et al., 2012) was not considered effective for this due to a special geometry for the proposed trapezoidal RSW. The pile-LTP foundation was then replaced by a pile-reinforced concrete slab foundation. The trapezoidal RSW is required to be supported by a rigid foundation in accordance with the R57 Specification.

The pile-slab foundation consisted of groups of 750 mm diameter pile in a staggered 4 m by 3 m arrangement supporting a 750 mm thick reinforced concrete slab. The piles were designed as ground improvement piles without direct structural connection to the concrete slab. The RSW and slab are partially supported vertically but the slab can 'slide' over the top of piles when subjected to lateral loads, hence it forms a semi-rigid foundation support that can reduce the build-up of forces in the piles when building up the RSW. In addition, shear ligatures were eliminated in the concrete slab to reduce reinforcement congestion and to improve construction speed.

Although the cost of constructing a pile-slab was higher than that of the pile-LTP, there were two advantages of adopting a pile-slab foundation for the RSW:

1. Having a rigid foundation significantly reduces the vertical movement of the lower and upper tier of the RSW that has the potential to cause deformation within the reinforced zone hence causing additional strain in the steel straps, adding an extra complexity to the RSW design.
2. The pile-slab foundation also provides the opportunity to accommodate utilities inside and above the concrete slab. The utilities were rigidly supported and would not be affected by long term creep of the soil waste below the slab.

The fire hydrants and the deluge pipes were supported by a 2.2 m long slab cantilevered from the first row of piles (Figure 7). The fourteen conduits could either be embedded in the concrete slab or directly placed over the slab with a concrete encasement. The conduits were later relocated to behind the RSW to suit the construction program.

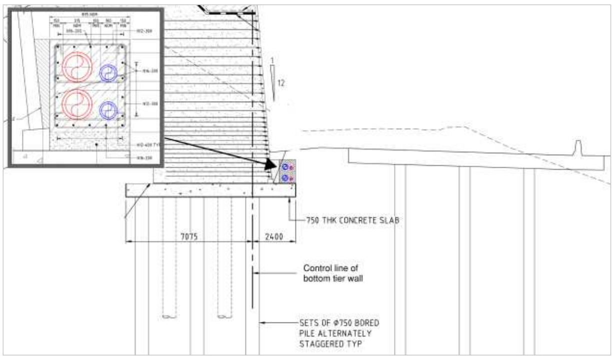

Figure 7. Extended concrete slab supporting two 315 mm diameter deluge pipes and two 180 mm diameter fire hydrant with concrete encasement.

4.3 *Numerical modelling of pile-slab foundation*

Since the foundation system of the two-tiered trapezoidal RSW has a complex arrangement (piles configurated in a staggered manner), the design was performed using a three-dimensional finite element analysis (FEM) using Plaxis3D. The FEM 3D models were setup at selected locations that were identical to the proposed pile arrangement and construction sequence to assess the pile-slab foundation's behavior. A wall section of 12 m long was adopted in FEM 3D that consisted of 15 piles in the pile-slab foundation. The model also incorporated the already constructed piled pavement structure in front of the two-tiered trapezoidal RSW to assess potential impact on the piled pavement structure (Figure 8).

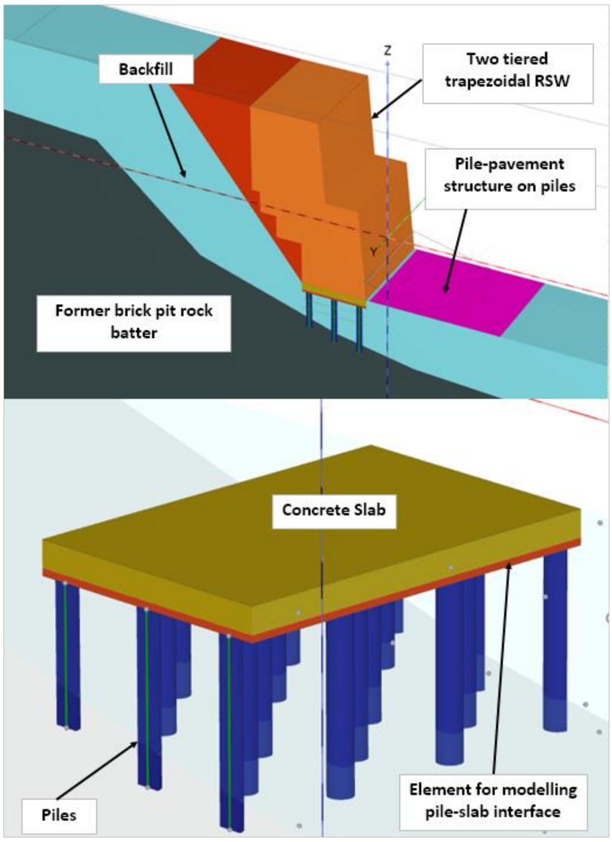

Figure 8. Plaxis 3D model developed for the trapezoidal RSW and foundation. Interfaces have been switched off for clarity.

Linear elastic volume pile (VP) elements were modelled to represent the piles and interface elements were also used to simulate the structural interaction between RSW and pile-slab, between slab and top of piles, and between piles and surrounding soils. The VP model was considered the best model to represent the piles in three-dimensional space as it can reflect the actual dimensions of the piles and contacts with other structures and soils.

Two other models were also carried out for comparisons - Piles in the pile-slab foundation were modelled as embedded beams (EB) and beams (B) connected to the concrete slab. The latter analyses were to compare pile deformation and actions in the piles with those obtained from the VP model. Note that in the latter two models, the piles were decoupled from the slab in order to reduce 'locked-in' pile stress that allows more slab movement relative to the piles. This resulted in about 15% decrease in pile forces. Pile head deformations from the EB and B models were similar, with forces from the EB model approximately 20% higher. It was noticed that there was a lack of soil flow around piles in the EB model at depth between 3 and 10m below the pile head. The relative movement between the pile and surrounding soil was not clear in the EB model.

Results of the VP model indicate a reduction of 15% to 20% of pile force while relative pile and soil movements were evident which are generally in line with Marjanovic et al., 2016 and Dao, 2011. Although the pile movements were slightly increased due to 'slippage' occurring around the pile-soil interface, pile forces were reduced from the previous 90% utilization of the EB and B models to around 77% utilization. The VP model has also eliminated the unrealistically high localised shear and bending forces in the slab at locations immediately above the pile head.

4.4 *Predicted wall deformation during construction*

Wall tilting, lateral and vertical movements were anticipated during construction of the trapezoidal RSW, given that the maximum height of the wall is up to 21 m. The estimated tilt of the upper and lower walls was less than 1 degree. The comparison between the predicted and recorded movements of the wall will be discussed in Section 5.2.

Bulging on the wall may occur and one of the mitigation measures implemented was to strengthen the wall face by increasing the number of soil reinforcement at locations where bulging was anticipated. The vertical spacings at the lower portion of the bottom tier wall was reduced from 500 to 250mm, as shown in Figure 7, while 10mm diameter soil reinforcement bars replaced the traditional 8mm diameter bars in the design. In the event that wall bulging occurs and becomes unacceptable, the bulging could be repaired using T-junction panels, a VSL product, at locations where large differential movement occurred.

5 CONSTRUCTION

5.1 *Piling works and reinforced concrete slab construction*

Construction of the wall foundation began in January 2019. Two piling rigs were used to construct 400 piles of 750 mm diameter. Pile lengths ranged from 12 to 30 m. A conventional bored pile technique was adopted for piles up to 18 m long. Bored pile with segmental casing was used for longer piles due to concern of excessive sidewall pressure. The segmental casing had an internal and external diameter of 800 mm and 880 mm respectively. The as-constructed pile diameter was slightly bigger than the design pile diameter. Piling works were completed in early June 2019 with approximately 5.8 km of piles constructed.

Construction of the concrete slab over the piles quickly followed. Reinforced concrete slab was 750 mm thick with top and bottom reinforcement. Excavation of up to 2 m deep in front of the existing sheet pile wall was required to make way for the slab (refer Figure 4). As there was a concern that the sheet piles may deflect and inducing additional movements to the piles, the stability of the sheet pile wall was strengthened with passive anchors. Furthermore, the first row of piles in front of the sheet piles was monitored during the excavation. Survey results indicated that only 1 to 2 mm pile head movement occurred during excavation.

5.2 *RSW Construction*

Construction of the RSW began in late September 2019. The construction proceeded from the west of SPI, near the SPI tunnel portal, towards the east. The construction went on day and night to ensure that the RSW was completed and all the utilities that the RSW was supporting were laid and tested in time prior to the opening of the WestConnex M8 tunnel in the first week of July 2020.

The bottom tier RSW was completed by Christmas 2019 (Figure 9) and the RSW reached its maximum height in early March 2020. Minor landscaping work was conducted above the wall until May.

Monitoring stations were set up on the RSW face panels at 30 m intervals to monitor the wall response to backfilling behind the panels. Five survey prisms were installed at each monitoring station, two survey prisms were placed on the face panel of the bottom tier RSW and three survey prisms were placed on the face panel of the top tier RSW.

Four settlement plates were installed above the bottom tier RSW and immediately behind the reinforced soil block. The purpose of these settlement plates was to monitor vertical movements behind the bottom tier RSW during backfilling.

Two shapes accelerometer arrays (SAA) were installed directly in front of pile P70 and P170 at the two highest wall sections. The SAAs were installed to capture the lateral movement of the piles relative to the concrete slab and RSW base during backfilling.

Figure 9. RSW construction progress as of Christmas 2019

5.3 *RSW movements*

Movements recorded from the top and bottom tiers of RSW during construction were generally in line with the predicted movements. Movements in the wall remained minimal during the building of the bottom tier RSW as the wall was supported by a rigid pile-slab foundation.

Movements in both top tier and bottom tier walls increased when top tier wall was constructed. The walls tended to rotate as the top tier wall was built at an offset of 4m from the bottom tier wall. Wall rotations on panels are evident in Figures 10 and 11 which provides the accumulative lateral and vertical displacement of the RSW panels, respectively.

Lateral and vertical movements predicted in the design were about 1.2 to 1.7 times the actual wall movements. These results indicate that the original design was conservative as it underestimated the elastic stiffness and strength properties of the fill materials placed in and behind the reinforced soil block.

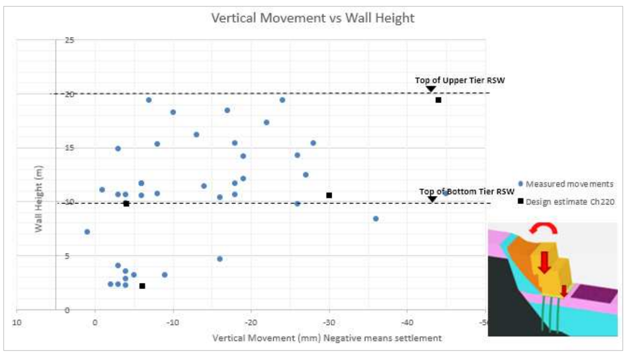

Figure 10. Accumulative vertical movement versus wall height at end of wall construction

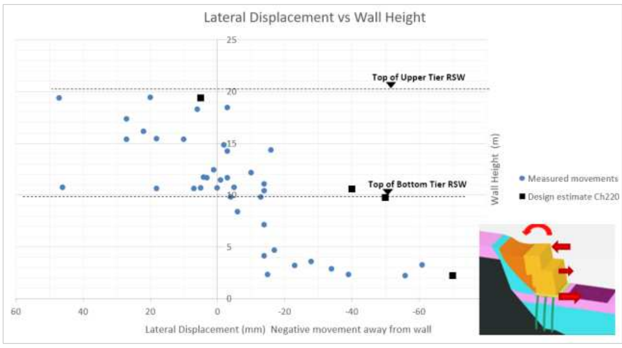

Figure 11. Accumulative lateral movement versus wall height at end of wall construction

Figure 12 provides lateral movements recorded from the pile-slab foundation at SAA P170. There was a small discrepancy in the top and bottom slab movement that indicates a small rotation occurred within the slab. The slab was not directly connected to any of the supporting pile hence the slab was not fixed against rotation.

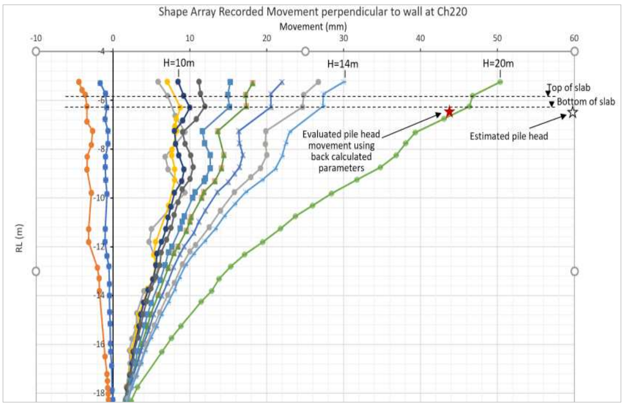

Figure 12. Lateral movement recorded by SAA at pile P170 versus the predicted and back calculated movements

The rates of lateral movement recorded from the wall panels were similar to those recorded from the pile-slab foundation during construction. The rates of movements were approximately 1 and 4 mm/m height of wall constructed during the construction of the bottom tier and top tier walls respectively. There was however a larger discrepancy in the rate of movement when the first 4 m of the top tier wall was constructed. The initial movements recorded from the wall panels were about two times the movements recorded by the SAA in the pile-slab. This discrepancy could be due to the rotation caused by the top tier wall as it was constructed at an offset to the bottom tier wall. Once the top tier wall became higher and the supporting backfill consolidated, the amount of wall rotation reduced hence the rate of lateral movement reduced.

No additional movements were recorded at the wall panels in the period leading up to the official opening of WestConnex M8. Long term monitoring will continue to assess the post construction performance of the RSW.

6 CONCLUSIONS

The two-tiered trapezoidal RSW was nicknamed "The Great Wall of St Peters" because of the challenges the project team faced, and the enormous amount of effort required to overcome these challenges. The unconventional two-tiered trapezoidal design was built over landfill and achieved the objectives assigned by the project team.

Upon completion of the RSW, the wall supports utilities that are essential to the tunnel operation as well as the leachate treatment plants at SPI. An additional 8, 000 m^3 of fill materials was retained on site by the RSW and an additional of 2,700 m^2 of parkland was created above the RSW for leisure. The benefit of retaining the fill materials behind the wall was substantial and outweighed the cost of the wall. More importantly, the fill materials were kept on site thus avoiding the transfer of an environmental problem elsewhere.

The wall was completed in time for the official opening of the WestConnex M8 on 5th July 2020 (Figure 13).

7 ACKNOWLEDGEMENTS

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Figure 13. Completed RSW.

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