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Impact of deep underground station excavation on existing assets in Sydney, Australia

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ABSTRACT: Deep excavations and tunnelling have the potential to adversely impact existing assets, and an engineering impact assessment is critical to identify and plan mitigation measures for impacted assets. A targeted geotechnical investigation, detailed analysis using reliable data and design of mitigation measures with well-planned instrumentation and monitoring can help reduce the risk of adverse impacts and failures. This paper discusses the challenges involved and the impact of excavation of a station box and TBM launching, as part of the Central Tunnelling Package of the Sydney Metro Project in Australia. The excavation was near sensitive assets where the presence of loose thick alluvial soil, paleochannel with high ground water table, and presence of The Great Sydney Dyke, presented significant challenges. The paper discusses the challenges and how predicted and acceptable effects were established for the sensitive assets and remediation planned for the successful design and construction of the station box.

1 INTRODUCTION

1.1 *Impact of tunnelling and station excavation on existing assets*

Tunnel construction and associated deep excavation work in urban cities have the potential to significantly impact the existing assets within the influence zone of the construction activities. This can include damage to or failure of impacted assets leading to litigations and/or project delays. Ground water changes caused by drained excavations and drawdown can affect stability of ground or cause contamination and affect water quality. Excessive ground movements and vibrations also can cause damage to sensitive infrastructure. During the planning and design of tunnelling activities it is important to have careful considerations to avoid adverse impact on any assets within the tunnelling influence zone. An assessment identifying the impact of tunnelling and deep excavations on all existing assets including underground utilities within influence zone, is an integral part of any tunnel construction. This includes checking for any adverse impacts and developing mitigation measures and contingency plans.

The challenges involved in the design and construction of retaining system for an underground station excavation at The Bays in Sydney's Inner West, near highly sensitive and heritage structures, are discussed in this paper. The station box was near a heritage structure and several other important assets. The TBM tunnel was to pass through the area with a shallow cover. Presence of The Great Sydney Dyke at this location with thick loose alluvial soils and the presence of a paleochannel with a high ground water table posed major challenges to design and construction. The high permeability of Hawkesbury sandstone in this location allowed depressurisation of overlying alluvial deposits, increasing the risk of ground settlement due to changes in effective stress.

This paper discusses how the design and construction of a robust retaining system was implemented, and the ground movement and ground water drawdown were predicted and its impact on the nearby assets assessed and mitigated, to successfully complete the work without causing any adverse impact on the nearby sensitive assets.

2 THE PROJECT

The Sydney Metro West project is part of Australia's biggest public transport project and will double the rail capacity between Parramatta and the Sydney CBD, transforming Sydney for generations to come. The project includes 24-kilometre twin tunnels excavated using double shield hard rock Tunnel Boring Machines (TBM), excavation and associated civil works for temporary support of the nine deep underground stations, (Figure 1) cross over caverns and access shafts. Acciona Ferrovial Joint Venture (AFJV) was awarded the design and construction of the Central Tunnelling Package (CTP). One of the most challenging aspects of CTP was deep excavation and tunnelling through The Bays station, located between Glebe Island and the White Bay Power Station (WBPS).

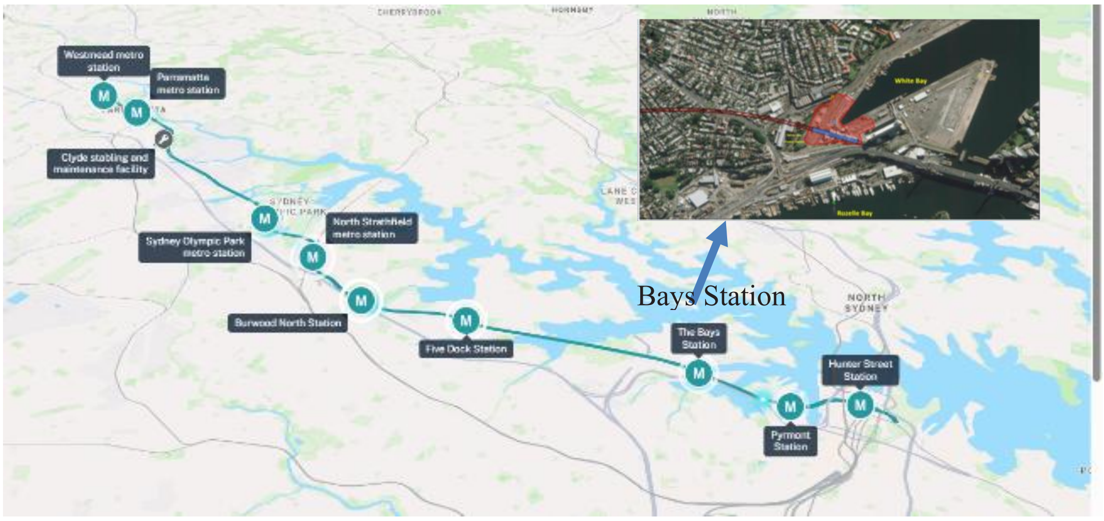

Figure 1. Sydney Metro West 24-kilometre alignment and Station locations

2.1 *The Bays Station*

The Bays station box (Figure 2) has a clear opening of 230m x 24m and 31m depth and is located within the White Bay industrial area, near the White Bay Power Station (WBPS) in an approximate East-West orientation. WBPS is a New South Wales (NSW) state heritage listed building built between 1912 to 1917. The existing ground levels varied between +2.7m to 4.3m AHD. The retaining system consisted of reinforced concrete secant walls embedded into competent rock, and laterally restrained by ground anchors, within the overburden soil. The system was designed with an intended design life of 10 years. Within the rock layers the retention system consisted of spot bolting combined with localized shotcreting below the toe of piles to the depth of excavation, to support and hold potential unfavorable rock wedges or any unstable discontinuities within the rock layer.

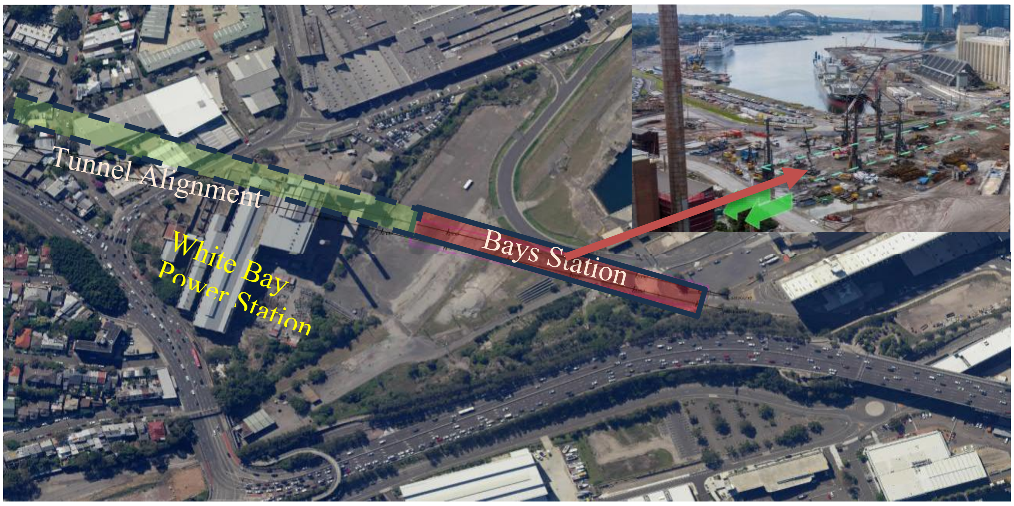

Figure 2. The Bays Station excavation, tunnel alignment and White Bay Power Station location with five piling rigs working simultaneously. The green arrows show the direction of TBM.

2.2 *Typical ground conditions and ground model*

The bedrock geology of The Bays area is characterised by a sub-horizontally lying Permo Triassic sedimentary sequence, approximately 230 million years old. The stratigraphic units expected to be encountered within the area under discussion, is expected to comprise of manmade fill materials followed by quaternary alluvium/estuarine sediments and the Hawkesbury Sandstone formation (Herbert, 1983).

The Great Sydney Dyke which is typically about 6 m wide, extends through the eastern and northern walls of the station box at The Bays Station as shown in Figure 3.

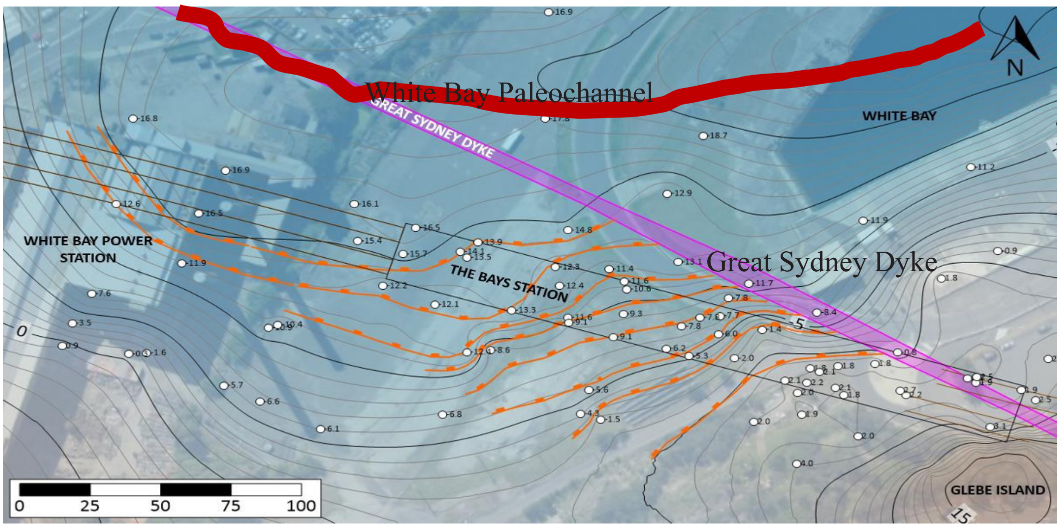

Figure 3. Great Sydney Dyke and the paleochannel

The presence of a palaeochannel in the vicinity near Johnstons Bay is also noted. The floor of the channel is about 36 m below sea level and is infilled with very recent Quaternary, mostly Holocene, and some older underlaying Pleistocene, alluvial deposits comprising rivers, sands, estuarine muds and marine clay deposits. Figure 4 shows the interpreted bedrock contour plan of The Bays area showing the top of highly weathered rock or better, at 1 m interval, based on the investigations done within the station locality.

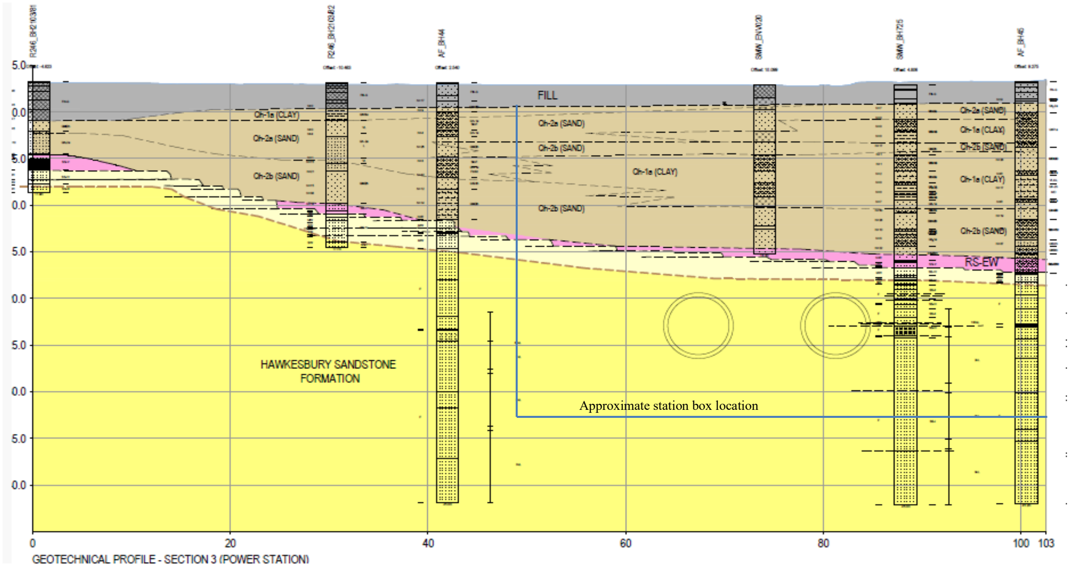

Figure 4 Ground conditions and geological long section at The Bays Station

The geological long section along the station box is shown in Figure 4. The top of rock is shallow at the White Bay Power Station location which indicates that the tunnel would have a thin rock cover above its crown which presents a challenge in terms of the potential impact on the foundations. The ground water table has been established to be between 1.7 m and 3.63 m below ground level (+0.58 and +1.44 m AHD) based on the readings from ground water monitoring wells. The design ground water level has been considered at ground level.

2.3 *Permeability of sandstone*

The station excavation below the rock level is designed to be drained excavation, however, the project specifications required that the inflow into the excavation should be limited to an inflow criteria of less than 5 L/s. Based on the borehole information and water pressure testing in boreholes, the vast majority of the lugeon values for typical Hawkesbury Sandstone was interpreted to be less than 1 uL ($1x10^{-7}$ m/s). However, when the sandstone contains more open defects as a consequence of faulting and shearing or stress relief near the surface or near the paleochannels, higher lugeon values of permeability are possible. Higher values of permeability of > 35 to 100 uL were obtained at few locations within the excavation zone where there were sub horizontal permeable features present. Even in good quality sandstone, the presence of sub horizontal defects could potentially cause large inflows into the excavation.

3 IMPACT ASSESSMENT OF EXISTING ASSETS

The project specifications required that the tunnelling contractors plan and execute their activities in such a way as to cause no adverse and unacceptable impacts on existing assets. There are several buildings, sensitive structures, heritage buildings and utilities within the influence zone of the tunnel and station excavations. As part of the initial design process, an engineering impact assessment was done to establish a zone of influence, (defined as an area within a 5mm settlement contour) by assessing the predicted ground movements due to tunnelling and station excavations (Gaba 2017). A four-stage risk-based approach in accordance with CIRIA PR30 was adopted, where predicted effects due to ground movement and ground water drawn down on existing assets, were compared against a set of established acceptable effects (Burland et.al. 1997, Boscardin and Cording 1989) in the first and second phases, to identify assets requiring detailed assessments. The Phase 3 assessment included identifying mitigation and protection measures and setting alert levels and contingency plans. An instrumentation and monitoring plan was then developed in Phase 4 to follow during the construction stage to monitor the actual impact.

3.1 *Engineering Impact Assessment*

The local geology, depth of cover to the tunnel and soil structure interaction, methods of excavation and type of retaining systems and their installation sequences and ground water conditions can all influence the impact of construction on existing assets. Ground movement resulting from tunnelling, surface excavations and ground water drawdown was estimated to assess the overall impact.

3.1.1 *Tunnelling induced settlements*

The tunnelling work included excavation by Tunnel Boring Machines (TBMs) as well as mined tunnels by road headers for station and ventilation caverns and adits and excavators with impact hammers/drum cutters for cross passages. The tunnel induced settlements were conservatively estimated considering the volume loss (V_L) at the surface with the surface settlement profile simplified as a Gaussian curve in cross section. The width of the settlement trough (k) is influenced by the geology and soil and rock parameters intercepted by the tunnel. Based on contractor experience from previous projects in similar geology, V_L and k values are adopted for the encountered ground conditions, as presented in Table 1 below.

Table 1. Volume loss and trough width parameters adopted for prediction of settlements

Geological Unit	Volume Loss V_L %	Trough Width Constant k
Soil or extremly weathered rock	0.1	0.60
Ashfield Shale (Class IV-V)	0.25	0.50
Ashfield Shale (Class I-III)	0.15	0.35
Hawkesbury Sandstone (Class IV-V)	0.20	0.60
Hawkesbury Sandstone (Class I-III)	0.15	0.60
Ashfield Shale/Hawkesbury Sandstone	0.25	0.40

3.1.2 *Surface excavation induced settlements*

The Bays Station excavation is retained by secant piles within alluvium and within rock with rock stabilisation, and the excavation is progressed from the surface using conventional techniques. Displacement profiles for the retaining walls are calibrated from numerical models, and before calibration the maximum vertical displacement in alluvial soil is assumed to be 70% of the maximum horizontal displacement.

3.1.3 *Groundwater induced settlement*

The tunnel is lined and fitted with a waterproofing gasket and is undrained and not expected to cause significant drawdown. The Bays Station excavation is tanked and retained within alluvium and is drained within rock with controlled drainage. An inflow limit is specified in the project specifications. A detailed hydrogeological model was developed by the consultants and water drawdown induced settlement was calculated as a function of the soil stratification, depth of overburden soil and the water drawdown. The hydrogeological assessment was done for two different scenarios of drawdown predictions. The red contours as shown in Figure 5 indicated the drawdown allowing total inflow to the station box of 5.2 L/s, adopted as Upper Bound scenario for the settlement impact. The hydrological studies predicted significant drawdown based on conservative assumptions and recommended grouting around the power station area thus reducing the ground water inflow into the excavations. A mitigated scenario 2, with rock permeability improved to an average of 1 Lugeon, and inflow to the station box of 3 L/s, is represented by the blue contours. This scenario has the bedrock below the secant pile wall assumed to be grouted around the perimeter of the station box. Grouting reduces the bedrock permeability to 1 Lugeon. This scenario has been adopted as Base Case (most probable) scenario for the settlement impact analysis presented in following section, noting that a third case Green Scenario was analysed as a sensitivity check but not further analysed. An illustration of each drawdown case is shown in Figure 5.

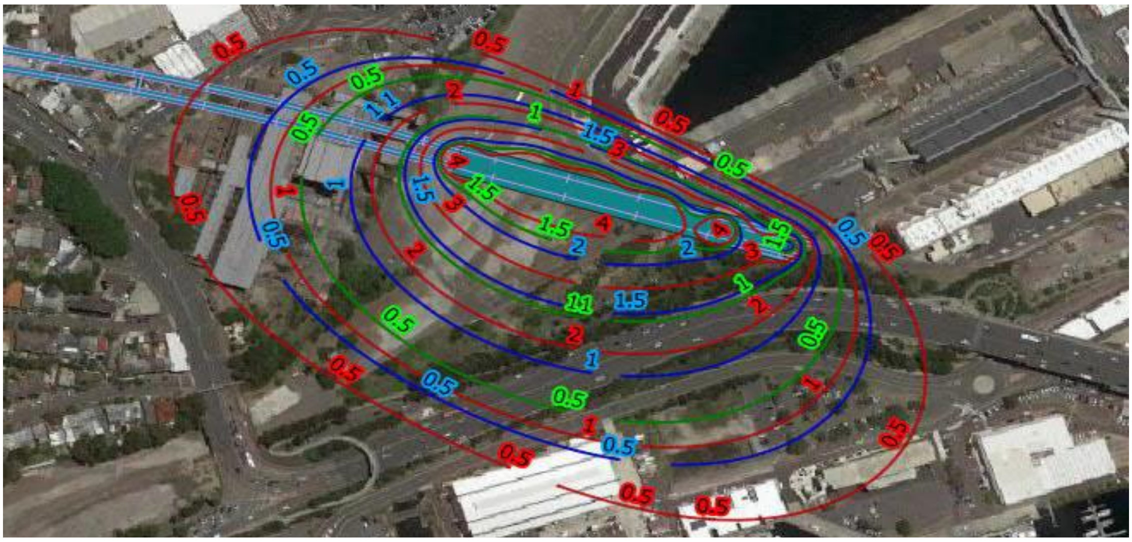

Figure 5. Predicted ground water drawdown around the Bays station area

A sensitivity analysis was performed where the maximum settlement exceeded the established acceptable limits, however, the building slopes and strains were found to be within the acceptable limits. Higher settlement magnitudes near the White Bay Power Station is attributed to the thicker alluvial soft soil deposits of the paleochannel, and water drawdown induced settlements.

3.2 *White Bay Power Station*

The White Bay Power Station is a heritage structure, built between 1912 and 1917. A part of the building is known to be on pile foundations", but more details were unavailable. The northeast corner of the power station is underlain by about 18 to 20 m of surficial fill and saturated alluvial soils over a stepped sandstone cliff profile. The pile foundations are presumed to be round timber piles and floating in the alluvium. The power station and its foundations were reportedly upgraded in 1956 but as-builts are not available. The TBM at the power station has shallow rock cover as shown in Figure 4 and there was concern of the impact on the heritage structure due to the tunnelling and station construction. The chimney of the power station (Figure 6a) has been analysed by advanced finite element modelling, to predict the displacements and stress experienced, based on the impact assessment results (Figure 6b).

Figure 6a. The Chimney of WBPS

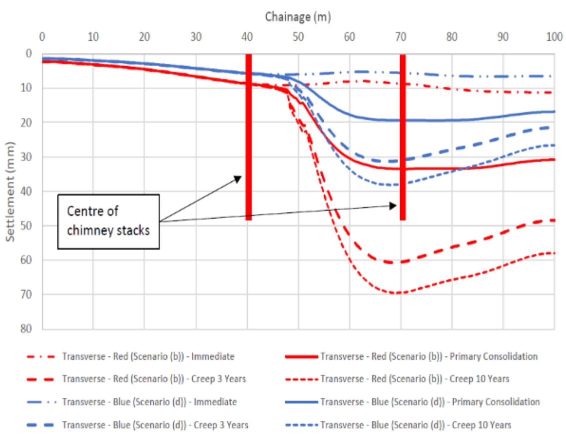

Figure 6b. Predicted settlements at the chimney location

The two chimney stacks are major contributing elements to the visual identity of the White Bay Power Station and needed to be retained in situ and conserved and interpreted as an integral part of the significance of it. Assessment of settlement has been undertaken using Plaxis 2D modelling using Mohr Coulomb material model. A structural 3D finite element modelling was also developed by the consultants, to examine the structure behaviour under predicted settlements. Based on the calculations using the predicted settlements and slopes, the top of chimney was predicted to experience lateral displacement of approximately 51 to 61mm for the two scenarios. Predicted settlements including the primary consolidation settlement, long term creep and immediate elastic settlement were considered in the analysis as shown in Figure 7b.

The results of analysis indicate that the groundwater drawn down without ground treatment results in higher amounts of settlements of the order of 70 to 80 mm at locations where alluvium is thicker. The settlement gradient was also the steepest in this case. It is noteworthy that the coefficient of consolidation of the clay layer varied from 1.6 M2/year to 160 m2 /yr as provided in the Geotechnical reports which resulted in a large variation in the prediction of time period when the predicted settlements will occur. After considering the ground improved by grouting to an average permeability of 1 Lugeon the settlements improved to about 30 to 40 mm. Several contingency plans were developed along with a rigorous instrumentation and monitoring plan, to monitor the ground movements and drawdown affecting the heritage structure and to take necessary action in accordance with the contingency plan if alert levels are exceeded. A watch and act system in a observational approach was adopted where if the ground movements were exceeded then back analysis of the data and installation of mitigation measures were to be immediately applied.

The settlements are predicted conservatively and instrumentation and monitoring along with contingency plans during construction was implemented to monitor and control settlements and trigger action plans if the acceptable settlement limits are exceeded. During construction the actual settlements (Figure 7) at and near the excavation areas were within the acceptable limits established for the structures, thus allowing the construction of the station box and tunnel to be successfully completed.

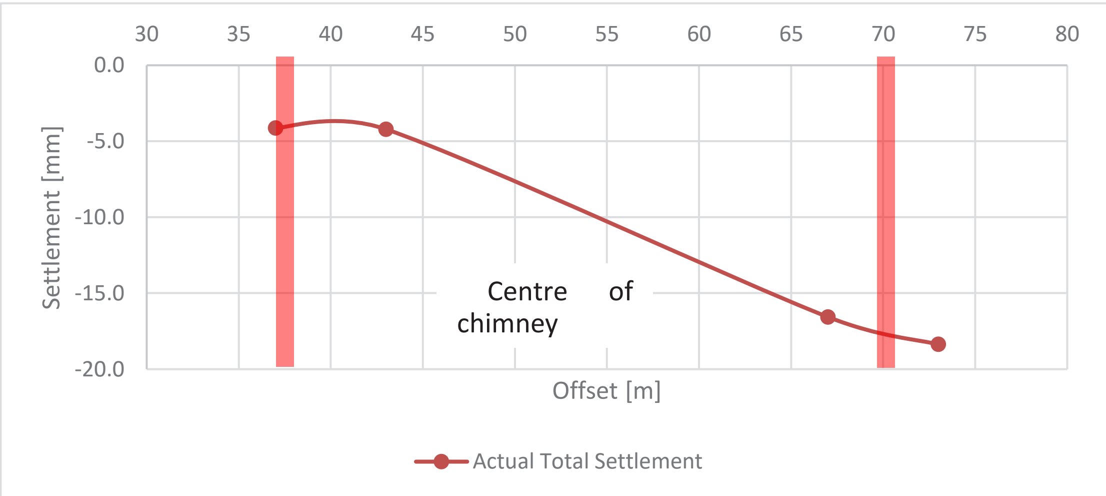

Figure 7. Actual settlements measured at Chimney Stack

4 CONCLUSIONS

The excavation of the Bays Station of SMW included one of the deepest applications of a secant pile wall to date along the shores of Sydney Harbour. The design and construction challenges at this location were overcome by the following approaches to successfully complete the work without causing any adverse impact on the WBPS.

- A reliable and robust ground model incorporating all the subsurface data by a thorough review of historical data and desktop study and a targeted additional geotechnical investigation
- Detailed geotechnical and hydrogeological assessments to establish a range of design parameters including hydraulic conductivity of ground. Geotechnical analysis to predict ground movements, and sensitivity analysis predicting a range of expected ground movements and drawdown for various probable scenarios.
- Establishing acceptable effects for the WBPS which could be compared against the predicted values to confirm that there is no adverse impact on the structure.
- A grouting program with curtain grouting around the box and grouting under the WBPS, targeting the permeability of 1 Lugeon to control the inflows to meet inflow criteria.
- A robust retaining wall design with secant pile walls tanked within the alluvium and rock stabilisation within the rock.

The work was successfully completed without any breach of the alert levels and additional improvement measures in the contingency plan were not warranted during the construction. The successful completion of this project is an example where early understanding of challenging ground conditions by targeted detailed ground investigations and detailed analysis and sensitivity assessments can help overcome such challenges successfully.

ACKNOWLEDGEMENTS

The authors extend their sincere gratitude to Sydney Metro for their support and permission to publish this paper. Additionally, the AFJV site team deserves recognition for their dedicated efforts in executing the challenging works, particularly during heavy rain events encountered during the excavation. The design consultants Typsa Jacobs JV efforts in the design are also thankfully acknowledged. The first author would also like to specially thank her previous employer Mott MacDonald for providing the opportunity to work on this prestigious project.

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