CMC RIGID INCLUSIONS AND GROUND IMPROVEMENT CONSIDERATIONS UNDER WIND TURBINE FOUNDATIONS

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ABSTRACT

Foundation systems for wind turbines are subject to large cyclic bending moments throughout their lifetime. In unfavourable ground conditions, the turbine foundation under these loads may not meet stability and serviceability requirements unless a form of foundation support is used including deep piling, stone columns, rigid inclusions, or other alternative measures which improve bearing capacity and reduce long term settlements. This paper describes the factors to be considered when choosing a foundation support option and presents a case study on the Controlled Modulus Column (CMC) rigid inclusion design supporting most of the turbine pad foundations at the Granville Harbour Wind Farm. The design of the CMC system was analysed using numerical methods which predicted that the bearing capacity, expected settlements and dynamic rotational stiffness would meet the turbine foundation design requirements.

Keywords: Ground Improvement, Wind Turbine, Rigid Inclusions, Controlled Modulus Columns

1 INTRODUCTION

Wind turbines are constructed on a range of foundation types that are chosen according to various factors including: i) if the environment is onshore or offshore, ii) ground conditions which can vary from high strength rock to soft silts, and iii) the water table elevation. Large wind turbines can also reach heights in excess of 120m causing significant bending moments to form at their base and when installed in areas with unfavourable ground conditions foundation support will likely be required. When soft ground conditions are encountered the turbines will likely be constructed on either a piled foundation (deep foundation) or a slab foundation with ground improvement supported by Rigid Inclusions or Stone Columns. This paper will address the design of such supports under onshore foundations.

In the cases where foundation support is required, choosing the most appropriate technique can be difficult due to the performance limitations, construction feasibility and cost constraints involved. This paper addresses the relevant principles and constraints for Stone Column, Rigid Inclusion and Deep Pile foundation solutions with reference to the *Recommendations for the design, calculation, installation and inspection of wind-turbine foundations* developed by the French Committee of Soil Mechanics (CFMS) in 2011. As a following case study, the design of a Controlled Modulus Column (CMC) system for the wind turbine foundations at the Granville Harbour Windfarm is described alongside the relevant strength and serviceability performance improvements.

2 DESIGN REQUIREMENTS FOR ONSHORE WIND TURBINE FOUNDATIONS

For the purpose of design, the lifecycle of a turbine can be broken into a set of critical load cases that represent the most significant conditions that the turbine will experience. These applicable load cases have been defined in the *Recommendations for the design, calculation, installation and inspection of wind-turbine foundations* (CFMS, 2011a). The *International Standard Wind turbines – Part 1: Design Requirements* IEC 61400-1: 2005 requirements are summarised in the CFMS 2011a and state that the following conditions are to be checked:

- Minimum foundation area in compression.
- Bearing capacity.
- Sliding resistance.
- Total and differential settlements.
- Stiffness;
    - Long term rotational stiffness $K_{\varphi LT}$.

  - Dynamic rotational stiffness $K_{\varphi dyn}$.
  - Stiffness requirements in displacement.
- Factor of safety against sliding and overturning.

3 GRAVITY BASES ON SOIL REINFORCEMENT BY STONE COLUMNS

Stone Columns consists of vertical columns made of cohesionless material that is driven into the ground and then compacted. This method of ground reinforcement creates a homogenous material with improved mechanical characteristics that provide greater bearing capacity, stiffness and settlement control underneath the foundation. The horizontal shear strength and internal friction angle is also improved which increases the factor of safety against sliding. Guidelines for the design of stone columns under turbine pad foundations are sourced from the CFMS 2011a and the *Recommendations for the design, calculation, construction and quality control of stone columns under buildings and sensitive structures* (CFMS, 2011b).

According to the CFMS 2011a, the Load Transfer Platform (LTP) is an important requirement below the turbine foundations supported by stone columns as it prevents subsequent construction disturbing the stone columns and ensures homogenous contact between the footing and soil. The CFMS 2011a further states that load transfer (especially shear force) must be obtained by means of a load transfer platform.

The design of Stone Columns under the turbine pad foundations rely on the principles of proportional load distribution between the soil and the Stone Columns via the LTP, as well as the limitation of the mobilised lateral earth pressure surrounding the Stone Columns. As the Stone Column behaviour depends on the soil confinement, the following limitations are noted:

- Lack of soil confinement in soft ground (undrained shear strength C_u < 20kPa or CPT resistance, q_c < 300 kPa) means it will be difficult to justify a bearing capacity greater than 250kPa at the Serviceability Limit State (SLS) or 350kPa at the Ultimate Limit State (ULS) (CFMS 2011a).
- The static deformation modulus (E) must be limited as Stone Column characteristics rely on the lateral confinement of the surrounding soil (CFMS 2011a).
- It may be necessary to include an extra row of stone columns outside of the peripheral rows under the foundation if the design relies on perfect column confinement (CFMS 2011a).
- Bulging Failure limits q_{re} must not be exceeded (CFMS 2011b).
- General Shear failure limits must not be exceeded (CFMS 2011b, Soyez 1985).
- Punching limits q_{rp} must not be exceeded for floating columns (CFMS 2011b).
- The effects of groundwater infiltration through Stone Columns should be assessed ensuring long term issues don't arise under the foundation i.e. trigger potentially collapsible material.

Due to the general limits of the soil confinement Stone Columns may not be appropriate where the ground conditions are soft or when they may form an unwanted drainage path. The significant benefits typically associated with Stone Columns are the cost advantages as both material and associated plant costs are usually low when compared to other foundation support options and with installation of the columns performed with relatively high productivity rates.

4 GRAVITY BASES ON SOIL REINFORCEMENT BY RIGID INCLUSIONS

Rigid Inclusions typically comprise of mortar or concrete elements that are bored into the ground via soil extraction or with soil displacement with the mortar or concrete cast in-situ. Rigid Inclusions may contain reinforcing steel which is installed into the wet concrete if the above methods are used. Rigid Inclusions may also be driven rather than bored using pre-cast concrete or steel columns. It should be noted that Rigid Inclusions are stated to be the preferred form of soil reinforcement when the static ground deformation modulus is less than 50MPa from the CFMS 2011a.

Rigid Inclusions are noted by the author to support the wind turbine foundations on the Fantanele & Cogealac wind farms which are currently the largest onshore wind farm project in Europe (Wind Europe 2013, Windpower Monthly 2019). These wind farms consist of 139 turbines of 2.5MW, with the turbine structures total height being about 150m above ground. The ground consisted of aeolian loss deposits over stiff clays or sandy silts underlain by rocky schist encountered down to 27m depth. Rigid Inclusions were installed at a grid between 4.5m^2 to 2.0m^2 to accommodate significant bending moments of between 35 000 to 76 000kNm (Plomteux and Ciortan, 2010).

Rigid Inclusions reinforce the soil to deliver similar benefits as Stone Columns by improving bearing capacity, increasing overall stiffness and providing settlement control. Unlike Stone Columns, Rigid Inclusions are not limited to the lateral confinement of the surrounding soil defining the characteristics of the semi-rigid elements. However as displacement effects due to differential shortening could occur, a detailed analysis of the soil-inclusion and inclusion-soil load transfer mechanisms are required. Guidelines for the design of rigid inclusions under the turbine pad foundations are sourced from both the CFMS 2011a and the National ASIRI Project for the Recommendations for the design, construction and control of rigid inclusion ground improvements by IREX in 2012.

The design of the Rigid Inclusions relies on the principles of the structural load being distributed between the soil and rigid inclusions via the LTP including resultant displacements of the inclusions and the surrounding soil. Loads on the inclusions are also limited by the settlement that occurs on the sub-base layer under the inclusion tip and the inclusion penetrating in the load-transfer platform. In addition to the need for Rigid Inclusions to provide adequate bearing capacity, the following geotechnical and structural requirements apply:

- The geotechnical resistance of inclusions is calculated according to pressuremeter or penetrometer methods for tip resistance, R_b and Positive skin friction, q_s for friction below neutral plane (IREX, 2012).
- Negative skin friction, for friction above the neutral plane, must be verified such that the friction τ of the soil along the inclusion shaft above the neutral plane does not exceed the limit value σ_v'. (IREX, 2012).
- The mean compressive force at the ULS is limited to f_{cd} and the mean compressive force at the SLS is limited to the minimum of $0.3f_c^*$ and $0.45f_c$. Where f_{cd} is the inclusion design compressive strength, f^*_c is the characteristic value for concrete or grout strength and f_c is the concrete compressive strength (CFMS, 2011a).
- The structural integrity of columns under stresses calculated from combined bending actions must be verified (CFMS, 2011a).
- The structural integrity of columns in shear must be verified following the requirements of Eurocode 2 part 12 for unreinforced inclusions (CFMS, 2011a).

Without the limitations of the soil confinement preventing using Stone Columns in soft ground conditions, Rigid Inclusions provide a foundation support solution applicable in most ground conditions. Although installation costs for Rigid Inclusions may be somewhat higher than Stone Columns due to sourcing material (mortar or concrete) and plant to outlying regions, productivity rates are generally quite high for rigid inclusions which helps to balance cost. As Rigid Inclusions are able provide foundation support to a wide range of ground conditions with relatively minimal plant components, they make an ideal solution to supporting most types of turbine foundations.

5 PILED FOUNDATIONS (DEEP FOUNDATIONS)

When design requirements cannot be met with ground improvement options then piles in a deep foundation system may be necessary. Piles in the deep foundation system provide greater rigidity than ground improvement solutions through the direct connection of the foundation to the piling elements which are anchored into deeper and significantly stiffer strata, usually rock. Typically, the piling solution under turbine foundations consist of installing piles in a circular ring or rings about the perimeter of the foundation pad where stresses are highest due to the overturning moments. Drawbacks for piling solutions often involve greater cost and time implications compared to ground improvement solutions. These factors include the need to transport more expensive and heavier materials, particularly steel reinforcement, to be brought to remote areas, more plant components to move the reinforcement and slower productivity. Installation of the structural connections typically as thick pile caps between the pile and footings also contribute to additional cost expenditures and time.

A key difference between piled foundations and rigid inclusion foundations is that they result in significantly higher bending moments and vertical stresses at the head of the pile which leads to greater reinforcement requirements as demonstrated through 3D analyses conducted by Pham *et al* (2018). For the specific scenarios modelled by Pham *et al* (2018), piling options were compared to rigid inclusions with a 500mm LTP and similar replacement ratios of 2.4%, 4.8% and 7.2%. The analysis showed that although the piling option represented only about 4% to 5% (less than 5mm) of the settlements of rigid inclusions, stresses in the piles were substantially higher with bending moments more than three times that of the rigid inclusions.

6 CMC RIGID INCLUSIONS IN GRANVILLE HARBOR WINDFARM

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 V126 wind turbine generators, each rated at 3.6MW with a maximum rated capacity of 111.6MW. The turbine foundation loads are shown in Table 1.

Controlled Modulus Columns (CMCs) was developed by Menard Soltraitement to support structures including wind turbines, warehouses, industrial buildings, medium weight housings, roads, railways, embankments, and storage tanks. The CMCs is predominantly used for sites with soft cohesive soils, loose sand, chalk, organic soil and peat. During the tender stage, several foundation solutions were considered including Piling, Stone Columns and Rigid Inclusions. Ultimately the solution chosen employed CMCs as Rigid Inclusions and was based on:

- High loads imposed by 3.6MW wind turbines make it difficult to justify allowable stresses in the soil and Stone Columns. This includes considering potential lateral expansion failure and punching failure of Stone Columns.
- The remoteness of the site and the expense required to control the quality of the Stone Columns in the variable ground conditions.
- Remoteness of the site means any additional machinery and materials needed, including steel for piling methods, results in significantly more expense.
- CMCs have a much faster installation rate than that of Stone Columns or Piling.
- Unlike Stone Columns made of free draining stone aggregate, CMCs do not create a preferential drainage path.

Based on the wind turbine manufacturer’s specifications, the foundation solution was required to provide a rotational stiffness in dynamic conditions, $K_{\phi\text{-dyn}}$, of not less than 54GNm/rad. The ground conditions were noted to be variable across the site with groundwater levels measured from 1.8m to 17.5m with an average in the order of 10m depth below natural ground level. Although the ground conditions varied, one of the more prominent soil profiles used in the design is summarised and shown in the table below.

Calculations were performed considering the foundation base geometry with an equivalent circular base derived from the area of the octagonal foundation pad. As the octagonal pad base has an area of 338m^2, the diameter of the equivalent circular base is 20.75m. For the given load types in Table 1, the design cases were calculated and the minimum area requirements for the foundation in compression due to overturning were deemed acceptable in accordance with the CFMS 2011a.

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

Table 2: Soil Profile

Soil Description	Depth to top of layer (m)	E_y (MPa)	E_m (Mpa)
Silt – Stiff	0.0	6.7	3.4
Clay – Firm	3.3	3.3	2.2
Clay – Firm-Stiff	12.0	5.0	3.3
Clay – Stiff-Very Stiff	19.0	11.0	7.3
Clay – Hard (*)	22.5	20.0	13.3

(*) Anchoring layer of CMCs

Calculations for bearing and settlement analysis however consider the reference area, S_{ref} and the corresponding reference stress, σ_{ref} which represent the relative compressed area and relative average loading which is equivalent to the compressed area, S_{comp} and the non-uniform loading over it. The reference area was derived according to the “half-moon” model defined in the CFMS 2011a. The non-uniform loadings over the compressed area S_{comp} are used for calculating local bearing capacity and allowable stress requirements for individual CMCs at each grid location. The relative compressed areas with the representation of the loadings per CMC location are shown in Figure 2, where larger circles represent a proportionally larger load at the CMC location.

Equivalent improved ground parameters were determined considering an axi-symmetrical calculation of a CMC unit cell using the quasi-permanent load case. The analysis utilised Menard in-house software that captures the distribution of the stresses and displacements from underside of the foundation slab, LTP, along the CMC, in the anchoring layer and throughout the surrounding soil. The Menard software is developed according to the analytical model MV2 explained in the ASIRI (IREX, 2012).

Stiffnesses determined and utilised in the design include the following:

- Equivalent modulus of reinforced ground: 79.8Mpa.
- Equivalent dynamic modulus of reinforced ground: 239.4Mpa.
- Long-term rotational stiffnesses in large-strain domain: 106.8GNm/rad.
- Long-term vertical stiffness: 5Mpa/m.
- Dynamic horizontal stiffness in small-strain domain: 338MN/m.
- Dynamic rotational stiffnesses in small-strain domain: 320GNm/rad > 54GNm/rad.

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

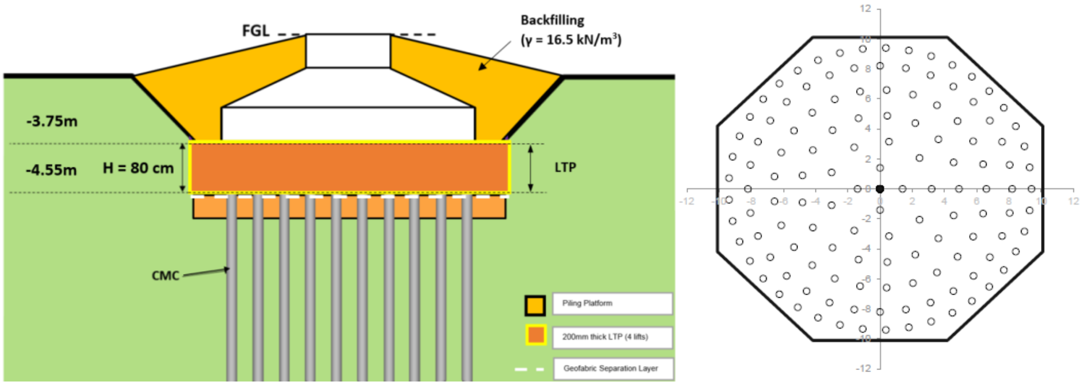
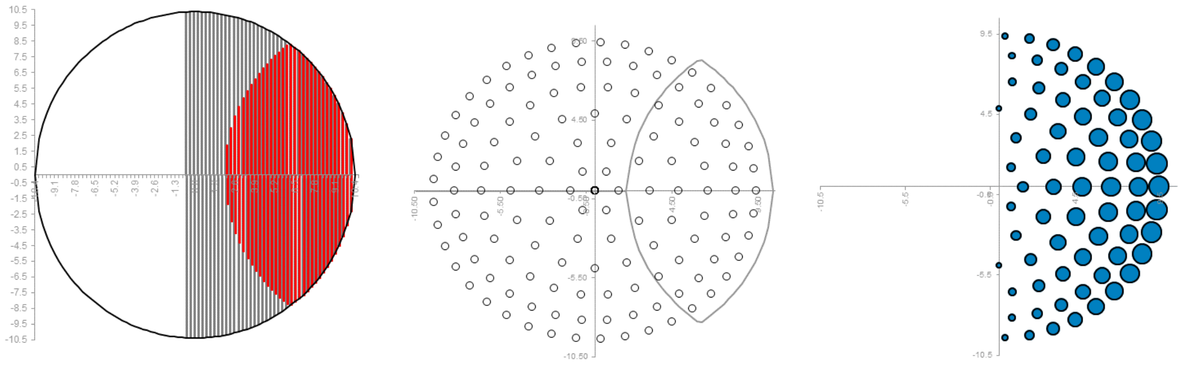


Figure 1 – CMC section and arrangement under modelled turbine pad at GHWF



(a) (b) (c)

Figure 2 – (a) Compressed area, S_{comp} in black hatching and reference area, S_{ref} in red hatching (b) Reference area, S_{ref} over CMC arrangement (c) Distributed load per CMC location over compressed area, S_{comp}

Table 3: Global Bearing Capacity Assessment

Type	Reference stress, σ_{ref} (kPa)	Reference area, S_{ref} (m^2)	Number of supporting CMCs, n	Bearing Capacity per CMC, Q_{CMC} (kN)	Mobilized load $\sigma_{ref} . S_{ref}$ (kN)	Allowable bearing capacity (kN)
ULS fund₁	263.9	155.7	58	555	41085	59888
ULS fund₂	306.8	99.2	41	555	30433	40306
ULS acc	208.8	139.0	54	610	29019	60361
SLS Rare	176.1	172.9	67	431	30433	51587
SLS QP	128.9	236.5	89	352	30478	62505

1: ULS fundamental case 1, 2: ULS fundamental case 2

Settlement and rotation of the foundation system were calculated from rigidities of the improved ground for SLS quasi-permanent load. Minimum, average and maximum settlement of the foundation were calculated to be 19 mm, 26 mm and 33 mm respectively with calculations showing differential settlement would be less than 3mm/m. Once the calculations were completed the wind turbine foundation system for the described ground profile consisted of an octagonal shaped gravity-based footing with 20.2m length and 3.75m depth of embedment. Static load tests verified the performance of the inclusion-soil response where the CMC was load tested to 440kN in accordance with the testing scheme in ASIRI (IREX, 2012) resulting in a total of 2.5mm of movement.

7 CONCLUSION

Although each foundation support system has its suitability in different scenarios, care should be taken for each type of support due to the nature of the mechanisms involved including; Stone Columns for the lateral confinement pressures particularly in soft ground, Rigid Inclusions for the differential shortening of inclusion to soil and Piling solutions for the large resultant bending moments and stresses in each pile. As windfarms are usually planted in outlying areas, the benefits of each foundation system need to also be reviewed against the associated costs which can increase significantly if more material or plant is required. The ground improvement design of CMC Rigid Inclusions under the GHWF highlights the effectiveness of this foundation support for large onshore wind turbines and demonstrates the properties of the reinforced soil.

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REFERENCES

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

(CFMS) Comité Français de la Mécanique des Sols et De Géotechnique (2011b) “Recommendations for the Design, Calculation, Construction and Quality Control of Stone Columns Under Buildings and Sensitive Structures”, Version No. 2

(IREX) Institute for Applied Research and Experimentation in Civil Engineering (2012) “ASIRI National Project. Recommendations for the design, construction and control of rigid inclusion ground improvements”.

Frank, R. and Zhao, S, R. (1982) “Estimation à partir des paramètres pressiométriques de l'enfoncement sous charge axiale de pieux forés dans les sols fins.” Bulletin de Liaison des Laboratoires des Ponts et Chaussées, 119, 17-24.

IEC 61400-1: 2005 (Wind Turbines – Part 1: Design Requirements)

Pham, H, V. Dias, D. Miranda, T. Cristerlo, N. and Araújo, N (2018) “3D Numerical Modelling of Foundation Solutions for Wind Turbines”, International Journal of Geomechanics, 18(12), 04018164.

Plomteux, C. and Ciortan, R. (2010) “Integrated Ground improvement solution for the largest wind farm project in Europe”, Proc 14th Danube-European Conference on Geotechnical Engineering ‘From Research to Design in European Practice, 2010. Bratislava, Slovakia.

Soyez, B. (1985) “Méthodes de dimensionnement des colonnes ballastées”, Bulletin de Liaison des Laboratoires des Ponts et Chaussées, 135, 35-51.

Wind Europe (2013), Ten biggest onshore wind farms in Europe, Viewed 28 February 2020, <http://www.ewea.org/fileadmin/files/library/publications/statistics/Ten_biggest_wind_farms_in_Europe.pdf>.

Windpower Monthly (2019), Ten of the best projects from the last decade, Viewed 28 February 2020, <https://www.windpowermonthly.com/article/1666828/ten-best-projects-last-decade>.