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Geotechnical design challenges associated with construction of the new AMCOR paper mill in Botany, NSW

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ABSTRACT

The new Amcor B9 paper mill in Botany, NSW, involved the design and construction of pile and slab foundations, temporary and permanent retaining structures, deep excavations, dewatering and ground improvement. There were numerous technical and design challenges, including tight settlement tolerances, significant cyclic loads, adjacent heritage structures and uncontrolled fill material. Construction staging meant that settlement sensitive infrastructure was constructed simultaneously with and adjacent to dewatering, excavation and dynamic ground improvement activities. Geotechnical design included the derivation of realistic and workable soil parameters from a combination of laboratory testing and *insitu* soil testing. Analysis and design was carried out using a combination of empirical calculations, slope stability, settlement and finite element software, while movement monitoring was carried out to compare predicted and actual displacements.

Keywords: piles, displacements, ground improvement, monitoring, dewatering, excavations

1 PROJECT AND GEOLOGICAL SETTING AND DERIVATION OF SOIL PARAMETERS

The project involved the construction of the largest recycled paper machine in Australia. The paper machine is 330 m long, 22 m high, and capable of producing 1.6 km of paper per minute. Construction commenced in early 2011 and new paper mill officially opened in early 2013. The early works contract was awarded to Baulderstone Construction Pty. Ltd. (now part of Lend Lease Corp. Ltd.), with the D&C contract awarded to a consortium headed by Leighton Contractors Pty. Ltd. (now CPB Contractors Pty. Ltd.), which included Golder Associates Pty. Ltd. as the geotechnical designer.

The site was underlain by uncontrolled fill materials, overlying quaternary deposits, overlying bedrock, further outlined in Table 1. Due to the depositional nature of the marine materials, and the uncontrolled nature of the fill materials, the ground profile was variable and presented significant foundation engineering challenges. This risk was managed through the use of deep foundations and ground improvement, as discussed further in this paper.

Table 1. Stratigraphic units

Unit	Depth (m)[a]	Description
1 – Uncontrolled fill	1 to 4	Construction rubble, pulped paper, excavated natural materials, including infilled ponds and old waste storage areas.
2 – Botany Basin sediments[b]	25 to 35	Fine to medium grained, loose to very dense sand and silty sand (strength generally increasing with depth), with occasional peat, clay, silt and cemented zones
3 – Bedrock	N/A	Generally sandstone, with laminate and siltstone zones

[a] Approximate depth below existing surface level to base of unit.
[b] Quaternary age deposits overlying bedrock, which can comprise up to four sub-layers; marine/estuarine/aeolian sands with clay and peat lenses, overlying aeolian sands, overlying estuarine/fluvial sands and clays, overlying marine/estuarine/fluvial/aeolian sands, clays and gravels (Hatley 2004).

The derivation of suitable soil parameters for these geological units, and their sub-units, was critical for the project, to ensure safe yet economic design. Parameters were derived from the results of geotechnical test investigation data and laboratory testing, carried out during preliminary investigations prior to detailed design. For critical construction activities, additional investigations, where possible through fill, were carried out to enable design efficiencies to be realised.

2 PAPER MACHINE

The operation of the paper machine produces high frequency and varied cyclic forces. Ongoing operation of the paper machine requires a stable foundation, as small differential settlements could result in poor paper production. This resulted in the requirement for strict settlement (<6 mm settlement) and differential settlement tolerances (<0.5 mm/m between adjacent foundations). Pile foundations were chosen to provide the necessary settlement control for the paper machine.

2.1 Pile design

The paper mill machine and associated housing facility, was constructed on impact driven 350 mm square segmental precast concrete piles. This type of foundation was chosen so that pile structural strength could be controlled and standardised. Geotechnical design required piles to be driven specific depths below ground surface level and achieve prescribed blow count/penetration ratios. In addition, the pile design had to be checked to ensure that the vibration frequency of the paper machine did not match the internal dynamic frequency of the piles, which could lead to spalling, cracking, reduced pile capacity and ultimately, foundation failure. Penetration depths were generally between 9 and 12 m.

2.2 Pile testing

All piles were impact driven under the supervision of a geotechnical engineer, to record blow counts and make recommendations for further driving or pile testing. This method of installation allows for checking that the pile bearing capacity is achieved through the correlation of blow counts and penetration. In addition, the following pile tests were carried out:

- Static load test (one pile from critical pile group tested)
- Dynamic load tests with CAPWAP signal matching (approximately 50% of piles)
- Re-strike tests (minimum one pile per pile group)

This testing regime allowed for an increase of the geotechnical strength reduction factor (Φ_g) from 0.54 to 0.70, in accordance with AS2159-2009, resulting in significant construction cost savings. The results of static load test recorded 6 mm settlement under 2000 kN loading (approximately double the ULS design load), indicating settlement limits should not be exceeded during paper machine operation. It is noted that the results, analysis and conclusions from these tests are not the purpose of this paper.

3 REJECTS SUMP PIT

A rejects sump pit was constructed after the piled foundations had been installed and construction of the main housing facility had commenced. The purpose of this pit was to allow temporary storage and dry out of reject pulp material from paper production.

Figure 1. Rejects sump pit construction

3.1 Effect of excavation on adjacent pile cap

The rejects sump pit was a 3 m deep excavation carried out a horizontal distance of 0.5 m from a pile and pile cap at the eastern end of the housing facility. A finite element model using 2D-PLAXIS software was created to simulate the construction sequence to obtain movement predictions. To confirm local soil stiffness, multiple dynamic cone penetrometers were carried out at the location of the excavation.

Once the model was created, it was used to assess movement effects of various sheet pile types with various embedment depths, in order to find the most cost effective sheetpile system, to control displacements at adjacent pile cap during subsequent excavation. Figure 2 showed that 7 m long, GU7N-D sheetpiles, with 3.5 m embedment below excavation, would result horizontal displacement at the top of sheetpile between 22 and 24 mm. Modelling showed maximum horizontal and vertical pile cap movements of 10 mm and 1 mm, which were within structural and serviceability tolerances.

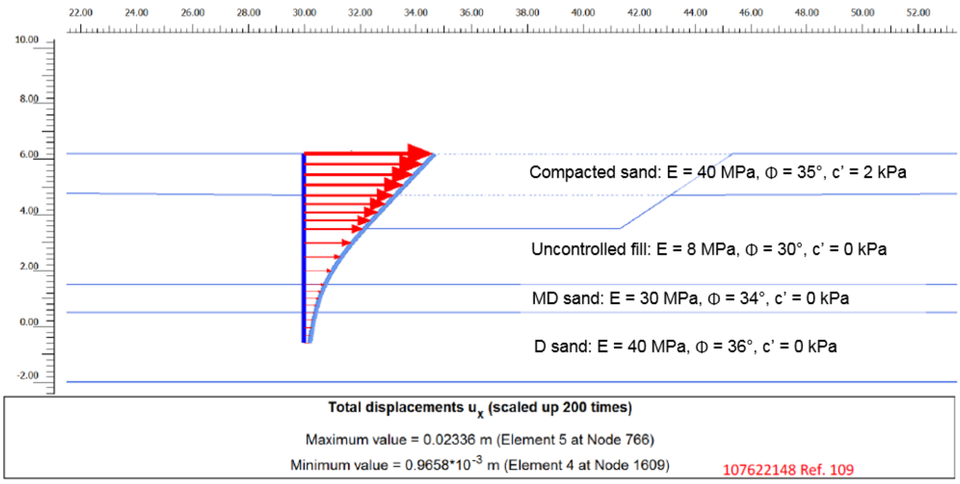

Figure 2. PLAXIS predicted movement of sheetpile

3.2 Monitoring and construction considerations

It was also recommended that the vibrations during construction should not exceed a Peak Particle Velocity of 20 mm/sec, to reduce the likelihood and proliferation of vibration induced densification of the sand and subsequent settlement below the housing facility (Gaba et al. 2003). Vibration and displacement monitoring devices were installed on the existing housing facility before sheetpile installation. Displacement monitoring was installed on the sheetpiles after installation and before excavation commenced. Displacements from the excavation are summarised in Table 2. The good match between predicted and recorded shows again the importance of realistic soil parameter derivation, to reduce the construction costs associated with overly conservative design.

Table 2. Displacement monitoring during rejects sump pit excavation

Survey mark location	Predicted (mm)	Recorded (mm)
Housing facility (average, horizontal)	3-5	2-3
Top of sheetpile wall (horizontal)	22-24	17-19

4 TEMPORARY DEWATERING

Temporary dewatering, required for the construction of three underground storage tanks, was carried out after piled foundations had been installed and construction of the main housing facility had commenced. These tanks were to temporarily store excess stormwater captured on site during high rainfall events, to reduce the impact on the surrounding stormwater system. It was necessary to assess the effects that dewatering activities would have on the recently constructed and existing infrastructure.

4.1 Effects on piles, local infrastructure and heritage structures

The location of the stormwater tanks were close to settlement sensitive infrastructure, services, heritage structures and critically, the recently installed piles of the housing facility. A finite element model using 2D-PLAXIS software was created to simulate the effect of dewatering and excavation activities. From this model, horizontal proliferation of water draw-down could be modelled, and induced settlement predicted. A series of groundwater monitoring wells and survey marks were installed, with trigger levels set up, so to monitor the effects of dewatering, as shown in Table 3 and Figure 3.

4.2 Effects of cohesive lenses and rainfall

A CPT was carried out at the location of each stormwater tank, identifying occasional clay and peat lenses within the silty-sands at each location. From this, the natural sand unit was modelled with a lower hydraulic conductivity value, and isolated bands of clay and peat were included in the model. Without reducing the hydraulic conductivity of the sand unit or modelling cohesive zones, the predicted groundwater drawdown and associated settlement were assessed to be close to allowable limits of surrounding infrastructure.

Table 3. Vertical settlement during dewatering

Survey mark location	Predicted (mm)	Recorded (mm)
Heritage structure	5	<3
Paper machine housing facility	5-7	<2
Local infrastructure and utilities	5-10	<8

This modelling methodology produced reduced groundwater drawdown adjacent to the dewatering site. Results from movement monitoring (refer Table 3) justified this assumption as predicted settlements were not exceeded. Figure 3 shows that even with the reduced conductivity and influence of cohesive zones modelled, the recorded groundwater drawdown was still less than predicted. It also shows that rainfall events resulted in groundwater recharge. The proximity to the ocean and associated tidal movements are likely to have also increased groundwater recharge rates (Somerville 2005).

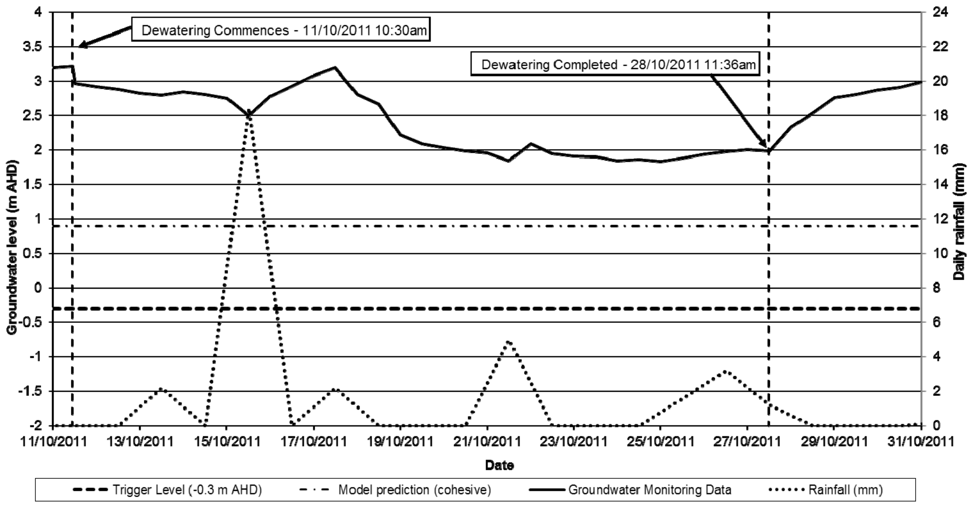

Figure 3. Groundwater drawdown during dewatering

4.3 Construction notes

Initially, geotechnical input was not requested for dewatering design and structural design of temporary shoring. However, during the initial dewatering and excavation activity, localised liquefaction was occurring at the base of excavation. Geotechnical assessments of the as-constructed excavation concluded that there were inadequate spacing of spearpoints and capacity of groundwater pumping system. In addition, the geotechnical assessment indicated that there was insufficient strutting and bracing of temporary shoring. It was therefore recommended to the client to increase the number of spearpoints, the capacity of the pumping system, and the number and capacity of struts/bracing.

This resulted in construction delays, and could have been avoided if geotechnical input was requested during excavation and dewatering planning.

5 STORAGE FACILITY

The paper and equipment storage building, located immediately north of the paper mill machine, was not subjected to the same high, cyclic and dynamic loads as the paper mill. The main design loads were dead loads, associated with the storage of paper rolls (weighing up to 47 tonnes) and equipment. Although not as stringent as the paper mill building, settlement (<15 mm settlement) and differential settlement tolerances (<1 mm/m between adjacent and orthogonal foundations) were still strict. Shallow foundations following ground improvement was chosen for the storage facility building.

5.1 High energy impact compaction (HEIC)

Based on preliminary geotechnical investigation data available during tender and detailed design, it was inferred that uncontrolled fill consisted predominantly of granular materials, including sands, gravels and construction rubble. Investigation data also indicated that fill material within the footprint of the storage facility extended to depths of about 2.5 m. HEIC was therefore the preferred method to improve the subsurface materials in this area, as this was deemed to be the most cost effective option.

During HEIC, there was a localised area at the southern section of the storage facility where the HEIC results were not satisfactory. Subsequent proof rolling of the area confirmed inadequate compaction of the subsurface materials. Further investigation was recommended, with CPTs and GPR carried out to define and delineate the substandard subsurface materials.

5.2 Preload

From the results of CPTs and GPR, numerous isolated and one extensive unsatisfactory layer, inferred to be either cohesive materials or old pulped paper, were identified. It was therefore recommended that a 3 m high preload be constructed on site, with monitoring plates installed to monitor and assess vertical displacement. Preload was constructed in two stages; an initial 1.3 m high preload in place for 5 weeks, and full height (3 m) preload in place for 5 weeks. Figure 4 shows the predicted vs recorded settlement at the centre of preload, showing a good correlation. Preload was removed after 12 September.

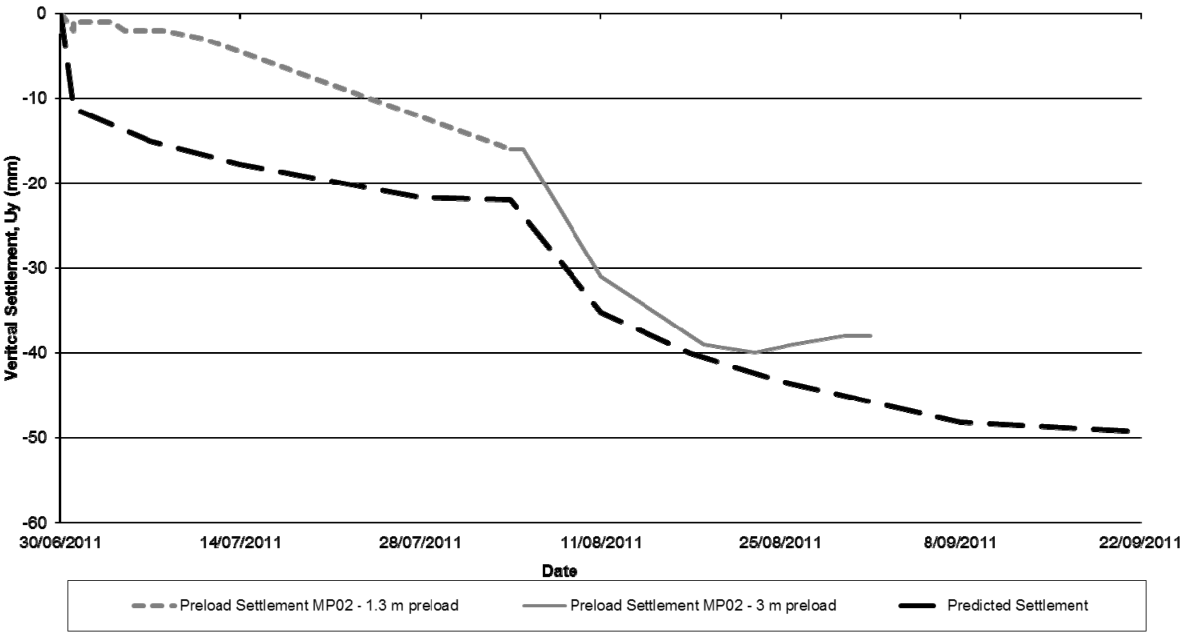

Figure 4. Settlement monitoring results from preload

The settlement data shown in Figure 4 indicate that the unsatisfactory layers were likely reworked cohesive material, not pulped paper. Settlement behaviour of pulped paper would mimic very soft and soft clays, with a high coefficient of secondary consolidation (0.03 to 0.06). This is due to pulped paper not only undergoing primary and secondary consolidation, but also degradation (or decomposition), which is time dependant. The graph indicates predominantly immediate settlement and primary consolidation, indicating well drained and thin cohesive materials. The small settlement under 1.3 m preload indicates the material was likely a reworked, firm to stiff clay, with a preconsolidation pressure of approximately 25 kPa.

5.3 Lessons learnt

During tender and detailed design, limited investigation data was available. An additional investigation was not carried out, due to the assumption of the homogeneous nature of fill materials in this area. Supplementary investigations in this area at pre-construction stage would have allowed for a better strategy for ground improvements in this area, reducing construction costs. However, D&C contracts are often structured with milestone payments and funds released only after certain construction activities are complete, meaning approval of funds for preliminary activities is often hard to justify.

6 MULTIPLE CONSTRUCTION ACTIVITIES

This project highlights some of the challenges associated with multiple construction activities occurring simultaneously on a reasonably small construction site. Early engagement with clients, as well as geotechnical input to construction staging, is critical. Construction staging is often decided through a critical path strategy, with critical activities and paths decided logistically and with contractual requirements.

It is necessary therefore, as geotechnical consultants, to ensure that construction staging allows for consideration of the effects certain activities will have on ground conditions, which may affect the long term performance and serviceability of built infrastructure. However, as this is not often the case, as geotechnical consultants, it is necessary to be able to propose construction methods that will reduce these potential impacts.

7 CONCLUSION

This project highlights the importance of three things which can overlooked by contractors:

1. *Sufficient preliminary investigations:* If additional geotechnical investigations were carried out during pre-construction, costs incurred during construction could have been reduced.
2. *Geotechnical input to construction staging:* Some of the construction activities discussed in this paper, could have been carried out prior to the installation and construction of settlement sensitive infrastructure. Although this resulted in some interesting geotechnical analysis; it could have reduced design and construction costs incurred by the contractor.
3. *Derivation of realistic geotechnical parameters:* Over-engineered and conservative design can result in unnecessary and avoidable construction costs. This is often due to the reliance on empirical data and conservative design parameters. This can be avoided by carrying out targeted and specific laboratory testing, the right suite of investigation methods and using the results obtained in creating good quality models.

There were also interesting facets of this project, which as consultants, we can learn from:

- The awareness that frequency of cyclical and dynamic loading, should be checked against proposed foundations internal frequency.
- Recommending extensive pile testing, although costly, can result in a much greater cost saving during construction due to the increase of Φ_g.
- The influence of clay and peat lenses in quaternary deposits, can help reduce the hydraulic conductivity of these materials, influencing analysis results and construction methodology.
- The effect of tidal water movements on dewatering activities, and the need for collaborative design, including geotechnical input to dewatering, shoring and bracing design.

- The behaviour of landfill materials, such as pulped paper, exhibit settlement characteristic akin to soft to very soft clay due to degradation/decomposition. It is therefore important to identify areas where these materials may be present, during early design stages.

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