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Optus Stadium enabling works ground improvement

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ABSTRACT: Prior to construction of Perth's Optus Stadium, the ground profile consisted of approximately 1 m of sand capping followed by typically 4 to 6 m of landfill and soft Swan River Alluvium, which was up to approximately 30 m deep. Rather than installing wick drains and surcharging that were used for the pre-construction site works, an alternative ground improvement solution was proposed for the civil enabling works, which accelerated the construction process by eliminating extensive surcharging wait periods and offered an environmentally friendlier solution with less groundwater migration and control. In the process, approximately 200,000 m of Controlled Modulus Columns (CMC) were designed and installed, including the world's second longest CMC. Dynamic compaction was applied to 10,000 m^2 of landfill to pre-collapse potential voids. Other geotechnical techniques implemented were prefabricated vertical drains and installation of 18 m long sheet piles.

1 INTRODUCTION

1.1 *Project description*

In June 2011, the State Government of Western Australia announced that a new stadium would be built in Perth's eastern suburb of Burswood, on the northern section of the Burswood Park golf course (Harvey, 2011). Construction of the project commenced on 7 December 2014, the project was completed in 36 months (Optus Stadium, 2017a) and was officially opened on 21 January 2018 (Optus Stadium 2018). The stadium capacity in AFL (Australian Football League) mode is 60,000 persons, making it the third largest stadium in Australia (Optus Stadium, 2017b).

The new stadium, also known by naming rights sponsorship as Optus Stadium, is a multi-purpose stadium and will host a variety of sports and entertainment events including Australian Football League (AFL), International and Big Bash League cricket, soccer, rugby league and union plus concerts (Optus Stadium 2018).

In addition to the stadium itself, the project includes a grassed practice field, an elevated plaza area around the stadium spectator stands, paved pedestrian areas leading from the stadium to public transport links, a nature-based playground, a bus hub with associated paved pedestrian plaza between the stadium and bus hub, and roads around the sports precinct.

1.2 *History*

Burswood Peninsula was a series of sand bars and islands that were described as mudflats at the time of colonisation and substantially different in shape and appearance as recognised today. The currently known shape and form is a result of river bank works and infilling over the peninsula, comprising a combination of dredged material sourced from the river, placement of uncontrolled fill whilst the site was used as a refuse tip and clean sand fill placed as a containment barrier.

The rubbish disposal site was gazetted in 1946 and extended to cover a large section of the peninsula. Initially, domestic rubbish was placed to the south and industrial rubbish to the north, but in later years there was little distinction. A tree burning area operated in the 1950s and 1960s where car tyres were also known to have been burnt. Placement of dredged fill occurred from the 1950s and dredging of the remaining mudflats within the present Swan River occurred between 1966 and 1971. Further industrial material and sand fill was placed over previously dredged and fill materials during the construction of the Great Eastern Highway in the late 1960s. Dumping of domestic waste ceased in 1972; however, dumping of inert solid waste such as building rubble and sand continued until 1985 (Golder Associates, 2012).

The site then converted into a golf course that was opened in 1987 and remained operational until the initiation of the stadium project construction works in 2013. The golf course was low lying with average surface elevations of less than 4 m AHD (Australian Height Datum), except where localised fills were placed to create a more challenging golfing layout. (Golder Associates, 2012).

1.3 *Ground conditions*

A geological cross section of the site is shown in Figure 1. The ground units at the project location can be summarised as:

- Capping layer: typically, a 1 m clean sand layer but occasionally with lesser or greater thicknesses.
- Uncontrolled fill: a layer containing sand, gravel, steel, concrete, bricks clay pipes, etc. with variable thickness of approximately 2 to 12 m in the stadium project's area. The large number obstructions within the fill caused shallow refusal of a noticeable number of CPTs (Cone Penetration Test).
- Swan River Alluvium (SRA): soft, organic, highly compressible clayey silt to silty clay up to 26 m thick that have sedimented into a paleochannel. The thickness of the SRA generally increases from approximately 2 m along the site boundary close to the rail station to 26 m in the deepest section of the paleochannel. The CPT cone resistance of this layer was generally very low and close to null. A sample CPT profile is shown in Figure 2.
- Sandy channel deposits (SCD): generally medium dense to very dense sand and sandy silts or clays. The thickness of this unit varies between 10 m and 25 m.
- Kings Park Formation (KPF): typically encountered as very dense sand to gravelly sand. Although the name suggests a rock-like material, material recovered from boreholes were largely an uncemented sandy soil.

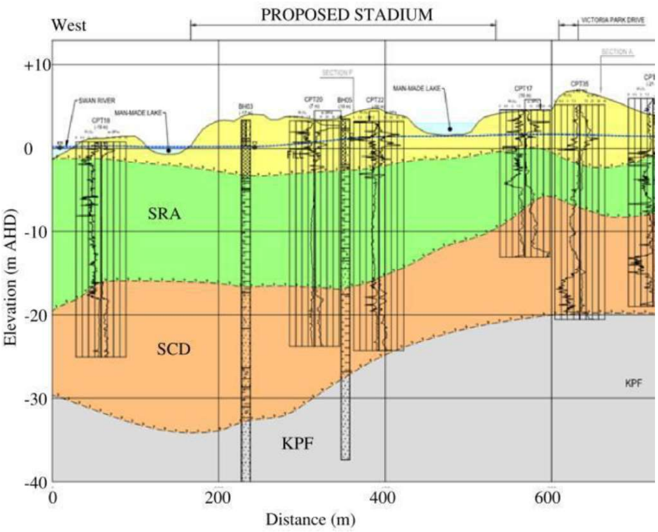

Figure 1. Geological cross section

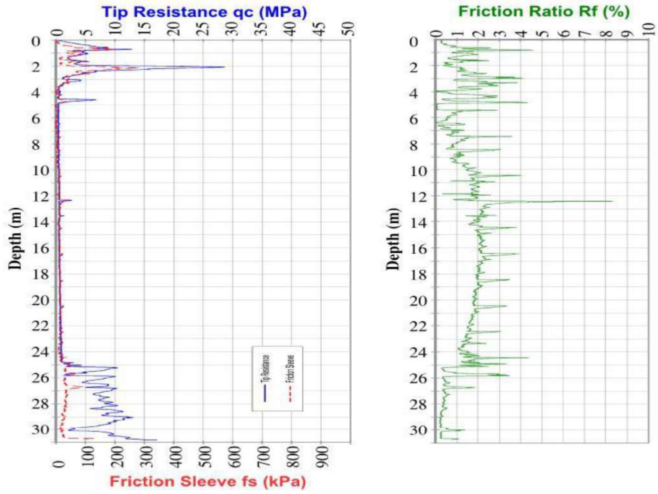

Figure 2. A sample CPT profile

Groundwater level was typically from ±0 m AHD to +1.5 m AHD.

1.4 *Project requirements*

It was evident from the geotechnical investigations and early calculations that the in-situ ground would not be able to adequately support the filling for reaching final project levels and any structures that were to be constructed. It was decided that the stadium structure would be supported on piles and all other areas would be subjected to ground improvement. The long-term geotechnical criteria were specified as shown in Table 1.

Table 1. Long-term geotechnical criteria

Location	Maximum post construction movement		
	Vertical (mm)	Horizontal (mm)	Differential
Pitch	100 mm	50 mm	1:250
Piled structure	N/A (piled structure)	50 mm (piles without dead load) 100 mm (piles with dead load)	200 mm Pitch – Stadium Interface and Pitch – Plaza Interface N/A beneath piled Structure
Areas within 25 m of piled structure	300 mm	100 mm	1:100
Roads	300 mm	150	1:100
Key Plaza / Precinct Areas	300 mm	150	1:100

1.5 *Ground improvement conforming solution*

1.5.1 *Concept*

Once it was established that the in-situ ground state would not be able to satisfy the project's geotechnical requirements, conceptual guidance ground improvement schemes were developed for programming, sequencing of works and costing purposes. In this scheme, the treatment adopted in areas with SRA was envisaged to be either a combination of prefabricated vertical drains (PVD) with surcharging or alternatively stone columns with the possibility of surcharging.

In the first scenario, PVD would be installed through the fill and into the SRA. If the PVD were to extend into the SCD, then some water would have been discharged into the SCD. A permeable drainage layer had to be placed on top of the PVD to allow the discharged water during soil consolidation to flow into a temporary seepage drain and then to an on-site water treatment facility. An engineered fill layer composed of clean granular material would then be placed to compensate for ground consolidation. This layer would then be subjected to the surcharge, which would be removed once acceptance criteria were satisfied.

The second scenario was very similar to the first; however, PVDs would be replaced by stone columns.

Dynamic compaction was also envisaged for pre-collapsing and crushing any existing voids or cavities within the fill area.

1.5.2 *Pre-construction site works*

Prior to the construction of the Stadium, ground improvement was carried out as part of the Pre-Construction Site Works (State Government of Western Australia, 2013). The treated areas included the manmade irrigation lake, the stadium pitch, the bus hub central, the practice pitch and a pedestrian assembly area.

The ground improvement work included the installation of PVDs, dynamic compaction, and surcharging (The West Australian, 2014). The PVDs were installed to the base of the SRA at 1.1 m triangular spacing across the required areas (AEOL, 2014).

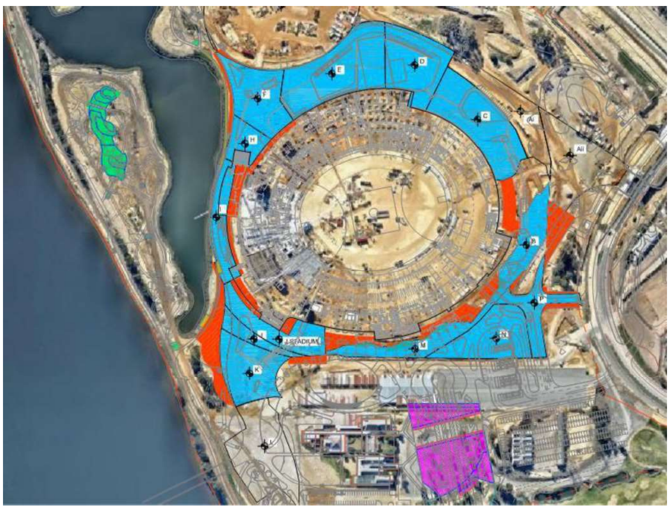

Figure 3. Ground improvement areas of the civil enabling package

Morton (2014) has reported the measured ground settlements that were achieved due to consolidation of the SRA. The measured settlements over a period of 260 to 300 days was from approximately 530 mm to 1080 mm. Morton has reported one settlement plate in more detail and has recorded 822 mm of settlement under a surcharge of 5 m over a period of 300 days. He used Asaoka's method of (1978) to estimate that the ground had undergone 90% consolidation by then.

2 CIVIL ENABLING WORKS GROUND IMPROVEMENT

2.1 *Alternative ground improvement solution*

The civil enabling works ground improvement package was part of the stadium construction project and included the plaza around the stadium structure, the pedestrian assembly areas, the internal roads and parking areas, the Boardwalk, Chevron Parkland BHP Amphitheatre and the bus hub. These areas are shown in Figure 3.

Whilst the principal contractor, of the project received conforming ground improvement proposals, they awarded the ground improvement works to a design and construct ground improvement specialist contractor who had proposed an alternative ground improvement solution based on the application of *controlled modulus columns* (*CMC*) and *dynamic compaction* (*DC*). During the project, an area with PVDs was also added to the scope of works.

2.1.1 *Controlled Modulus Columns*

CMCs are cementitious columnar rigid inclusions that are installed in soft soil to improve foundation behaviour by increasing bearing capacity and reducing total and differential settlements. The columns are typically installed in a grid and footing or surface loads are generally distributed between the soft soil and the CMCs by an engineered fill, which is called *load transfer platform* (*LTP*).

CMCs are installed by piling-type rigs that are equipped with specially designed displacement augers, which are composed of a penetrating helical tip and a cylindrical hollow stem follow-up section with an inversely sloped helix. As the auger penetrates the soil by screwing, the cylindrical section displaces the soil laterally, the inversely sloped helix prevents the soil from moving up, and the volume of spoil generated by this method is thereby reduced to negligible amounts compared to cast in-situ piling solutions such as CFA or bored piles. During the auger extraction process, low strength grout or concrete is pumped through the hollow stem to form a columnar inclusion with a diameter that is usually 250 to 450 mm (Hamidi et al, 2016).

CMC's modulus of elasticity is much greater than that of in-situ soil or inclusions composed of granular material. Using the equation proposed by ACI (2011), the modulus of elasticity for concrete with 10 MPa can be calculated to be approximately 15 GPa. Typically, CMC modulus of elasticity is 50 to 3,000 times that of the soil stratum (Masse et al., 2009). In comparison, Debats (2012) comments that the ratio between the modulus of a stone column and the modulus of the surrounding ground should always be limited to not more than 6 to 10, which will yield moduli that are hundreds of times less than the CMC modulus. Similarly, Croce et al. (2014) suggest a linear correlation between secant Young modulus of jet grouted columns and uni-axial compressive strength. The correlations factors are highly variable but are in the range of 280 to 1,200 in gravel and sand, and from 100 to 500 in silt and clay. This means that for a jet grouted column with 5 MPa strength, Young modulus can range from 1.4 GPa to 6 GPa, which are significantly less than what is achieved by the CMC.

Contrary to the scatter of strength values in soil-cement mixing techniques such as jet grouting and deep soil mixing that are the result of soil variability, the CMC's modulus of elasticity is highly predictable as grout or concrete is produced in a batching plant, then pumped into the column without mixing with in-situ soil; thus, the name of the technique being Controlled Modulus Column.

Once grout or concrete sets, the CMC becomes a self-binding columnar inclusion that does not rely on the external confinement from the soil for stability. However, stability of non-cementitious inclusions that are composed of granular material, such as stone columns, are dependent on the surrounding soil, and the inclusion will fail by bulging once its internal horizontal stresses exceed the limit pressure of the soil (Barksdale and Bachus, 1983).

The amount of vibration that is generated by CMC installation is essentially the same as CFA piling, which can be an advantage when peak particle velocity limits prohibit the application of vibratory based ground improvement techniques such as dynamic replacement, rapid impact compaction, impact rolling or stone columns.

The CMC auger displaces the soil laterally; thus, the amount of generated spoil will be negligible compared to drilled or bored piling techniques. This feature can be advantageous for reducing spoil removal costs, especially if the soil is ground is contaminated or contains acidic soils.

CMC production is higher than cast in-situ piling techniques as the columns are typically non-reinforced and design requires installation depths that can be noticeably shorter than piles. Similarly, it is the author's experiences that CMC production rates are several times more than other ground improvement inclusion techniques, such as jet grouting, deep soil mixing or stone columns.

To the knowledge of the author, at the time that Optus Stadium was under construction the deepest CMCs that had ever been installed were 42 m for oil tanks near New Orleans (Hamidi et al., 2016). The second deepest CMC was reported to be 34 m long, also for another oil tank project near the Mississippi River (Varaksin et al, 2016).

2.1.2 *Dynamic compaction*

The concept dynamic compaction is to improve the soil's mechanical properties by transmitting high energy impacts to loose soils that initially have low bearing capacity and high compressibility potentials. The impact creates body and surface waves that propagate in the soil and re-arrange the grains in a denser configuration, which results in the decrease of voids, increase in soil grain contact points and therefore improvement of soil properties. (Hamidi et al, 2009).

The impact energy is delivered by dropping a heavy weight or pounder from a significant height. The pounder weight is most often in the range of 80 to 250 kN although lighter or heavier pounders are occasionally used. Drop heights are usually in the range of 10 to 20 m although higher or lower drop heights are sometimes applied.

The depth of influence is the depth where there is no more observable improvement in the soil. Menard and Broise (1975) developed an empirical equation in which the depth of influence was less than the square root of the impact energy; i.e. the product of the pounder weight by the drop height. Others, e.g. Varaksin (1981) have added a reducing factor or a combination of factors to the equation.

Dynamic compaction has proven to be a very efficient technique for collapsing cavities, even in dissolved rock. Chaumeny et al. (2008) have reported the application of DC for pre-collapsing active rock cavities and sinkholes that were encountered on a strip of approximately 1.5 km along German Federal Highway A71.

2.2 *Advantages of the alternative ground improvement solution*

The advantages of the proposed ground improvement solution included:

- Elimination of major earthworks for transporting surcharge fill to site, placing the material and removing it from site: The West Australian (2014) has reported that more than 740,000 tonnes of sand were placed across the site during Pre-Construction Site Works. Elimination of large volumes of surcharge fill in such magnitudes would improve road and site traffic safety, reduce carbon emissions, cost and placement time that must be performed in controlled lifts to prevent shear failure of the surcharge.

- Time saving by elimination of very long wait periods for soft soils to consolidate under surcharge loads: Similar to what has been presented by Morton (2014), implementing PVDs with surcharge loading could have required wait periods in the order of one year to achieve the desired consolidation.
- Long-term creep settlement reduction: The concept of installing CMCs eliminates or minimises any effect that the SRA secondary compression or creep may have. The magnitude of secondary compression has a direct relationship with the soil's susceptibility to secondary compression as measured by the secondary compression index and by the time ratio; i.e. the ratio of total time from load application to the time required to complete primary consolidation. By shortening the time required to complete primary consolidation with the use of PVD, the ratio of total time (design life) to time for primary consolidation increases and would by itself cause the amount of secondary compression to increase (Balasubramaniam et al, 2010). Therefore, whilst surcharging reduces the magnitude of creep, its effectiveness is dependent on surcharging period and the longer the surcharge can be left in place, the greater the effect of the surcharge in reducing creep. However, for practical reasons, surcharging period has to be limited to meet construction programming and it is not possible to yield optimal efficiency for reducing creep.
- Greater design flexibility to late changes in project requirements: By using PVDs and surcharging, any decisions to relocate or introduce new structures, or to increase project levels would have resulted in the requirement to add more surcharge and extend the wait period, but redesigning CMCs for these changes would be much simpler with lesser impacts on the construction schedule.
- Elimination or significant reduction of penetration difficulties into the obstructed fill: The experience of the author is that the PVD mandrel cannot penetrate very hard ground and many types of obstructions such as concrete segments, bricks, etc, and exertion of excessive penetration force could damage the mandrel. Consequently, pre-drilling, pre-punching or even coring becomes inevitable in such ground conditions. AEOL (2014) reports that during the Pre-Construction Site Works the construction team pre-punched holes through the fill in advance of the PVD installation. Whilst a CMC auger may also require pre-drilling for penetrating hard ground or large obstructions such as concrete beams, it is the author's experience that the CMC auger is able to penetrate ground with small obstructions much more efficiently that the PVD mandrel without pre-drilling.
- Significant reduction in lateral displacement: Fill loading generates shear stresses and strains near the boundaries of the loaded area, which lead to deformation of soil outward from the fill loaded area. The magnitude of shear stresses that are a function of loading intensity in comparison to the undrained shear strength profile determines the magnitude of the horizontal deformation profile at the boundaries of the fill loaded area. Horizontal deformation generally has a finite value at ground surface, then increases with depth to a maximum at about one third of the soil thickness and afterwards decreases to zero at near the bottom of the soft ground (Mesri and Khan, 2012). Research published by Kelly et al. (2018) indicates that at Ballina test site, the ratio of horizontal deformation at the toe of the embankment to settlement at the centre of the embankment and settlement at the toe were respectively 14% and 48%. These figures suggest that other construction works must be sufficiently postponed for horizontal deformations to reduce to tolerable figures in areas that are surcharged. However, the effect of installing rigid inclusions on the surrounding is significantly less and more readily manageable if sequencing and design is done properly. Consequently, it would be possible to commence many activities simultaneously or with significantly reduced wait times, which directly results in an optimised construction schedule of the global project.
- Elimination of complicated groundwater controls and management systems: Consolidation of soft soils by surcharging results in reduction of the soil's void ratio. The water in the void's will mainly flow out of the soil medium through the shortest path, i.e. the PVDs that discharge water to the superficial sand blanket, which overlies the landfill. The extracted water will therefore have to be collected, carefully monitored and treated to ensure that contaminated water does not enter the Swan River. Controls and monitoring would include deep cut-off walls (30^{+} m deep sheet piling along the river shore), a water treatment facility in advance of water disposal, field monitoring and laboratory analyses of groundwater contaminants. However, the concept of ground improvement by utilising CMCs is based on the distribution of loads between ground inclusions and in-situ soil, not consolidation of the soft soils and reduction of

voids, which consequently results in water flow and discharging.

- Reduction of DC treatment area: The purpose of DC was to pre-collapse any voids in the ground to prevent sinkholes from occurring when the stadium became operational. The concept of ground improvement by inclusions is based on distribution of loads between the inclusions and the ground by arching through an engineered fill, also known as the load transform platform (IREX, 2012). The engineered fill that had to be placed above the CMC working platform to reach final project levels was thick enough to allow arching; hence, superficial loads would transfer to the CMCs by arching over any potential voids. Consequently, application of dynamic compaction for stabilising the existing fill was needed only in areas that did not require treatment by CMC.

2.3 *Geotechnical works*

2.3.1 *Installation of sheet piles*

In conformance with the environmental approvals that were granted prior to the award of the ground improvement works, 18 m long sheet piles were installed along a 150 m long strip next to the river-fed lake. With consideration of the strength of the SRA, it was not possible to drive a single sheet pile to its final depth in one setup because the installation of subsequent sheet piles would drag or misalign the previously installed sheet piles. Hence, installation was partially and repetitively performed until the desired depth was achieved without deviation of verticality or alignment. Design and installation of CMCs

An area of approximately 60,000 m^2 of the project was treated using CMCs. With consideration of the variability of SRA thickness throughout the site, history of previous site loadings by placement of the landfill and capping layer, application of various loading systems generated by placement of engineered fill to reach final project levels, uniform and point loads applied to the ground, and different long-term ground performance requirements that are summarized in Table 1, numerous staged calculations were performed using commercially available finite element analyses software. These analyses were performed in the forms of both axi-symmetrical to assess the performance of single columns or as plane strain to study the mass behaviour of the ground.

To allow for the most accurate modelling and achieving realistic stress conditions, the loading stages that were assumed in the analyses included:

- Initial stress generation under the self-weight of the SRA to reach an over-consolidation ratio of 1
- Placement of landfill and capping
- Re-initialising displacements at start of CMC installation
- Placement of CMC working platform
- Placement of load transfer platform, engineered fill to final ground level and an activation fill of 1 m thickness
- Maintaining the activation fill for two months to consolidate the ground sufficiently to satisfy project requirements
- Removal of the activation fill to pavement underside, installation of pavement and application of 10 kPa design service load
- Verification of stresses within the CMC for a short-duration 1-day uniform live loading of 20 kPa

As shown in Figure 4, CMCs were installed using two rigs from working platform level and keyed into the SCD. At the beginning of the works, the rig's drilling pressure and crowd force was calibrated by installing a column next to the location of a CPT and comparing the readings with the cone resistance.

Approximately 10,000 CMCs with a total length of about 200,000 m were installed during the works. In line with common practice CMC design, most CMCs were designed as non-reinforced ground inclusions; however, a number of columns were reinforced with steel cages to allow for special loading conditions, such as the application of lateral loads.

The shallowest and average CMC installation depths were respectively 8 m and 20.6 m.

The deepest CMC that was installed in the project measured 34.51 m, making it the world's second longest CMC.

In addition to the numerical analyses that were performed to design the ground improvement works, load tests were also performed on single CMC columns to verify actual performance. Measured settlements were less than 5 mm under 500 kN loading. Also, inclinometers were installed to measure the effect of CMC installation on the ground surrounding it.

2.3.2 *Design and application of DC*

Dynamic compaction was applied to an area of approximately 10,000 m^2 that was not reinforced by the CMCs and required treatment to mitigate the risk of future sinkholes and void collapses.

Whilst the conforming acceptance criteria for verifying void collapse assumed the classical approach of defining minimum values for CPT, SPT (Standard Penetration Test) and plate load tests, Hamidi et al. (2011b) propose the utilization of acceptance criteria that most directly target the design requirement, which in this case was mitigating the risk of void collapse.

Whist the application of field tests that are performed in a grid with a certain spacing would have demonstrated that the ground has gained

Figure 4. Installation of CMCs at Optus Stadium

strength after treatment and could have possibly concluded that the voids had therefore collapsed, an observational system was adopted that was able to directly verify the status of ground at the location of each DC print. In this method, the depth of each DC crater was assessed and compared to other surrounding prints that were known not to have voids. Similarity of crater depth would demonstrate that the print had been compacted and any potential small size voids had sufficiently crushed. However, an out-of-normal crater size would indicate the presence of a large size void that needed further attention and crushing. Figure 5 shows the application of dynamic compaction at Optus Stadium.

The basis of vibratory ground improvement techniques is the re-arrangement of soil grains into denser configurations by waves that are generated from the treatment processes. These waves can have damaging or destructive effects on nearby structures and facilities. Research (Langefors et al, 1958, Edwards and Northwood, 1960, Siskind et al, et al., 1980) indicates that damage is more closely related to ground particle velocity rather than to displacement or acceleration.

Hamidi et al. (2011a) have developed a correlation for prediction of peak particle velocity (PPV) that is generated by dynamic compaction

Figure 5. Application of dynamic compaction at Optus Stadium

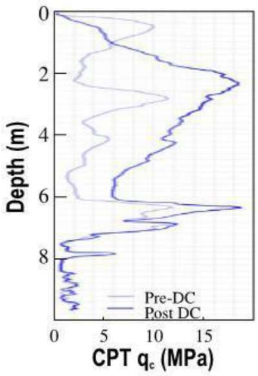

Figure 6. Comparison of CPT results before and after DC

using pounder drop height, pounder weight and distance to DC print. Hamidi et al. (2012) have also demonstrated that it is possible to reduce DC vibrations on average to half by installing vibration isolation open trenches.

Project specifications required that PPV be limited to 10 mm/s at the Golf Club House, underpass construction and HV Switchgear and 5 mm/s at the PTA rail signaling box. Hence, DC zones that would potentially exceed the vibration acceptance criteria were identified and DC energy per blow was accordingly revised to ensure conformance. Site measurements indicated that DC generated PPV at the HV Switchgear was less than 2 mm/s, which was less than vibrations generated by other construction equipment and passing trains.

Prior to dynamic compaction production a heave and penetration test was carried out to verify the DC design parameters. Upon completion of the works, informative CPTs were undertaken to record ground strength. Figure 6 compares the CPT cone resistance of the ground before and after treatment.

2.3.3 *Installation of PVDs*

PVDs were installed in an area of approximately 8,000 m^2 using a triangular grid with 1.1 m spacing. Installation was performed using a mast that was mounted on a 40-ton excavator. The fill thickness of approximately 50% of the installation locations were pre-punched using a vibratory driven rod to facilitate the PVD mandrel's penetration into obstructed ground.

3 CONCLUSION

Optus Stadium is an example of good engineering practice that was developed by proposing an alternative ground improvement process using controlled modulus columns for treatment of soft soils and dynamic compaction for pre-collapsing voids within an old landfill. Application of these technologies eliminated surcharging long wait periods, allowed the simultaneous commencement of other activities and reduced the project's overall project construction programme. Additionally, the problem of water discharge into Swan River was altogether avoided by changing the design concept from soft soil consolidation to soft soil reinforcement. This conceptual conversion also changed the load transfer mechanism, which resulted in minimisation of areas that required treatment for mitigation of void collapse risk.

Optus Stadium project has also been a major and world scale geotechnical achievement as approximately 200,000 m of CMC were installed, including the world's second deepest column, which measures 34.51 m.

4 ACKNOWLEDGEMENT

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