GROUND IMPROVEMENT OF GRANVILLE HARBOUR WIND FARM FOUNDATIONS USING CMC

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ABSTRACT

Granville Harbour Wind Farm is located on a remote site that is approximately 35 km northwest of Zeehan on Tasmania's west coast. The project includes 31 wind turbines with the capacity to generate 112 MW of power when it is complete. Each giant turbine is 137 m from ground level to rotor hub and 200 m from ground level to blade tip. The site's ground profile consists of extremely weathered to highly weathered volcaniclastic breccia overlain with stiff clays, silts and embedded basalt cobbles. At 27 turbine locations, the ground did not meet the project's requirements and specific measures were required to improve the foundations' behaviour. Whilst piling is commonly used for improving bearing and reducing ground settlements of foundations of highly sensitive structures, in an innovative first-time approach in Australia, an alternative foundation solution using Controlled Modulus Column (CMC) rigid inclusions was considered and developed to allow the safe operation of the turbines more affordably. During this process, foundation systems were designed for eight ground models. Approximately 44,000 m of CMC were installed to support the wind turbines. The longest and shortest columns were respectively 4.5 m and 22.8 m. Quality control and assurance included the installation of trial columns, concrete testing, integrity testing and static load testing of the columns.

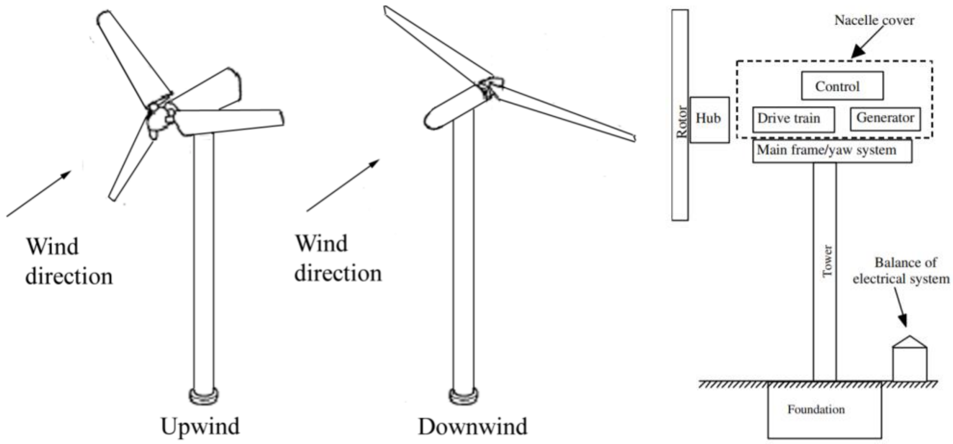
1. INTRODUCTION

Wind power is currently the cheapest source of large-scale renewable energy (Clean Energy Council).

Australia has some of the world's best wind resources in its south-western, southern and south-eastern regions. There is also good access to available onshore wind resources. At the same time, wind energy is the fastest growing renewable energy source for electricity generation in Australia (Australian Renewable Energy Agency) and Clean Energy Council (2019) reports that in 2018, the country's wind farms produced 33.5% of its clean energy and supplied 7.1% of the overall electricity.

Wind power is generated into useable electricity by converting the kinetic energy of the atmosphere with wind turbines. In this process the force of the wind is converted into a torque that is then used to propel an electric generator to create electricity. Wind energy power stations that are more commonly known as wind farms commonly draw on the output of multiple wind turbines through a central connection point to the electricity grid (Australian Renewable Energy Agency).

The most common type of wind turbine is the horizontal axis wind turbine (HAWT), which has an axis of rotation that is parallel to the ground. Figure 1(a) shows two wind turbines with upwind and downwind rotor configurations.



(a) (b)

Figure 1: HAWT (a) with upwind and downwind rotor orientations, (b) major components (Manwell et al, 2002)

As shown in Figure 1(b), the main components of a typical HAWT are (Manwell et al, 2002):

- Rotor: blades and the supporting hub
- Drive train: exclusive of the rotor, the rotating parts of the wind turbine, which usually consists of shafts, gearbox, coupling, mechanical brake, and generator
- Nacelle and main frame: wind turbine housing, bedplate and yaw system
- Tower and the foundation
- Machine controls
- Balance of the electrical system: cables, switchgear, transformers and electronic power converters

Wind turbine design loads are described by the IEC (International Electrotechnical Commission, 2019) and include:

- Gravitational and inertial loads: static and dynamic loads that result from gravity, vibration, rotation and seismic activity.
- Aerodynamic loads: static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.
- Actuation loads: loads resulting from the operation and control of wind turbines, which include torque control from a generator or inverter or both, yaw and pitch actuator loads and mechanical braking loads.
- Other loads: These loads include wake loads, impact loads, ice loads and tower loads, resulting for example from vortex-induced vibrations.

International Electrotechnical Commission (IEC, 2019) specifies that load cases will be determined from the combination of operational modes or other design situations, and that all relevant load cases with a reasonable probability of occurrence will be considered, together with the behaviour of the control system. The design load cases used to verify the structural integrity of a wind turbine will be calculated by combining:

- Normal design situations and appropriate normal or extreme external conditions
- Fault design situations and appropriate external conditions
- Transportation, installation and maintenance design situations and appropriate external conditions.

There are not many publications about onshore wind turbine foundations. Manwell et al. (2002) have noted the obvious that the foundation must be enough to keep the turbine upright and stable under the most extreme design conditions. They further add that at most sites, the foundation is constructed as a reinforced concrete pad with its size chosen in such a manner to allow concrete weight to provide resistance to overturning under all conditions. Sometimes turbines are installed on rock in which case the foundation may consist of tensile elements for resisting the overturning loads.

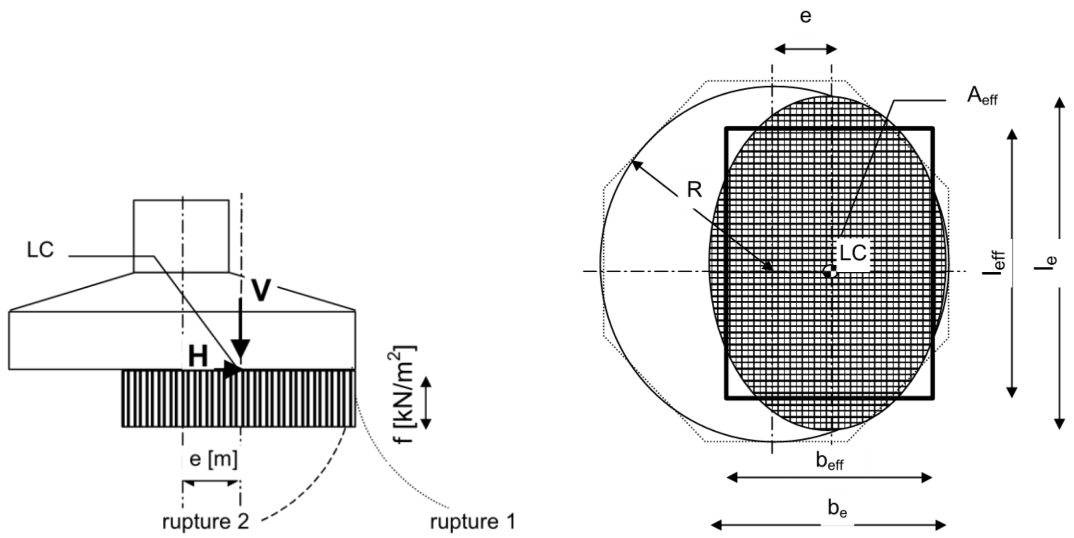
Manwell et al. (2002) have presented a cost study analysis by Johnson (1985) for horizontal axis wind turbines constructed within the period of the 1950s to 1980s, which shows that the cost of foundations was 16.1 to 31.4% of the total cost. No information has been provided about the foundations, but with consideration of the construction period, it can be assumed that the foundations were straight-forward without application of advanced foundation construction systems.

Det Norske Veritas (DNV) and Riso National Laboratory (DNV and Riso, 2002) are more informative about the possibility of encountering unformidable ground conditions and note that depending on the ground conditions, onshore wind turbines are usually supported by either pads or by piles. However, there is no reference to the option of ground improvement. DNV and Riso further add that once a foundation concept has been selected and a foundation design is to be carried out, the geotechnical issues that need to be addressed are:

- Bearing capacity and geotechnical stability, e.g. against sliding and overturning
- Degradation of soil strength in cyclic loading
- Consolidation settlements
- Differential settlements
- Scour and erosion

As shown in Figure 2, for gravity-based pads, all forces acting on the foundation, including forces transferred from the wind turbine, are transferred to the foundation base and combined into resultant forces H and V respectively in the horizontal and vertical direction at the pad-soil interface. These forces act at load centre LC with an eccentricity e from the pad centre (DNV and Riso, 2002).

Even in its simplest form, bearing capacity analysis for wind turbine foundations is more complex than most foundations. DNV and Riso (2002) define an effective foundation area whose geometrical centre coincides with the load centre and follows as closely as possible the nearest contour of the true area of the foundation base. For a circular foundation with radius R, an elliptical effective foundation area A_{eff} can be defined as:



(a) (b)

Figure 2: (a) Gravity-based pad foundations under idealised conditions (b) circular and octangular footings with effective foundation area marked out (DNV and Riso, 2002)

$$A_{eff} = 2\left[R^2 \arccos\left(\frac{e}{R}\right) - e\sqrt{R^2 - e^2}\right] \tag{1}$$

$$b_e = 2(R - e) \tag{2}$$

$$l_e = 2R\sqrt{1 - \left(1 - \frac{b}{2R}\right)^2} \tag{3}$$

Aeff can be represented by a rectangle with the following dimensions:

$$l_{eff} = \sqrt{A_{eff}\frac{l_e}{b_e}} \tag{4}$$

$$b_{eff} = \frac{l_{eff}}{l_e} b_e \tag{5}$$

The above formulas for the circular foundation area can be used for double symmetrical polygons (octagonal or more) if a radius equal to the radius of the inscribed circle of the polygon is used for the calculations.

2. HISTORY OF SPECIAL FOUNDATIONS AT AUSTRALIAN WIND FARMS

According to Wikipedia, there are 94 wind farms in Australia. The author is not aware of any publications regarding the foundation systems of these wind farms; however, due to his work association, is informed that ground improvement has been utilised for the wind turbine foundations of two projects.

2.1. PORTLAND II WIND FARM AT CAPE BRIDGEWATER

Cape Bridgewater Wind Farm is the second stage of Pacific Hydro's four-stage Portland Wind Energy Project in southwest Victoria. Completed in 2008, the 58 MW wind farm comprises of 29 Senvion MM82 wind turbines that are rated at 2.05 MW, have a maximum hub height of 69 m and a maximum blade tip height of 110 m (Pacific Hydro).

The geology at the site comprised dune sands derived from limestone deposits. During the geotechnical investigation works for the development, 10 of the 29 wind turbine locations were identified as having ground conditions that did not satisfy design requirements. Dynamic compaction (Hamidi et al, 2009) was identified as the most practical solution for treating 3 to 10 m of sand to allow the use of shallow pad footings with diameters of 14 m.

2.2. WOOLNORTH III WIND FARM AT STUDLAND BAY

Studland Bay is situated on Woolnorth grazing property on the North West tip of Tasmania. The wind farm was constructed and commissioned in 2007. There are 25 Vestas V90 wind turbine generators at the site, giving a total installed capacity of 75 MW. The turbines are mounted on top of towers that are 80 m high with blades that are 44 m long. Studland Bay produces approximately 2 percent of Tasmania's electrical energy needs (Woolnorth Wind Farms).

Five of the wind turbine locations showed very poor ground conditions with SPT blow counts in the upper 10 m of silty sand frequently in the range of 0 to 7. Compaction Grouting (Chu et al, 2009) was adopted and carried out to treat these wind turbine foundations.

3. GRANVILLE HARBOUR WIND FARM

3.1. PROJECT DESCRIPTION

Granville Harbour Wind Farm (GHWF) covers an area of approximately 800 hectares and is currently under construction near Zeehan, on the west coast of Tasmania. When complete, the wind farm will host 31 Vestas V116 wind turbine generators, each rated at 3.6 MW with a maximum rated capacity of 111.6 MW, which will be enough to power approximately 46,000 homes.

The turbine foundations were designed for the heavier loads of the Vestas V126 wind turbines as shown in Table 1.

Table 1: Wind turbine foundation loads

Load type SLS/ULS*	N= Vertical (kN)	H= Horizontal (kN)	M= Moment (kNm)
ULS Fundamental	5,600	900	121,200
ULS Accidental	5,600	1,000	128,200
SLS Rare	5,600	900	121,200
SLS quasi-permanent	5,700	600	73,300

*SLS: service limit state; ULS: ultimate limit state

3.2. GROUND CONDITIONS

The geology of the site predominately consisted of outcropping Paleogene-Neogene (Tertiary) age basalts. Neoproterozic age siltstone and shales of the Oonah formation were exposed in small areas of the site due to the erosional downcutting of creeks. The geological map indicated the presence of non-marine deposits of gravel, sand, silt and clay between the Tertiary volcanic material and the Neoproterozic rock.

The geotechnical investigation of the site indicated a more complex geology with intersection of volcaniclastic sediments. The boreholes generally indicated a similar pattern of deposition to those Tertiary volcanics with tuff and breccia being deposited possibly in a submarine environment being capped with more effusive eruption products such as basalt. The erosion of previous Tertiary volcanics added complexity to the geology, which was noted to have resulted from sea level changes that left valleys within the palaeotopography. These were subsequently infilled with additional volcanic materials of potentially different composition. The topography was further modified by groundwater level changes and retrogressive spring induced creek incision during the Quaternary with further modifications that were possibly due to landslide activity.

The investigation included soil electrical resistivity testing and soil thermal resistivity testing at 33 locations, 5 test pits across the site, geophysical surveys using seismic surveys at 36 locations, 37 boreholes with at least one borehole at each proposed wind turbine generator location, Standard Penetration Tests (SPT), pocket penetrometer (PP), shear vane tests and collection of soil, rock and groundwater samples for laboratory testing. Additionally, 127 Cone Penetration Tests (CPT) were carried out with a minimum of two tests per wind turbine location. Of these, 51 tests encountered shallow refusal within cobble zones around 2m or 8m depths without reaching the full depth to rock.

It was observed that the ground profile encountered was:

- Topsoil: a thin layer of up to 0.5 m thick, which was typically sandy or gravelly silt, containing organic material

- Alluvium: generally consisting of loose to dense sands and gravels with variable silt content, fine to coarse and typically sub rounded to rounded, mostly quartz.
- Residual Soil to extremely weathered material: derived from weathering of the volcanic ash/tuff, volcaniclastic breccia and basalt, generally comprising of soft to very stiff silts with variable sand content.
- Tertiary Basalt: variable weathering from highly weathered to fresh, low to very high strength, typically highly fractured with very close to close defects. Typically considered as ‘floaters’ or discontinuous layers up to 5 m thick in the boreholes.
- Tertiary aged Volcaniclastic Breccia/Agglomerate: variable weathering from highly weathered to fresh, low to very high strength minerals, typically highly fractured with very close to close defects.
- Extremely weathered Metasediments: weathered to hard gravelly clay/silt, encountered in only two boreholes. Zones of highly weathered, very low strength rock within the extremely weathered matrix.
- Metasediments/Phyllite: variable weathering from highly weathered to slightly weathered, very low to very high strength typically highly fractured with very close to close defects.

Whilst the geotechnical investigation suggested highly variable ground profiles with various strength, SPT blow counts in the range of 0 to 8 were recorded at depths of 1 to 20 m in approximately two thirds of the boreholes indicated that some wind turbine foundations would not be able to safely transfer the superstructure loads to the ground.

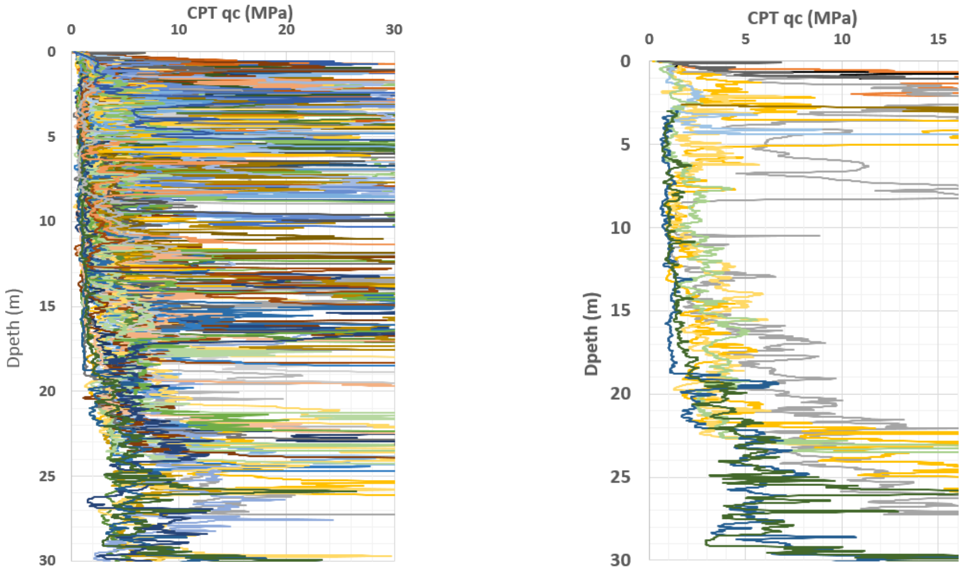
Groundwater levels were measured to be 1.8 to 17.5 m with an average in the order of 10 m depth below natural ground level.

The geotechnical assessment of the ground conditions indicated that the location of 27 wind turbines would not be able to satisfy design requirements for construction of gravity-based footings, and specific geotechnical methods had to be employed.

3.3. FOUNDATION SOLUTION: CONTROLLED MODULUS COLUMNS

Several options including piling to competent rock and various forms of ground improvement were considered for improving foundations behaviour. The solution that was ultimately chosen was the application of Controlled Modulus Columns (CMC) with the intent to reinforce the ground in such a way to provide the required mechanical characteristics that would allow the implementation of gravity-based footings and with the foundation behaving as if it were resting on a homogenous ground.

Based on the wind turbine manufacturer’s specifications, the foundation solution required a rotational stiffness in dynamic conditions, $K_{\phi\text{-}dyn}$, of not less than 54 GNm/rad to avoid the coupling phenomena with the machine’s mechanical components.



(a) **(b)**

Figure 3: (a) CPT profile throughout the site, (b) CPT profile in one of the zones

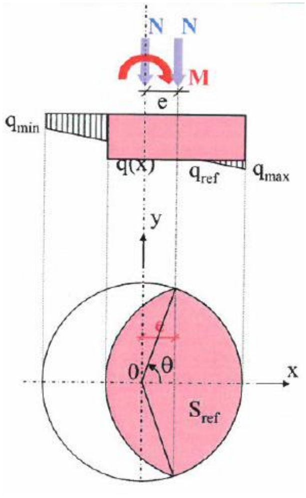


Figure 4: Reference load applied uniformly on reference area, CFMS (2002) with modifications

3.3.1. Foundation Design

As can be observed in Figure 3(a) the ground strength was highly variable throughout the site; hence, the site was divided into 8 zones with similar ground profiles and detailed design was carried out for each profile. This paper will consider only one of the profiles, for which the CPT profiles are shown in Figure 3(b), but the same procedure was used on all other profiles.

For design purpose the groundwater levels were assumed to be at the foundation base as the footing design did not consider the footings to be submerged.

For calculation purposes, in accordance with the recommendations of the French Committee of Soil Mechanics and Geotechnical Engineering (CFMS, 2011), whilst the footings were octagonal shaped, they were considered to be circular with surface areas equivalent to that of the octagons.

Similar to DNV and Riso (2002), CFMS (2011) recommendations for calculation of wind farm foundations with CMC are also based on the concept of an equivalent compression area that has been uniformly loaded. This concept is shown in Figure 4 and formulated in Equation 6 and Equation 7.

$$S_{ref} = R^2(2\theta - \sin 2\theta) \tag{6}$$

$$\theta = \cos^{-1}\left(\frac{e}{R}\right) \tag{7}$$

Where S_{ref}= reference area with equivalent uniform load q_{ref}.

Various load cases that are shown in Table 1 were considered in the design of the foundation system.

An axi-symmetrical calculation of a CMC unit cell was carried out to determine the equivalent Young's modulus of the improved ground using the quasi-permanent load case, which was the dominant load case throughout the service life of the wind turbines. Other parameters that were determined and utilised in the design included:

- Equivalent modulus of reinforced ground: 79.8 MPa
- Equivalent dynamic modulus of reinforced ground: 239.4 MPa
- Long-term rotational stiffnesses in large-strain domain: 106.8 GNm/rad
- Long-term vertical stiffness: 5 MPa/m
- Dynamic horizontal stiffness in small-strain domain: 338 MN/m
- Dynamic rotational stiffnesses in small-strain domain: 320.2 GNm/rad > 54 GNm/rad

Global bearing capacity of the foundation system was assessed for each load case. Similarly, local bearing capacity was checked for the most heavily loaded CMC cell. The results of this calculation indicated that the global bearing capacity in SLS and ULS were respectively 264 kPa and 385 kPa.

Settlement and rotation of the foundation system were calculated using the rigidities of the improved ground for SLS quasi-permanent loadings. Minimal, average and maximum settlement of the foundation were calculated to be respectively 19 mm, 26 mm and 33 mm. Calculations showed that differential settlement would be less than the targeted value of 3 mm/m at quasi-permanent loading.

The foundation system for the wind turbines of the described ground profile consisted of octagonal shaped gravity-based footings with 20.2 m lengths and 3.7 m depths of embedment. The footings were underlain by load transfer platforms that were 0.8 m thick and resting on 133 CMCs, which were arranged in 6 concentric rings. The columns had diameters of 0.45 m and were 22.8 m long. The required compressive strength of the columns was 20 MPa.

3.3.2. Construction and Quality Control of CMCs

In all 3,333 CMCs measuring a total length of more than 41,630 m were installed at the location of 27 wind turbines. 10 of these columns, measuring a total length of 117 m, were for calibration of CMC installation rigs and lengths against the ground conditions. Depending on the ground conditions, the number of columns per wind turbine foundation varied from 107 to 133. The shortest and longest columns were respectively 4.5 m and 24.2 m long.

It was expected from the early stages of project study that the site would face construction challenges. The location of the site was relatively isolated and required pre-planning and organisation to ensure the proper and continuous supply of material, namely concrete, to the site. The wind turbines were spread throughout the site and inter-site access routes and associated travel times had to be envisaged and implemented in advance.

Furthermore, to the knowledge of the author, the world’s longest CMCs in a wind farm project have been installed in up to 27 m of loess deposits at Cogealac Wind Farm in Romania (Plomteaux and Ciortan, 2010, Coghlan et al, 2016) and no other wind farm project has utilised CMCs within the range of the deepest CMCs that were designed for Granville Harbour Wind Farm. Whilst almost all CMC rigs could have reached the project’s shallow and mid-range depths of installation, the deepest CMCs that had to be installed were beyond the typical range of CMC rigs. Hence, as part of the advanced planning stage, two rigs with the ability to reach the deepest required installation depths were resourced and allocated to the project. Even though the site was massive in size, due to the constrained footing sizes, scatter of wind turbine locations and distances between them, it was possible for only one rig to operate at each wind turbine location and consequently, as shown in Figure 5, it became necessary to support each CMC rig with its own ancillary equipment, namely concrete pump and excavator.

To the knowledge of the author, the 24.2 m long CMC that was installed in this project is the world’s second deepest CMCs in a wind farm project.

At the beginning of the project a number of calibration CMCs were installed nearby existing geotechnical exploration holes at the various ground profiles that had been used as the basis of design. The objective of these columns was to calibrate the geotechnical data against the rig’s driving forces. This information would then be used to determine the fine-tuned actually required depths of the columns.

Figure 5: Installation of CMC at Granville Harbour Wind Farm

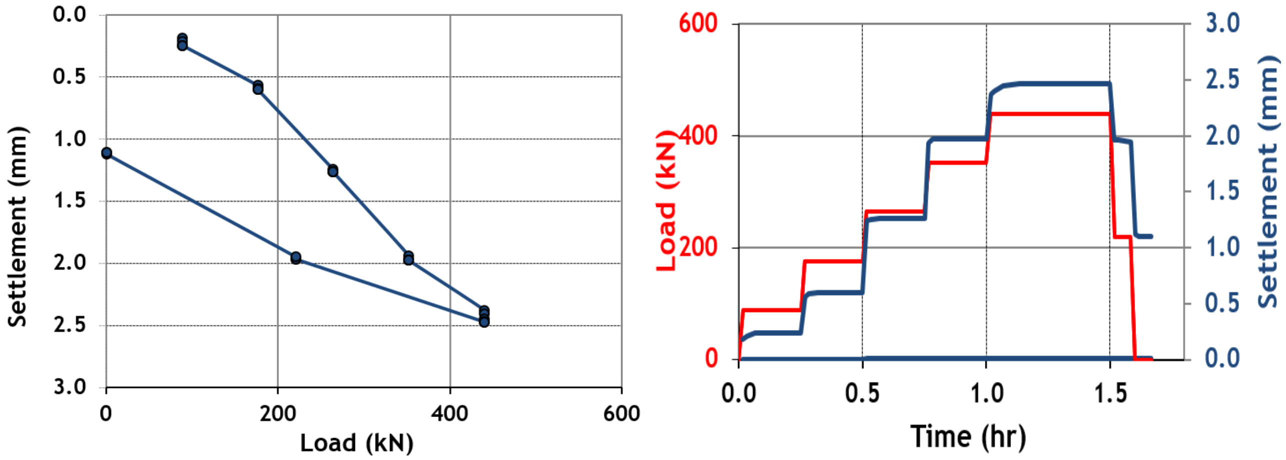


Figure 6: Static load test of an 18.9 m long CMC

As part of the quality control programme, installation records were automatically generated using special software. This information included CMC number, date and time of construction, penetration rate during drilling, rotation speed, drilling torque, column depth, uplift speed, concrete volume injected and concrete pressure.

Quality control tests included daily concrete slump tests, daily concrete unconfined compressive strength, and 15 pile impedance test (PIT) per wind turbine. It was envisaged that 2 static load tests would be carried out per wind turbine, subject to be relaxed at a later stage depending on performance of tested columns. Figure 6 shows the results of a static load test for an 18.9 m long CMC that was subjected to a loading of up to 440 kN. As the displacement per loading stage remained less than 0.02 mm/min on at least two consecutive measurements, in accordance with ASIRI (IREX, 2012) recommendation loading period in each stage was contained to 15 minutes.

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4. CONCLUSIONS

Whilst wind energy is the fastest growing renewable energy source for electricity generation in Australia, there are no local publications on the use of special foundation measures for strengthening the ground for wind turbine structures. To the knowledge of the author prior to Granville Harbour Wind Farm only two Australian wind farm projects had utilised ground improvement, namely dynamic compaction and compaction grouting.

For the first time in Australia, CMC ground improvement technique has been used for 27 wind turbine foundations at Granville Harbour Wind Farm. Whilst specific site constraints required advanced planning of resources and material, the project was successfully completed within the intended period. This project has also set a world record by incorporating the world's second deepest CMC in a wind farm project.

5. ACKNOWLEDGEMNT

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6. REFERENCES

Australian Renewable Energy Agency, Wind Energy. Viewed 12 June 2019, https://arena.gov.au/about/what-is-renewable-energy/wind-energy/.

Chu, J., Varaksin, S., Klotz, U. & Mengé, P. (2009) State of the Art Report: Construction Processes. *17th International Conference on Soil Mechanics & Geotechnical Engineering: TC17 meeting ground improvement*, Alexandria, Egypt, 7 October 2009, 130.

Coghlan, K., Plomteux, C. & Racinais, J. (2016) Execution & Engineering Principles of Control Modulus Column (CMC). *First Southern African Geotechnical Conference*, Sun City, South Africa, 5-6 May, 19-24.

Comité Français de la Mécanique des Sols et De Géotechnique (2011) Recommendations for the Design, Calculation, Installation and Inspection of Wind-Turbine Foundations, Revision 1.1. 109.

Clean Energy Council (2019) Clean Energy Australia Report 2019. Clean Energy Council, 82.

Det Norske Veritas & Riso National Laboratory (2002) *Guidelines for Design of Wind Turbines, 2nd Edition,* Copenhagen, Jydsk Centraltrykkeri, 294.

Hamidi, B., Nikraz, H. & Varaksin, S. (2009) A Review on Impact Oriented Ground Improvement Techniques. *Australian Geomechanics Journal,* 44, 2, 17-24.

International Electrotechnical Commission (2019) IEC 61400-1 Wind Energy Generation Systems - Part 1: Design Requirements. Geneva, Switzerland, 173.

IREX (2012) ASIRI National Project: Recommendations for the Design, Construction and Control of Rigid Inclusion Ground Improvements, Presses des Ponts, 316.

Johnson, G. L. (1985) Wind Energy Systems, Prentice-Hall, Englewood Cliffs, N.J.

Manwell, J. F., McGowan, J. G. & Rogers, A. L. (2002) *Wind Energy Explained – Theory, Design and Application,* electronic version, John Wiley & Sons

Pacific Hydro, Cape Bridgewater Wind Farm. Viewed 23 June 2019, http://www.pacifichydro.com.au/english/projects/operations/pwep/cape-bridgewater/.

Wikipedia, Wind Power in Australia, Viewed 21 June 2019, https://en.wikipedia.org/wiki/Wind_power_in_Australia.

Woolnorth Wind Farms, Studland Bay. Viewed 23 June 2019, https://www.woolnorthwind.com.au/wind-farms/studland-bay.

Plomteux, C. & Ciortan, R. (2010) Integrated Ground Improvement Solution for the Largest Wind Farm Project in Europe. *From Research to Design in European Practice*, Bratislava, Slovak Republic, 2-4 June.