Analysis of the Impact of Uncertainties on the Estimation of Geotechnical Engineering Properties of Soil from SPT on the Design of Aerogenerators Foundation

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Abstract. In geotechnical engineering, it is common to use data from only one field test (SPT test) to predict input stiffness parameters in the study of stress *vs.* displacements behaviour of foundations. This is made from correlations available in the literature for different kinds of soils. As a result, the variation that occurs between different correlations may be significant and must be critically analysed with respect to the accuracy of the foundation design and, consequently, its safety. In this context, this paper aims to study the impact of the variations of friction angle (ϕ') and Young's modulus (E) predicted by several different correlations from field SPT measurements available in the literature. Based on the estimations, four groups of estimated results were defined with the corresponding values of ϕ' and E within such groups (for high and low values of both ϕ' and E). Such values were applied in a numerical Finite Elements Method (FEM) model of an aerogenerators foundation to calculate vertical displacements and stress fields. In the groups in which only one of the parameters was varied, it was observed that the Young's modulus has a significant influence on the displacements, while that was not the case for the friction angle in the investigated foundation, due to predominant, linear-elastic condition in the investigated foundation. The paper demonstrated the significant variation in geotechnical analysis that can occur with the use of different input correlations in geotechnical studies. These uncertainties lead either to overestimate or to underestimate the foundation design, which may affect economy and safety, thus emphasizing the need for more accurate field tests and more laboratory investigation and control.

Keywords: Foundation Behaviour, Numerical Modelling, Soil Parameters, Geotechnical Measurements.

1 Introduction

The use of wind power gained prominence for being an abundant source of renewable energy in some regions of the world. It can reduce fossil fuel consumption. In this context, this is concomitant with the ONU's 7th Sustainable Development Goal: to ensure access to affordable, reliable, sustainable, and modern energy for all. Wind energy provides several socioeconomic and environmental benefits, and is one of the most cost-effective energy sources in Brazil (ABEEÓLICA, 2020).

In this context, the aerogenerators structures and soil under the foundation must be studied from the engineering point of view. The onshore wind turbines are supported in reinforced concrete foundations. Due to technological advances that cause the increase of tower's height and blades length, larger foundations of the order of hundreds of cubic meters and with high diameters are more and more common (SILVA, 2014). In addition to structural considerations, geotechnical analyses are needed to ensure proper design and the stability of the tower.

One of the biggest challenges for geotechnical studies considering Brazilian sites is related to the geotechnical investigation. There are significant differences between Brazil and France with respect to the employed tests (MILITITSKY, 2019). In Brazil, most commonly, the Standard Penetration Test (SPT), exclusively, is performed, while in France the Pressiometric Ménard Test (PMT) is conducted, and, in some cases, it is accompanied by seismic tests, as well as laboratory triaxial tests with field materials. Even in more developed countries that is not always the case, and in countries under development it is seldom the case.

Thus, analysis of the stresses and displacements is necessary to design and, for that, the geotechnical investigation is of paramount importance to determine parameters of soil such as Young's modulus, Poisson ratio, friction angle, cohesion, unit weight and dilatancy angle. These parameters can be estimated with a laboratory testing campaign. However, the extraction of undeformed samples is, usually, logistically and economically impractical. Alternatively, different authors propose the use of correlations with the required input parameters and the results obtained from the Standard Penetration Test (SPT). This test is the most common to be executed, being the most widely used in foundation projects in Brazil and in many cases, the only one to be done (CINTRA et al, 2013). It consists of penetrating the soil with a standard hammer of 65 kg forced into the hole with strokes of 75 cm of height and counting the number N_{SPT} of strokes needed to penetrate 30 cm.

The practice of determining only SPT results during geotechnical investigations to estimate values of the engineering properties, such as the friction angle (ϕ') and the Young's modulus (E), leads to strong variability, following the different available correlations and the experience of the analyst, affecting the design directly. Then, the choice of the most appropriate method the field conditions can affect the final analysis and this will be evaluated in this article. Thereby, the objective of this study is to evaluate the interference of the input parameters variation on a numerical modelling of stresses and displacements under the aerogenerator foundation and to analyse the influence of such uncertainties on its design.

2 Methodology

The research presented in this article deals with the variation of input parameters in a numerical structural modelling of wind turbines' foundation. The idea is to understand the stress and displacement behaviour when different methods to determine the resistance and deformability parameters are used, for understanding which range of variation on estimated input parameters affects significantly the results in terms of the analysed stresses and displacements.

Data from the Cacimbas wind farm (located in Trairi-Ceará-Brazil) was used. Figure 1 presents (a) the location of Ceará and (b) the location of Trairi.

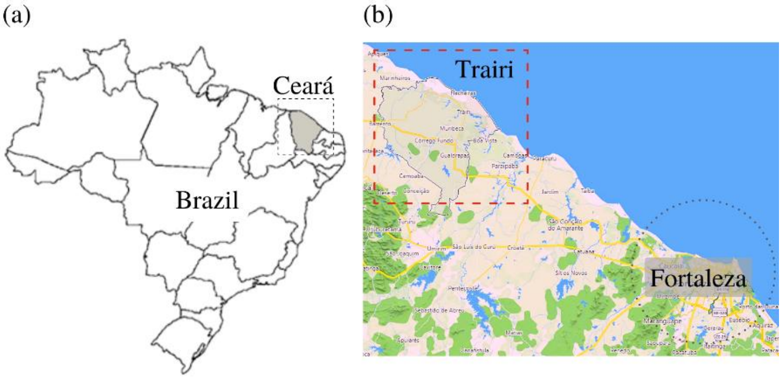

Fig. 1. Location of (a) Ceará and (b) Trairi on Brazilian map.

In this site, the geotechnical campaign was conducted, consisting of seven SPT tests ranging between 14m and 22m of depth. The obtained geotechnical profile is presented in Figure 2.

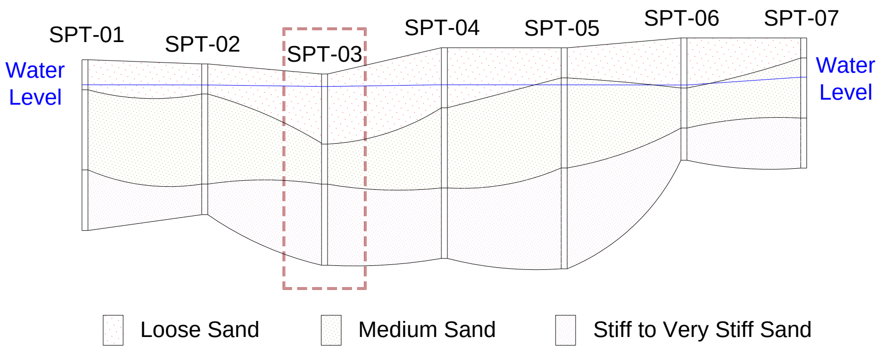

Fig. 2. Geotechnical profile of Cacimbas site.

SPT-03 was chosen for the investigations in this paper. The reason for this choice is because the water is at a more critical level, with most part of soil in a saturated condition. Figure 3 presents in more details the SPT profile with variation of number N as a function of the depth.

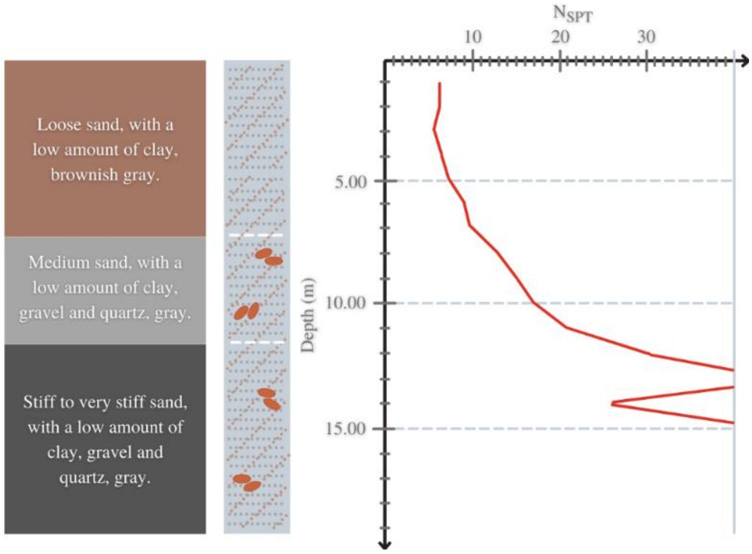

Fig. 3. Geotechnical profile of Cacimbas wind farm site.

From the presented data, analysing the variation of sand compactness, the foundation was conceptually divided into five layers of soil: (i) loose sand from 0 meter to 6 meters; (ii) one medium sand from 6m to 8m; (iii) another medium sand from 8m to 10m; (iv) another medium sand from 10m to 12m; and (v) a stiff to very stiff sand from 12m to 80m. The 80m depth is related to the boundary condition of the model and the intermediate layers, composed of medium sand, were divided to predict the variable parameters (ϕ', E) with greater precision. Based on those layers, the geotechnical parameters fixed (γ, γsat, c', Ψ and ν) were obtained with typical values from the literature for similar materials, as presented in Table 1.

Table 1. Soils parameters estimated from SPT-03 of the Cacimbas wind farm.

Parameter	Layer 1	Layer 2, 3 and 4	Layer 5	References
Moist unit weight of soil – γ	18 kN/m^3	19 kN/m^3	20 kN/m^3	Godoy (1972)
Saturated unit weight of soil – γ_{sat}	19 kN/m^3	20 kN/m^3	21 kN/m^3	Godoy (1972)
Cohesion – c'	10 kPa	10 kPa	10 kPa	Moura *et al* (2014)
Dilatancy angle – Ψ	0°	5°	10°	Pinto (2006), Moura *et al* (2014)
Poisson's ratio – ν	0.3	0.3	0.3	-

Based on the presented data, the parameters ϕ' and E were estimated using different correlations from field SPT measurements available in the literature. To determine ϕ', the correlations used were: Kulhawy & Mayne (1990) – Propositions 1 and 2, Wolff (1989), De Mello (1971), Godoy (1983), Teixeira (1996), Meyerhof (1959) – Yoshida (1988), Muromachi (1974), Hatanaka & Uchida (1996). To determine E, the correlations used werere: Mikhejev (1961), Bowles (1996) – Propositions 1 and 2, De

Mello (1971), Décourt et al (1989), Teixeira & Godoy (1996), Trofimenkov (1974), De Freitas et al (2012), Makwana & Gandhi (2019) and Afonso (2016). The expressions are given in Tables 2 (for friction angle) and 3 (for Young's modulus).

Table 2. Correlation methods considered for friction angle estimation.

Expression	References
$\phi' = [15.4\ .\ (N_1)_{60}]^{0.5} + 20$	Hatanaka & Uchida (1996)
$\phi' = 28 + 3.75\ .\ \sigma'^{-0.012}_{v}\ .\ N^{0.46}_{60}$	Meyerhof (1959) – Yoshida (1988)
$\phi' = 27.1 + 0.3\ .\ (N_1)_{60} - 0.00054\ .\ {(N_1)_{60}}^{2}$	Wolff (1989)
$\phi' = \sqrt{20.N} + 15$	Teixeira (1996)
$\phi' = 20 + 3.5\ .\sqrt{N}$	Muromachi (1974)
$\phi' = 54 - 27.6034\ .\exp\exp\ (-0.014\ .\ (N_1)_{60})$	Kulhawy & Mayne (1990) Proposition 1
$\phi' = \mathrm{tag}^{-1}\left(\frac{N}{12.2 + 0.2\ .\ \sigma'_v}\right)^{0.34}$	Kulhawy & Mayne (1990) Proposition 2
$\phi' = 28° + 0.2\ .\ N$	Godoy (1983)
$\phi' = \mathrm{acrtg}\left(\frac{0.712}{1.49 - \sqrt{\frac{N}{0.28\ .\ \sigma_v' + 27}}}\right)$	De Mello (1971)

Table 3. Correlation methods considered for Young's modulus estimation.

Expression	References
$E = (15000 \text{ to } 22000)\ .\ln N_{55}$	Mikhejev (1961)
$E = (2600 \text{ to } 2900)\ .\ N_{55}$	Bowles (1996) – Proposition 1
$E = 6000\ .\ N_{55}$	Bowles (1996) – Proposition 2
$E = 3.(N - 3)$	De Mello (1971)
$E = 3.5\ .\ N_{60}$	Décourt et al (1989)
$E = \alpha.K.N$	Teixeira & Godoy (1996)
$E = 43.1\ .\ (\log\ N_{60})$	Trofimenkov (1974)
$E = 8000\ .\ N^{0.8}_{60}$	De Freitas et al (2012)
$E = 0.3925\ .\ N_{60} + 54.25$	Makwana & Gandhi (2019)
$E = 2.9\ .\ N + 2.7$	Afonso (2016)

3 Results and Discussions

3.1 Parametric Study and Numerical Modelling Conditions

The trends of the estimation results for ϕ' are presented in Figure 4. They consider the correlations from Table 2 and the SPT results from Figure 3.

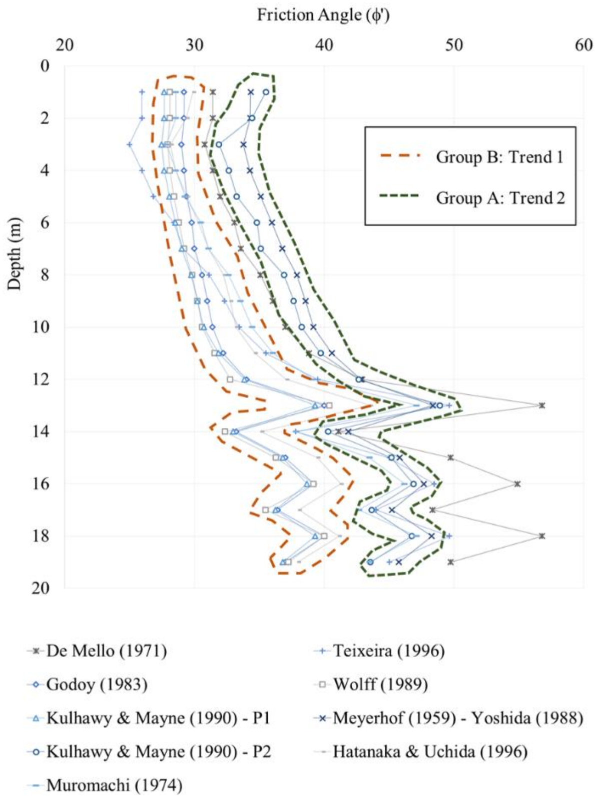

Fig. 4. Groups of behaviour trend for friction angle as a function of the depth.

Based on the behaviour presented by the chosen correlations, it is noted that there are two defined trends formed. The trend 1, by Kulhawy & Mayne (1990) – P1, Wolff (1989) and Godoy (1983), and the trend 2 by Meyerhof (1959) – Yoshida (1988) and Kulhawy & Mayne (1990) – P2. The other methods do not show representative behaviour, compared to the methods cited and considering the soil type. In this case, the soil is a sand and based on literature, the friction angle should have values around 28°-35°, as shown by Pinto (2006), Cintra et al (2011) and others authors in literature, proving that De Mello (1971) and Teixeira (1996) were not representative of the range of common values. The Muromachi (1974) and Hatanaka & Uchida (1996) were excluded because they did not exhibit similar behaviour to any of the groups.

Group A was chosen as reference, because based on local experience and observations by Gonin et al (1992), this trend is more adequate for sand in the relative density observed in the SPT test. Group B was chosen to model the situation varying the input parameters, but, in general, for local experience, these values have a low order of magnitude.

The trends of the estimation results for E are presented in Figure 5. They consider the correlations from Table 3 and the SPT results from Figure 3.

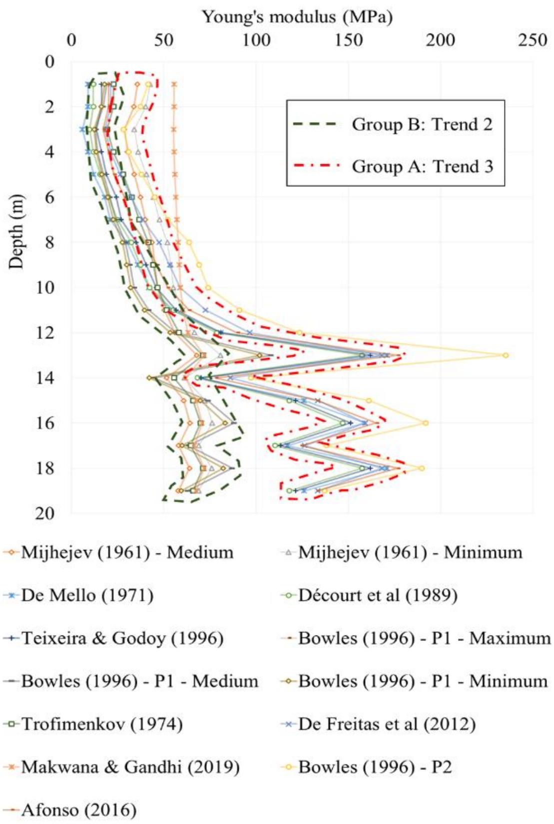

Fig. 5. Groups of behaviour trend for Young's modulus as a function of the depth.

Based on the behaviour presented by the correlations, it is noted that there are three defined trends formed. Group A comprises De Mello (1971), Décourt et al (1989), Teixeira & Godoy (1996), De Freitas et al (2012) and Afonso (2016). This group is formed by methods developed by Brazilian authors and represents the highest values found. Based on this and considering the local experience and results shown by Correia (2004), this group was utilized as reference.

Group B was formed by the behaviour trend of Mikhejev (1961) with minimum ($E = 15000.\ln N_{55}$, cf. Table 3) and medium ($E = 22000\,.\ln N_{55}$, cf. Table 3) considerations, Bowles (1996) – Proposition 1 with minimum ($E = 2600\,.N_{55}$ cf. Table 3) and medium ($E = 2750\,.N_{55}$, cf. Table 3) values and Trofimenkov (1974). The variation of relative density is not significative (Correia,2004) and based on this information, the Group B was considered for varying the input parameters in the FEM modelling.

For the numerical analyses, when it comes to the soil, the SPT-03 was considered to determine parameters and layers of soil. In the model generated, five layers were utilized within the considered depth of 80m., Basic geotechnical parameters were based on Table 1, and soil constitutive behaviour analysed according to Mohr-Coulomb theory and input parameters based on the groups evaluated in Figures 4 and 5.

The finite element mesh was created in a parallelepiped format with 160 m x 160 m x 80m. In the lateral boundaries, only horizontal displacements were fixed at zero. In the bottom boundary all the displacements were zero (Figure 6a). The mesh of Finite Element Method (FEM) comprises 10-node tetrahedral elements (Figure 6b). A mesh sensitivity analysis was performed considering default software meshing “very coarse”, “coarse”, “fine” and “very fine” compared to “medium”. Based on obtained results, it was chosen to use the medium mesh, given that the variation is not significant and this mesh adequately represents the situation in the numerical model.

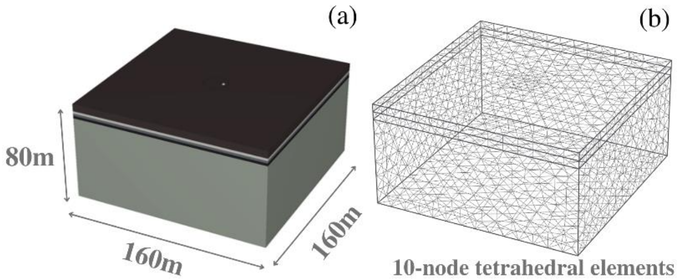

Fig. 6. Geometries of the considered numerical model of the foundation soil for (a) the soil layers-limit and (b) the finite elements mesh format. Boundary conditions consider zero-horizontal displacement on the sides and fixed condition at the bottom.

With respect to geometry and parameters of the foundation concrete structure, it is used the data provided by Imanzadeh et al (2021) that considers a reinforced concrete with elastic behaviour; thus, the parameters were 25 kN/m^3 for unit weight, 30 GPa for Young’s modulus and 0.2 for Poisson’s ratio. The characteristics of the foundation was a superficial structure, circular with 19.8m of diameter and 4.2m of depth in which is a rigid plate element on PLAXIS 3D (Figure 7).

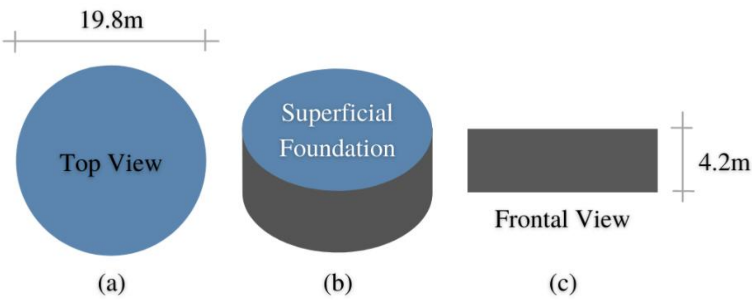

Fig. 7. Geometry of foundation: (a) top view; (b) perspective view and (c) frontal view.

The considerations related to the load take in to account a concentrated force resultant of the structure weight (vertical) and wind force (horizontal) eccentric with equivalent distance to the ratio of moment (M) to vertical force (W). This study only considers static loading, so that the dynamic effects needed to be accounted through reserve factors in the prediction of moment and wind force. The values adopted in this paper were based on data from Imanzadeh et al (2021), with the moment (M) being equal to 109.6 MN.m, structure weight (W) equal to 17.3 MN and the wind force (Fwind) equal to 1.37 MN. The resultant load is applied in the top of foundation, disregarding the superstructure effects.

3.2 Displacements Under Foundation

The displacements under the foundation (cf. Figure 8) were obtained considering the variation of input parameters (ϕ', E) per group (calculated from some of the correlations in Table 2 and 3, as explained in Section 3.1). To analyse the displacements, the -4.50m of depth was fixed to evaluate the behaviour on horizontal position. To evaluate the behaviour as a function of the depth, four points were considered, as indicated in the Figure 8. The points 1 and 4 indicates the end of the foundation, point 2 is the middle and the point 3 is where the load is applied.

To analyse the influence of the input parameter variation, it was considered four different groups: AA, AB, BA, BB The group AA is the group of reference, with the most adjusted results for ϕ' and E. The group AB varies the friction angle and BA varies the Young's modulus. Lastly, the group BB varies both parameters. Figure 8 shows the behaviour as a function of the depth.

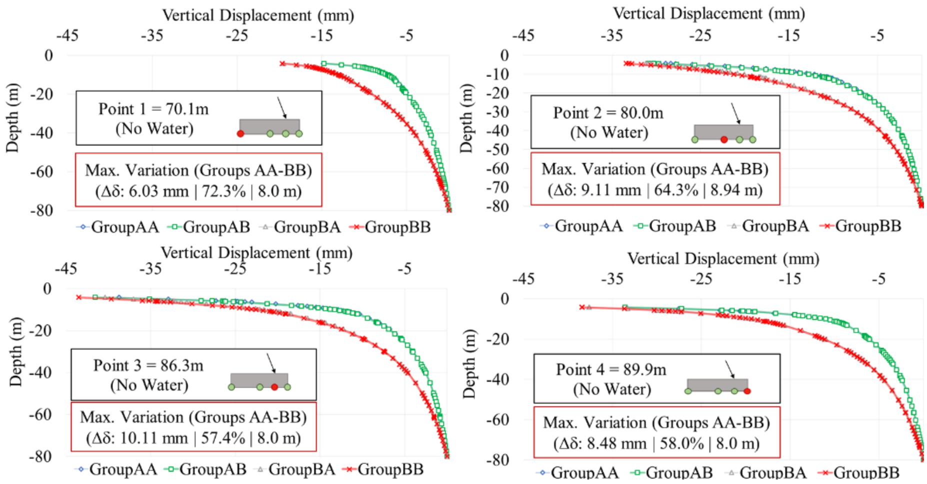

Fig. 8. Effect of input parameters variation in the displacement per point: (a) Point 1; (b) Point 2; (c) Point 3 and (d) Point 4.

As seen in Figure 8, the variation of ϕ' (group AB compared with group AA and group BA compared with group BB) do not generate a significant difference in the curves. The variation of E (group BA and group BB compared with group AA and group AB) generates a significant difference in the curves. Analysing the behaviour of vertical displacements, it is possible to see the highest values for point 3, followed by Points 4, 2 and 1. It happens because the load is applied in Point 3 and this affects the region of Points 4 and 2 after point 3. The Point 1 is the least affected because it is on the opposite side of the load application. The maximum variation of vertical displacements occurred at 8.00m of depth, except to Point 2 (8.94m of depth). The values vary from 6.03mm to 10.11mm when the Mohr-Coulomb Theory (LAMBE & WHITMAN, 1991) was utilized to predict foundation behaviour using PLAXIS 3D.

Observing the behaviour of the defined groups, two trends are evident, one for groups AA and AB and other for groups BA and BB. This means that the variation of friction angle does not affect the results while the Young's modulus causes a variation in the results.

The fact that the friction angle does not generate any significant variation in the results is associated with the fact that most of the analysed model behaved in elastic conditions, so that this parameter did not affect the generated displacements. For the same reason, the Young's modulus affects the results because this modulus exactly represents the change in soil elasticity.

In order to design the structure accurately and in favour of safety, it is necessary that a more complete geotechnical investigation campaign is carried out, so that these parameters can be obtained from laboratory tests and not by correlations. Errors can be on the order of 72%. In the case where only the SPT test is performed, the professional's local experience and specific methods for the region provide a direction, but they may not be enough to confirm the generated predictions, which highlights the importance of carrying out geotechnical tests.

4 Conclusions

This paper showed the importance of evaluating the input parameters for displacements results in wind farm foundations. To understand this, the SPT was utilized to provide friction angle and Young's modulus estimations through correlations methods with N_{SPT} number. The variation obtained by each correlation method reinforces the importance to use methods within the limitations in which it was developed, as a place of estimation and types of soils, as well as considering the local experience. Professional experience and literature records can guide estimates based on other case studies, but do not guarantee adequate accuracy.

The effect of the input parameters variation was evaluated, observing a discrepancy in the results for the Young's modulus variation, while there is no significant variation for the change in the friction angle. Errors in the estimation of E may cause prediction errors of the displacements and stresses of the order of 72%. The variation that occurred for E and not for ϕ' is expected due to the elastic condition of the soil in proper foundation designs. This fact demonstrates the importance of carrying out tests to obtain the parameters, mainly E, so that the input parameters have good accuracy and consequently give representative outputs.

The paper demonstrated that there is significant variation in geotechnical analysis that can occur with the use of different input correlations in geotechnical studies. These uncertainties lead either to overestimate or to underestimate the foundation design, and may affect economy and safety, thus emphasizing the need for more accurate field tests, to reduce them as much as possible.

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