

Application of a multi-technique ground engineering solution to overcome geotechnical and physical challenges in Docklands

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ABSTRACT

A high-grade mixed-use development has been proposed in the heart of Melbourne, Australia situated on the banks of the Yarra River. The proximity of the project to an existing heritage-listed seawall dock structure required the detailed design and analysis of proposed foundation and retention system to ensure all adjacent structures were protected and the project specifications and performance criteria are met. The proposed project consisted of a single level basement in very soft clays with a high groundwater table and deep foundation piles socketed into a bedrock at depths exceeding 35m. This paper describes the methodical process of assessing and implementing a sheet pile solution to protect and maintain the integrity of the existing seawall for the enabling and pile installation works. The building is supported by deep foundation Continuous Flight Auger (CFA) piles with column loads exceeding 35MN with dynamic pile testing being carried out for performance verification. The paper also shares the application of the wet mass soil mixing (MSM) ground improvement technique combined with the conventional soldier piled wall for an internal deep excavation to construct the core and lift overrun structures for the building. The purpose of the MSM was to act as a bottom strut to a soldier piled wall and a barrier to control lateral and vertical flow of soft soils and groundwater.

Keywords: CFA piling, pile testing, sheet piling, mass soil mixing, ground improvement

1 INTRODUCTION

In challenging ground conditions such as soft soils with a high groundwater table, the geotechnical proposal often requires careful considerations and technical assessments to formulate an efficient and safe ground engineering solution for a project. Coupled with physical constraints such as an existing heritage dock with old timber piles, the practicality and constructability of any substructure solutions becomes exponentially difficult.

A new riverfront development in the heart of Melbourne has been proposed, which consists of a luxury hotel, offices and private residences. Sat on an approximately 7,000m² acreage, this 20-level structure and a basement is expected to be a high-profile landmark building for the upcoming decades. This project is located in a challenging geotechnical setting where very soft soils and a high groundwater table are present. There is also a heritage-listed crane and dock structure that had to be retained and the existence of hundreds of old timber piles in the ground.

This paper describes the following challenging aspects of the project in detail:

- Geological and structural conditions
- Considerations of various piling techniques for the foundation and retention solutions
- Pile testing and performance verification
- Physical constraints and formulation of the perimeter retention solution
- A hybrid piling and ground improvement solution for deeper core excavations

To resolve all the geotechnical, structural and physical challenges in this project, a multi-technique ground engineering solution comprising deep Contiguous

Flight Auger (CFA) piles, sheet piles and wet mass soil mixing (MSM) was successfully implemented.

2 GEOLOGICAL AND STRUCTURAL CONDITIONS

2.1 Geological Conditions

The geology of the site is of typical Yarra Delta depositions (Neilson, 1992) of Quaternary/Tertiary sediments underlain by Silurian age Melbourne Formation. The Quaternary/Tertiary sediments logged in the geotechnical boreholes at this site comprised a layer of fill, Coode Island Silt (CIS), Fishermens Bend Silt (FBS), Moray Street Gravels (MSG) and the Melbourne Formation (MF) siltstone. Table 1 shows the typical geological profile of the site. The groundwater table was reported to be about 1m below existing surface levels.

Table 1. Typical geological profile

Material	Depth (m)	Description
Fill	0 – 0.8	Soft to firm
CIS	0.8 – 13.0	Very soft to firm
FBS	13.0 – 24.0	Firm to stiff
MSG	24.0 – 28.0	Dense to very dense
MF	28.0 +	Extremely to highly weathered

From a ground engineering perspective, the geology presented some key challenges that must be considered, as below:

Coode Island Silt

- This is a soft marine clay deposit, which is unsuitable for founding of foundation piles.
- Bored piling through this material requires temporary support such as drilling fluid or casing.

- Driven precast and CFA piling are typically efficient to penetrate this stratum.
- Together with a high groundwater table, retention piling solution can be challenging from a stability and deflection aspects. Typical options, such as diaphragm wall, secant piles and sheet piles that form a continuous wall, can be considered.

Moray Street Gravels

- This granular-based medium dense to very dense profiles can be a suitable founding layer for the precast driven piles or lightly loaded piles.
- This profile was expected to be unstable for open bored piling where temporary support such as drilling fluid or casing is likely to be required. Due to the depth and thickness of this geological layer, this can present adverse construction and commercial impacts by using this method of piling.
- CFA piling can efficiently penetrate through this layer if suitable piling equipment and experience crew are available. If designed appropriately, CFA can be founded within these layers by considering the effect due to the presence of the weaker interbedded clay layers.

Melbourne Formation

- This layer is suitable to support the large structural loads. At a depth of 30+m, it can present constructability and quality concerns for bored and CFA piling and the possible impact on cost and program.
- Bored piling using support fluid or casing can be relatively slow and expensive depending on the magnitudes of loads to be supported.
- CFA piling will likely be the most efficient solution.

2.2 Structural Loading Conditions

While the proposed development can be considered a medium rise structure, the main structural columns have ultimate loads up to 35MN. The structural core has been predominantly governed by dynamic loads from earthquakes. The core analysis indicated large ultimate compression, tension and shear loads in selected areas of the core of up to 30MN, 5MN and 1.5MN, respectively.

To carry an ultimate compression load point of around 35MN, the foundation options considered were:

- About 10 to 12 number of 400mm square precast piles driven to the MSG layer.
- 2 number of 750mm diameter CFA piles founded in the siltstone bedrock.
- 1 number of 1,200mm diameter bored pile founded in the siltstone bedrock.
- From a settlement perspective and also considering the potential risk founding piles in the gravels, the CFA and bored solutions were regarded as the more robust option.

- The large number of driven precast piles under a column can also have an adverse impact on the pile cap size and its constructability in soft soil conditions compared to the other piling alternatives.
- Due to the limited spatial dimensions in the core, the driven precast piling option was deemed physically impractical as a large number of driven piles will be required to carry the core loadings.

2.3 Commercial Conditions

For the foundation piling solution, an important consideration was the cost and programme not only for the piling scope, but to holistically consider the relevant items related to the piling proposal, such as pile caps and spoil volume.

From the commercial assessment carried out for the case of the ultimate column load of 35MN, the CFA piling options were determined to be the cheapest and the fastest solution with everything considered. The precast driven piling option was found to be the most expensive (by about 40%) considering the largest pile cap requirement with part of the savings from no spoil cost and also the slowest by about 30%.

3 CONSTRUCTION AND TESTING OF CFA PILES

As the CFA piles were heavily loaded, the design of the piles required the pile to be drilled to refusal in the siltstone. Therefore, the capability of the piling equipment was one of the main considerations due to the nature of the project. The piling rig used on this project was the Fundex F3500 as shown in Figure 1. The rig is one of the largest CFA machines in the world, which weighs about 120T with available torque of 45Tm and an extraction force of about 100T. Because of its capabilities, the rig has been successfully used to install CFA piles of sizes between 450mm and 1,200mm and frequently to depths in excess of 35m.

It was important to ensure the piles were drilled to genuine refusal, and that there were real time instrumentations on board to monitor the drilling conditions to help ascertain the refusal criteria (Chong, 2020a). An under-powered rig may encounter premature refusal nominally in the residual or extremely weathered siltstone. This could cause additional and unexpected pile settlements during the service life of the structure. With the F3500 rig, it was found that pile refusal occurred in highly to moderately weathered siltstone with a rock socket of at least 2m and this was evident from the rig instrumentation records. Figure 2 shows an example of the instrumentation record during the penetration process.



Figure 1. The Fundex F3500 piling rig

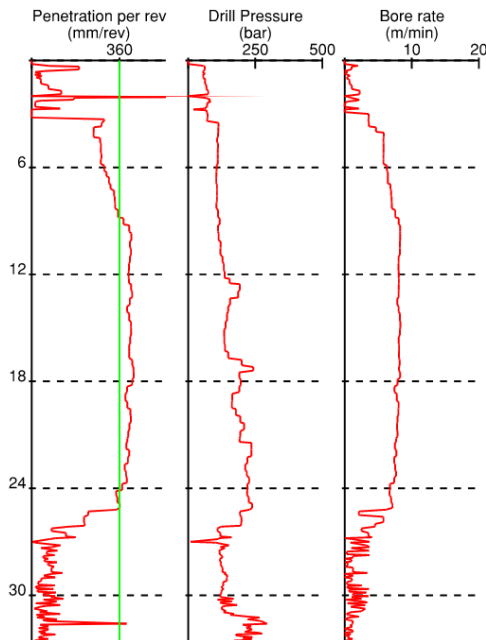


Figure 2. Instrumentation records during pile penetration

9 number of dynamic pile tests were carried out on a combination of 600mm and 900mm diameter piles. A 20T test hammer, as shown in Figure 3, was utilised. Based on the construction controls implemented and testing analysis carried out, the overall test results are as follows:

- 600mm piles proved a load of 3,000kN at 10mm settlement and 5,500kN at 20mm settlement.
- 900mm piles proved a load of 11,000kN at 15mm settlement and 17,000kN at 30mm settlement.
- 1/3 of the load was mobilised on the shaft.
- 2/3 of the load was mobilised on the base.

It is important to note that the pile load-settlement results above are closely related to the construction method, rig capability, quality controls and experience of the piling contractor.



Figure 3. The 20T test hammer set up for dynamic load tests

4 DESIGN AND CONSTRUCTION OF THE PERIMETER RETENTION SYSTEM

The proposed development requires the construction of a one-level basement in very soft soils and high groundwater table. The reference design provided by the client was a secant piling scheme, as shown in Figure 4a.

The light grey circles in Figure 4a are the existing timber piles. As evident, some locations of the secant piles appear to clash with the timber piles. It is also noted that a secant solution requires a guidewall which will be further impeded by the timber piles. As the secant piling solution offers little to no flexibility in terms of the pile positions, it was determined that this was an impractical solution. Figure 4b shows a typical guidewall construction and configuration.

An alternative solution in the form of sheet piling was proposed. Due to the shape and a relatively more flexible nature of the sheet, this solution offered practical benefits from a constructability and spatial perspectives. Figure 5 shows the layout of the sheet pile proposal. While there were still locations where clashing was possible, the sheets have a small degree of flex that can help realign the sheets in order to avoid clashing with the timber piles. Figure 6 depicts the sheet piles in close proximity to the timber piles.

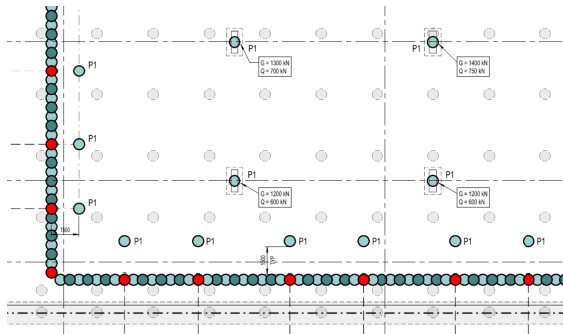


Figure 4a. Reference scheme of secant piles



Figure 4b. Typical guidewall installation and construction

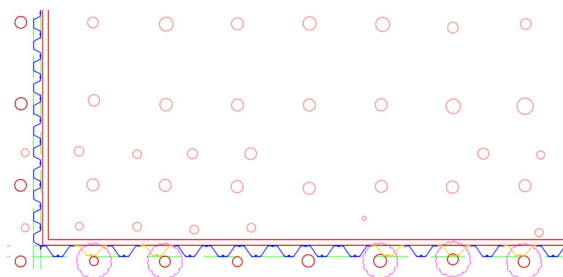


Figure 5. Layout of the sheet pile proposal



Figure 6. Proximity of the sheet pile to the timber pile

The sheet piles were designed as a cantilevered system to aid the excavation and construction of the proposed basement. The sheets were successfully installed by resolving the reduced amount of clashes to form a continuous wall.

5 DESIGN AND CONSTRUCTION OF RETENTION SYSTEM FOR DEEPER CORE EXCAVATIONS

The main core proposed for the structure required a deeper excavation with a retained height of about 4.5m. In this ground condition, it was anticipated that lateral soil and water movements will be a key challenge in the design and construction of the retention system. The options considered during the design development phase were secant piling and sheet piling. The secant piling option which requires a guidewall was determined to be the costliest with the longest programme for the piling scope only. The sheet pile option was about 10% cheaper and faster, however the availability and lead time for the material was deemed a significant risk. Both the secant and sheet options would require two rows of temporary props to ensure the excavation is safe and within the deflection criteria imposed.

A further involvement by the piling contractor helped to develop a hybrid retention system comprising CFA soldier piles with wet mass soil mixing (MSM) infill wall in between the soldier piles and a mass soil mixed base strut. This solution was found to be effective in a given geological and design conditions (Chong, 2020b). The MSM construction method involves a specialised arm with a central nozzle and a mixing head being attached typically to an excavator-based machine (Figure 7). Cement binders are injected through the nozzle and mixed with soils at depths through the rotation of the mixing head. The mixing arm is moved vertically, backwards and forwards in the soil until a reasonably homogeneous mixed soil is attained. The main purpose of this solution is to improve the characteristics, such as strength and permeability of the in-situ soils (Chong, 2023).

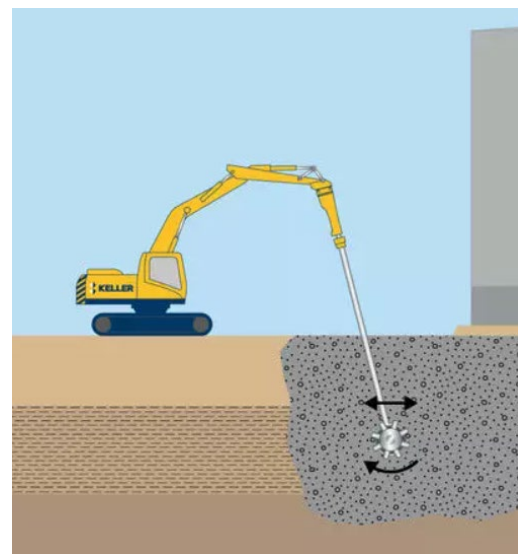


Figure 7. The MSM technique

The advantages of the hybrid retention solution were identified as follows:

- An effective barrier for lateral soil and water movements with the MSM curtain wall.
- A MSM base strut acting as a support to the retention system and providing a relatively firm and dry base to launch the construction of the core (acting as a barrier for vertical water flows).
- Requires only one row of temporary prop with the MSM base strut acting as supports to the retention piles. This resulted in further optimisation of the soldier pile depth, wall deflection and the stability of the wall.
- The cost and programme were similar to the other two options for the piling component.

Figure 8 shows the setup of the mixing plant on site. Figure 9 shows the mixing arm mounted on an excavator-based machine on site.



Figure 8. Mixing plant on site

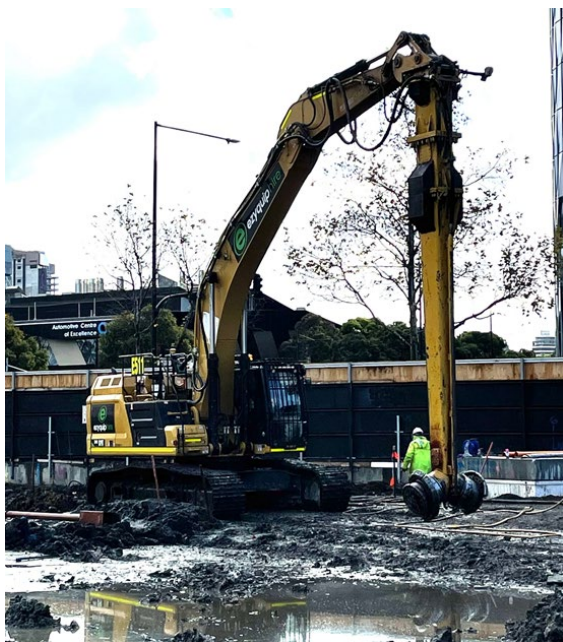


Figure 9. The MSM machine set up on site

The design of the hybrid retention system performed using 2D finite element software PLAXIS 2D. Figure 10 shows the cross-section and details of the numerical simulation. One row of temporary steel props was adopted to provide lateral support to the CFA soldier piles during the excavation works. The

Mohr-Coulomb constitutive model was adopted for the soils and the MSM material.

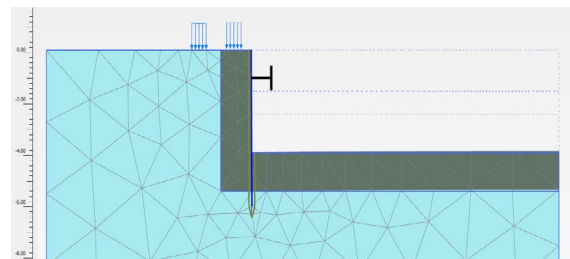
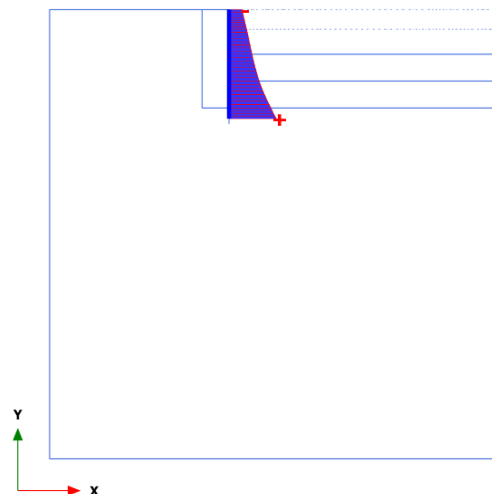


Figure 10. Numerical modelling of the core retention system

Figure 11 presents the estimated lateral deflection of the retention wall. Multiple sensitivity studies were performed to investigate the sensitivity of upper and lower bound strength and deformation parameters of the CIS and the MSM. It was found that the design parameters for the MSM required a uniaxial compressive strength (UCS) of 1MPa, an undrained shear strength of 250kPa and a modulus of 100MPa.



Total displacements u_x (scaled up 200 times)

Maximum value = 0.01314 m (Element 9 at Node 1203)

Minimum value = 3.578×10^{-3} m (Element 1 at Node 217)

Figure 11. Estimated lateral wall deflections

The CFA soldier piles and MSM were installed on site. As per the quality control requirements, wet MSM soil samples were retrieved for testing in the laboratory. The results obtained indicated the strengths were generally around 1.5MPa which was above the design requirement. The wall monitoring also indicated conformance with the design estimations. Figures 12 and 13 show the condition of the core excavation with the base and side walls of the retention system exposed.



Figure 12. Core excavation



Figure 13. Core excavation

6 CONCLUSION

This landmark private development project presented unique challenges to engineers and contractors, such as:

- Geotechnical: Very soft soils with high groundwater table dictating not only the cost and programme of the ground engineering solutions, but also the safety and stability of the retention system.

- Structural: High building loads of the columns and cores.
- Physical: The presence of an existing dock structure and a large number of old timber piles

To resolve these issues, a multi-technique ground engineering solution consisting of deep CFA foundation piling, sheet piling and a hybrid CFA soldier pile with mass soil mixed infill wall and base strut. The primary factors driving the innovative solution are as follows:

- A CFA piling foundation system was determined to be the most efficient solution from a cost, program and efficiency perspectives compared to other piling techniques such as bored pile and precast driven piles.
- The verification through dynamic pile testing proved the geotechnical performance of the CFA piles.
- The sheet piling solution was adopted as the perimeter retention system due to its relative flexibility and practicality in resolving the clashes with existing old timber piles.
- For the deeper core excavations, it was found that the hybrid CFA soldier pile with MSM infill wall is a more effective solution than the more conventional secant pile and sheet pile options. The advantages of the hybrid retention system include a good horizontal and vertical control for soil and water flows, a reduction in the temporary propping requirement, better factor of safety in terms of wall stability and a relatively firm/dry base for the construction of the core structure.

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