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Pile analysis and design for Optus Stadium

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ABSTRACT: Bounded by a lake and fill for a piling platform and supporting a structure to hold 60,000 patrons, the Western Concourse and Western Quadrant of Optus Stadium had specific site challenges. The piled concourse was designed to incorporate ground improvement, and ongoing ground movements as a result of soft soil creep associated with raising ground levels across the site. A modification of the original pile section allowed a cost-effective installation that minimised project delays, maximised local fabrication and simplified installation for the contractor.

1 INTRODUCTION

1.1 *Optus Stadium*

The 60,000 seat, multipurpose sporting and entertainment venue is constructed on the Burswood Peninsula, to the east of the Perth metropolitan central business district in Western Australia.

The stadium was founded on 2694, 350mm and 400mm square reinforced precast concrete piles. Pile caps connected the piles to the stadium structure and supported a suspended slab. The piles were driven to founding level in the dense sand of the Kings Park Formation.

The sporting precinct, surrounding the stadium, was founded on numerous forms of ground improvement including controlled modulus columns (CMCs), dynamic compaction, surcharging and polystyrene fill, in a variety of locations.

1.2 *Western Concourse and Outer Stadium Piles*

The Western Concourse comprises an area of land west of the stadium, between the stadium and the lake. Figure 1 shows a cross section of the lake, Western Concourse, stadium and pitch.

The Western Concourse is part of a quadrant (quarter) of the stadium, which is structurally independent from other quadrants, separated by a movement joint (Fig. 7). The stadium ground floor slab is a concrete suspended slab.

The Western Concourse was founded on ground improvement comprising 350mm controlled modulus columns (CMCs), spaced from 1.3m to 1.8m, some with steel reinforcement cages to 12 or 18m. The original piled foundation solution to support the stadium comprised a combination of square reinforced precast concrete piles:

- 350NT type (4 N24 longitudinal bars) and;
- 400NT type (4 N28 longitudinal bars).

Following the original pile design (by others), Arup were requested to:

1. Review the original pile foundation design
2. Where the review indicated insufficient pile foundation capacity, undertake a redesign of the foundations such that all design actions including the anticipated lateral ground movements could be withstood, whilst also minimising project delays and utilising a simplified construction method

The pile assessment and redesign undertaken by Arup comprised piles in the Western Quadrant that were yet to be installed (the majority of piles in GL L, M and N from GL 2-22).

1.3 *Ground profile and soil conditions*

The ground profile consists, from pile founding layer to surface: Kings Park Formation (KPF), Sandy Channel Deposits (SCD), Swan River Alluvium (SRA), Uncontrolled Fill (Fill). An example profile is shown in Figure 1 and there was relatively little variation in soil profile within the Western Concourse.

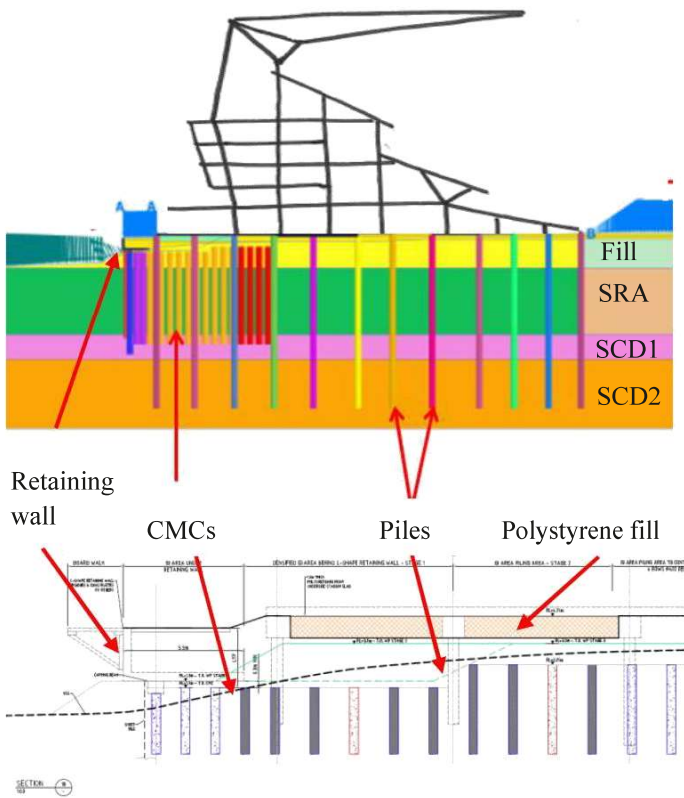


Figure 1. Vertical cross section through Western Concourse

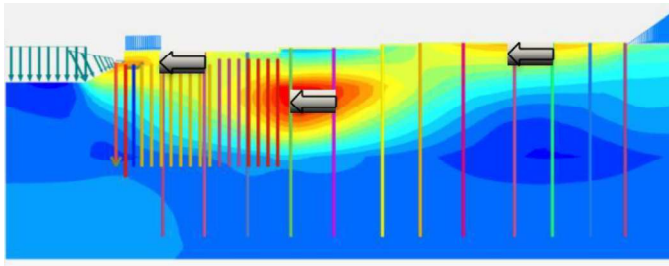


Figure 2. Example of long term lateral displacement field.

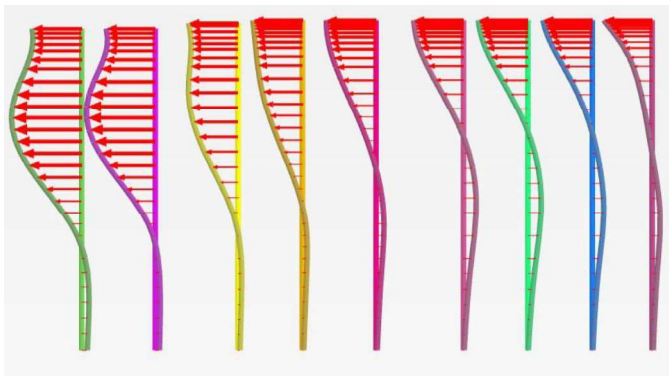


Figure 3. Example of long term lateral displacement profiles at pile locations.

In respect to the pile design, and in particular the effects of lateral ground movements on the piles, the main unit of interest is the SRA which comprises soft to firm dark grey silt and clay. The key soil material parameters adopted for the SRA are unit weight of 15kN/m^3 , undrained shear strength of $15+1.5z$, with z as meter depth of SRA and creep parameter C of 0.045 .

Figure 1 shows SCD in two layers and no KPF as this was considered more important for the prediction of lateral ground movements.

2 PILE DESIGN

2.1 Lateral Ground movements

Immediately adjacent to the Western Concourse, the ground was raised 2.5m above pre-construction levels for the piling platform and to cast the stadium floor slab on grade. Ground beneath the Western Con-course area is predicted to undergo long-term ground movements as a result of consolidation of the SRA due to raising of ground levels.

Plaxis analysis was conducted (by the ground improvement contractor) to assess the location, direction and magnitude of the anticipated movements. An ex-ample Plaxis analysis result is provided in Figure 2, with the profiles of lateral ground movement at pile locations along a gridline shown in Figure 3, showing a predicted ground movement in the upper soil layers towards the lake.

2.2 Soil and stadium movement

The stadium ground floor slab is a concrete diaphragm which rigidly connects the top of the piles. It undergoes seasonal thermal expansion and contraction and shrinkage towards the core walls. As the stadium is split into quadrants, separated by a movement joint, each quadrant is structurally independent, how-ever has continuous finishes.

The long term lateral ground movements are predicted to occur predominately towards the lake.

The direction of the ground movement and slab movement can be in opposition, and it is the relationship between the movement at the top of the pile from the ground movements, and slab movement, that induces pile actions in the form of bending and shear.

The design is required to allow the Western Quadrant (of which the Western Concourse piles are part) of the stadium to move somewhat to relieve stresses and strains, but not too far that would compromise strength and serviceability of the stadium structure.

2.3 Original pile design reassessment

Initial review by Arup indicated that the original pile design would not be able to withstand the predicted long-term lateral ground movements. The laterally

loaded pile analysis was conducted using the software Oasys ALP, which allows the bending moment and shear force effects of lateral ground movements onto piles to be quantified (Figure 4). The pile bending moments and shear forces as a result of the lateral ground movements were combined with other lateral actions transmitted to the piles from the superstructure (e.g. wind loading, seismic loading) in accordance with AS2159. A detailed pile-by-pile analysis was conducted as shown with pile actions plotted in Figure 5.

It was found that the majority of the piles were over capacity, as a result of the anticipated lateral ground movements which were predicted to continue to occur following pile installation.

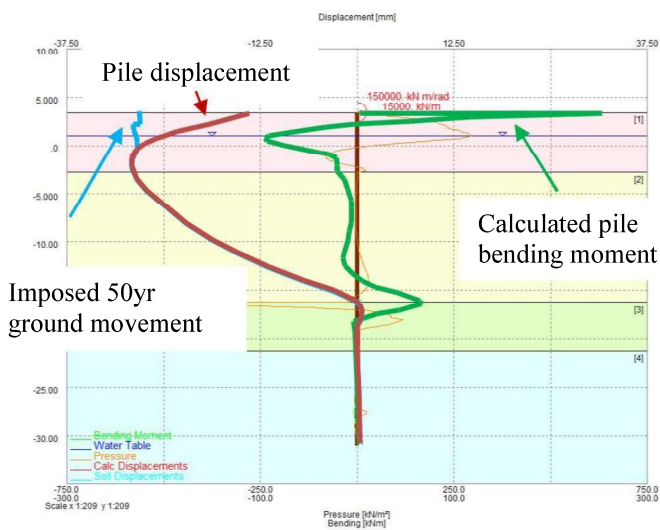


Figure 4. Example of long term lateral displacement profiles at pile locations.

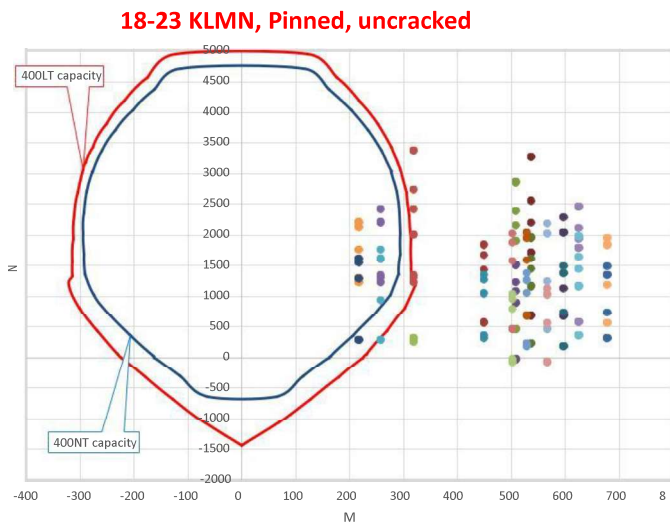


Figure 5. Example of axial pile capacity assessment chart, Moment vs Axial load.

2.4 Options assessment

An alternative pile design was required for the Western Concourse. This was in addition to a modification of ground improvement and the installation of polystyrene blocks (where possible), in-lieu of regular earthworks filling to minimise ground movements. The following options were considered:

- Increasing reinforcement in the piles
- Additional piles and new layout
- Larger, different type piles: Bored, CFA, Driven Steel
- Ground improvement with shallow foundations
- Re-use of original concrete pile design with a steel sleeve around the upper critical section of the pile

The magnitude of the lateral pile actions on the piles precluded the first two options. The remainder of the options were mainly discounted due to compatibility with existing, constructed portion of the stadium (e.g. to minimise differential settlement from differing foundation type) and construction considerations. It was considered that due to procurement ease of the original concrete pile section, cost, time and rig and contractor availability, that the steel sleeve option was most suitable.

2.1 Option selection

The option selected was a steel sleeve over the upper portion of the concrete pile to shield it from lateral ground movements. This arrangement is shown in Figure 6. Instead of the more typical sleeve arrangement, where the sleeve is 'floating', the sleeve for Optus Stadium was designed such that it was structurally connected to the pile cap and slab. This allowed the shielding of the inner concrete pile against the lateral ground movement in the critical upper zone.

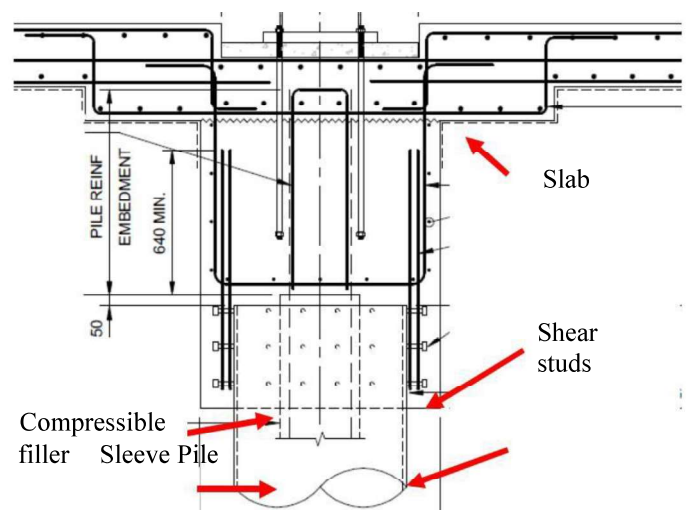


Figure 6. Vertical cross section of pile design

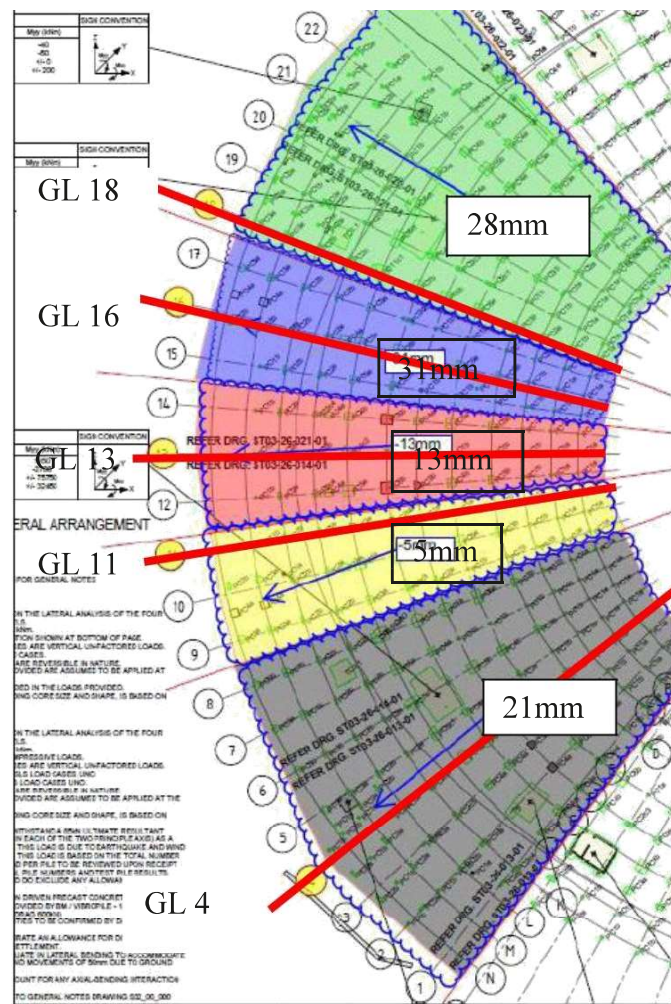


Figure 7. Gridlines (GL), modelled in Plaxis analysis, zones, and slab deflections in Plaxis

It also allowed the steel sleeve, which was embedded in the upper stiff fill materials, to provide the majority of lateral foundation restraint against super-structure lateral loading (e.g. wind and seismic loading).

The sleeve length was selected to protect the inner concrete pile to the depth at which it could withstand design actions from lateral ground movements. Compressible filler was placed between the steel sleeve and the precast pile to minimise transfer of actions from the sleeve to the precast pile.

2.2 Design process

The design process initially required input from the piling contractor, who required to confirm fabrication constraints and installation tolerances. This influenced the sleeve thickness and minimum internal diameter of the sleeve.

To capture the changing geometry over the large analysis area, five two-dimensional Plaxis analyses were conducted by the ground improvement contractor. The Plaxis analysis results were then applied to a number of piles, as defined by the gridline zone, e.g. gridline 13, shown in Figure 7.

The slab deflections in each analysis was compared with the adjacent gridline and with the overall quadrant slab movement prediction, as shown in Figure 7 to form a range of boundary conditions to model pile head restraints.

Significant interaction was required with the structural engineers responsible for the pile cap and slab design. As a result of the structural connection between the sleeve and the pilecap (which was required to provide lateral restraint against the superstructure lateral loading), the sleeve transferred large moment and shear loading to the pile cap due to the lateral ground movements. Structural details were required for the shear and moment transfer between sleeve and pile cap and the precast pile and pile cap (Fig. 6).

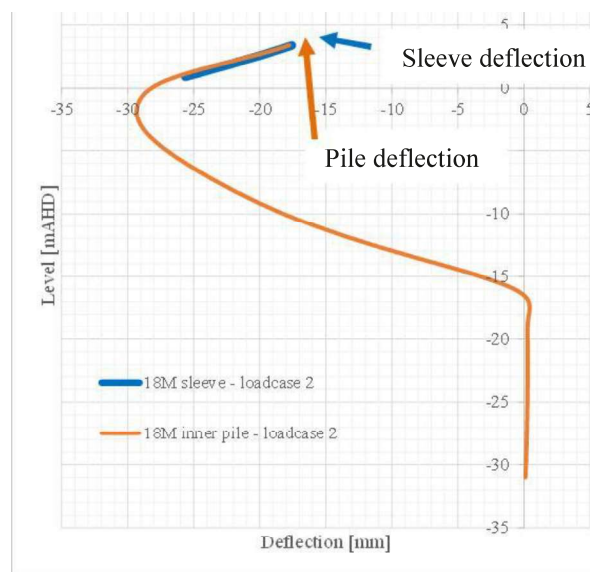


Figure 8. Deflection compatibility between pile and sleeve

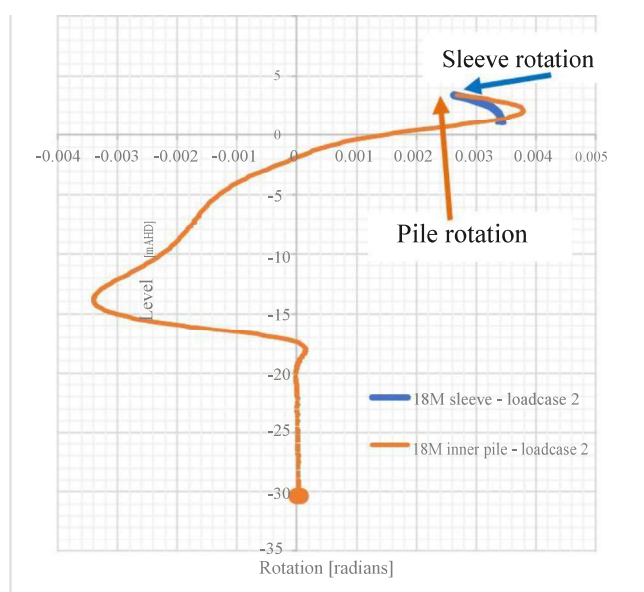


Figure 9. Rotation compatibility between pile and sleeve

The steel sleeve connection incorporated welded shear studs.

A range of slab deflections and moment and shear boundary conditions at the head of the pile were modelled to bound the problem. Iteration of these boundary conditions was required to ensure the compatibility of deflection and rotation between the precast pile and the outer sleeve as shown in Figures 8 and 9.

As the outer sleeve provided protection to the inner concrete pile against lateral ground movement within the sleeved section and provided the majority of the required capacity against superstructure lateral actions, the concrete piles were found to have sufficient capacity against all combined design actions (Figure 10).

2.1 Construction sequence

To minimise additional ground movements on piles, the ground improvement (i.e. CMCs), the retaining wall and retaining wall foundation were installed prior to the piles. This meant that ground improvement and piles had to be installed within tolerances to prevent clashes.

2.2 Validation

There is inherent uncertainty in predicting ground movements. Therefore, instrumentation and monitoring were specified to validate the ground movement predictions.

However, monitoring is affected by construction activities which limited the extent to which long-term ground movements could be assessed in the Western Concourse prior to pile installation.

For a limited time period (approximately 2 months between May-June 2015), where construction activities were limited in the area under consideration, ground movements in the fill were observed and were found to be broadly in accordance with the Plaxis pre-dictions of soil movement. Surveyed slab movement between January and May 2016 was also broadly in accordance with Plaxis slab movement predictions, when the predictions of the various 2D plane-strain Plaxis models were combined in structural modelling software to assess global quadrant slab movement.

As part of the design options selected, it was advised that an extensive monitoring regime was implemented. The purposes of the monitoring was: to con-firm ground movements, to confirm actions in the pile, and to confirm slab movement. The monitoring proposed comprised instrumented piles, inclinometers, settlement plates and structural monitoring. The spacing and layout is shown in Figure 11. Reading of the instrumentation was undertaken prior to completion of the stadium project and is currently on-going.

In addition, relatively large ground movements occurred during the CMC installation, posing a risk to

adjacent ground improvement (used to minimise ground movements). CMC static load tests were conducted to assess if the CMCs had sufficient capacity to provide the required support to a retaining wall located along the Western concourse area. These tested CMCs achieved the required test loads.

3 CONCLUSION

The piled stadium foundations adjacent to the Western concourse area was designed to incorporate ground improvement, and ongoing ground movements as a result of soft soil creep associated with raising ground levels across the site. A modification of the original pile section allowed a cost-effective installation that minimised project delays, maximised local fabrication and simplified installation for the contractor.

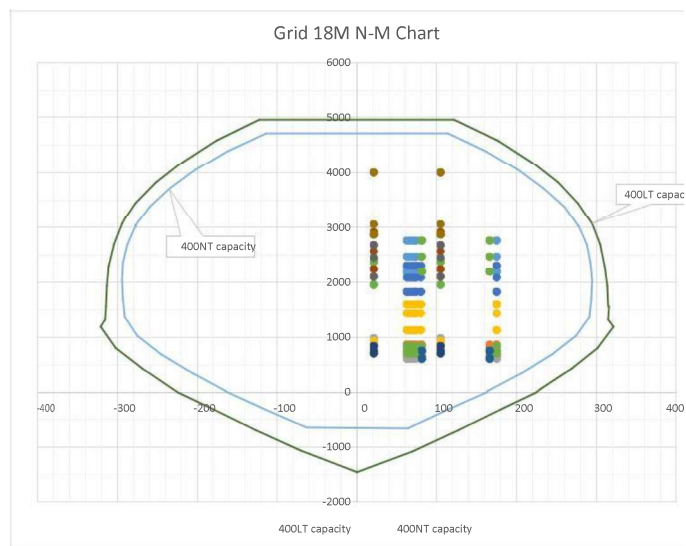


Figure 10. Redesign pile capacity chart.

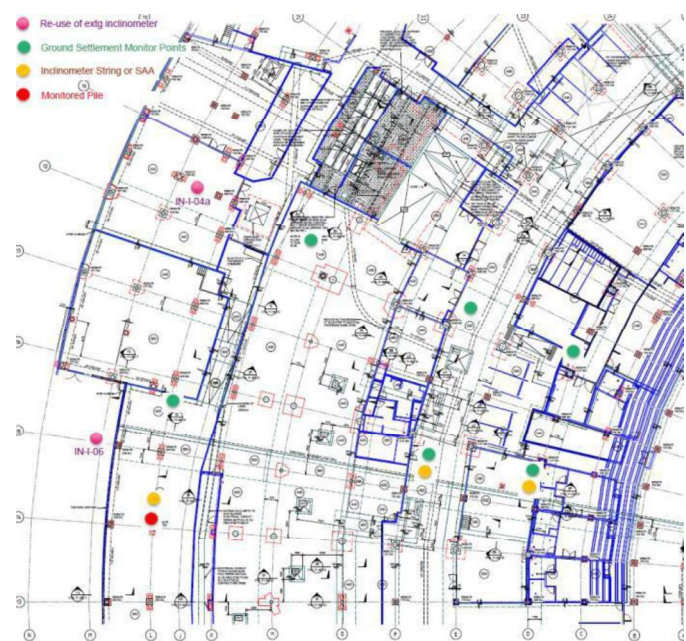


Figure 11. Ground monitoring instrumentation plan

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