# Integrated Ground Improvement Solution for Windmill Foundation Support in soft soils

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ABSTRACT
Wind energy has become a major component of government policy and power generation sustainability programs to reduce greenhouse gas emissions at a relatively low cost. Wind power is becoming even more cost-effective as the industry develops larger turbines and the price of fossils fuel continues to rise. Being able to economically support large windmill foundations becomes a significant factor of wind farm project feasibility. As an alternative to deep piling, a fully integrated ground improvement solution has been developed using Controlled Modulus Columns (CMC) to enable more economical solutions for the various and stringent windmill manufacturer requirements. This paper presents an overview of the various procedures used for designing technically sound and cost effective CMC Ground Improvement solutions and provides details on the Fantanele and Cogealac projects which, once completed, will be the largest onshore wind farm in Europe with a total capacity of 600 MW where CMCs have been used to support the gravity based wind turbine foundations.

RÉSUMÉ
L'énergie éolienne devient un composant majeur dans les politiques gouvernementales de réduction des gaz a effets de serre. Celle-ci est produite à des coûts de plus en plus compétitifs au fur et à mesure que les éoliennes deviennent plus puissantes et que le prix des énergies fossiles continue d'augmenter. La rentabilité et la faisabilité des projets de fermes d'éoliennes dépendent de plus en plus du coût des fondations. Les Colonnes à Module Contrôlées (CMC) ont été développées comme alternative aux solutions traditionnelles de pieux dans le but de répondre de façon plus économiques tout en répondant strictement aux exigences des fabricants d'éoliennes en termes de comportement des fondations. Cet article présente un aperçu des techniques de dimensionnement des CMC et détaille le plus grand projet éolien européen (600MW) de Fantanele et Cogealac où les CMC ont été choisies pour traiter les sols compressibles sous les fondations.

## 1 INTRODUCTION

### 1.1 Ground improvement with semi rigid inclusions

The concept of semi-rigid inclusions has been used for loads support in construction projects for hundreds of years. In medieval ages, networks of wood piles were often installed under structures to stabilize soft grounds. The concept is to globally improve the soil using semi-rigid vertical reinforcement elements.

CMC main design premise is to optimally distribute foundation loads between the columns and the soil. Column diameter, spacing and strength properties are selected to reduce anticipated settlements to acceptable levels (Liausu et al, 2001). Once improved with CMCs, the soil behaves like a composite material, with an equivalent vertical modulus depending on the soil properties and on the characteristics of the inclusion network:

- Spacing and Column diameter
- Penetration depth into the bearing stratum
- Thickness of the load transfer platform placed above the CMCs
- Ratio of Column and soil modulus

The behavior of an individual inclusion is predicated on reaching an equilibrium under load (Combarieu, 1988) as shown on Figure 1. While the inclusion is being compressed by the load, negative skin friction is acting in its upper part and positive skin friction in its lower part. When the equilibrium is reached, the stresses acting on the inclusion can be divided in 4 components:

- The vertical load, Q at the top of the inclusion
- The negative skin friction acting on the upper portion of the inclusion
- The positive skin friction acting on the lower portion
- The vertical reaction at the tip

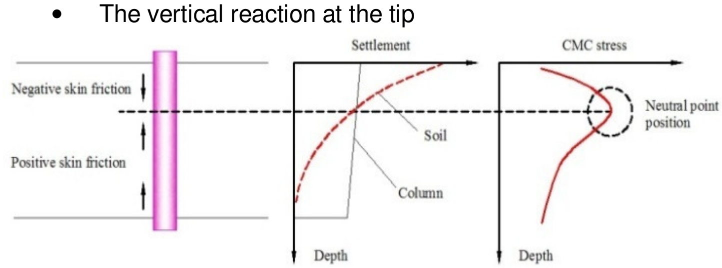


Figure 1: Settlement distribution between soil and an isolated inclusion

The foundation load of the structure is usually distributed to the network of inclusions by the load transfer platform (LTP). Figure 2 shows how the load is distributed from the structure to the bearing layer.

The load distribution between CMCs and surrounding soil is based on reaching an equilibrium between deformations of the CMCs and the surrounding soils. The design of a network of inclusions is thus based on a proper assessment of the distribution of stresses and deformations in the soil and the inclusions.

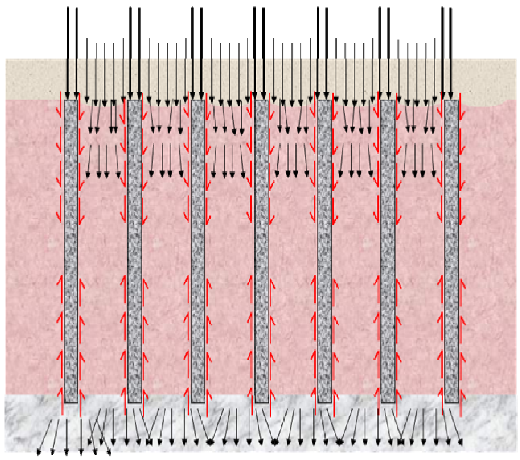

Figure 2: Load distribution between soil and an inclusion network

## 1.2 CMC and design methods

CMC are inclusions installed using specially designed means and methods. The principle of the CMC soil improvement system is to create a composite material with improved geotechnical characteristics. The CMC diameter, spacing and material strength properties are designed to provide a composite soil that will have bearing capacity and settlements adapted to the specifications of each project. Depending on soil conditions and CMC design, an improvement ratio of 2 to 10 times the initial compressibility can be obtained.

A load transfer platform (LTP) consisting of well compacted granular material is usually required above the CMCs to distribute the loads between the CMCs and the surrounding soils through arching as shown on Figure 2.

The design of CMCs also takes into consideration the load transfer through friction along the sides of the CMC as well as the compressibility of the composite soil and CMC foundation support system

## 1.3 Means and Methods of CMC construction

CMCs are installed with a specially designed displacement auger, powered by equipment with high torque capacity and high static down thrust, CMC installation displaces the soil laterally with virtually no spoils or vibrations.

When the required depth or the preset drilling torque criteria is reached, a column is developed by pumping a highly workable grout-fly ash-cement mix through the center of the hollow stem auger. The grout flows under moderate pressure (typically less than 500 kPa) and is discharged at the tip of the auger while the drilling tool is extracted to create a high capacity grout column. Because no vibration is generated, this system can be used in close proximity to sensitive structures. Minimal disturbance of the surface layer is generated during the installation process with virtually no spoils. No soil mixing takes place during the low-pressure grouting. Figure 3 shows the installation process.

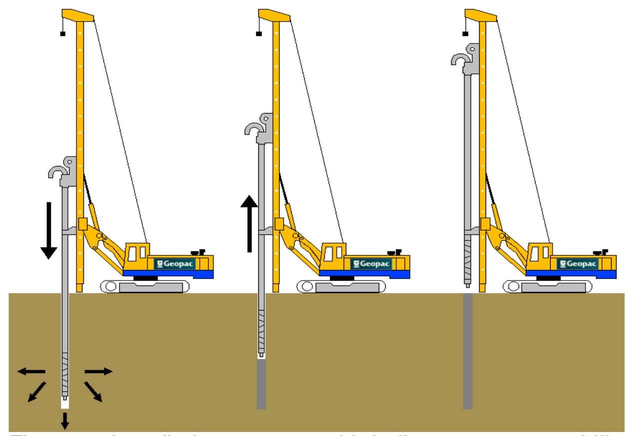

Figure 3: Installation process with hollow stem auger drill rig

All phases of installation are closely monitored by an on-board computerized recording device. As the auger is advanced, its penetration speed, torque, down thrust and depth are recorded. During the withdrawal phase, the speed of extraction, grout pressure and volume injected are also recorded. This real time monitoring ensures that each CMC is installed as per design.

# 2 DESIGN OF WIND TURBINE FOUNDATION SUPPORTED BY CMC

## 2.1 Design parameters

### 2.1.1 Wind turbine gravity foundation geometry

The gravity foundations of large wind turbines are typically octagonal, with external diameters varying from 15 to 30m and a base level usually located at 2 to 4 m below existing ground level. If required, additional fill can also be added above existing ground level for additional vertical load and rotational stability as shown in Figure 4.

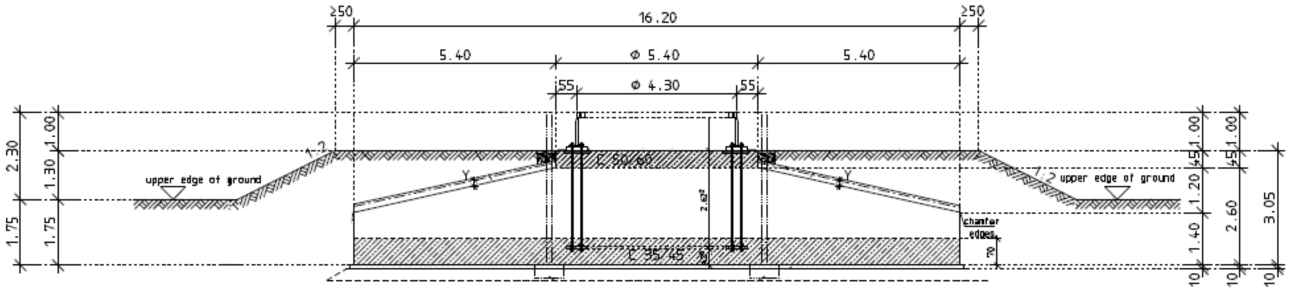


Figure 4: Typical foundation geometry with additional fill

Groundwater elevation can vary depending on precipitation and must be taken into consideration in the different loading scenarios.

### 2.1.2 CMC Columns elevation layout

As shown on Figure 5, the platform from where the CMCs are installed is typically at a lower elevation to allow for the construction of the load transfer platform once the ground improvement work is completed.

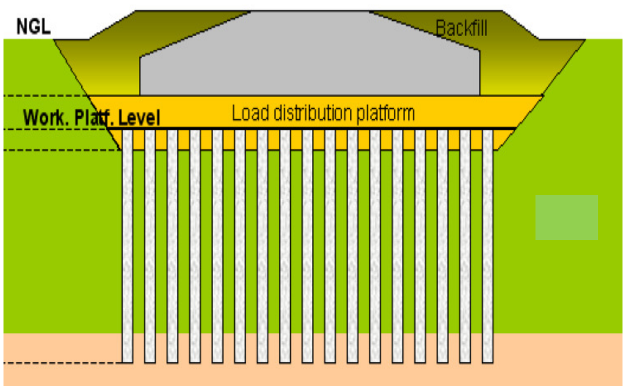


Figure 5: typical CMC elevation layout

### 2.1.3 Loading conditions

In order to take into account the various loading conditions of wind turbines during their design life, twenty-two conceptual situations are defined including assembly, disassembly, power generation, extreme winds, safety mode, breakdown, etc.

Usually more than six hundred different loading conditions are defined from those conceptual situations and the design governing load cases are finally extracted for the design of the foundation system in order to check for lift-off, overturning, lifting, shear failure, etc.

A composite load case, called DLC 1.0 or lift-off is defined for normal conditions and power generation, in which the highest load cases have been excluded. Maximum load cases are also extracted for extreme and accidental conditions.

For each of those load cases, the value of vertical and horizontal resultant forces applied to the soil, together with torsion and overturning momentum (as shown in Figure 6) are given. Buoyancy is taken into account for the foundation when required, for cases of high water table or in cases of possible accumulation of infiltration water.

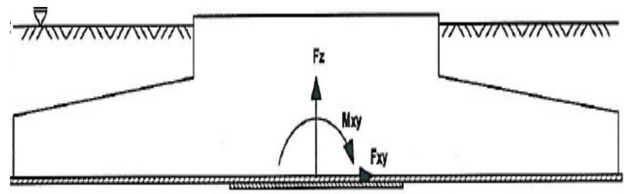


Figure 6: Loading forces and bending moments

## 2.2 Design of Ground Improvement

### 2.2.1 Technical specifications

Wind turbine foundations support vertical and horizontal loadings together with very significant overturning moment. Design specifications required by the manufacturer thus usually include the following:

- Bearing capacity under Serviceability Limit State and Ultimate Limit State conditions (under a triangular shape distribution of stress with typical maximum pressure at the edge of the foundation). Typical SLS design values vary between 175 to 300 kPa.
- Maximum differential settlement (typically 3mm/m) during the full design life of the wind turbine.
- Global overturning stability of the structure.
- Resonance: In order to avoid resonance at the soil/foundation interface, a minimal rotational stiffness has to be provided under cyclic loadings and vibrations. (i.e. under deformation in the range of $10^{-4}$ m/m) ,
- Deformation and inertial forces from seismic loading (if applicable).

### 2.2.2 Analytical approach

The design of the ground reinforcement is conducted in order to provide equivalent properties to the reinforced soil compatible with the above technical specifications.

Based on the shape and intensity of the stress distribution under the foundation (as shown in Figure 7) for each governing load case, a preliminary CMC layout (as shown on Figure 8), with spacing and diameter is defined based on allowable bearing capacity.

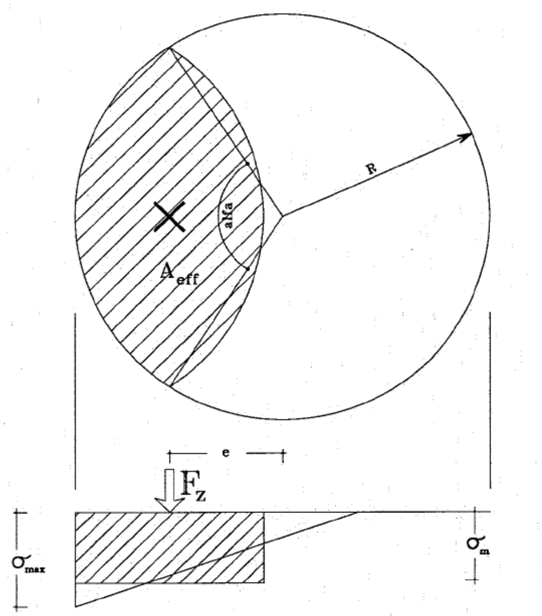


Figure 7: example of compression stress distribution (Compressed area and equivalent reference area)

The CMC spacing is then adjusted in order to match the required equivalent deformation properties.

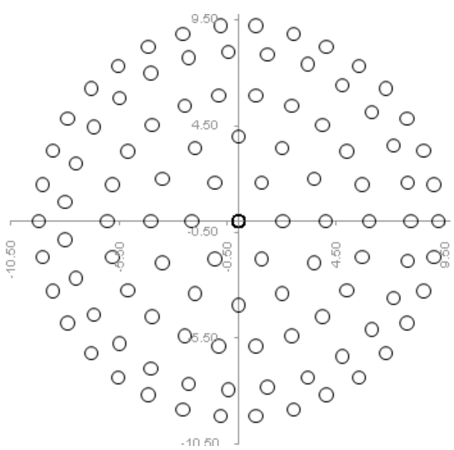

Figure 8: Typical CMC layout

Thickness and characteristics of the load transfer platform (density, friction angle, etc) are defined in order to minimize the transmission of horizontal stress to the non-reinforced concrete columns and to allow an optimal distribution of stress between the soil and the CMC.

A specific software package has been developed by the Geopac/Menard Group. Based on the different load cases, CMC layout and soils parameters, the software calculates actual loading conditions in each CMC under the wind turbine (compression, shear and bending moment) which provide for verification of required safety factor over the grout mix design.

Based on equivalent stiffness of the reinforced soil in each direction, the software also gives an estimation of the deformation of the foundation under each load case.

### 2.2.3 Finite Element Analysis

Deformation criteria being fundamental for the proper utilization of the system, the design process is generally associated with a finite element analysis in order to estimate more precisely the deformation of the foundation under combined vertical load, horizontal load and bending moment. Finite Element analysis is done using triangular elements, elasto-plastic material characteristics and is typically based on the Mohr-Coulomb model.

Distribution of stress inside the load transfer platform, between the soil and the CMC and throughout the soil mass can also be more accurately estimated with finite element techniques.

The design process comprises two main steps:

1. Axial-Symmetrical analysis of unit cells centred on one CMC in order to calculate the stress distribution between the soil and the CMC and to estimate the local equivalent properties of the reinforced soil (See Figure 9 – negative stress means that the ground is compressed)
2. 3D analysis where the reinforced soil is replaced by an equivalent homogeneous soil in order to calculate the global deformation of the foundation under each load case (see Figure 10)

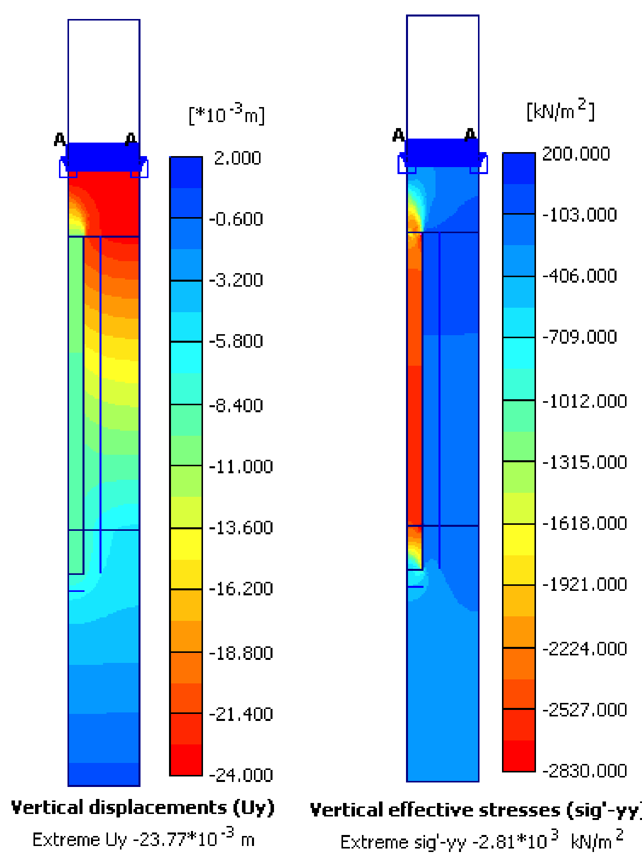


Figure 9: Step 1 – Axial symmetrical analysis

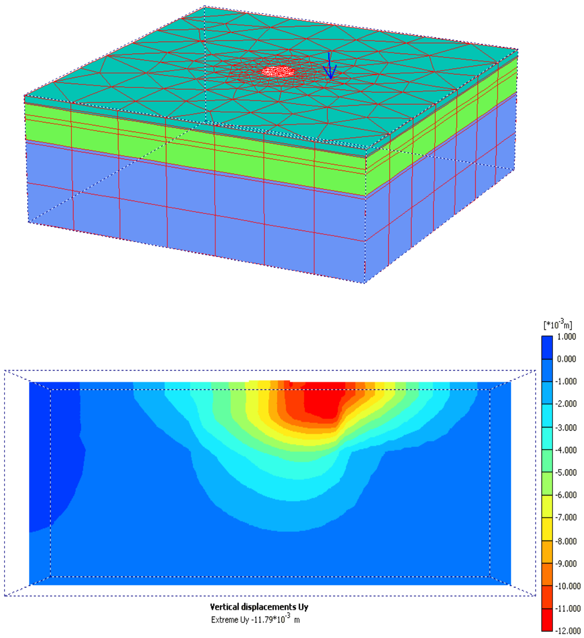


Figure 10: Step 2 – 3D model and vertical deformation

## 3 FANTANELE AND COGEALAC WIND FARM

### 3.1 Description of the project

Fantanele and Cogealac wind farms will have a total capacity of 600 megawatts and will create the largest onshore wind farm in Europe. The first phase of the project is located near the village of Fantanele, in Constanta County, and comprises 139 wind turbines with unit power of 2.5 MW. Hub height and blade diameter are 100 m, the total height of those structures is thus about 150 m above ground (See Figure 11).

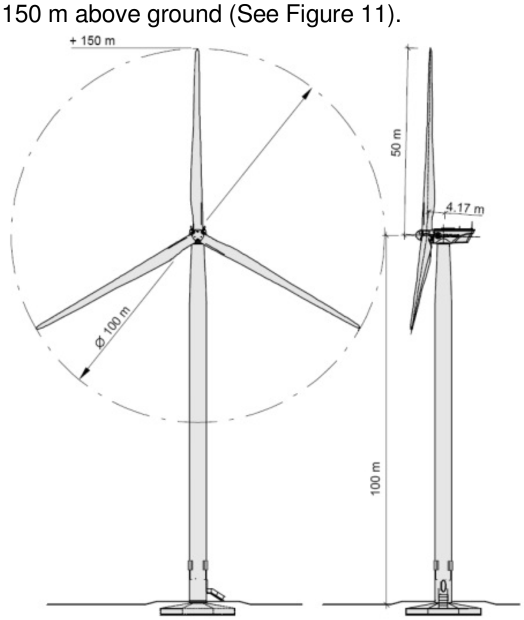


Figure 11: Wind Turbine dimensions

The project extend over an agricultural area of 8.5 km x 9 km. Distance between each turbine is about 500 m. Ground elevation varies about 80 m between lowest and highest turbine location.

### 3.2 Soils conditions

As is typical of this part of Europe, soil conditions throughout the site consist in rocky green schist substratum underlying a layer of macroporous aeolian yellow loess deposits of variable thickness over medium stiff reddish clay or sandy silts. At the location of the wind turbine, depth of the schist substratum varies throughout the site between 0 and 27 m below natural ground level (Figure 12).

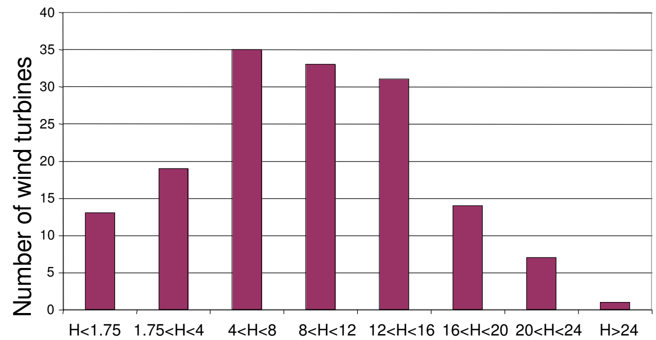


Figure 12: Depth distribution of the green schist substratum

Water table fluctuates at depth exceeding 20 m, usually within the reddish clay and sandy-silts below the loess deposits. Those geotechnical conditions imply three foundation configurations:

- Superficial substratum ($H < 1.75$ m), where the 1.75 m deep surface foundation can be built directly into the schist layer,
- Shallow substratum ($1.75$ m $< H < 4$ m) where soft soil can easily be excavated and replaced with well-compacted granular material down to the schist layer. The footing foundation is then built directly on top of this granular platform filled up to -1.75 m/NGL,
- Deep substratum ($H > 4$ m) where soil replacement is no longer an economical and technical possibility deep piling or ground improvement is then required to support the wind-turbine foundation.

Loess is aeolian sediment formed by the accumulation of wind-blown silt and lesser amounts of sand (about 6 to 26%) and clay (about 8 to 25%). It is homogeneous, with poorly graded grain size distribution (2 to 50 µm) and without stratification. It is also crossed by vertical capillaries resulting from degradation of ancient root elements. Typical geotechnical properties of the loess deposits throughout the site are the following:

- Natural water content: $w = 7.0$ to $17.1\%$
- Plastic limit : $w_p = 9.1$ to $18.7\%$
- Liquid limit : $w_L = 28.2$ to $47.2\%$

- Plasticity Index : $I_P$ = 13.6 to 34.6%
- Consistency coefficient : $I_C$ = 0.65 to 1
- Watering sensibility : $I_{m3}$ = 1.7 to 10.2%
- Porosity : n = 36 to 44%

In natural state, this loess is un-saturated (water content is 7 to 17%), highly porous (n > 40%) but loosely cemented by calcium carbonate. Particle cementation gives un-saturated loess apparent medium/high mechanical properties (Oedometer Modulus between 200 and 300 kPa ($M_{23}$) > 9 MPa, $q_c$ = 3 to 8 MPa). However, when humidified, increasing water content spread rapidly through high porosity and vertical capillaries, destroying cementation bonding. When, in addition, loading is applied, potential increase in water content can induce very quick and significant additional settlement and thus gives a "collapsible" character to the loess.

Oedometer test, with forced instantaneous saturation (Figure 13), allows evaluation of dry loess behaviour (red dash line) and wet loess behaviour (black continuous line). Deformation between wet and dry loess for applied pressure p [kPa] gives a coefficient $i_{mp}$[%] which is a measurement of the water sensibility of the loess. This coefficient is used to classify the loess (Group A or B).

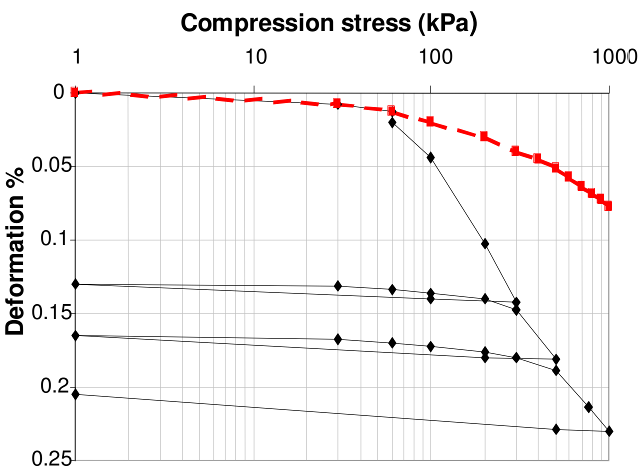


Figure 13: Oedometer test in dry (red dash) and wet (black continuous) conditions.

### 3.3 Ground Improvement solution

As an alternative to deep piling, a fully integrated ground improvement solution was proposed and developed, based on the intensive use of CMC combined with a compacted soil/cement load distribution platform. The main goal of the ground improvement was to concurrently deal with the following various stringent requirements of the project:

- Avoid the collapsible character of the loess deposits,
- Achieve the required SLS and ULS bearing capacities,
- Ensure acceptable long term differential settlements,
- Deal with the effect of wind turbine vibrations,
- Avoid resonance between foundation and turbine,
- Design to resist seismic conditions,

All necessary measures needed to be taken in order to avoid the humidification of the foundation soil from water infiltration that might come from rains or other sources (irrigation, etc). The concept was to prevent the use of any materials with higher permeability than the natural soil in order to avoid the creation of preferential infiltration path through the foundation soil.

### 3.4 Load Transfer Platform

Well-compacted granular material is normally used for the load transfer platform because it provides good compaction properties, high modulus and friction angle. Such a platform had to be excluded on this project because it would have created a highly permeable layer that would have attracted all surrounding water, which would have eventually infiltrated the foundation soil between the inclusions and cause collapse of the host soils.

A solution was developed using a dry mix of 6% cement and excavated site loess material. A laboratory test campaign has been conducted in order to define and adapt optimal mixing quantities correlated to resulting permeability, deformation modulus and resistance characteristics and to adapt mix design to the technical requirement of the project. Resulting properties are the following:

- Deformation modulus at 90 days : 3 500 MPa
- Compression strength at 90 days: 2.8 MPa
- Tension strength at 90 days : 0.43 MPa
- Permeability at 96% OPM : < 8.10-9 m/s
- Water content at optimal density : 17.4%

This material was mixed in a dedicated batching plant and roller compacted (96% OPM) in thin layers (< 0.25 m) at the bottom of the excavation. The 0.35 m thick working platform plus 0.55 m thick load transfer platform have been constructed with this compacted material. This platform has a very low permeability (< $8.10^{-9}$ m/s) and acts as an impervious layer that prevents infiltration of water to the foundation soil. This platform is installed over the entire excavation surface and is extended 2m beyond the exterior edges of the foundation (about 20 m diameter).

### 3.5 CMC solution

In order to deal the collapsible potential of the loess, the execution of the inclusions was required to be done with a technology that induces compaction of surrounding soil. Vibro-methods could have been adapted but would have required pre-drilling because of cementation of the material that makes it very difficult to penetrate with vibro-equipment. Pre-drilling and extraction of material would have compromised the foreseen compaction effect and the vibro-method technologies. Those methods were therefore abandoned. The presence of water sensitive loess also prevented the use of stone columns that would have drained all surrounding water and facilitated deep infiltration of water in the bottom deposits where collapsible potential is the highest due to higher vertical loading. As a consequence, a CMC solution was proposed to compact the surrounding soil, increasing its load bearing capacity and reducing its collapse potential.

Incorporated material needed to have lowest possible permeability, and a special mix of cement mortar, with reduced free water content and minimum porosity was adopted. Natural porosity of the loess was between 36 and 44%, with typical value being 43%. The collapsible nature of the loess is considered to be eliminated when porosity is reduced down to n < 40%. In order to reduce the porosity of the loess to 40% and mitigate the risk of water sensitivity, a densification ratio of about 5% was required. The installed grid of CMC ranged between 4.5 m² in the centre of the foundation and 2.0 m² on the perimeter, corresponding respectively to a densification ratio of between 2.2 and 5.0%. A typical CMC grid is shown on Figure 14. A side row of columns was installed around the exterior edge of the foundation in order to confine the treatment and ensure the compaction of the loess over the whole footprint of the foundation. Moreover, the columns were executed on site from the peripheral row toward the centre in order to enhance the compaction effect by peripheral confinement of the soil. Final density of the loess after installation of CMC has been controlled and tested on site with penetration test in between columns. CMC installation induces a total reduction of the collapse potential on the edges of the foundation where the highest loadings are applied and a partial reduction of the collapse potential in the centre of the foundation where the lowest average load is applied.

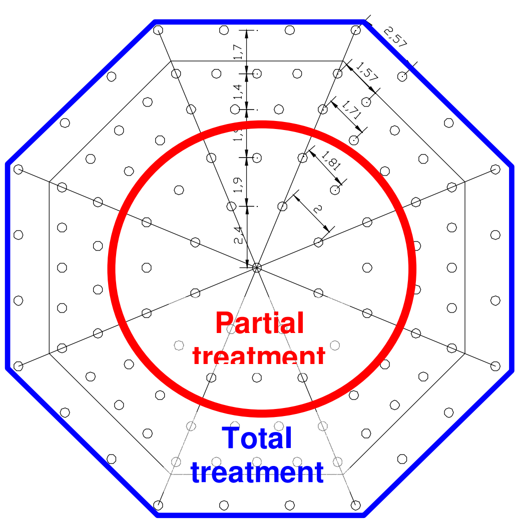


Figure 14: Typical CMC grid

Under high loading from the wind turbine foundation (edge pressure of 300 kPa under SLS conditions and 450 kPa under ULS conditions), a distribution of stress is created between the columns and the soil (see Figure 15). The Modulus of the columns has been specially designed to create the highest concentration of stress as possible within the columns in order to minimize the applied stress to the foundation soil in between the columns.

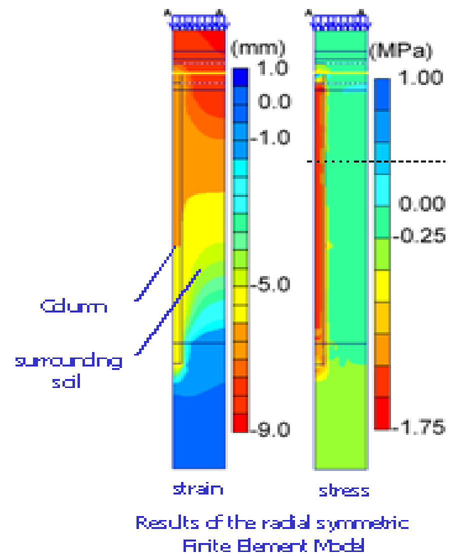


Figure 15: Typical distribution of stress between Columns and surrounding soil

The higher the applied stress is, the higher the risk of humidification which subsequently increases the risk of collapse and deformations. Maximum additional effective stress in the foundation soil is very limited at only 15 to 40 kPa (see Figure 16), corresponding to 10 to 15% of applied stress. This limited additional stress in the foundation soil is thus an additional insurance of the limited effect of a potential soils collapse.

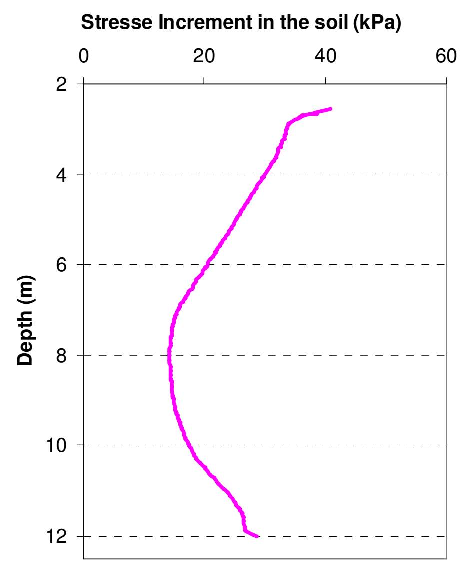


Figure 16: Vertical stress Increment in the foundation soil.

In addition, the inclusions have been designed to resist seismic action ($a_g$ = 0.16 g and earth quake critical period (TC) = 0.7 s) and a steel reinforcement was installed in the columns over the upper 4 m.

## 4 CONCLUSION

In order to deal with the difficult soil conditions combined with the stringent design requirements of wind turbine structures, the use of CMC has proven to be an economical foundation solution well suited to soft soil depth variation and collapsible soil conditions. CMC also proved to be very effective in terms of reducing overall project schedule.

CMC are very effective in difficult foundation conditions such as loose/soft fine grained soils and organic soils that can't be reliably improved using other ground improvement methods.

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