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Basement diaphragm walls and foundations of Sydney's tallest building, Crown Sydney Hotel Resort – challenges and solutions

Soutènement en paroi moulée du parking souterrain du plus haut bâtiment à Sydney, le Crown Sydney Hôtel Resort – défis et solutions proposées

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ABSTRACT: Crown Sydney Hotel Resort is the Stage 1C component of Barangaroo South located alongside of Sydney Harbour on the western side of Sydney's central business district. This hotel is being developed as a single mixed-use high-rise tower of 72 stories (271m high), rising over a multi-level podium and a 3 level basement car park (total 75 levels). The basement of the tower includes a perimeter retaining wall comprises 33 diaphragm wall panels, which resists and transfers the out of balance soil and water loads to the 36 internal barrettes by means of multi levels of slab diaphragms. The barrettes along with more than 200 piles including bored compression piles, tension piles, sleeved piles and permanent plunge column piles form the foundation of the main tower. AECOM were engaged as designers of the foundation works by Piling Contractors Bauer Australia Joint Venture (PCBAJV) who constructed the foundation works as the D&C foundation contractor. The depth of foundation elements varies from 25 m to 50 m bgl. This paper presents innovative aspects of the design and construction and solutions utilised to overcome the complex challenges in this project. A comprehensive geotechnical and structural design methodology including 2D and 3D numerical modelling utilising a web-based real time instrumentation and monitoring (I&M) has also been discussed in this paper. This project was nominated as a finalist in the prestigious Ground Engineering Awards held in London in the category of "International Project of the Year" in 2018.

RÉSUMÉ : L'Hôtel Crown Sydney Resort est la phase 1C du développement urbanistique Barangaroo South, qui est situé dans la baie de Sydney, à l'ouest du quartier financier. L'hôtel est conçu comme une tour à usage mixte de 72 étages (271m de haut), qui s'élève sur une estrade de plusieurs niveaux ainsi que trois étages de parking souterrain (au total 75 étages). Le sous-sol de la tour comprend 33 panneaux de paroi moulée, qui résistent et transfèrent les poussées dissymétriques du sol et de l'eau aux 36 barrettes internes grâce aux trois niveaux de dalles. Les barrettes et plus de 200 pieux, comprenant des pieux en compression, en tension, des pieux forés tubés et des poteaux prefondés, constituent les fondations de la tour principale. Le bureau d'études AECOM a été engagé en tant que designers des travaux de fondations par le groupement d'entreprises Piling Contractors Bauer Australia Joint Venture (PCBAJV) qui était en charge du design et de la construction des fondations. La profondeur des fondations varie de 25m a 50m sous le niveau du sol. Cet article présente les aspects innovants du design, de la construction et des solutions retenues pour surmonter les défis complexes de ce projet. Il montre également l'ensemble des aspects structurels et géotechniques du design, y compris la modélisation numérique 2D et 3D en se servant de monitoring et instrumentation en temps réel. Ce projet a été finaliste du prestigieux Ground Engineering Awards (Londres) dans la catégorie « Projet International de l'année » 2018.

KEYWORDS: Diaphragm wall; deep foundation; tall buildings; top-down construction; tension pile

1 INTRODUCTION

Crown Sydney Hotel Resort is the Stage 1C component of Barangaroo South located alongside of Sydney Harbour on the western side of Sydney's CBD. This hotel is being developed as a single mixed-use high-rise tower of 72 stories (271m high), rising over a multi-level podium and a 3 level basement car park (total 75 levels). Crown Sydney Hotel Resort will be the first 6-star luxury hotel in Sydney. The construction of the project began in mid-2016 and was completed in December 2020.

AECOM engaged to provide engineering design services for concept design, detailed design and construction support of the Perimeter Retaining Walls (PRW) and In Ground Structures for the basement excavation and foundations of the project. In order to meet the overall project deadlines for Stage 1C with all foundation elements constructed in-situ from ground level a full top-down methodology for concurrent construction of the tower and basement excavation was adopted. Plunge columns used to share the tower and podium loads and to facilitate the top-down construction by providing support to the slabs. After the installation of Perimeter Retention Walls (PRW) with diaphragm walls, the tower and podium foundations and the ground floor slab, the construction of the tower and podium occurred concurrently with the excavation and construction of the basement works.

The basement of the tower comprises a 13 m deep excavation which has been retained by 33 diaphragm wall (D-Wall) panels (Figure 1. Crown Sydney Hotel Resort basement foundatio n plan). D-Walls were designed to act as structural elements with following functions:

- Resist and transfer the earth pressure to internal barrettes by means of multi levels of slab diaphragms,
- Transfer high vertical and lateral loads from the building above (including wind and earthquake) during and post construction to class IV sandstone or better,
- Prevent the inflow of groundwater into the basement during construction and in the permanent state.

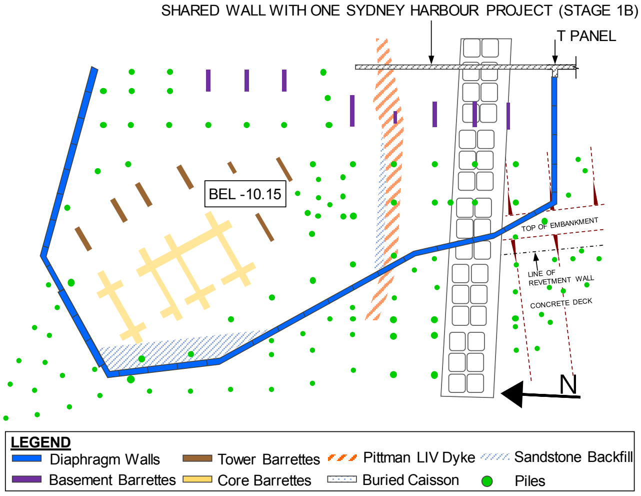


Figure 1. Crown Sydney Hotel Resort basement foundation plan

2 PROJECT CHALLENGES AND SOLUTIONS

2.1 *Ground conditions*

From 1840 to 1925, the Barangaroo South area was occupied by a gasworks and also has been developed and used for a variety of industrial, commercial and maritime activities. A series of timber finger wharves were then built across the Barangaroo precinct with several extending over the Crown Sydney Hotel Resort site. In the 1970s, to create wharfs for ship berthing, a seawall comprised of caissons was built at the Barangaroo precinct. Then, the precinct was backfilled with uncontrolled fill and paved (Azari et. al 2019). The caissons consisted precast concrete segments filled with sand which were constructed over a gravel platform with the sea floor dredged prior to placement. Since the construction of Port Botany in 1979, the terminal activity started to decline. The container ships no longer stopped in Sydney harbour by 1990s and the Barangaroo precinct was used as an open space for mass gatherings and temporary passenger terminal for cruise liners. The development of Barangaroo South in 2010 and 2020 is shown in Figure 2.

The ground conditions challenges, influenced by the historical developments of the site, are summarized below:

- Reclaimed site with highly variable uncontrolled fill up to 20m thick,
- Contaminated fill (adjacent to former gasworks site),
- Highly variable rock levels including buried rock cliffs,
- Dyke and infill clay bands within sandstone,
- Buried piles, slabs, ground anchors and other old structures (timber logs and steel piles),
- Buried rock armour and revetment, with sandstone boulders up to 600mm,
- Buried reinforced concrete caisson (old sea walls),
- Ground water level.

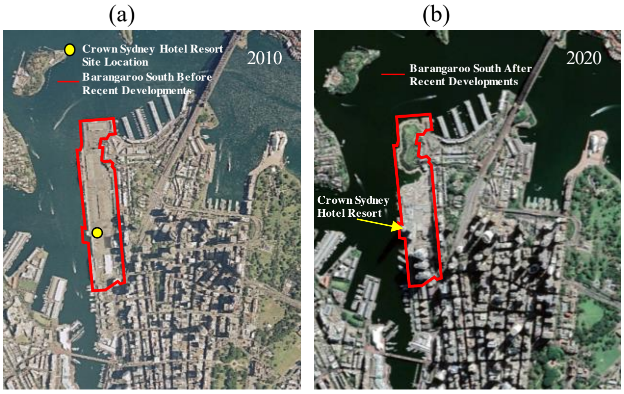


Figure 2. Stage 1C of Barangaroo South Site: (a) 2010 and (b) 2020 (After Parsa-Pajouh et al 2021).

The results of desktop study and site investigations indicated that the ground units of the site comprised highly variable uncontrolled fill with possible voids and obstructions such as buried steel piles, timber piles and steel scraps. The ground conditions of the site have been characterised based on a comprehensive site investigation program as follows (Crown Sydney Hotel Resort, Geotechnical Investigation, Revision 2, 2016):

- 10 preliminary boreholes (by client)
- 105 proof holes to map rock surface and to investigate in-ground obstacles
- more than 60 geotechnical boreholes up to the depth of 57.5 m (during detail design stage)
- Field tests such as Packer Testing to measure the rock permeability
- Comprehensive laboratory testing (soil / rock)

The result of the comprehensive site investigation was used to build a 3D ground models (i.e. Surfer and BIM). A 3D snapshot from the BIM model showing PRW is presented in Figure 3. The fill is underlain by alluvial sediments and residual soils. The bedrock is Hawkesbury Sandstone, which is typically a medium to coarse grained sandstone. The sandstone was classified according to Pells et al. 1998**Error! Reference source not found.**. The rock classes were derived for each cored borehole, using the log descriptions, Uniaxial Compressive Strength (UCS) and Point Load Tests (PLTs). A focus of the drilling was to identify the top of rock and rock weathering and classes with depth.

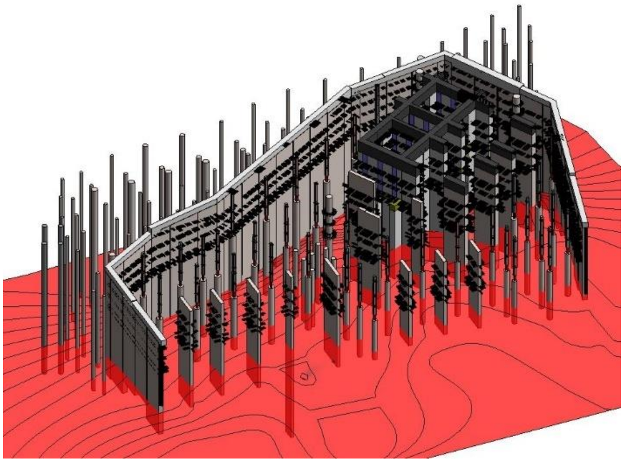


Figure 3. A 3D snapshot from the BIM model showing PRW, In-Ground Structures and tower foundations in relation to the Rock levels

The sandstone at Barangaroo site is known to fall towards the west (i.e. into Darling Harbour). Typically, in Sydney Harbour, rock levels fall as a series of sub-horizontal benches separated by sub-vertical cliff lines.

The Sydney Region is crossed by several basalt and dolerite dykes. The Pittman LIV dyke is mapped in proximity to the site in an east-west direction. The dyke comprises extremely weathered to fresh dolerite. The width of the dyke and the dyke zone was found to vary between 3 m and 5 m including potentially offshoots, fractured rock and extremely weathered dolerite interface with sandstone (up to 100 mm thick). The zone of influence of the dyke was assumed to be 1 m on each side. The dolerite was subdivided into three units based on degree of observed weathering for the purpose of foundation and socket design. The location of Pittman LIV dyke in relation to the Site is depicted in Figure 1. Crown Sydney Hotel Resort basement foundation plan.

The design groundwater level was considered at +1.5 m RL on active side of the D-Walls for the temporary case (i.e. during construction) considering the Highest Astronomical Tide (HAT) level, recorded groundwater tidal fluctuations and recorded water levels at Fort Denison from 31 May 1914 to 31 December 2006 (Watson et al. 2008).

The design groundwater level behind the D-Walls was taken as + 2.335 m RL for the long term and the basement assumed as a fully tanked structure. This groundwater level includes the anticipated increase in water levels associated with a 1 in 100-year extreme weather event as well as an allowance for global warming.

2.2 *Design*

The Crown Sydney Hotel Resort basement was designed to serve several functions including resisting and transferring the global out of balance earth pressures to internal barrettes (i.e. core, tower and basement barrettes) by means of D-Walls and basement slabs. Further, this basement is connected to an adjacent existing basement (Stage 1B – One Sydney Harbour) which itself supports three towers. The geotechnical design of the basement was conducted to predict the soil-structure interaction including displacements, bending moments and shear forces of D-Walls, basement slabs and barrettes for the temporary and the long-term conditions. The 3D modelling also informed the methodology for the pile design considering lateral movement and eccentric loads and P-Δ effects on the piles. The settlement of the adjacent ground surface due to the excavation of the basement was also estimated. The design challenges are summarized below:

- Cost – due to the complexity of the project, all tenders were initially over budget and the client requested to re-visit and optimise the design to provide innovative and cost-effective tender design,
- Integrated tower structure, tower core with the D-Walls, slabs and foundations, and hence the complex load path and load sharing among various structural elements,
- Asymmetric/complex geometry and large out of balance earth pressure,
- Highly variable ground profile,
- Hydrogeology and dewatering during excavation,
- Full Top-Down construction,
- Deep and heavy loaded piles in compression and tension in variable ground conditions,
- Complex interfaces with the adjacent excavation (One Sydney Harbour project, Stage 1B),
- Temporary works – crane foundation – the world's largest capacity tower crane (i.e. with the ability to lift up to 330 tonnes in a single lift and 20 tonnes at 110m distance).

At the concept design during the tender stage, it was realised that the basement walls were under significant twist and stress concentration due to the location of the core being at the corner of the basement footprint creating significant torsion and inefficient overall performance. Therefore, the alternative design and value engineering were carried out by adding the shear walls and barrettes at the opposite location of the core to balance the centre of rigidity to minimise the basement twist and reduce stress on the D-Walls. The proposed shear walls also replaced with some of the piles of the plunge columns. To better understand the behaviour of the basement, the finite element (FE) approach was used to undertake the complex soil structure interaction (SSI) analysis considering the asymmetric shape of the excavation, highly variable ground profile and complex configuration of the structural elements. The SSI analysis was carried out using PLAXIS 2D/3D programs in various scales to optimise the socket depth, the reinforcement ratio of basement elements and improve the overall performance of the basement. The Hardening Soil model was adopted for more accurate and realistic simulation of the soil materials' behaviour. Additional scope of the ground investigation (i.e. 67 boreholes) was undertaken to improve the accuracy of the 3D numerical model and optimisation of the design. The integrated geospatial and BIM (GEOBIM) solutions were used to facilitate the modelling and optimisation process (Figure 3). The analytical method was used to determine the earth pressure and validate the results of the numerical analysis. The consistency of overall deformation of the floor diaphragm and the distribution of lateral forces in the resisting structural elements were assessed by comparing the results of PLAXIS 3D and 2D models. Then the structural models were calibrated against the PLAXIS 3D model to facilitate structural analysis and design considering soil structure interactions. The complex interfaces with the adjacent structures and excavations (i.e. One Sydney Harbour project basement, Stage 1B) were included in both the PLAXIS 3D and the structural models. The design optimisation was achieved by an ongoing collaboration and coordination with stakeholders throughout the design stages. To provide flexibility in the construction staging of the adjacent basement at the shared wall, a sensitivity analysis was undertaken to assess various scenarios. Figure 4 depicts example views of the PLAXIS 3D model. Foundations and the rock socket depths for the d-walls, barrettes and piles were designed to resist combined compression, uplift and lateral loads. Shaft adhesion values have been adopted considering the pile load tests (O-Cell) results carried out by Bauer Foundations Australia in the adjacent site (Barangaroo Stage 1A). Axisymmetric numerical analysis in comparison with traditional methods have been used to better understand the pile behaviour, in particular in tension mode. Indicatively, tension and compression load of approximately 10 MN and 200 MN have been considered in foundation design, respectively.

To construct the Sydney Crown Hotel Resort, the world's largest capacity tower crane was erected. The tower crane was used to lift large steel columns and beams, some weighing up to 100 tonnes, in the congested Barangaroo site. Only four piles were designed to transfer the loads of the crane to the deep rock layers near the harbour. The designed piles carried over 10MN compression loads with the lateral loads transferred to the basement structure. To make the walls and excavation more efficient, the dewatering levels designed as 1m below the staged excavation levels, and hence monitoring wells with recharge system and a comprehensive real-time groundwater monitoring program was implemented to control and validate the design assumptions.

To validate the design and to mitigate the potential construction risks, a comprehensive web-based real time instrumentation and monitoring plan was designed and implemented, including uniaxial and biaxial in-placed inclinometers, strain gauges, survey markers, reflectometers and groundwater piezometers.

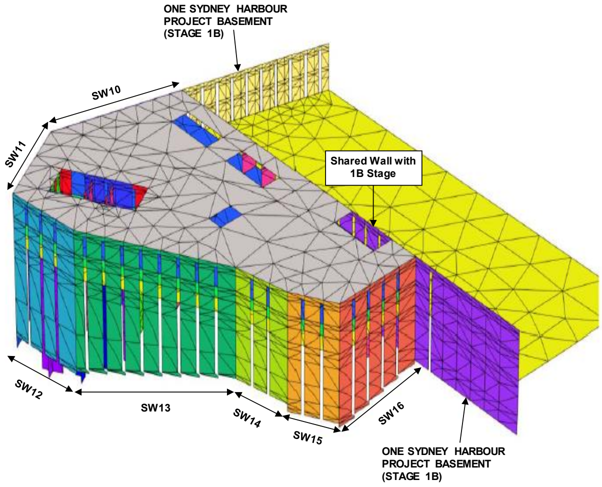
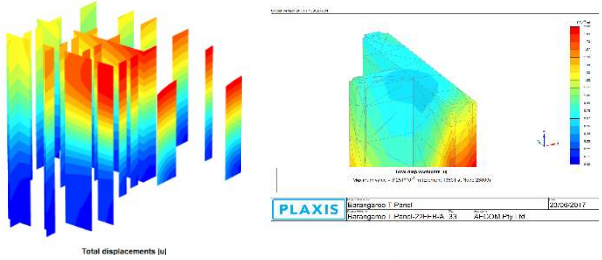


Figure 4. A sample view of PLAXIS 3D model



(a) (b)

Figure 5. A sample of PLAXIS 3D model output; (a) total displacement of core barrettes and (b) total displacement of a T panel

2.3 *Construction*

The D-Wall panels and barrettes were constructed by excavating the panels under bentonite to the required depth using clamshell grabs and hydraulic trench cutters. The diaphragm wall construction was undertaken in a series of panels in a planned sequence. Every second panel constructed initially as primary panels followed by the construction of the secondary and closing panels between the previously constructed primary panels.
The construction challenges are summarized below:

- Constructability,
- Restricted space on site,
- Complex ground conditions and high (tidal) ground water level,
- Contamination (asbestos and hydrocarbons); required restricted working hours, working sequences, strict waste classification and disposal regime,
- On-site geotechnical verification.

2.3.1 *Constructability*

There was an integrated collaboration throughout the design stages among the design and the construction teams to ensure a constructible design has been delivered safely considering element sizes, weights, volumes and considering the tight program and the site constraints.

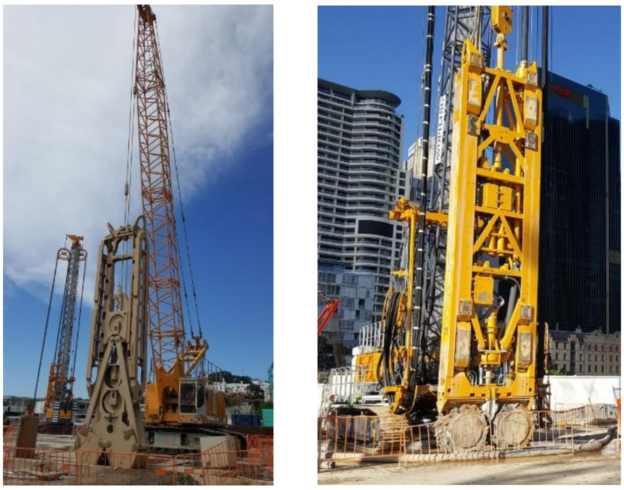
2.3.2 *Restricted space on site*

Diaphragm walls and barrettes elements were designed to maximise off-site fabrication. This provided adequate space on site to build the bentonite plant, wastewater treatment plant and handling and interim storage of contaminated spoil. During construction, a comprehensive critical path sequencing plan was developed and adopted to facilitate the spoil removal and concreting process.

2.3.3 *Complex ground conditions and high (tidal) ground water level*

The frequent variation of the groundwater level (tidal effect), variable depth of fill, and the high soil permeability, increased the risk of ground collapse and bentonite loss during the excavation and construction of D-Walls and barrettes. To mitigate the risk, ground pre-treatment was carried out along the D-Walls alignment and at every barrette location (Azari et al 2020).

The excavation of D-Wall panels and barrettes was carried out in two stages due to the complex ground conditions. A clamshell grab was used to excavate fill, alluvium and weak or highly weathered rock in each panel. Hydraulic trench cutter was used to continue the excavation into the rock (Figure 6). Bentonite slurry was used to support the sides of the excavation.



(a) (b)

Figure 6: (a) Clamshell grab; (b) Hydraulic trench cutter (after Azari et al 2020)

2.3.4 *Contamination (asbestos and hydrocarbons)*

To mitigate the risk of exposure to potential contaminated spoil and asbestos, strict health and safety measures were implemented. Full-time Occupational Hygienist and Specialists were present at the site for the duration of the construction. The construction site was segregated into two zones of Dirty and Clean Zones as follows:

- Dirty Zone – indicated that works need to be conducted with asbestos controls in place, including the wearing of respiratory protection and disposable coveralls.
- Clean Zone – indicates that works can be conducted without asbestos controls

The Dirty Zones and access walkways were delineated by high fencing and geofabric. Regular air monitoring for asbestos and other nominated key contaminants, pertinent to the area of works, was conducted. And prior to decommissioning each Dirty Zone, the Occupational Hygienist inspected the area and provided a visual clearance of the ground surface. Furthermore, all equipment which needed to leave the Dirty Zone, was required to be cleaned to remove gross contamination prior to traversing a designated Clean Area. Segregated remote spoil storage bays were established for spoil for removal off-site for ex-situ remediation/decontamination.

2.3.5 *On-site geotechnical verification*

An appropriate construction methodology as well as extensive site observation were required to achieve high quality construction. A full time on-site geotechnical engineer with full collaboration with the design team inspected the foundation design requirements. Rock socket requirements for D-Walls and barrettes were (a) achieve specified socket roughness, (b) clean panel bases, and (c) Socket to be founded in specified rock class. Proper excavation tools were employed to achieve adequate roughness in the diaphragm wall and barrette sockets.

To clean the base of the panels, the hydraulic cutter was required to be kept at the base of the excavation to pump out debris and working bentonite while fresh bentonite was pumped from the bentonite plant to the top of the panel.

Extensive site observation was undertaken to closely monitor and record the construction progress on site. Daily excavation records and site observations were compared with the available borehole logs. The comparisons indicated that the clamshell grab refusal generally occurred in sandstone Class V or low strength sandstone Class IV (Rock classification as per Pells et al. 1998). Comparing borehole logs with the recorded site observations indicated that the hydraulic trench cutter penetration rate reduces with increase in rock strength. The results show that the penetration rate halved from approximately 2 m/hr (i.e. 6.7 - 8.4 m3/hr) for sandstone Class IV to 1 m/hr (i.e. 3.4 – 4.2 m3/hr) for sandstone Class III. These penetration rates could be an indication of ground conditions in comparison to adjacent boreholes and the design assumptions.

2.4 *Sustainability*

The sustainability and environmentally friendly practices of the different options were in the forefront of the decisions throughout the design and construction process of the in-ground structure of Sydney Crown Hotel Resort.

The green concrete and high strength steel were used to minimise the carbon emission of the construction. The green concrete used reduced amount of Portland cement, reclaimed/recycled water and crushed slag aggregate. High strength steel was used for the plunge columns to reduce the amount of steel and fabrication work.

The ex-situ remediation of spoils from foundations work and basement excavation was used to convert the previously contaminated wharf into a usable commercial and public space. Moreover, the 3D modelling of soil structure integration assisted to optimise the design (e.g. reduce the depth of the panels). For instance, the optimisation helped to reduce the concrete volume and steel tonnage by approximately 10% from the original reference design.

3 CONCLUSIONS

This paper presented the challenges and adopted solutions during the design and construction process of the Sydney's tallest single mixed-use tower, Crown Sydney Hotel Resort. The in-ground structure of this tower was constructed in a highly variable and complex ground profile.

The ground conditions of the site were influenced by the historical developments such as the former gasworks and a variety of industrial/commercial/maritime activities. The results of a comprehensive site investigation program were used to reliably characterise the ground conditions and also generating 3D ground models (i.e. Surfer and BIM).

A combination of 2D and 3D finite element approaches was used to undertake SSI analysis considering the asymmetric shape of the excavation, highly variable ground profile and complex configuration of the structural elements. Integrated geospatial and BIM (GEOBIM) solutions were used to facilitate the modelling and optimisation process. Analytical method was used to determine the earth pressure and validate the results of the FE analysis. The structural models were calibrated against the PLAXIS 3D models. The design optimisation was achieved by an ongoing collaboration and coordination with stakeholders throughout the design stages.

The diaphragm wall panels and barrettes were constructed by excavating the panels under bentonite to the required depth using clamshell grabs and hydraulic trench cutters. The construction challenges were constructability, restricted space on site, complex ground conditions, high (tidal) ground water level, contamination and the tight program. The collaboration between the design and construction teams and using off-site fabrication overcome the site constraints. The ground pre-treatment was carried out along the diaphragm walls and at every barrette location to mitigate the risk associated with the complex ground conditions and high (tidal) ground water level. Moreover, the excavation of diaphragm wall panels and barrettes was carried out in two stages. A clamshell grab was used to excavate the fill, alluvium and weak or highly weathered rock in each panel. Hydraulic trench cutter was used to continue the excavation into the rock. Extensive site observations and a detailed construction methodology was used to meet the design requirements.

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