# Soil-Structure Interaction Analysis of a Wind Turbine Spread Foundation: a Case Study.

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**Abstract.** Wind is a renewable source of energy, and its use occurs through the conversion of translational kinetic energy into rotational kinetic energy, through the use of wind turbines to generate electricity. The present work deals with the consideration of Soil-Structure Interaction (SSI) in a specific case of a wind turbine tower supported on an "insulated footing" surface foundation. That said, a case study will be presented, which aims to analyze the interaction of the wind tower foundation with the soil, verifying the use of additive materials to concrete, and the SSI. To carry out the study, the computational tool, Diana FEA finite element modeling software, was used, which allows the modeling and analysis of the structure by the finite element method. The results obtained in this work allowed to enrich the discussion on soil-structural interaction.

**Keywords:** Wind turbines, Soil-structure interaction, Finite Element Method, foundation and modeling.

## 1 Introduction

Wind turbines are responsible for harnessing the kinetic energy of the wind from the driving force that makes the blades rotate and developing the mechanical energy to generate electricity, basically consisting of a rotor, nacelle and tower. Two factors that can influence the power generation capacity of the turbines are the rotor diameter and the height of the tower, thus being able to reach higher wind speeds. (EPE, Offshore Wind Roadmap). From a structural point of view, the towers must withstand different loads depending on the incident loads, and the foundations must be dimensioned to support this load.

The structure that supports the tower is a shallow foundation that can be supported directly on the ground, or supported on piles. Due to the great demands that the structural element of foundation is subjected to, the footing are usually strongly reinforced in order to combat the acting forces and avoid the collapse of the system.

The case under analysis verifies the SSI of a foundation that supports the wind turbine tower supported directly on the ground, verifying the replacement of the reinforcement of concrete, by steel fiber elements, thus reducing the need to assemble the surface foundation, which would result in savings in materials and time.

## 2 Methods

To study the foundation, the method of this work consists of carrying out a comparative analysis of three different approaches using the finite element method software Diana FEA. Initially, a Spread Footing consisting of concrete without reinforcement, will be analyzed in two different situations, first with the bottom nodes of the spread footing to have fixed translations, and the second, with the spread footing to be supported by a soil, which was assumed to have a linear elastic behavior. In the second approach, two distinct materials will be considered, i.e., steel and concrete, as the model will consider the spread footing to be made of reinforced concrete, finally, the third approach will consider the whole foundation to be made of fiber-reinforced concrete. In all three approaches a verification of the stresses at the foundation will be presented. For this, data (equipment, soil, materials and service load) from an existing foundation were used.

The SSI will be verified through a comparative analysis of the models elaborated supported on the ground (elastic support) and fixed supports, in order to present the variation of the behavior of the footing in terms of stresses and in the structural element.

## 2.1 Wind Turbine

The wind turbine of the model used as the basis for the article is the ACCIONA AW 116/3000, coupled to a 120-meter high concrete tower, with a rotor diameter of 125 meters and its blades. The foundation model is a solid circular-section direct footing that is widely used in the market as a solution for the foundation of the wind turbine tower.

In this article, the loads, including the safety factors, were provided by the manufacturer, which provides the workload, in the combination identified as "Extreme Loads", according to table 1 (Acciona, Calculation Report).

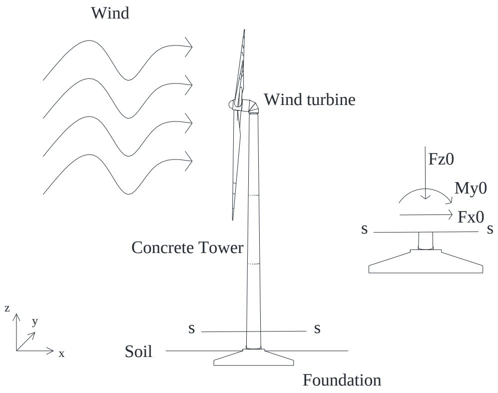


Figure 1. Simplification of stresses and bending moment in the foundation.

Table 1. – Loads transmitted by the Acciona type wind turbine to the foundation

| Load Acciona 3.0 MW | Fz0 | Fx0 | My0 | Mz0 |
|---|---|---|---|---|
| Extreme Loads | -12802 kN | 1288 kN | 111875 kN.m | 2516 kN.m |

## 2.2 Structural Design of the Foundations

The analytical approach for the foundation design was divided into pre-design and design. The pre-dimensioning was based on the theory of Teng 1962, which determines the stresses for eccentrically loaded circular spread footings. The result of the pre-dimensioning allowed the analytical dimensioning of the foundation, illustrated in figure 2.

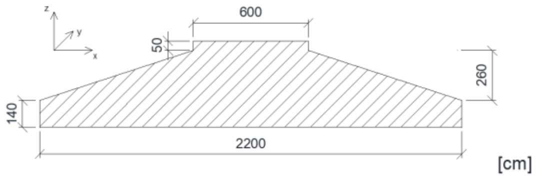


Figure 2. Foundation geometry.

The structural design of the foundation was prepared based on the calculation method of the European Concrete Committee (CEB-70). The reinforcement obtained in the project was lower than the minimum recommended for American Concrete Institute (ACI 318), specified for bent elements, soon the reinforcement indicated in the ACI was adopted, which in this case is of ϕ25 mm each 12.5 cm, distributed radially.

### 2.3 Connection detail between the tower and the foothing

The action of the wind on the wind turbine generates efforts of great magnitude, which are transferred to the base through the tower coupled to the foundation element. The applied moment, upon reaching the top of the foundation, is stabilized by a couple of efforts, which combat the moment received by the structural element. To avoid the accumulation of tensile stresses in the upper part of the footing, which would require a concentrated reinforcement to combat this tension, the model for anchoring the wind turbine tower to the footing will be of the cage type. This detailing allows the transfer of pull-out torque stresses from the upper part of the foundation to the lower part of the foundation, preventing the appearance of pulling forces generated by pull-out in the upper part of the footing.

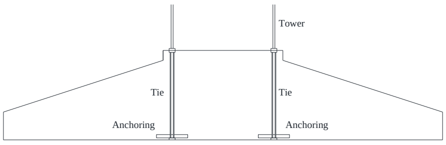


Figure 3. Detail of the tower anchorage to the footing.

### 2.4 Soil-Structure Interaction (SSI)

The SSI process is nothing more than the reciprocal influence generated between the superstructure and the foundation system, starting still in the construction phase and extending until reaching a state of equilibrium: stabilized stresses and deformations, both in the structure and in the massive soil (Colares, 2006).

An independent analysis of the foundation components, considering the supports of the footing at fixed points, results in false design results, since the flexibility of the support directly interferes with the design of the structure.

### 2.5 Mesh

The meshes of the model are formed by adaptive quadratic elements, with a mesh size of 0.50 meters for the footing and 1.0 meters for the ground mesh, according to the model in Figure 4. The model that was elaborated considering a general three-dimensional model of structure.

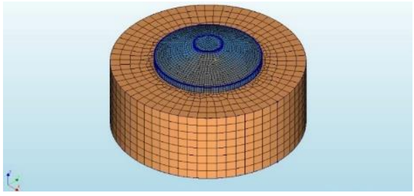
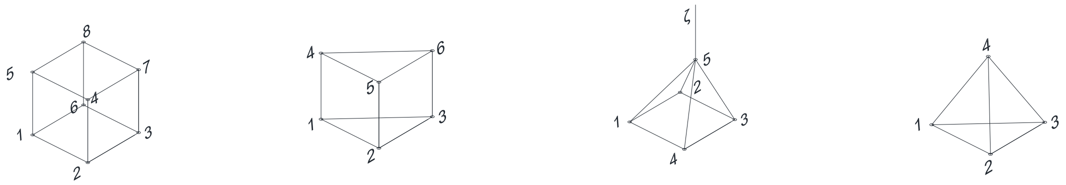


Figure 4. Foundation and soil mesh on Diana FEA.

The types of solid elements available in Diana that were used in the modeling the soil and the foundation were HX24L, an eight-node isoparametric solid brick element, based on linear interpolation and Gauss integration, TP18L, an six-node isoparametric solid wedge element, based on linear area interpolation in the triangular domain and a linear isoparametric interpolation in the direction, PY15L, an five-node isoparametric solid pyramid element, based on linear interpolation and numerical integration. TE12L, an four-node, three-side isoparametric solid tetrahedron element, based on linear interpolation and numerical integration.

The reinforcement was modeled with bar elements, the number of integration points is dependent on the element the particle of the reinforcement grid is embedded in.



(a) (b) (c) (d)

Figure 5. (a) HX24L element. (b) TP18L element. (c) PY15L element.(d) TE12L element.

## 2.6 Material properties

Table 2 below presents the materials used in the study, and the Figure 6, the constitutive law in tension for the SFRC material.

Table 2. Material properties

| Description | Material | Nomenclature | Value |
|---|---|---|---|
| Young’s Modulus | Concrete | E | 37.5 GPa |
| Poisson's ratio | Concrete | υ | 0.20 |
| Density | Concrete | ρ | 2450.0 kg/m³ |
| Young’s Modulus | Soil | E | 45.0 MPa |
| Poisson's ratio | Soil | υ | 0.33 |
| Density | Soil | ρ | 1631.6 kg/m³ |
| Porosity | Soil | n | 0.25 |
| Young’s Modulus | Steel | E | 210.0 GPa |
| Density | Steel | ρ | 7850.0 kg/m³ |

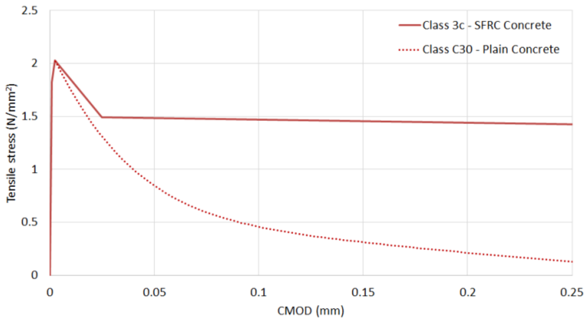


Figure 6. Constitutive law in tension for the SFRC material.

## 2.7 Structural analysis

The Spread Footing analysis consisting of unreinforced concrete was developed as a linear static analysis is a review where there is a linear relationship between applied forces and displacements. It is applied in structures where the stresses remain in the linear elastic field of the material used. The results of the linear analysis demonstrate the behavior of the structure before cracking.

In the second approach, the models elaborated in reinforced concrete and fiber reinforced concrete were analyzed with non-linear analysis, where the response of the structure is disproportionate to the addition of loads. This analysis considers physical nonlinearity and geometric nonlinearity which studies the geometric imperfections of the structure. The results of the non-linear analysis demonstrate the behavior of the structure with cracking.

# 3 Results and discussion

## 3.1 Vertical Displacements

The displacements obtained in the footing supported on the ground were 15.07 mm.

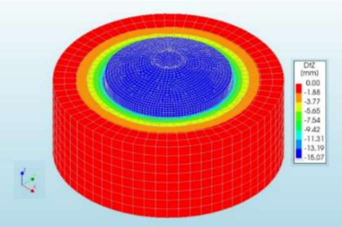


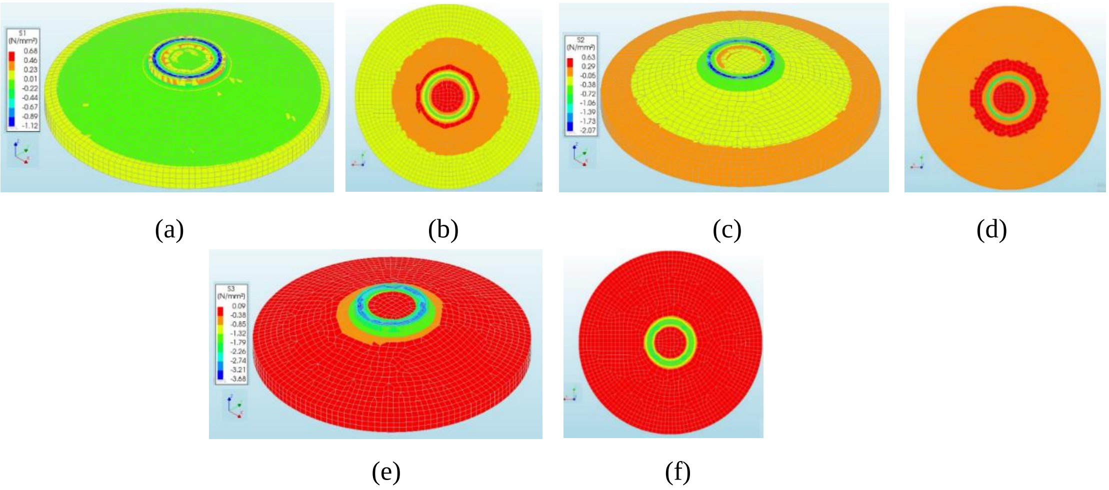
Figure 7. Displacements on the foothing.

## 3.2 Linear elastic analysis results for concrete

Table 3. Summary of analysis of stresses

| Analysis | Type of analysis | Boundary Foundation | Material | Figure |
|---|---|---|---|---|
| 1 | Linear Elastic | Rigid support | Concrete | Figure 8 |
| 2 | Linear Elastic | Supported under the ground | Concrete | Figure 9 |

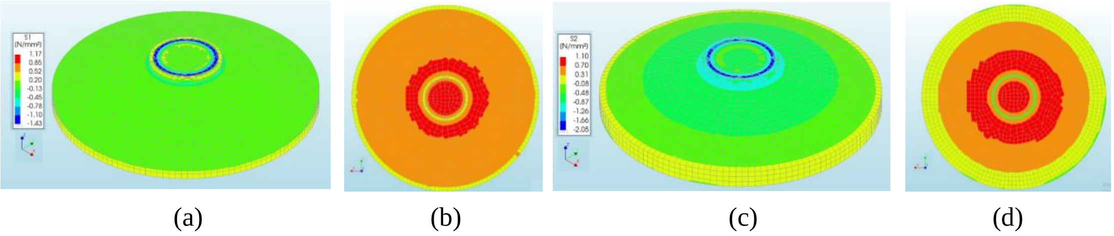
2



(a) (b) (c) (d)

(e) (f)

Figure 8. (a) Cauchy Principal Stresses, isometric view, S1. (b) Cauchy Principal Stresses, bottom view, S1. (c) Cauchy Principal Stresses, isometric view, S3. (d) Cauchy Principal Stresses, bottom view, S2, (e) Cauchy Principal Stresses, isometric view, S3. (f) Cauchy Principal Stresses, bottom view, S3.



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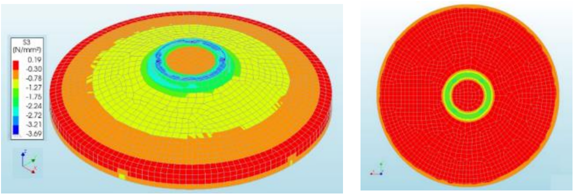


(e) (f)

Figure 9. (a) Cauchy Principal Stresses, isometric view, S1. (b) Cauchy Principal Stresses, bottom view, S1. (c) Cauchy Principal Stresses, isometric view, S3. (d) Cauchy Principal Stresses, bottom view, S2, (e) Cauchy Principal Stresses, isometric view, S3. (f) Cauchy Principal Stresses, bottom view, S3.

To compare the distribution of stresses, Table 4 presents the results obtained. The main stresses presented are S1, with the highest main stress, S2, with the intermediate main stress, and S3 with the lowest main stress.

Table 4. Comparative analysis of results

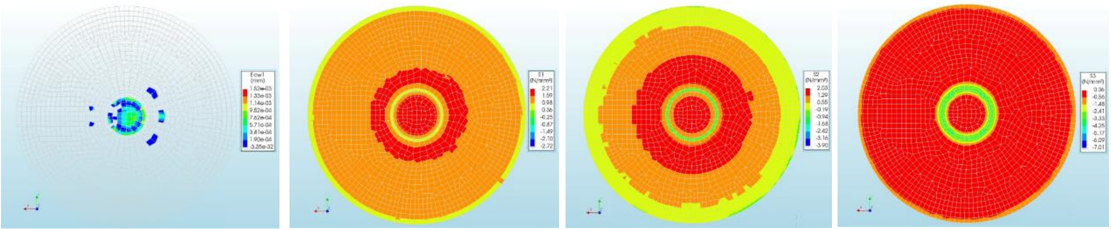
| Model Concrete Support Fixed | S1 | S2 | S3 |
|---|---|---|---|
| Highest stress | 0.68 N/mm² | 0.63 N/mm² | 0.09 N/mm² |
| Lowest stress | -1.12 N/mm² | -2.07 N/mm² | -3.68 N/mm² |
| Model Concrete Support Deformable | S1 | S2 | S3 |
| Highest stress | 1.17 N/mm² | 1.10 N/mm² | 0.19 N/mm² |
| Lowest stress | -1.43 N/mm² | -2.05 N/mm² | -3.69 N/mm² |

### 3.3 Non-Linear analysis results for concrete

Due to the results of the linear analysis, in which the stresses generated in the foundation were not enough to crack the concrete, a non-linear analysis was carried out where it was verified how many times it was necessary to increase the service load to generate cracking in the foundation.

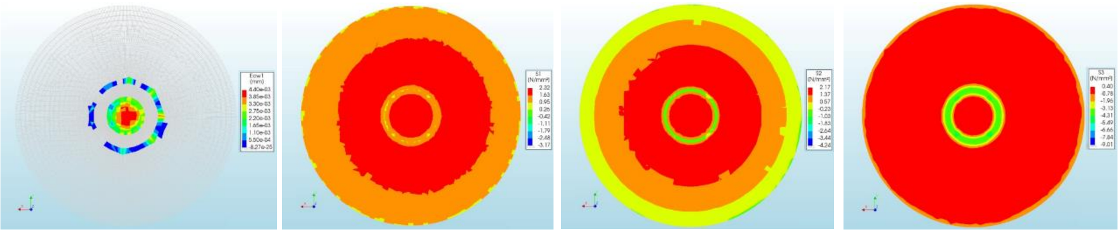
Table 5 Summary of analysis of stresses on the crackin

| Analysis | Type of analysis | Boundary Foundation | Material | Figure |
|---|---|---|---|---|
| 1 | Non-Linear | Supported under the ground | SFRC | Figure 10 |
| 2 | Non-Linear | Supported under the ground | Reinforced Concrete | Figure 11 |

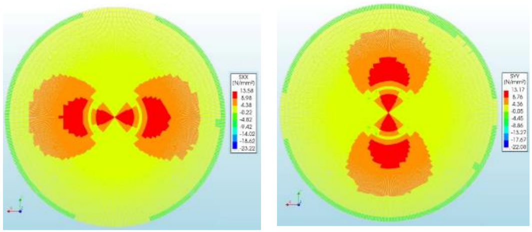


(a) (b) (c) (d)

Figure 10. (a) Cracking start SFRC - 1.9 times service load. (b) Cauchy Principal Stresses, bottom view, S1. (c) Cauchy Principal Stresses, bottom view, S2. (d) Cauchy Principal Stresses, bottom view, S3.



(a) (b) (c) (d)



(e) (f)

Figure 11. (a) Cracking start Reinforced Concrete - 2.4 times service load. (b) Cauchy Principal Stresses, bottom view, S1. (c) Cauchy Principal Stresses, bottom view, S2. (d) Cauchy Principal Stresses, bottom view, S3. (e) Reinforcement Cauchy Total Stresses, Sxx. (f) Reinforcement Cauchy Total Stresses, Syy.

To compare the results in the developed models, Table 6 presents the results obtained. The crack width shown refers to the direction of axis S1, which has the highest tensile stress, and is the region that cracks first.

Table 6. Comparative analysis of results

| SFRC | S1 | S2 | S3 |
|---|---|---|---|
| Highest stress | 2.21 N/mm$^2$ | 2.03 N/mm$^2$ | 0.36 N/mm$^2$ |
| Lowest stress | -2.72 N/mm$^2$ | -3.09 N/mm$^2$ | -7.01 N/mm$^2$ |
| Reinforced Concrete | S1 | S2 | S3 |
| Highest stress | 2.32 N/mm$^2$ | 2.17 N/mm$^2$ | 0.40 N/mm$^2$ |
| Lowest stress | -3.17 N/mm$^2$ | -4.24 N/mm$^2$ | -9.01 N/mm$^2$ |

It should be noted that the results of the SRFC, for 1.9 times the service load, which allowed the opening of cracks, were only achieved with 2.4 times the same load by reinforced concrete.

# 4 Conclusions

With the results obtained, it is concluded that the behavior of the stresses in the foundation, on a flexible base, differs considerably from that modeled on a rigid base, which is significant, showing the importance of considering the flexibility at the base of the footing.

In the models developed, the stresses generated at the base of the footing are below the magnitude necessary for the cracking of concrete by traction. A comparative analysis of the SFRC and reinforced concrete models showed that for the initiation of cracking, it is necessary to amplify the service load by 1.9 times in the SFRC, while in reinforced concrete this load increment would be 2.4 times.

The advantage obtained in the reinforced concrete model, in relation to the SFRC model, was the attenuation of the tensile stresses at the base of the footing, since in this numerical model the stresses that were previously absorbed exclusively by the concrete elements, were transferred to the steel elements, absorbing part of the stresses that would be used for the concrete, which justifies the later cracking in the reinforced model.

The analysis showed that although the standard recommends a minimum reinforcement to be applied, the analysis of the finite element model does not indicate the need for foundation reinforcement. An analysis of thermal stresses is necessary to confirm this conclusion, but what is usually observed in similar foundations are massively reinforced structures, which numerically proves not to be necessary.

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