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Soil Behavior Under Onshore Wind Turbine Foundation-Case Study in Brazil Using New French EOLIFT Technology

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Abstract

In the face of future climatic and demographic challenges, the development of renewable energies is essential to face environmental challenges. The public works profession is involved in innovation, in the construction of production facilities (power stations, wind farms) and transport (technical galleries, underground and aerial networks), in connection with laboratories and universities. In the framework of the new French technology EOLIFT (for EOlienne LIF Ting) project, allowing the erection to take place at high wind speed without the use of large cranes, numerical analysis of the soil response at a spread footing interface of a very tall onshore wind turbine was conducted using a finite element method. The motivation of this study is to understand the soil structure interaction and the behavior of turbine foundation of this new EOLIFT technology. After presentation of project and geotechnical investigations of the study case in Brazil, it was chosen to study two cases of the superstructure effects on a rigid foundation laid on the soil or buried: (1) with generalized concept of the torsor applied on the foundation, (2) considering a more realistic superstructure representation using structure elements. The results showed the foundation's depth influence. Finally, Case 2 is better to describe different construction phases of wind turbine.

Keywords: Geotechnical investigation; Soil-structure interaction; Slender structures; Wind turbine foundation; Numerical modelling; Differential settlements

Introduction

Currently, the increasing needs of renewable energy demand new research in the field of wind turbines. According to Global Wind Energy Council (GWEC), worldwide installed wind power exceeded 500,000 MW in March 2017. Around the world, this form of electricity production is growing at a rapid pace, with an average annual growth rate of 30% over the previous decade. In order to make wind energy more competitive against fossil energy, technological innovations in recent years aim at increasing the power and the effectiveness of the turbines. This requires higher wind turbines to obtain stronger and more regular wind. When the soil has sufficient bearing capacity (with or without soil treatment), tall slender structural systems, can be founded on shallow foundations. They are generally embedded in the ground, during strong wind to prevent risks again tilting, overturning or as the case may be moving or slipping. For that, the foundations of those structures should be designed carefully to ensure long-term stability.

Tall wind turbines are classified in the 3rd geotechnical category which includes the types of structures constructed in unusual conditions of soil and load [1]. Furthermore, the design and construction of the foundations of these superstructures require understanding the mechanical behavior of the soil which supports them. The system of loads under the foundations is complex and not easy to identify the soil-structure interaction. They include not only static loads as gravity but also cyclic and dynamic loads such as aerodynamic effects, start-stop phase of turbine, turbulence etc. For the foundation design of such slender structures, an eccentric inclined load, resulting from the wind load and the structure's self-weight, is generally considered. The failure by heaving or by sliding of the structure should be particularly examined. Generally, the soil failure is often associated with the excess of vertical load. For these slender structures, the analysis must consider the horizontal loads. To avoid sliding, the shear developed between the footing base and soil underneath is necessary. To extend such study, similar problems should be also examined experimentally

and numerically in 3D with different soil configurations, such as soil nature, soil properties, soil layers geometry and ground water level. The 3D analysis seems to be mandatory in order to get a better understanding of soil behavior.

The French Society for Soil Mechanics and Geotechnics (2011) gives specific descriptions on the design, the execution and the control of wind turbine foundations, which are principally based on the Eurocode 7 [1] and the French Guide 62-V (1993). These common referential documents are usually used for homogeneous soils. For generally complex natural geological conditions such as thickness layer variation and soil heterogeneity, finite element methods (FEM) are more suitable. The FEM is particularly useful for identifying the patterns of stress- strain distribution in the soil. Many constitutive models are presented in the literature and may model the mechanical behavior of soils at various degrees of accuracy [2-4]. Some commonly used models are the Mohr-Coulomb failure criterion, Hardening soil model, Hardening soil-small model and Soft soil model [5,6]. Amongst them, the Mohr-Coulomb model is generally considered as a first order approximation for soil behavior. This model is relatively simple and widely used among practicing engineers for the works of first and second geotechnical categories [1]. To use the other behavior laws, it is necessary to have many parameters, which are not easily to measure. Generally, the properties are defined from database, own at each experimental tests or literature review on similar soils.

The study of tall onshore wind turbines also takes part in the EOLIFT project managed by FREYSSINET International, in partnership with the Laboratory of Mechanics of Normandy-INSA Rouen Normandy and the Laboratory of Waves and Complex Media-University of Le Havre. This project is sponsored by French government agencies within the program for the investment of the future and the call for expressions of interest "Big Wind Turbine" launched in 2011. As part of an AMI ADEME project, the international group FREYSSINET has recently developed a new technology, consisting in the construction of large onshore wind turbines, made up of precast concrete cylindrical elements assembled by pre-stressing. Erection of such towers performed using a purpose-made system, called EOLIFT, allowing the erection to take place at high wind speed without the use of large cranes. The first construction site is located on the TRAIRI site, in the state of CEARÀ in the NE of Brazil. To represent the construction site in the numerical model, it is necessary to have a large set of data which characterize the construction site in different conditions (static, cyclic, dynamic) which are difficult to identify or to know due to a lack of data [7]. The problem of transmission from the wind to the superstructure and then, to the soils is always difficult and needs to study with more detail.

The ground investigation on the construction site was realized with the Standard Penetration Test, SPT [8,9] to determine geotechnical profile variability of superficial soils and to follow the wind tower distribution in the field. The soil strain modulus and the internal friction angle values were deduced from the existing correlations with the measured value of SPT-N [10-12]. Next,

the displacement and the stress fields under the wind turbine foundation were studied with considering the Mohr-Coulomb as a soil behavior. The project manager defines the loads of the superstructure and the Service Limit State (SLS) data was used.

In the present research paper, after the description of the project and the procedure to define the geotechnical data, some focus will be put on the numerical analysis of stress and displacement distributions in the soil under a large circular spread footing for wind turbines under static loads with a finite element method using Plaxis3D© software [2,13]. The main objective of this research paper is to analyze the effects of loads distribution and the wind either by classical method with torsor (forces and moment) applied on the foundation and either by considering the main superstructure's elements (tower, hub and blades) and wind as a horizontal force applied at the blade level. Of course, torsor elements are equivalent at the distributed loads by the superstructure. In the first case, the resulting loads are eccentric inclined load applied in a point and in the second case; the distributed loads under the superstructure are applied on an annular area corresponding to the interaction superstructure-foundation base. The numerical modeling by Plaxis 3D© with the Mohr-Coulomb model (MC), using the geotechnical properties of soil along with different construction phases, is successfully performed for these estimations.

First Prototype of Wind Turbine in the World Using the Eolift Technology

The current study will consider one of the areas in which FREYSSINET Company specializes, namely wind-powered generators. It will be specifically focused on soil displacement and stress under the foundation for wind-powered generators, deployed in Brazil. These displacement and stress could be caused by static, cyclic and dynamic loading due to the structure own weight and wind forcing.

EOLIFT technology

FREYSSINET Company developed a new concrete tower design and construction concept for craneless erection of towers (EOLIFT system), with potentially no limit on tower height and weight of concrete components.

The EOLIFT system offers a solution with:

- a) Local pre-casting of the tower concrete segments on the wind farm site using local resources, thus maximizing local contents with also positive effect on carbon footprint,
- b) Erection using purpose-made erection equipment, allowing all workstations to be located at or near ground level thus improving the safety of all operations
- c) No wind constraint since the erection equipment is designed to work up to a wind speed of 20m/s, which represents the maximum wind speed for 95% of the time on an average wind farm.

FREYSSINET Company implemented its EOLIFT technology in Brazil in 2016 on a prototype farm in TRAIRI, in the State of CEARA,

where a wind farm already exists, because the geographical location, ocean influence and trade winds give many potentials for wind energy production. Three EOLIFT systems were commissioned for the project and 20 towers (hub mounted with 2.7MW turbines) were erected. This prototype project enabled an “in-situ” comparison between the efficiency of the EOLIFT system (Figure 1) and the classic erection method with high-capacity cranes. The trade wind conditions are favorable because a wind farm is already

on the spot. FREYSSINET Company is therefore seeking new financial partners to develop this activity and secure market share in the field of tall towers for onshore wind farms using this French technology. Erection under these conditions requires controlling the wind speed and having a good soil quality under an EOLIFT system foundation, not sensitive to differential settlement [14] to ensure its stability and therefore the safety of assembly operation.



Figure 1: Tower erection (EOLIFT system).

Geological setting and local soils conditions of TRAIRI site

The construction of wind turbine site is located in Brazilian state of CEARA and specifically on the TRAIRI site. The latter is divided into four areas (Cacimbas, Estrela, Ouro Verde and Santa Monica, Figure 2). It is situated between Fortaleza and Acaraù River where littoral coast is oriented, ESE-WNW. The tropical climate is characterized by the wet and dry seasons, with wind intensity determined by the meridional shift of the Intertropical Convergence Zone [15]. The precipitation is negatively correlated with the wind power and between sea surface temperatures. The

littoral landforms of CEARA state, Northeast of Brazil are the results of many geological events, such as the opening of the Atlantic Ocean during Cretaceous Period (110 Millions) and many phenomena linked to the climatic and eustatic evolutions [16-18]. A detritic sediment from Neogene (when the world level marine was very down inducing important erosion phenomena, named Formation Barreiras) is characteristic of the coastal zone. A vast field of active and stabilized sand dunes is on the coast of CEARA State (Figure 2). Paleo dunes are generally in red sand covered with vegetation, and overlie Barreiras Formation [19], the actives are much whiter (Figure 2).

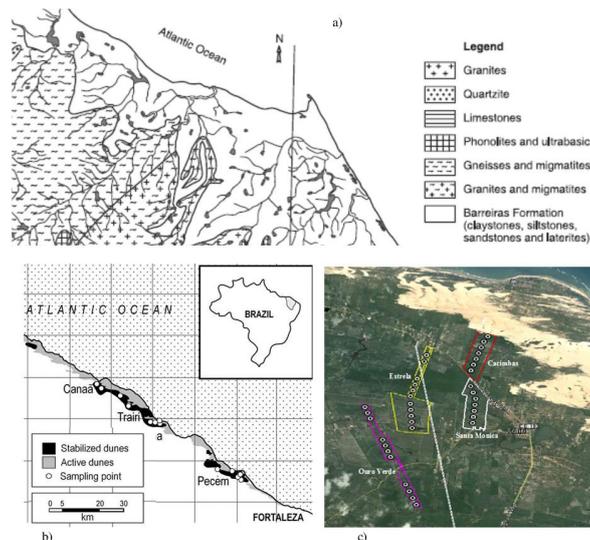


Figure 2: a) Part of the lithology map of the site of TRAIRI (Zuquette et al. [12]), b) Littoral sediments along the coastal of State CEARA (Tsoar et al. [15]), c) Lines of tall wind turbine on TRAIRI site.

Their thickness varies between 2 to 30m, according to wind direction and intensity. Residual soils from Barreiras Formation mainly consist in unconsolidated materials formed from sandstones, siltstones and claystones. The weathered profiles are very variable due to the spatial distribution and frequently comprise three layers from highly, moderate to slightly weathered, in gradational contact with the bedrock [15,19]. The littoral area of CEARA state is very sensitive to urban development (harbors, constructions, dams, seaside resorts) and is characterized by high sediment transport with intense erosion process. In this condition the littoral erosion increases, helped by natural process with migration of transgressive dunes where the most important transport elements are the wind and the waves [19,20].

Ground investigation and SPT procedure

The aim of the ground investigations was to provide details of the stratigraphy from the littoral complex. In this case, an underground investigation was decided. The designers had considered that there is sufficient information to assess construction risks. In the ground investigation, to determine lateral variability of superficial soils, Standard Penetration Test (SPT, ASTM, 2011), Lawson et al. [21] are realized to follow the wind tower lines in the field. The Standard Penetration Test is a dynamic penetration test, which allows defining the soil nature and resistance to penetration. Based on SPT test, geotechnical sections of the ground can be established about the type of soil constituting the different parts of the ground. They were organized one by one on the site of each tower wind. The SPT is carried out in a borehole by driving a standard split spoon sampler (length 450mm), using repeated blows of a hammer (weight 63.5 kg) falling through 762mm. The penetration resistance N is the number required to drive the split spoon at the last 300mm, because the first part is considered to have been disturbed. Known as an old equipment for investigation, Terzaghi was the first using the term Standard Penetration Test at 1947 [22]. To unify equipment and practice, the International Reference Test procedure was published in 1988 [23] and Clayton [24,25] gives procedures and standards adopted around the world. SPT data can be corrected for a number of site-specific factors to improve its repeatability. SPT is a simple test with advantages and disadvantages [8,9], often underlined but always largely used in the world [26].

In spite of the critical look at this test, it seems that many authors use it to establish correlations with shear parameters or to estimate the liquefaction potential of the soil under dynamic loads. Recent studies, indicating the still very frequent use of this test in the world [9,25,26]. SPT-N values were correlated with many soils or weathered rock properties, with many empirical relations but with a large database of information. Many researchers have asked themselves the question about the quality of this parameter and the possibility to give satisfactory correlations with the large range of parameters. However, it is found in the recent literature review, many studies about this field test showed good agreements [8,27,28].

In sands, the N value has been found to be influenced by the effective overburden pressure, relative density, particle size

and over-consolidation [29]. To its advantage, this *in situ* test associates a measure of soil resistance with the taking of disturbed samples allowing at least their visual identification. However, the interpretation of the test is difficult because of numerous problems of execution related to different technical parameters and to the state of the soil, thus different authors made corrections. Among the proposed relations for the correction of the value of N is that of Liao and Whitman, 1986.

$$(N_1)_{60} = C_N \cdot N_{60} = C_N \cdot \frac{E_m C_B C_s C_R N}{0.6} \quad (1)$$

where $(N_1)_{60}$: specific correction to SPT, C_N : correction coefficient of the effective stress, E_m : correction coefficient of hammer efficiencies, C_B : borehole diameter correction, C_s : sample barrel correction and C_R : rod length correction. Bowles [12], Skempton [29], Seed et al [30], and Robertson et al [31] have proposed the values for E_m , C_B , C_s et C_R . Tokimatsu et al [32] have proposed the following formula to estimate the value of C_N with the effective stress expressed in kgf/cm² (1kgf/cm² = 98.1 kPa).

$$C_N = \frac{1.7}{0.7 + \sigma'_v} \quad (2)$$

Given its widespread use around the world and studies on threshing and propagation of waves, some authors have proposed to establish correlations between the measured value of N and the common soil parameters: soil strain modulus (E_s) and the internal friction angle (ϕ'). These values of E_s and ϕ' are calculated from different semi-empirical models. In the literature, very little research proposes correlation between the SPT results and the soil strain modulus. Bowles [12] & Mikhejev [33] have proposed the semi-empirical models to estimate the soil strain modulus using relationships as presented in Table 1. These authors mentioned that these models are applicable to sandy soils. However, it can be seen that the soil strain modulus value given by these two models varies by a factor of 2 or more. In this research study, a mean value of soil strain modulus was chosen within the range proposed by these two models.

Table 1: SPT semi-empirical models to estimate the soil mechanical parameters, E_s in kPa and ϕ' in degree

Authors	Soil Mechanical Parameters
Mikhejev [34]	$E_s = (15000 \text{ to } 22000) \ln N_{55}$
Bowles [12]	$E_s = 500(N_{55} + 15)$
Kulhawey et al [13]	$\phi' = 54 - 27.6034 \exp(-0.014(N_1)_{60})$
Wolff [13]	$\phi' = 27.1 + 0.3(N_1)_{60} - 0.00054(N_1)_{60}^2$

On the other hand, with respect to the internal friction angle, Kulhawey et al. [10] & Wolff [11] proposed for sandy soils, semi-empirical models using relationships as presented in Table 1. These two models are consistent and give almost the same values of internal friction angle. A soil investigation field consisting in 36 SPT with a maximum depth of 22.45m has defined the organization of layers of sand and their mechanical characteristics. Figure 3 shows

the poor-quality soil situated in the first meter's depth in the case of the CACIMBAS area geotechnical section. The low consistency soil is situated in more or less than 3m, and from that depth it becomes

moderately too much more consistent. One note that a lateral variation of the thickness of the layers and also a general increase of the compaction with depth.

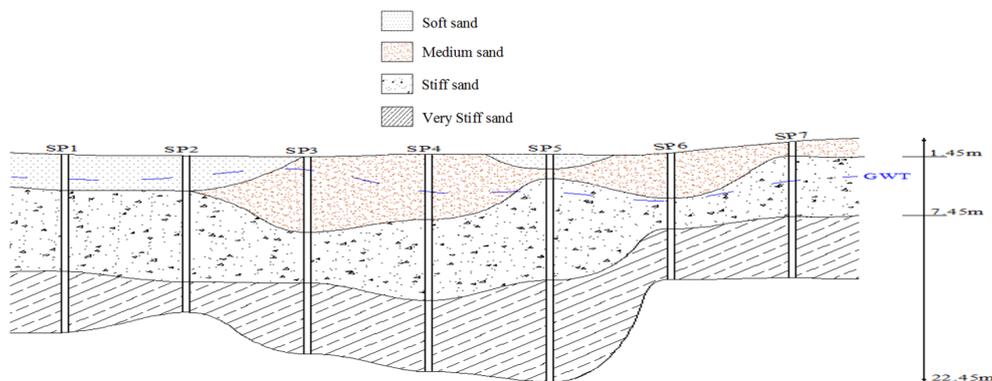


Figure 3: Geotechnical profile of CACIMBAS site in Brazil, (GWT: Ground Water Table).

In this research paper, it was decided to study a foundation of the wind turbine on borehole SP3 of CACIMBAS (Figure 3). However, one can consider three representative layers (Table 2). The soil conditions were assessed, prior to tendering, using SPT, combined with the taking of disturbed samples for both visual classifications and sieve analysis. The revealed strata were mainly sands and silts. The mean measured SPT values for the three representative soil

layers and for the borehole SP3 of CACIMBAS site are presented in Table 2. As one can see, the measured SPT values increased as depth increases. The value of N varies between 7 and 40. Table 2 shows also the soil parameters (E_s , θ') deduced from the correlations using the borehole SP3 of CACIMBAS on the TRAIRI site. The other soil parameters values are considered from the similar case studies in the literature [19,34] and are collected in Table 2.

Table 2: Soil properties and mean measured SPT values according to the boring SP3 of CACIMBAS area.

Parameters	References	Medium Sand (0-6) m	Stiff Sand (6-12) m	Verry Stiff Sand (12-80) m
Soil behavior	-	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
γ_d (kN/m ³)	Zuquette et al. [19]	18	18	18
γ_{sat} (kN/m ³)	Zuquette et al. [19]	20	20	20
E_s (MPa)	Table 1	18	27	40
C' (kPa)	Zuquette et al. [19], Rogers D [35]	10	10	10
θ' (°)	Table 1	28	30	35
Ψ (°)	Zuquette et al [19]	10	11	13
ν	Common used value	0.3	0.3	0.3
N	-	7	15	40
N_{60}	-	5.4	12.62	33.2
$(N_1)_{60}$	-	4.86	11.4	30
N_{55}	-	5.89	13.77	36.22

γ_d : dry unit weight of soil, γ_{sat} : saturated unit weight of soil, E_s : soil strain modulus, C' : cohesion, θ' : friction angle, ψ : dilatancy angle, ν : Poisson's ratio

The level water table was noted many times, but level variations and flow conditions were not sufficiently followed. Non-hydrogeological study was performed during a representative and meaningful time to understand the seasonal effects. This difficult point will be not discussed here, but it remains an important point [26]. In this research study, it is considered that there is no

water table and then the interstitial pressure is zero, therefore the effective stresses are equal to the total stresses. Mohr-Coulomb's law as a soil behavior was considered because correlations were established with (E_s , θ'), the other soil parameters were taken from literature review [19,34].

Numerical Method and Assumptions

Numerical methods have been widely employed to solve problems related to geotechnical engineering. They, nowadays, have been largely used due to some advantages compared to analytical methods and experimental works, such as reduced calculation time, cost-effectiveness aspects, complex problem-solving ability, and acceptable accuracy. A finite element code using Plaxis 3D © [2] was used to perform finite element modelling. Theoretical principles of the Plaxis are based on a finite element method that has been developed specifically for analysis of deformation and stability in geotechnical engineering projects. This software can design and perform advanced finite element or limit equilibrium analysis of soil and rock deformation and stability, as well as soil structure interaction and groundwater and heat flow.

The soil behavior laws implemented in Plaxis software such as Soft soil, Hardening soil, Cam Clay laws, isotropic elastic, Mohr-Coulomb models may be applied [2,35]. Based on the behavior of materials, an appropriate model should be selected. A mesh optimization has been carried out beforehand to ensure the good convergence of calculations. More information about the theoretical principles of the Plaxis can be found in <https://www.bentley.com>.

Moreover, to validate the numerical computation, the numerical simulations realized with the 3D finite element code were validated by comparison with analytical solutions in the case of a circular foundation resting on an elastic soil.

Soil data

From the basic underground investigations, a large and detailed bibliography was done to determine engineering properties and to establish site specific correlations between parameters, fabric and engineering properties. SPT values were discussed, and the Mohr-Coulomb law behavior was chosen on the one hand, for its simplicity and it requires few soil parameters, on the other hand, because it fairly well describes the behavior of the *in-situ* soils. Mohr-Coulomb parameters are defined in Table 2. Two layers (medium 6 m thickness, stiff sand 6 m thickness) laid on very stiff sand. Horizontal stratification, without thickness variations have been considered. The geotechnical properties increase with depth, from medium sand to very stiff sand. Yield surface of this model is an extension of Coulomb’s friction law to general states of stress [2]. It should be mentioned that this soil behavior does not consider the damage of soil modulus and it cannot be used to evaluate the soil fatigue under a foundation [36].

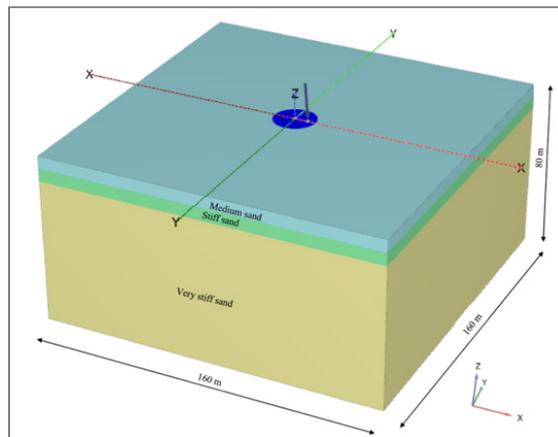


Figure 4: Model geometry in the finite elements code 3D for the foundation laid on the ground surface.

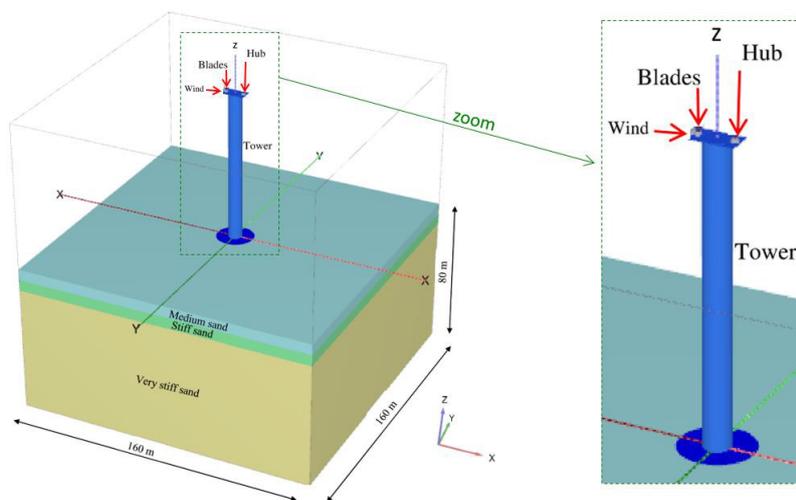


Figure 5: Model geometry in the finite elements code 3D for the superstructure laid on the ground surface.

No ground water level was considered, as the data are not sufficiently credible without hydrogeological investigations. Two cases were studied: A foundation on the ground surface and a foundation at a depth of 4.2m by considering two mechanical representation of the loads in static conditions. The depth ratio D/B (depth/diameter of foundation) ranges from 0 to 0.21. In order to consider effect of layering and mechanical properties of subsoil on the displacements and the soil stresses, the geometry modeled in finite element code was extended down to the influence depth of the foundation, which is given to be eight times of circular foundation width (Figure 4 & 5) [37].

Mechanical data of the superstructure

It is important to clarify the behavior of the soil structure interface under cyclic and dynamic loadings, but because of the lack of experimental data, only the structure behavior in static conditions

is examined Figure 6. Indeed, the loads created by dynamic effects (aerodynamic effects, start-stop phase of turbine, turbulence etc.) are not sufficiently known. FREYSSINET Company has defined the static loading conditions with Service Limit State (SLS) data, respectively vertical and horizontal forces F_z , F_x , and the moment M as shown in Figure 4 & 7. The weight of the superstructure is 17.3MN. A horizontal force of 1.37MN and a moment of 109.6 MN.m represent the wind value effect. One must be careful, the study is realized a preferential the wind direction imposed in x axis, whereas in reality it is a variation zone defined by compass. As the convention in soil mechanics, all values depending on axis z (gravity direction) are given positive, so the problem is symmetric in the plane (x,z). From industrial information, one can accept that the weight of superstructure is the superposition of different elements: tower (50%), hub (34%) and blades (16%) [7]. In this study, the direction of the wind is defined by the blades position (Figure 7).

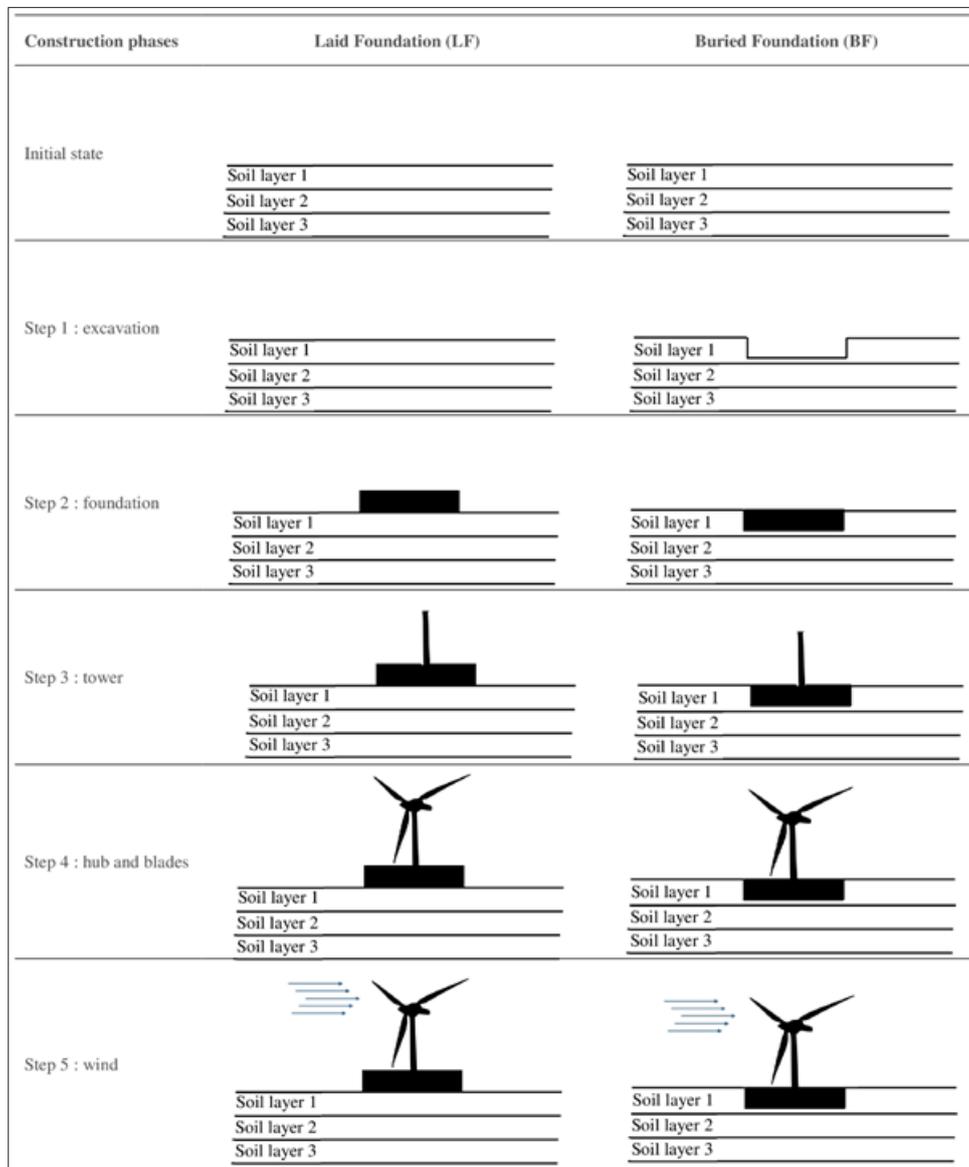


Figure 6: Schematic presentation of the main construction phases step by step.

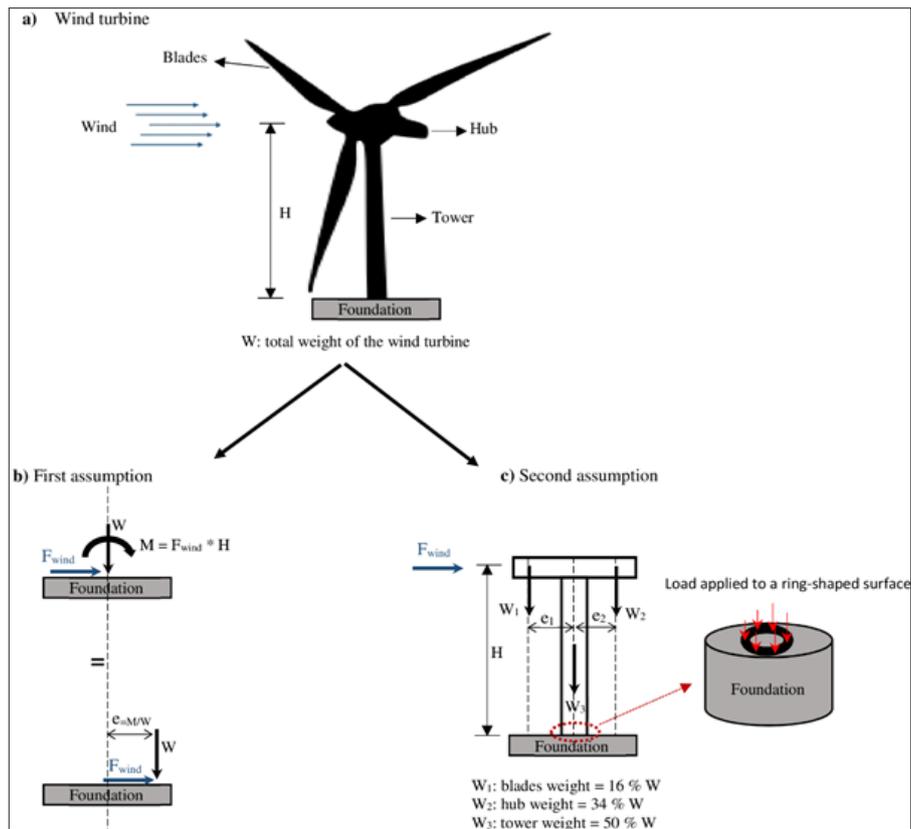


Figure 7: Schematic presentation of the load distribution of the superstructure on the foundation.

To model the moment applied at the top of the foundation, two hypotheses are studied:

- The first is to apply the moment at the center of gravity of the foundation, in addition to vertical and horizontal loads (Figure 7).
- The second is to apply an eccentric inclined force, whose eccentricity, multiplied by the vertical component of the inclined force, generates an equivalent moment (Figure 7). The idea is to compare these two approaches and analyze their equivalence.

In this study, a circular wind turbine concrete foundation with a diameter of 19.8m and a depth of 4.2m is modeled as a rigid plate element in 3D finite elements code. The modeled soil mass is a parallelepiped volume of 160m of side in the horizontal plane and 80m of depth (Figure 4 & 5). The boundary conditions imposed at the parallelepiped edges are a zero-horizontal displacement on the sides and fixed at the bottom (Figure 4 & 5). Assuming an elastic behavior of the reinforced concrete foundation material, the unit weight, the Young's modulus and the Poisson's ratio are respectively 25 kN/m³, 30 GPa and 0.2. The soil-structure interaction at the base of the concrete foundation is characterized by a soil-concrete friction angle $\delta = 2/3 \theta'$ where θ' is the friction angle of the soil.

The loads are represented either as a torsiorequivalent system applied on the rigid plate (Figure 4 & 7), by using the structures elements available in the database of 3D finite elements code (Figure 5 & 7). The main construction phases, step by step were simulated. Figure 6

summarizes these different construction steps. A concrete tower with the height of 80m is also modeled as a rigid plate element. A hollow concrete cylinder with the external and internal diameters of respectively 7.2m and 6.8m, was used as a tower as shown in Figure 7. The equipment (blades and hub) is represented with vertical forces (Figure 5 & 7). Two cases have been considered: The foundation is located on the ground surface and the foundation is buried to a depth of 4.20m, with a 0.21 value of embedment ratio of the plate.

For the foundation simply laid (noted LF) on the ground surface, there are three steps, foundation construction, vertical load and eccentricity of inclined load or moment. For the buried foundation (noted BF), there are four steps, with added excavation phase before the foundation's construction. A torsor is a mathematical tool well known to describe the movements of solids and the mechanical actions they undergo from their environment. The loads (total weight of the tower, the hub and the blades and wind effects) are represented by a torsor, defined as a set of two fields, F the resultant and the moment applied at the gravity center (Figure 4 & 7). It could be replaced by the resultant applied at an eccentricity defined by $e = M/F$. This method, named Meyerhof theory is common in soil mechanics [12].

With the other method using structure elements, the total weight of wind turbine is defined with the tower weight (50%), hub weight (34%) and blades weight (16%) as shown in Figure 7. The wind effects represented horizontal force, applied at the top of superstructure, at the center of the blades (Figure 5). In this case, it

is not necessary to apply a moment, because it is created normally by the construction and the position of the horizontal force applied at the center of the blades. It is assumed that the action of the wind occurring after the construction of the superstructure. The superstructure is represented by the total weight (tower, blades and hub). Finite element mesh, which comprises 10-node tetrahedral elements, was generated automatically regarding the maximum allowable element size.

Results and Discussion

In all cases, the soil failure is not reached and the soil remains in the elastic domain. The level of loads is lower than the bearing capacity of soil. This point has been also verified by analytical

methods (EC 7) based on Terzaghi’s principles [38]. Generally, the calculation of this type of structure is governed more by the criterion of deformation than the criterion of rupture. They are significantly affected by wind and consequently the lateral forces are important. The calculation of the global construction (without steps) is in agreement for the final displacements and the mechanical stresses [39]. The bearing capacity of the soil is reached for many high values. In all cases, the total displacements and the vertical stresses at the level -4.5m in the plane of the wind (x,z) were observed. So, the results are presented in Figure 8 & 9. In the case of laid structure, the superficial layer, in medium sand has a thickness of 6m, whereas, in the other case, the thickness is 1.8m.

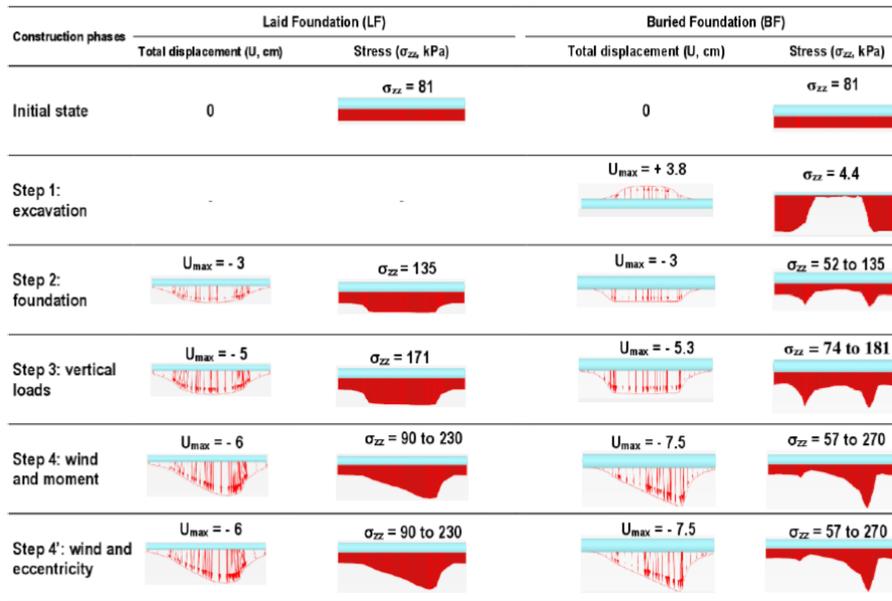


Figure 8: Displacement and stress profiles at 4.5m/ground surface for laid and buried foundations submitted to the resultant torsor (x: -20m, +20m).

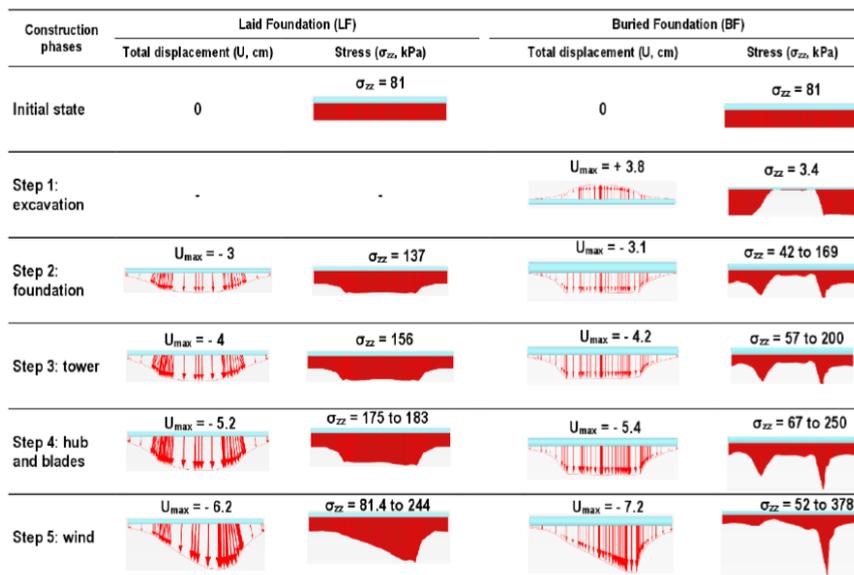


Figure 9: Displacement and stress profiles at 4.5m/ground surface for laid and buried foundations submitted to the superstructure (x: -20m, +20m).

Torsor analysis

If the loads are represented by torsor elements step by step or all together, the same results are obtained at the final step. The superposition principle is valid because the soil behaves in linear elastic manner. Figure 8 collected the results at a depth of 4.5m, either 4.5m under the laid foundation, either 0.3m under the buried foundation (with an excavation phase) under vertical loads. These results show a symmetric behavior. If the foundation is laid on the ground surface, the profile displacement is similar to Gaussian curve and the distribution stresses under the foundations are uniform. If the plate is buried, after excavation an uprising is observed, then the profile displacement is uniform and the distribution stresses show arching effect like under a rigid plate.

Under eccentricity or moment, it is noticed that for laid foundation, an asymmetric curved profile displacement and trapezoidal to triangular stresses distribution. Of course, the same results are obtained for the two representations of the eccentricity rule (step 4') and moment (step 4). For buried foundation, the profiles of displacement became triangular. Stress distribution is also modified to triangular profile, but it is reduced compared to the laid foundation. Integrating an excavation phase with a depth of 4.2m and also the diameter (19.8m) are important for the final results and reducing the thickness of the first layer modifies the soil response regarding both displacements and stresses.

There is a clear difference related to the embedding of the foundation where torsor is applied at the center of foundation. It is logical to find a weaker displacement with a laid foundation because the diffusion of stress is as a function of depth. The initial state stress is similar at 4.5m depth, but the impact of the stress-strain distribution is significant for the shape of profiles

but insignificant for the average values. The thickness of the layer between the bottom of the foundation and the observation level has an important effect as a mattress. This is conformed to the soil mechanic assumption based on the theory of plates developed by Boussinesq [39] if the foundation is rigid or flexible. There is an intermediate depth in the soils, where the rigidity of the plate or the foundation has a smaller effect. When the soil mattress thickness between the base of the foundation and the observation level is important, the profile becomes more and more flexible, depending on the deformation modulus of the concerned soil.

Interaction soil structure analysis

It was observed a similarity of the displacements and stresses for each characteristic step with the consideration of the main elements of the superstructure giving the same efforts. Integrating an excavation phase is also important for the final result and reducing the thickness of the first layer modifies the soil response regarding both displacements and stresses. Although the representation with the superstructure reveals a moment of gravity related to the difference of the distributions of the superstructure weight, which is increased by that of the wind (Figure 5 & 7).

The advantage of using the main elements of the superstructure (tower, hub and blades) is to show a moment of gravity before the application of the effects of the wind. The tower weight is represented by an annular uniform load and not with a vertical force applied to the center of the foundation as shown in Figure 7. It is more in conformity with the real case. A curved displacement profile is associated to a constant stress profile, and a constant displacement profile is associated to a curved stress profile (Figure 9). This is in agreement with the knowledge about the flexible and rigid foundation assumption in soil mechanics [40].

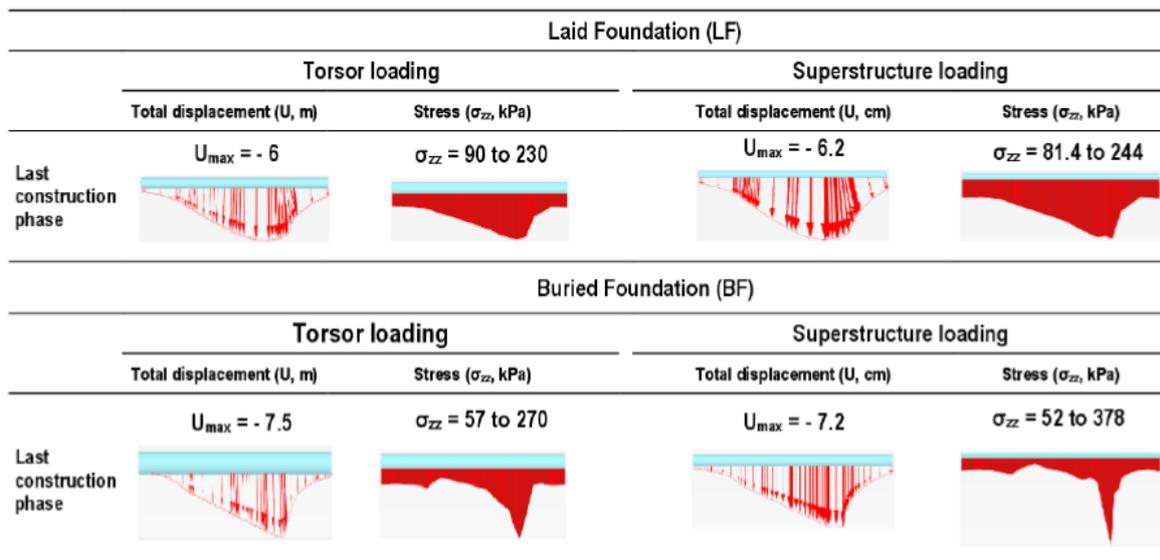


Figure 10: Comparison of the two loading systems for the last construction phase.

When the horizontal force simulated the wind is applied at the center of blades, it results reversal and tilt. Differential settlements occur and can become prejudicial to the wind tower. The maximum displacement values are nearly similar, but the shape of the curves is different. The thickness of soil between the base of the foundation and the observation level (4.5m) has an important impact on all the profiles. However, the comparison between the two methods (Figure 8 & 9) is not very significant for displacements (a difference about of 0.2mm), but significant on the stress's profiles (difference about 100 kPa for maximum stress). This was shown in Figure 10 where the comparison of the two-loading system is presented for the last step of construction phase. To understand the depth factor reduction (0 and 0.21), the influence of the observation level in the two cases (laid and buried superstructure) is examined with depth. As the initial stress state depends on the depth, (it must be remembered that soils are naturally pre-stressed materials), and the impact of the excavation phase, the differences between Laid Foundation (LF) and Buried Foundation (BF) are more important [41].

The depth of the plane observation has a significant effect on the distribution of stress in soils. So, one can discuss the mattress effect between the base of the foundation and the observation level. The scenario is more realistic with superstructure. Indeed, one can also visualize the tower deformation (Figure 11). This research study is simplified, but this finite element code 3D can give some help to the wind tower designers. The project manager often divides the problem, one for superstructure, the other for the soil bearing capacity. Here, it is shown the possibility to increase the knowledge between soil-structure interaction, of course with some simplifications, but it remains interesting. To clarify the effect of the thickness of the layer between the base of the foundation and the level of observation, the calculations were completed only for the superstructure in both laid and buried configurations. Gradually, this thickness in both cases was increased. It must not be forgotten that for the laid structure, the superficial layer, in medium sand has a thickness of 6m, whereas, in the other case, the thickness is 1.8m, and the ground soil is stratified (Figure 12).

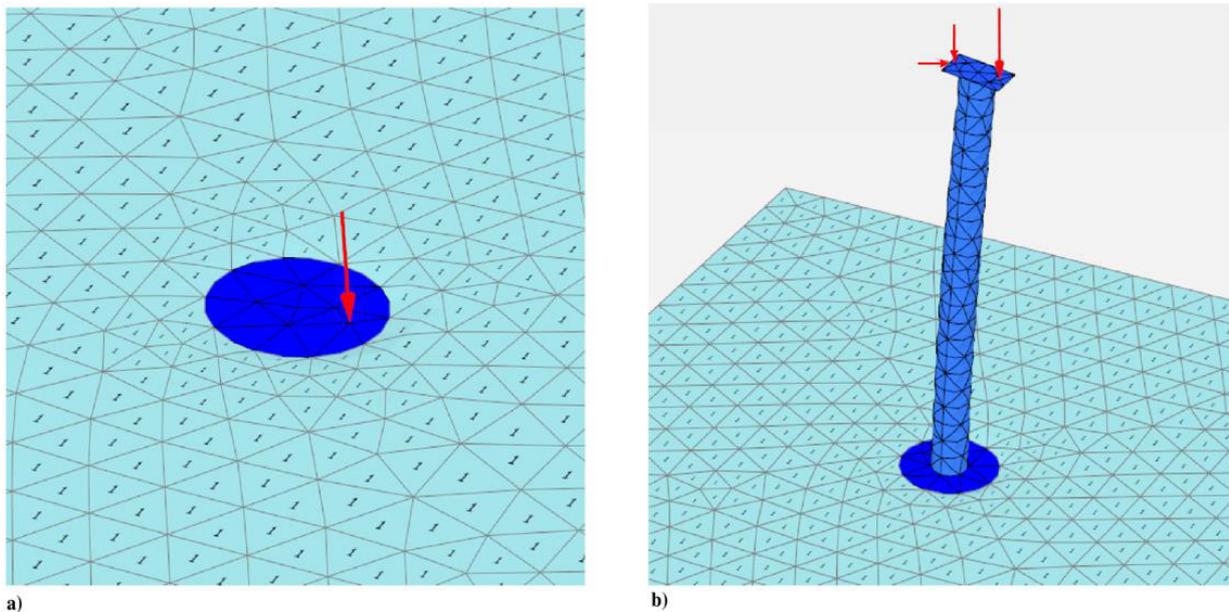


Figure 11: Zoom of the deformed mesh scaled up 20 times a) foundation laid on the ground surface, b) superstructure laid on the ground surface.

In the case where foundation is laid at ground surface, the profile was examined at 4.5m under the foundation. In the case of the buried foundation, the profile was examined at 0.3m under the foundation (Figure 12). When the soil thickness between the foundation and the observation level is small, the effect of the embedment depth is important. For a thickness of 0.3m under the foundation in both configurations, the maximum displacement is -7.2cm for the buried foundation and -11.1cm for a foundation

simply laid (Figure 12). For a thickness of 4.5m under the foundation in both configurations, the maximum displacement is -4.7cm for the buried foundation and -6.2cm for a foundation simply laid (Figure 12). Moreover, the greater the thickness increases, the more the shape of the deformed surface becomes curved. This thickness is the function of a mattress, which modifies the distribution of displacements, from uniform to curved, under vertical loads. The effect of the moment creates a tilt [42].

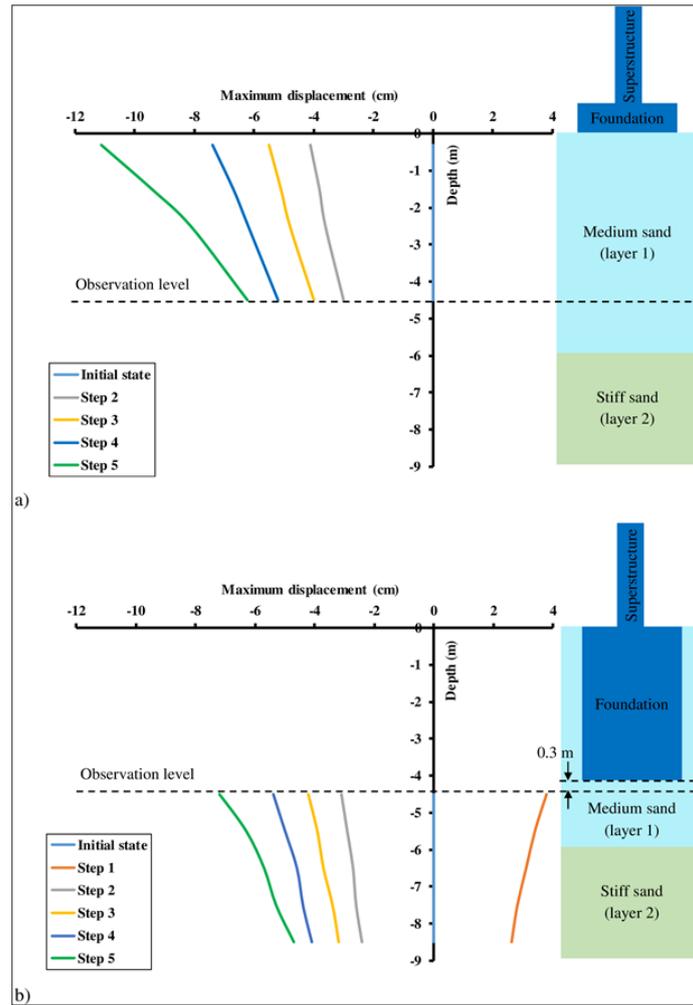


Figure 12: Maximum displacements under the foundations at different levels according to the different construction phases a) laid foundation, b) buried foundation.

It is worth to remember the important conditions in soil mechanics, about the soil-structure interaction. Figure 13 is an example of the stress profiles observed following the soil-structure interaction under a flexible and rigid foundation. For a rigid foundation, near to the ground soil, arching effect appears. With wind effect, the profile becomes triangular similar to a flexible foundation. The stress difference ($\sigma_{max} - \sigma_{min}$) for each construction phase at different levels is presented in Table 3. After comparing the columns levels -0.3 (LF)m, -4.5 (LF) and -0.3m (BF) in the Table

3, the difference of stresses is higher for buried foundation. In LF condition, stresses decrease because of Boussinesq effect and homogeneous soil, but not for BF, because the properties of second soil layer (stiff sand) have an influence on the results. When the loads are not only vertical (steps 4 and 5, Figure 9) for both buried and laid foundations, the difference increases and at the same time the shape of the profiles is approximately modified from uniform to triangular for the rigid case.

Table 3: Stress difference ($\sigma_{max} - \sigma_{min}$) in (kPa), for different construction phases at different levels.

Buried Foundation (BF)	Level: - 0.3m (Soil Layer 1)	Level: - 1.3m (Soil Layer 1)	Level: - 2.3m (Soil Layer 2)	Level: - 4.5m (Soil Layer 2)
Initial state	0	0	0	0
Step 1	77.6	80.7	87.1	67.5
Step2	127	104.4	67.9	46.7
Step 3	143	110.6	71.8	47.5
Step 4	183	114.7	70.5	52.5
Step 5	326	169.1	118.6	88.4

Laid foundation (LF)	Level: -0.3m (Soil layer 1)	Level: -1.3m (Soil layer 1)	Level: -2.3m (Soil layer 1)	Level: -4.5m (Soil layer 1)
Initial state	0	0	0	0
Step 2	31.2	83	70.7	54.7
Step 3	129.3	110.8	94.9	53.2
Step 4	171.6	149	129.4	99.4
Step 5	270.1	234.3	206.2	162.6

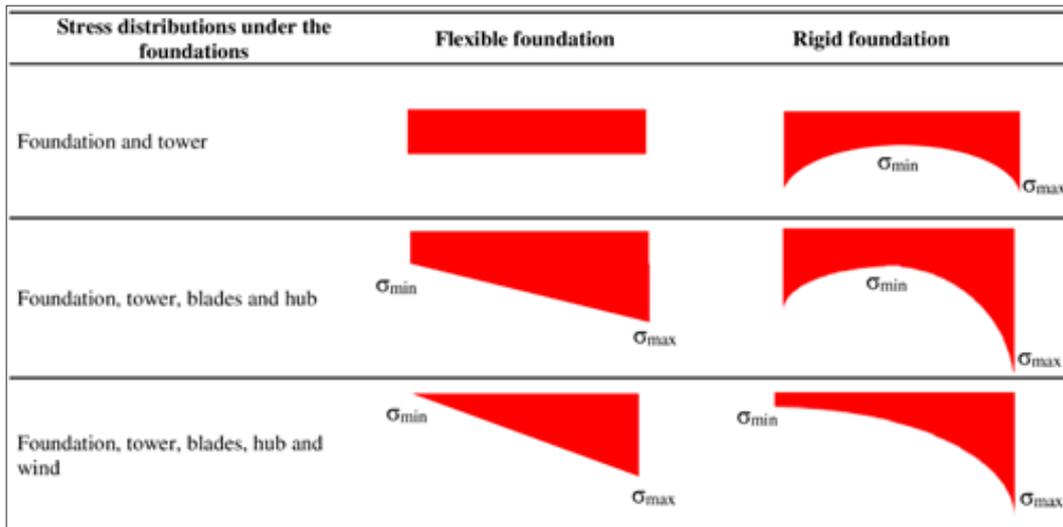


Figure 13: Comparison of the shape of stress profiles according to the elasticity theory in soil mechanics [38].

In soils mechanics, the increasing of average stresses is defined by $(\sigma_{min} + \sigma_{max})/2$ brought by a superstructure depending on the construction steps and progressively reducing with the depth. By using the initial stress (σ_{ini}), defines as a geostatic stress at the observation level, a dimensionless relative factor is defined to compare the results more easily [43].

$$Relative\ factor = average / ini_{state} = \frac{(\sigma_{max} + \sigma_{min}) / 2}{\sigma_{ini}} \quad (3)$$

The consideration of an excavation phase is very important for the stress fields, because the geostatic stress fields influence

it. When the dimensionless relative factor is determined, the calculated values according to the stresses data are near between the two cases except for the observation level of -0.3m for the laid foundation, because the numerical calculation gives very small negative stresses near to zero. These negative values have no physical signification where soil cannot support traction (Figure 14). Finally, the comparison of the displacement and stress fields in the two cases at the final step is presented in Figure 15. The affected zone by the construction is more important if the foundation is laid, for both displacements and stresses [44,45].

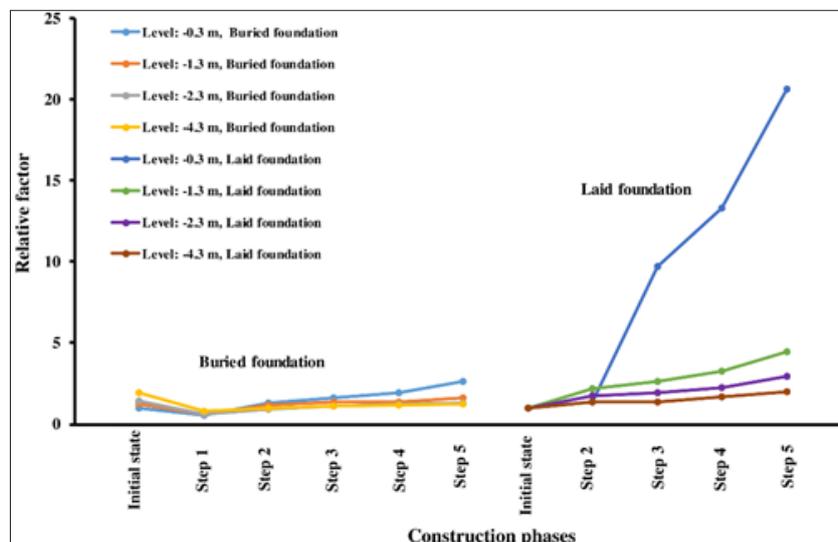


Figure 14: Relative factor for different construction phases, with the depth foundation at different levels.

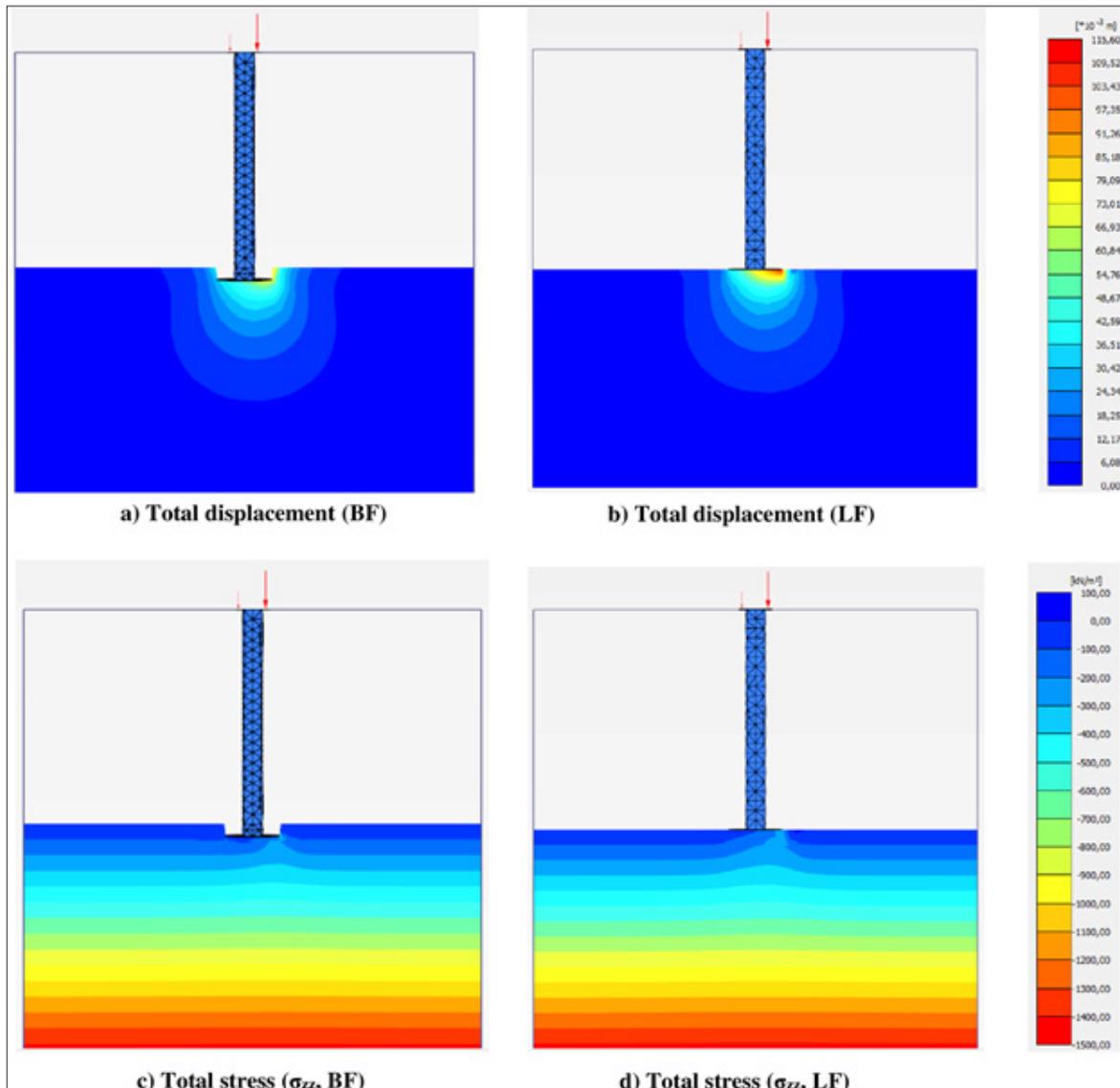


Figure 15: Comparison of displacement iso-values and diffusion of stresses only in soils (BF: Buried Foundation, LF: Laid Foundation).

Even, the representation of the superstructure actions gives near results compared to torsor representation, it is chosen to adopt the superstructure representation, not more difficult to be used, because it presents a better scenario of the construction while introducing the wind effect. To deepen this study, it is necessary to consider complex phenomena such as construction phasing during the implementation of the EOLIFT system, soil fatigue related to the dynamic loading imposed by the structure, as well as the presence of fluctuating water tables. This study is currently underway.

Conclusion

Firstly, it is important to underline that the design presented here is an adaptation of the site of TRAIRI, where wind turbines farm was built by FREYSSINET thanks to the EOLIFT system. The site is located near the littoral coast in CEARA State, where wind intensity is determined by the meridional shift of the Intertropical Convergence Zone. The geotechnical soil investigation was done

by the Standard Penetration Test (SPT). Although, SPT is the most commonly used method in the world for in-situ soil investigations, it provides only limited information, such as penetration resistance with N value. Some correlations have been proposed to determine the soil mechanical properties from the measured value of N. However, the correlations allow determining only the Mohr Coulomb parameters. The soil parameters deduced from the correlations were used in the design of a wind turbine foundation, after detailed literature review. In geotechnical application, for numerical modeling, horizontally stratified site is generally investigated. To represent the variation of the layer thickness is more difficult, but it would be possible to approach the geological conditions.

In this project, the representation of the loads by torsor or by using structure elements are similar and the results (displacements and stresses distributions) are neighbor, however the step-by-

step construction is more detailed in the second case. Indeed, a moment appears because of the different weight between hub and blades. The similarity of the results is also linked with the rigidity of the concrete foundation (a plate of 4.2m thickness with concrete characteristics). However, there is a clear difference related to depth factor reduction (depth foundation/diameter of the foundation) because it has introduced a phase excavation and consequently modification in the stress-strain state. The embedding of foundation of the wind turbine tower (laid or buried), has a significant effect on the distribution of the profiles of displacements and stresses according to the observation level. To complete this first analysis, it could be decided to adopt the second representation with taking into account superstructure elements. The interaction soil/foundation/ superstructure could be adapted to study the cyclic and dynamic effects with different interface conditions. However, to be able to follow the cumulative displacements during functional cycles, it would be necessary to introduce parameters to describe the damages of the materials during a cycle number, intensity and frequency of the wind effects, defined by compass from the studied site. *In-situ*, some wind turbines have been instrumented at the soil-foundation interface to follow the evolution of stresses and displacements in long-term service. As soon as the data of these measurements are acquired, a comparison with the numerical results will be carried out and it will be the object of a new publication in this journal.

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