

ORIGINAL ARTICLE

Assessment of Brazilian onshore wind turbines foundations

Avaliação de fundações de turbinas eólicas terrestres brasileiras

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Abstract: Onshore wind turbine foundations are subjected to large overturning moments. The wind action imposes cyclic and dynamic loading conditions which occur in extreme and service scenarios. Deep foundations, when used, transfer this large overturning moment through a pile group which combines the axial and lateral resistance of all piles. The paper explored the key aspects of onshore wind turbine foundations in Brazil. The main reason to explore this subject is that several authors consider onshore wind turbine foundations a well-understood topic; however, limited data from actual situations have been published, especially in developing countries where wind energy projects have only recently started. Thus, a survey of Brazilian energy companies and foundation designers was conducted, and the first Brazilian database of wind turbine foundations was created. This database contains data from more than three thousand Brazilian wind turbine foundations. The key aspects, types and dimensions of these foundations were summarized. Worldwide, concrete gravity foundations are the most used foundation type for onshore wind turbines. In Brazil, 43.3% of wind turbines have shallow foundations, essentially concrete gravity, and 56.7% have deep foundations, mostly continuous flight auger piles. This first stage of the research identified that Brazilian wind turbine foundations are significantly different from the ones of other countries. Approximately 70% of Brazilian wind turbine deep foundations used continuous concrete flight auger piles, most of them embedded in sandy soils. Concrete and steel are the main materials used in wind turbine structures.

Keywords: onshore wind turbine, wind turbine foundation, wind turbine structures, concrete in wind turbine structures, Brazilian wind turbine foundation database.

Resumo: As fundações das turbinas eólicas terrestres estão sujeitas a grandes momentos de tombamento. A ação do vento impõe condições de carregamento cíclicas e dinâmicas que ocorrem em cenários extremos e de serviço. As fundações profundas, quando utilizadas, transferem estes momentos de tombamento através de um grupo de estacas que combina a resistência axial e lateral de todas as estacas. O artigo explora os principais aspectos da fundação de turbinas eólicas terrestres no Brasil. A principal razão para estudar este assunto é de que vários autores consideram as fundações de turbinas eólicas terrestre um tópico bem compreendido, entretanto, apenas dados limitados foram publicados de casos reais, especialmente em países em desenvolvimento, onde projetos de energia eólica foram iniciados só recentemente. Assim, foi realizada uma pesquisa com empresas brasileiras de energia e projetistas de fundações para criar a primeira base de dados brasileira de fundações de turbinas eólicas. Esse banco de dados contém informações de mais de três mil turbinas eólicas brasileiras. Os principais aspectos, tipos e dimensões dessas fundações foram resumidos. Em todo o mundo, as fundações de concreto por gravidade são o tipo de fundação mais usado para turbinas eólicas terrestres. No Brasil, 43,3% das turbinas eólicas tem fundações rasas, essencialmente de gravidade de concreto, e 56,7% são de fundações profundas, principalmente estacas hélice contínuas. Essa primeira etapa da pesquisa identificou que as fundações de turbinas eólicas brasileiras são significativamente diferentes de outros países. Aproximadamente 70% das fundações profundas de turbinas eólicas brasileiras usam estacas de concreto tipo hélice contínua, a maioria delas embutidas em solos arenosos. O concreto e aço são os principais materiais usados nas estruturas de turbinas eólicas.

Palavras-chave: turbinas eólicas, fundações de turbinas eólicas, estruturas de turbinas eólicas, concreto em estruturas de turbinas eólicas, banco de dados de fundações de torres eólicas brasileiras.

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Conflict of interest: Nothing to declare.

Data Availability: Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data are not available.



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1 INTRODUCTION

In the last decade, the world's wind energy installed capacity has significantly grown up, reaching 539.6 GW by the end of 2017 [1]. Most of this installed capacity is in China (34.9%), USA (16.5%) and Germany (10.4%) [1], [2]. Currently, wind energy corresponds to approximately 4.6% of the total electricity generated worldwide [3], [4]. Brazil occupies the eighth position in the world ranking of installed capacity with 12.76 GW, leading Latin America [1].

In Brazil, hydropower is the leading source for electricity generation, supplying over 65% of the electricity [5]. However, expanding the immense hydropower installed capacity is currently an obstacle. Therefore, due to the great wind potential, wind energy installed capacity has recently advanced to assure electricity energy diversification, safety and expansion. In 2012, Brazil had only 2.5 GW of wind energy installed capacity. In 2016, Brazil increased its wind power capacity by 23.1% due to the installation of 2.0 GW new wind farms. Brazil's wind energy installed capacity already comprises 7.1% of 151 GW total Brazilian installed capacity [6]. It is important to emphasize the role of the Brazilian Government to expand wind energy generation through policy incentives. Alternative Sources Incentive Program (PROINFA) conducted Feed-In Tariffs (FIT) policies, and later, long-term auctions supported by National Development Bank (BNDES) credit lines [7], [8]. It's forecasted that Brazil will have a wind energy installed capacity of 16.4 GW by 2020. Up to 2018, no wind turbine was installed offshore in Brazil.

Wind farms consist of an ensemble of wind turbines. The main components of these wind turbines are the foundation, grid connection cables, tower, nacelle, generator, and rotor blades. Foundation is a crucial component which transfers permanent and variable loads from the structure to the ground throughout wind turbine's lifespan. As a result of structure height and slenderness, wind turbine foundations are subjected to large overturning moments due to the presence of considerable horizontal loads, primarily caused by wind [9]. The wind imposes a cyclic and dynamic loading condition which occurs in extreme and service scenarios. The progressive increase in the turbine size, tower height, and rotor diameter, implied in significant increase in the overturning moment at the foundation, which can raise the tower and foundation costs [2]. Although the foundations are a key component of a wind turbine, wind farm locations are mostly based on energy assessments and, as a result, it is common that the construction sites are geotechnical unfavorable [10]. Horgan [11] identified five influential foundation design variables, which include surface roughness, soil type, construction materials, generating capacity and tower height. According to Hassanzadeh [12], the type and the size of a wind turbine foundation are chosen according to the geotechnical conditions of the site, rated power of the wind turbine, and the type of the tower.

Currently, offshore wind turbine foundations are an area of intense research [13]–[15]. Several authors described onshore wind turbine foundations as a well-understood area [11], [16]. However, limited data on onshore wind turbine foundations actual situations have been published, especially in underdevelopment countries which wind energy projects have recently started. Additionally, several studies conducted onshore wind turbine foundations analyses and comparisons based on ordinary assumptions about actual foundations [11], [17]. Several life-cycle assessments were conducted based on limited wind turbines foundation samples [18]–[20].

As onshore wind turbines foundations were seldom explored, this research investigated the status of onshore wind turbine foundations in Brazil and compares it with the current worldwide status. The main aspects concerned were technology status of wind turbines, including rated power, rotor diameter, hub height and tower type; foundation loading, and characteristics of the foundations, such as types, dimensions, and geotechnical aspects.

2 MATERIALS

The Brazilian Association of Wind Energy (ABEE) provided a database with Brazilian wind farms statistics, which included wind turbines rated power, rotor diameter, and tower height, of almost all wind turbines located in Brazil. A survey with Brazilian energy companies and foundation designers was conducted, and the first Brazilian database of wind turbine foundations was created. Many of the largest Brazilian wind energy companies provided useful data between 2017 and 2019. The names of companies and wind farms have been anonymized due to our confidentiality agreement. The database has data from 24 different wind energy companies, totaling 284 wind farms, 3,031 wind turbines and 6,798 MW of installed capacity, which represents approximately 52% of the Brazilian total installed capacity. The commercial operation years of these wind projects started mainly from 2012 to 2019, except for one wind project from 2008 and another two from 2006. The wind farms were mainly from the following states: Bahia, Rio Grande do Sul, Piauí, Rio Grande do Norte, Ceará and Pernambuco. These states are mainly located by the northeast and south coast of Brazil, which have strong and constant wind conditions. Additionally, these Brazilian states have the largest wind energy installed capacity among the twelve Brazilian states with wind farms (Figure 1).

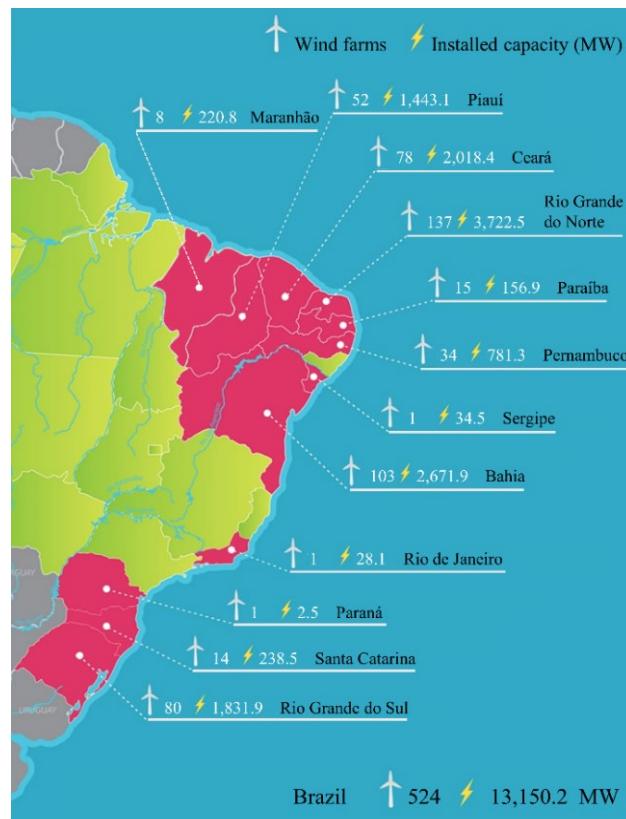


Figure 1. Brazilian map of wind energy installed capacity by state in April 2018. Artwork source: Chaussé [21]. New data source: Brazilian Association of Wind Energy [22].

This database was created mainly based on the foundation design report and geotechnical investigation report. Wind turbines geotechnical investigations were mostly based on Standard Penetration Tests (SPT), which were performed once per wind turbine foundation, and when necessary combined with Rock Core Drilling tests. Occasionally, the geotechnical survey included laboratory tests and geophysical methods. More advanced in situ investigations, such as cone penetration test (CPT), pressuremeter test (PMT) and flat dilatometer test (DMT), were not conducted, at least for the data acquired. When deep foundations were used, dynamic or static pile load tests were usually performed on one pile per foundation and according to the Brazilian standards. Additionally, the survey acquired data of wind projects with different levels of information. Therefore, the analysis used different amounts of data, i.e., distinct number of wind turbines, which will be constantly specified.

3 TECHNOLOGY STATUS

To evaluate the technology status of wind turbines in Brazil, it was necessary to acquire data of wind turbines rated power, rotor diameter, and tower height. The Brazilian Association of Wind Energy provided a database with those information of almost all wind turbines located in Brazil. This subsection presents the results of this database which was provided by the end of 2017 first semester. Five wind farms statuses were considered: in operation; ready to operate; in trials; under construction; and engaged. It was verified that there were 5,054 wind turbines in operation in Brazil by the end of 2017 first semester, and 271 wind turbines already in trials or ready to operate. It is expected that these numbers will increase due to the installation of 1,006 wind turbines under construction and 1,654 wind turbines already engaged, which should be operating until 2020.

Figure 2a-c shows the wind turbine's rated power, rotor diameter, and hub height according to the year of installation for five wind farms status. Usually, wind farms had several wind turbines with the same rated power, rotor diameter or hub height values. A few remarkable dates were emphasized due the importance:

- April 2002 Alternative Sources Incentive Program (PROINFA) started to assure electricity energy diversification and expansion;

- January 2007 Governmental Acceleration Program (PAC) started to boost infrastructure; and,
- December 2009 occurred the first exclusively wind energy auction [23]. It was verified that wind turbines rated power mostly ranged from 1,5 MW to 3,0 MW, while the average rated power for wind turbines in operation, trials, and ready to operate was around 2,0 MW (Figure 2a).

Since 2009, “wind energy auditions included a stipulation prohibiting to import wind turbines with a nominal capacity below 1,5 MW” [17]. The rated power annual average and annual cumulative average have been constantly increasing. The wind turbines under construction or already engaged, for example, had an increase of rated power, with an average value of 2.3 MW (Figure 2a). However, since 2014, it was noticed a constant maximum rated power value of 3.0 MW and was observed an increase in the minimum value of wind turbine rated power (Figure 2a). The wind turbines rotor diameter mostly ranged from 80 to 125 meters (Figure 2b). The wind turbines in operation, trials and ready to operate, the average rotor diameter was 96 meters.

The rotor diameter annual average and annual cumulative average have been constantly increasing as well. The wind turbines under construction or already engaged, for example, had an increase of rotor diameter, with an average value of 112 meters. However, since 2014, it was noticed a constant maximum rotor diameter value of 125 meters, and it was observed an increase in the minimum value of wind turbine rotor diameter (Figure 2b).

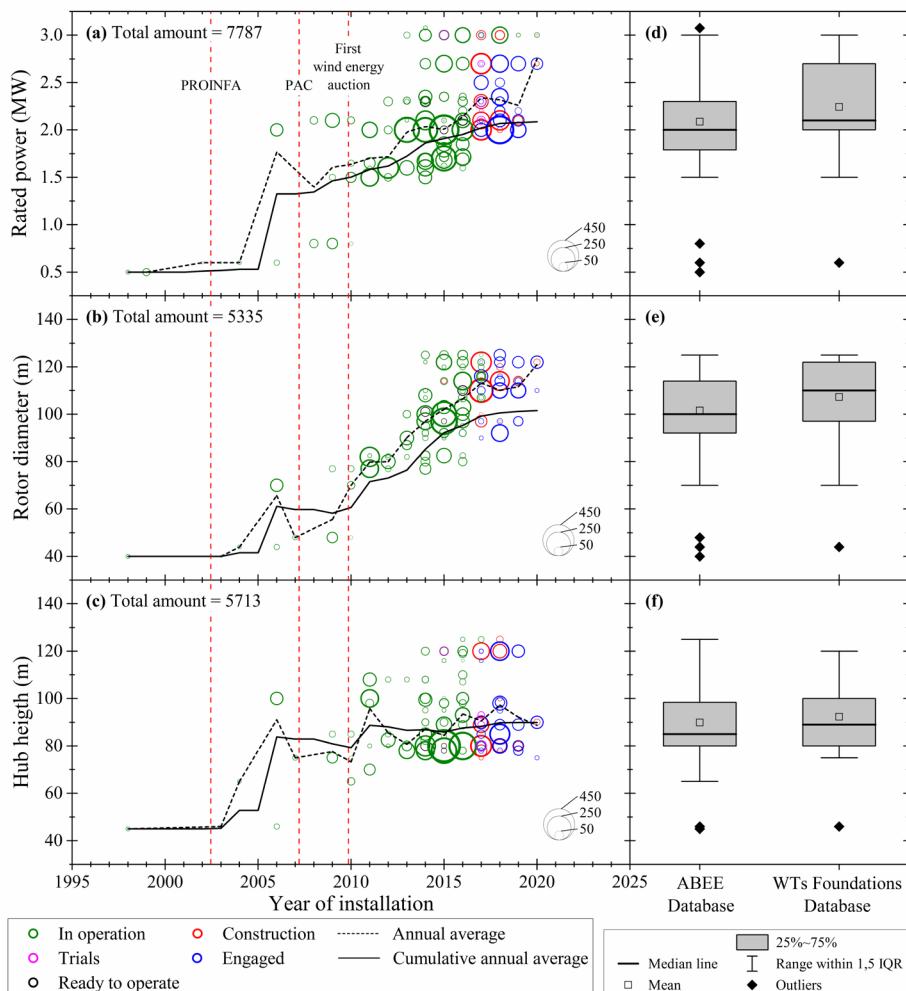


Figure 2. Bubble charts of wind turbines (a) rated power, (b) rotor diameter, and (c) hub height according to the year of installation for five wind farm status. The size of each circle indicates the amount of wind turbines data. Additionally, box plots for ABEE database and wind turbines foundations database of: (d) rated power, (e) rotor diameter, and (f) hub height.

The wind turbines hub height mostly ranged from 80 to 125 meters as well (Figure 2c). For example, for the wind turbines in operation, trials, and ready to operate, the average hub height was 88 meters. However, the hub height annual cumulative average was held almost constant since 2011, despite the annual average fluctuation. Additionally, the wind turbines hub height range was held almost constant between 80 and 125 meters (Figure 2c). The average international values of rated power, rotor diameter, and hub height were like those observed in Figure 2a-c. Similarly, an increase was verified in the average rated power and rotor diameter in recent years, while the average hub height was held almost constant.

Figure 2d-f compare the results for the ABEE database, i.e., Figure 2a-c data, and the wind turbines foundations database of the rated power, rotor diameter and hub height. Wind turbines foundations database exhibited: median rated power of 2.1 MW, with 50% of the values between 2.0 and 2.7 MW; median rotor diameter of 110 meters, with 50% of the values between 97 and 122 meters; and median hub height of 89 meters, with 50% of the values between 80 and 100 meters. In general, wind turbines foundations database had slightly superior statistical distributions compared to the ABEE database. This result was expected since the wind turbines foundations database mainly contains data from 2012 to 2018, explaining the higher values observed compared with ABEE database, especially regarding wind turbines rated power and rotor diameter.

Figure 3 shows the correlation between the wind turbine's rotor diameter and rated power. Wind turbines under construction and engaged had a superior average value of rotor diameter and rated power than wind turbines in operation. An upward relationship between rotor diameter and rated power was verified. However, no relationship between hub height and rated power, R-squared of 0.237, and hub height and rotor diameter, R-squared of 0.148, was verified.

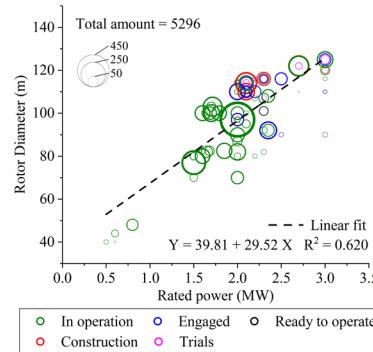


Figure 3. Correlation between wind turbines rotor diameter and rated power for five wind farm status. The size of each circle indicates the amount of wind turbines data. Based on: Brazilian Association of Wind Energy database [6].

According to the wind turbine foundation database, approximately 73.6% of the wind towers of the sample were made of steel, while 26.4% were made of concrete (Figure 4a). No hybrid steel-concrete towers were identified in the sample. The difference between steel and concrete towers was analyzed regarding wind turbines rated power, rotor diameter, and rotor diameter (Figure 4b). It was noticed that concrete towers were used when the hub height exceed 100 meters. Figure 4b shows that steel and concrete towers exhibited the same range of rated power and rotor diameter.

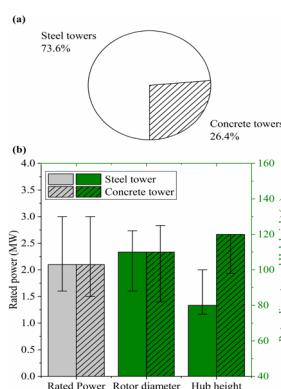


Figure 4. Wind turbine towers: (a) types of wind towers in Brazil for 2537 wind turbines of the sample; (b) minimum, median and maximum values of rated power, rotor diameter, and hub height for 1866 steel and 672 concrete towers of the sample.

4 FOUNDATION LOADING

Wind turbine foundations must resist to large overturning moments, which are directly influenced by the wind action depending on each site. The wind turbines are usually classified in three main classes according to the wind speed and turbulence parameters. Class I wind turbines are designed to withstand 10 minutes of 50 m/s extreme reference wind speed with a 50-years recurrence period at hub height. For Class II and Class III wind turbines, the extreme reference wind speed values are 42.5 m/s and 37.5 m/s, respectively. Therefore, the wind turbine class directly influences the overturning moment at the base.

Additionally, the wind turbine rated power, rotor diameter, hub height and tower type, such as steel and concrete towers, may influence the magnitude of the foundation loading; and thus, the foundation design. The effects of the rated power, rotor diameter, hub height and tower type on the overturning moment at the base were analyzed (Figure 5). Foundation loads were obtained from the wind turbine manufacturer technical report, which considered several scenarios and load combinations. Therefore, Brazilian design load cases consider the same requirements than worldwide. In turn, Brazil has minor earthquakes and blizzards issues.

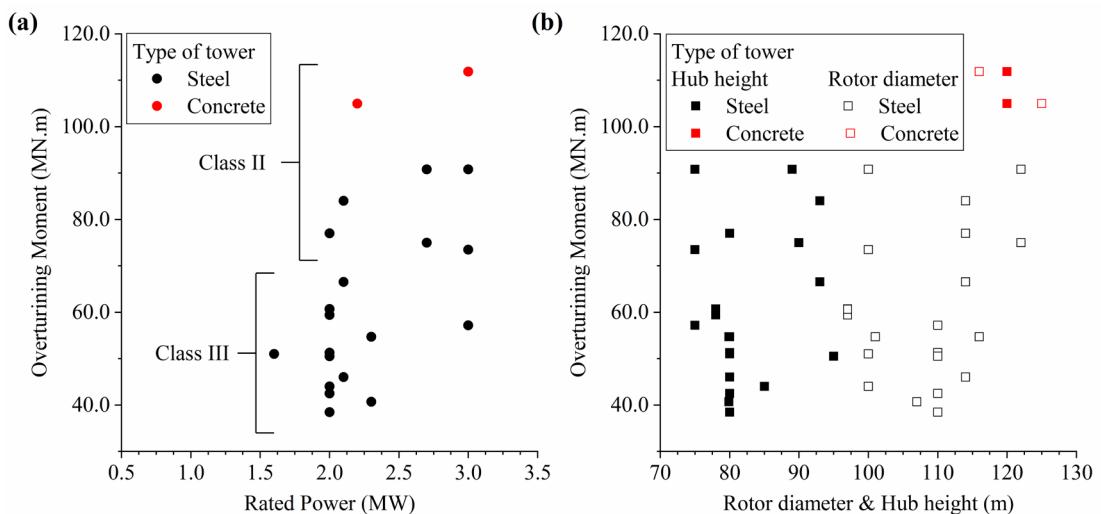


Figure 5. The effects of (a) rated power, (b) rotor diameter and hub height on the overturning moment at the base for 93 concrete and 1422 steel towers.

There is no correlation between overturning moment and rated power, rotor diameter or hub height. The overturning moment depends on the localization (or wind characteristics), structural and mechanical design of tower and turbine, and the advance of technology. However, the result of Figure 5 may indicate that it is necessary to verify the design criteria used to define the overturning moment.

Figure 5a displays the influence of the rated power for steel and concrete towers on the overturning moment at the base. A great spread of the overturning moment at the base was observed and a slight upward trend was identified. As expected, the wind turbine IEC class had more significantly influenced the overturning moment at the base. Class II wind turbines exhibited higher overturning moments at the base than Class III wind turbines. The concrete towers exhibited larger overturning moments at the base, regardless of the rated power. Figure 5b displays the effects of the rotor diameter and hub height for steel and concrete towers on the overturning moments at the base. A wide range of overturning moments at the base was observed for the range wind turbines rotor diameter, while larger overturning moments at the base were only identified for concrete towers. Additionally, a wide range of overturning moments at the base was identified for the range of wind turbines hub height of 75 to 95 meters. Concrete towers, which had higher hub height values, had exhibited larger overturning moments at the base. High hub height values led to the use of concrete towers (Figure 4b); and thus, this type of tower subjected the wind turbines foundations to larger overturning moments at the base.

5 FOUNDATIONS

The following analysis used data from the first Brazilian database of wind turbine foundations. It was observed that wind turbine foundations were composed of 43.3% of shallow foundations (SFs) and 56.7% of deep foundations (DFs). Figure 6 shows the percentages of foundation types. Clearly, concrete gravity SFs and Continuous Flight Auger Piles (CFAPs) DFs prevailed with around 40.0% each. Root piles DFs were used in 12.6% of the cases, while 7.5% of the wind turbines had other types of foundation, such as rock anchored SFs and steel driven piles DFs. These results were significantly different from the international practice, which presents a greater share of shallow foundations [24].

Wind turbines with concrete towers had exhibited larger overturning moments at the base; however, this did not influence the type of wind turbine foundation. The wind turbines with steel towers exhibited 50.9% of SFs and 49.1% of DFs, from which 70.9% were CFAP DFs. The wind turbines with concrete towers showed 49.1% of SFs and 50.9% of DFs, from which 87.6% were CFAP DFs. Although the tower type did not influence the foundation type, it clearly influenced the foundations dimensions (Table 1). The wind turbines SFs with concrete towers exhibited larger diameters and greater amount of concrete than wind turbines SFs with steel towers. The average increase of SF diameter and concrete volume were around 15% and 28%, respectively. For CFAPs DFs, the wind turbines with concrete towers exhibited higher values of pile cap diameter, pile cap concrete volume and number of piles than wind turbines with steel towers. CFAPs DFs pile cap diameter and concrete volume had an average increase of approximately 12% and 48%, respectively. In addition, CFAPs DFs with concrete towers exhibited, on average, nine piles more than the wind turbines with steel towers.

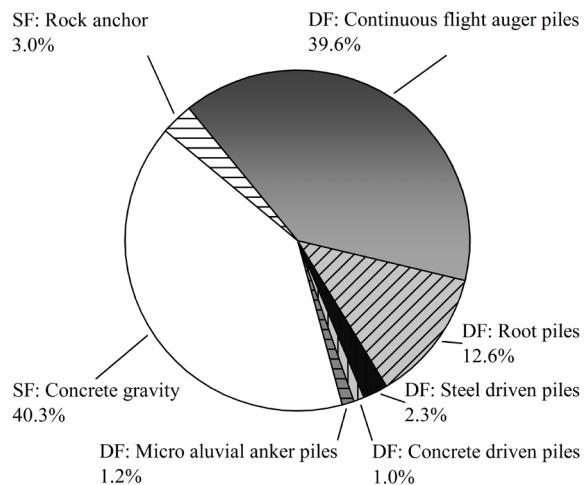


Figure 6. Types of wind turbine foundations, totaling 3,031 wind turbines.

Table 1. The effect of the tower type on the shallow and deep foundations characteristics.

Foundation	Tower type	
	Steel	Concrete
SFs	Number of data	950
	Diameter (m)	16.7 (1.4)
	Concrete volume (m ³)	321.7 (65.1)
CFAP DFs	Number of data	649
	Raft diameter (m)	15.5 (1.6)
	Raft concrete volume (m ³)	320.7 (44.2)
	Number of piles	23.3 (6.3)

Note: average and standard deviation values are presented.

5.1 Shallow foundations (SF)

As previously mentioned, SFs correspond to 43.3% of the onshore wind turbines foundations sample. However, there were different types of SFs and several soil reinforcement techniques (SRTs) that were used to improve the foundation performance. Table 2 displays the SFs types and SRTs used for 1,313 wind turbines total. The concrete

gravity SFs with no SRTs had 74.8% of the SFs sample, while concrete gravity SFs with SRTs had 10.7% of the sample. Rock anchored SFs exhibited 7.0% of the SFs sample. Additionally, it was identified that 7.5% of wind turbines SFs did not specify whether SRTs were used or not. Regarding the plan shape of SFs with or without SRTs, it was noticed that 88.4% of them had a circular plan shape, from which 5.0% were hollow inside, and 11.6% of them had a square plan shape. All the rock anchored SFs had a circular plan shape; however, 81.5% of them were hollow inside.

SRTs were used when certain subsoil layers exhibited poor geotechnical properties and geotechnical improvements were practical and economical. The main geotechnical properties improved were stiffness, shear strength and soil homogeneity. The SRTs were usually used by two approaches: all wind turbines SFs of a wind farm required SRTs; or a few wind turbines SFs of a wind farm required SRTs to replicate the same SFs in all wind turbines. The thickness and type of SRT depended on each wind turbine site condition. The SRTs used were soil-cement stabilization, crushed stone or cyclopic concrete and stabilization grouting. The soil-cement stabilization and crushed stone or cyclopic concrete techniques had a median thickness of 1.00 meter and a standard deviation of 0.75 meter, ranging from 0.25 to 3.50 meters. The jet-grouting technique usually exhibited 13 to 29 holes with 6 to 12 meters depth and 3 inches diameter.

Table 2. Types of SFs for 1,313 wind turbines of the sample.

SFs	Total number (%)
No reinforcement	982 (74.8%)
Soil reinforcement	140 (10.7%)
Soil-cement stabilization	56 (4.3%)
Crushed stone/cyclopic concrete	17 (1.3%)
Stabilization-grouting	67 (5.1%)
Rock anchored	92 (7.0%)
No available information	99 (7.5%)

SFs without SRTs included around 30% of concrete towers, while SFs with SRTs included 18.8% of the concrete tower. Rock anchored SFs included only steel towers. As previously mentioned, the type of tower influenced the SF dimension and material amount (Table 1). The average diameter of SFs was around 17.00 meters; however, the statistical distributions of SFs diameter according to the SF type were different. SFs without SRTs had a wide statistical distribution of foundation diameters, ranging from 13.50 to 20.75 meters. Rock anchored SFs exhibited a narrow statistical distribution of foundation diameter, ranging from 13.50 to 17.00 meters. The tower type and amount of data possibly influenced these extreme values observed. The average SFs height is approximately 2.60 meters, ranging mainly from 2.00 to 3.00 meters. The statistical distributions of SFs diameter were similar for different SFs types. Therefore, no significant influence of the SF type on the foundations diameter and height was identified.

The concrete volume used in SFs ranged from 210.5 m³ to 485.0 m³, with an average value around 345.0 m³. SFs with SRTs exhibited a higher statistical distribution of concrete volume than SFs without SRTs and rock anchored SFs. A wide range of steel amount was used in wind turbines SFs, ranging from 18,115 to 51,289 kg.

SFs without SRT had a median steel amount value of 28,500 kg, while SFs with SRTs and rock anchored SFs exhibited a median steel amount of 36,551 kg and 42,674 kg, respectively. In general, the lower part of the statistical distribution up to the median value were similar for rock anchored SFs and SFs with and without SRTs. The higher part of the statistical distribution could have been influenced by the sample size and tower types. SFs with SRTs and rock anchored SFs samples had only 138 and 92 wind turbines, while SFs with SRTs and rock anchored SFs samples exhibited 18.8% and 0.0% of concrete towers. Therefore, the SF type did not significantly influence foundation diameter, concrete volume, and steel amount.

Additionally, rock anchored SFs usually had 16 to 32 anchors of 4 to 9 meters depth and 6 inches diameter. All SFs were embedded in soil and exhibited a backfill to increase the overturning resistance, regardless of the SF type. The median backfill weight was 4471 kN with a standard deviation of 1614 kN and ranged from 1600 kN to 7722 kN.

The influence of the wind turbine characteristics on foundation dimension and material amount were analyzed for SFs in Figure 7. The SFs type had no significant effect as similar results were obtained when analyzing each SF type; thus, linear correlations were determined considering all SFs. A positive trend was observed of SFs diameter, concrete volume and steel amount with the wind turbine rated power, rotor diameter and hub height. However, low correlation factors were obtained, especially for the rotor diameter. The wind turbine hub height had moderate correlation factors. Overall, SFs diameter had higher correlation factors with technology status than SFs material amount. Additionally, Australian and United States wind projects exhibited similar results of concrete volume versus rated power [24].

The influence of low correlation of overturning moment that was shown in Figure 5 also define the result of the structural design as can be seen in Figure 7. It cannot identify the correlation between foundation diameter, concrete volume steel amount with rated power, rotor diameter and tower height.

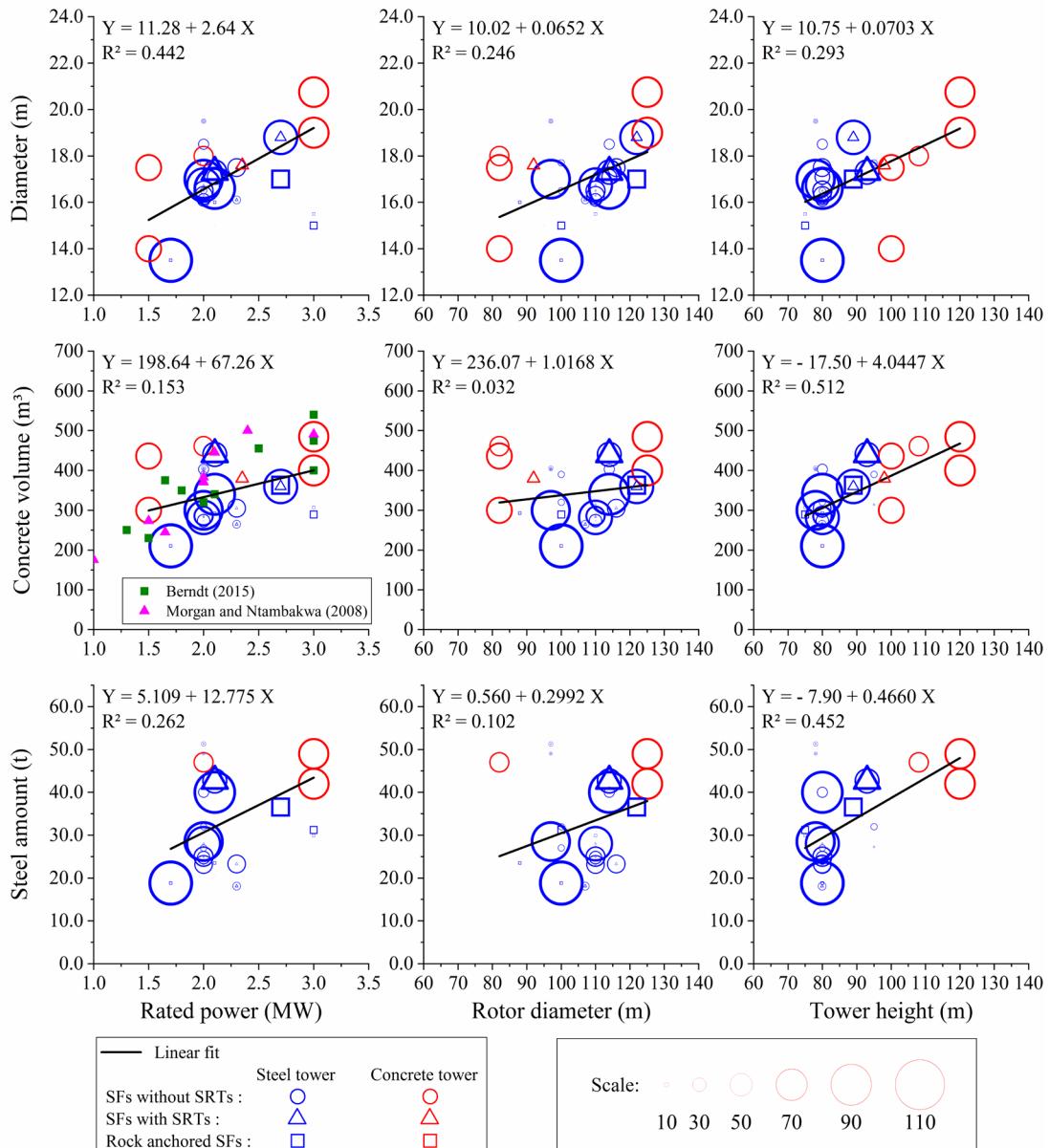


Figure 7. Effect of the wind turbine technology status on the diameter, concrete volume, and steel amount of 1,313 wind turbines SFs. The circles size indicates the amount of wind turbines.

Figure 8a shows the influence of SFs diameter on the concrete volume and steel amount. The concrete volume and steel amount increased with the SF diameter, as expected. For example, a 13 meters diameter SF would require 208 m³ of concrete and 15,114 kg of steel, while a 21 meters diameter SF would require 480 m³ of concrete and 51,450 kg of steel. Approximately, the rate of increase of concrete volume and steel amount per meter of SF diameter were 34 m³/m and 4,542 kg/m, respectively.

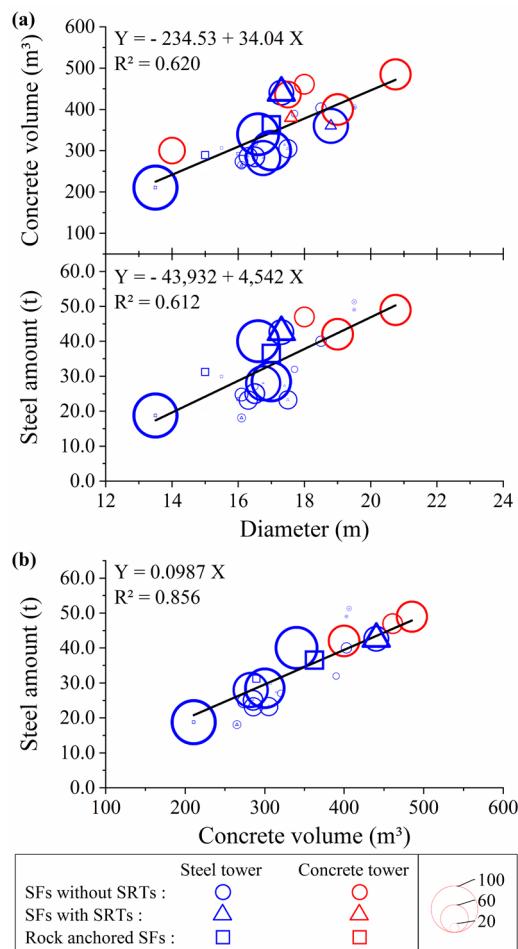


Figure 8. Influence of the SF diameter on (a) concrete volume and steel amount for 1,313 wind turbines SFs. Additionally, (b) reinforcement ratio of SFs. The circles size indicates the amount of wind turbines.

No significant influence of the SF type was noticed on SF diameter and material amount relationship. Figure 8 displays the steel amount and concrete volume relationship. It was noticed a reinforcement ratio of 98.7 kg of steel per m^3 of concrete. Additionally, concrete and steel towers had similar reinforcement ratios. For SFs with SRTs, the subground type was those that the foundation would be settled if no SRT was used. Wind turbines SFs were typically settled above soil layers (42.2%), above rock layers (36.5%) and weathered rock layers (21.3%). SFs without SRTs were predominantly settled above the soil and rock levels, with a great share of them, settled above sandy soils and sandstone. SFs with SRTs were predominantly executed to improve soil and weathered rock layers, with a great share of them conducted in sandy soils and weathered calcilutite rock.

Rock anchored SFs were predominantly settled above rock, especially migmatite and phyllite rocks, and a minor share of rock anchored SFs were settled above a thin soil layer overlaying a rock layer. In general, different types of SFs were used depending on the ground type, such as soil, weather rock and rock; in turn, in a few cases, different types of SFs were used at the same ground type.

A significant difference of the SPT impenetrable depth for SFs with or without SRTs and rock anchored SFs was identified (Figure 9). Usually, the SPT impenetrable depth is related to the presence of weathered rock or rock layers. Figure 9 shows that the wind turbine SFs without SRTs had a wide range of SPT impenetrable depth, with a median value of 3.5 meters. Wind turbine SFs with SRTs had a median SPT impenetrable depth of 5.0 meters, with 50% of them between 3.0 to 6.0 meters. In turn, rock anchored SFs were close to the ground level and had a narrow range of SPT impenetrable depth, with 75% of them lower than 3.5 meters. Additionally, 573 wind turbines SFs had data of water table level; however, 97% of them did not identify the water level.

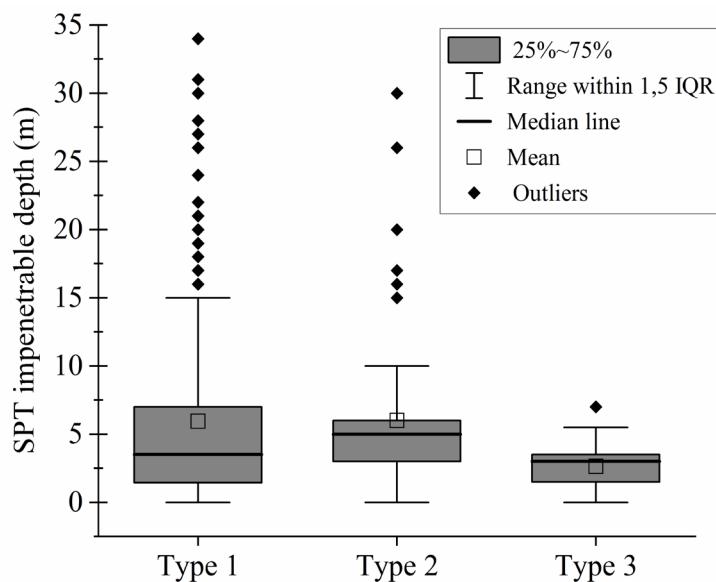


Figure 9. The SPT impenetrable depth for 464 SFs without SRTs (Type 1), 134 SFs with SRTs (Type 2) and 81 rock anchored SFs (Type 3).

The resistance and deformability of ground layer, above which SFs were settled, directly affects the foundation performance as well. The SFs were mainly designed based on Standard Penetration Tests results. The SF design used admissible stress until 350 kPa, ranging mainly from 200 to 350 kPa. Figure 10a shows a box chart of the N_{SPT} values at the base of SFs with or without SRTs. For clarity, the N_{SPT} results for the SFs with SRTs refer to the N_{SPT} values obtained before the SRT was executed. Additionally, the maximum N_{SPT} value considered was 50. For the SFs settled above soil layers, a significant difference on the N_{SPT} results was observed. The SFs without SRTs exhibited 75% of the N_{SPT} values higher than 24, with a median value of 40. In turn, SFs with SRTs exhibited 75% of the N_{SPT} values lower than 33, while the median value was 19. For the SFs settled above weathered rock layers, no significant difference of N_{SPT} results was observed. Most of the N_{SPT} values obtained were limited to 50, while lower values were statistically considered as outliers. In general, lower N_{SPT} values led to the necessity of SRTs. SFs with SRTs settled above soil layers used 60% soil-cement stabilization and 24% crushed stone or cyclopic concrete; in turn, SFs with SRTs settled above weathered rock layers used 70% stabilization grouting and 30% soil-cement stabilization.

Figure 10b shows the effect of the N_{SPT} value on the SFs diameter for different types of layers. A great amount of wind turbines exhibited the same foundation diameter and different N_{SPT} values. The same foundation is used for the several wind turbines of a wind farm; therefore, the lowest N_{SPT} value is critical for the foundation design. The SFs without SRTs diameter increased as the minimum N_{SPT} values decreased. In turn, the SFs with SRTs diameter increased as the minimum N_{SPT} values increased (Figure 10b). Wind turbines settled above clayey soils exhibited lower foundation diameter than wind turbines settled above sandy soils; however, wind turbines settled above sandy soils had a greater amount of data and, thus, a wider range of N_{SPT} values.

SFs exhibited RQD values ranging from 0 to 100%. SFs without SRTs exhibited 75% of the RQD values lower than 46% and a median RQD value of 20%. SFs with SRTs had all RQD values below 12%. Rock anchored SFs exhibited 75% of the RQD values higher than 20% and a median RQD value of 60%. A wide range of RQD values is observed as well, regardless of the SFs diameter. Rock anchored SFs had lower statistical distribution of foundation diameter than SFs without SRTs. Therefore, the SFs with or without SRTs had worse geotechnical properties than rock anchored SFs, while SFs with or without SRTs exhibited higher SFs diameter than rock anchored SFs. This outcome was expected as the use of rock anchor bolts reduced the required foundation diameter; however, in a few cases, different SFs types had the same RQD value and foundation diameter. As the rock types were similar between the SFs types, two hypotheses are possible: rock anchor bolts were needed and they were not done; or different companies, or foundation designers, use distinct foundation design approaches.

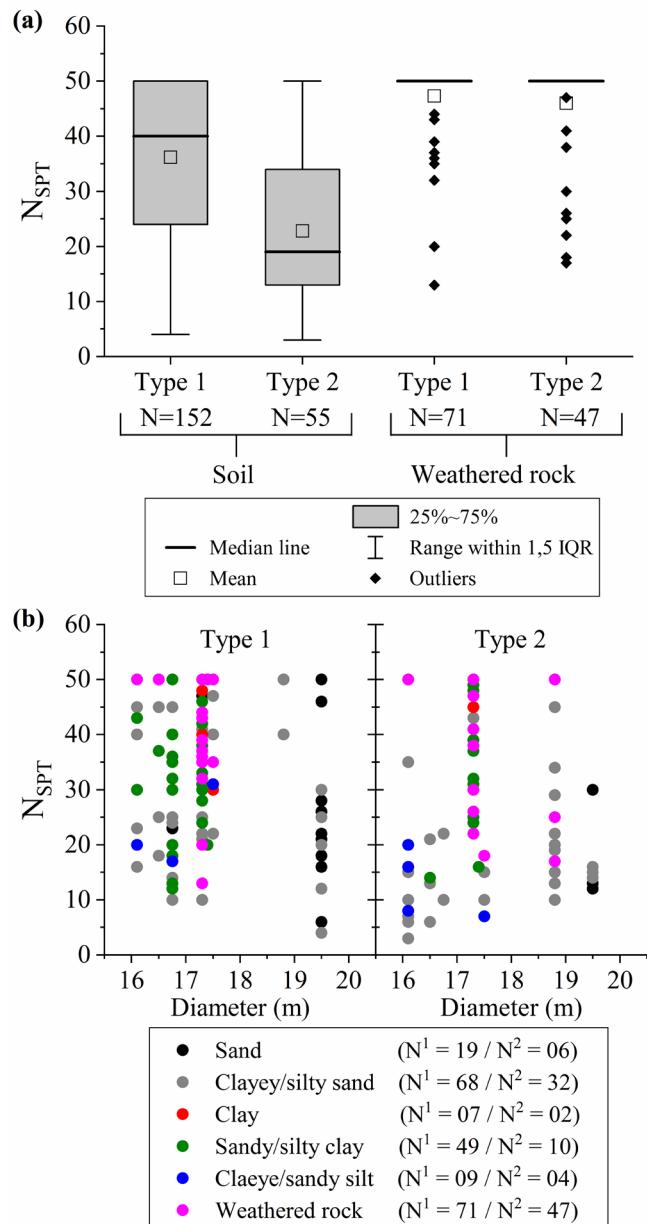


Figure 10. Wind turbine SFs settled above settled above soil and weathered rock layers: (a) N_{SPT} results for SFs with or without SRT; (b) N_{SPT} versus SFs with and without SRTs diameter for different types of ground layers.

5.2 Deep foundations

1,718 wind turbines used deep foundations, which represents 56.7% of the sample. Many types of piles were used on these deep foundations, including continuous flight auger piles, root piles, steel driven piles, concrete driven piles and micro alluvial anker piles. The next subsections will present the characteristics and geotechnical investigation data about these types of deep foundation. The CFAPs were predominant on the DFs sample (70%), followed by root piles DFs (22.2%). Steel driven piles, concrete driven piles, and Micro Alluvial Anker Piles (MAAPs) were used in 4.1, 1.7 and 2.0% of wind turbines DFs, respectively. Limited data was acquired for certain types of DFs and the following results must be cautiously analyzed.

All pile caps had a circular plan shape. However, around 30% of the pile caps were hollow inside and usually filled with backfill soil. As previously mentioned, although the tower type, concrete or steel, did not influenced the foundation type, it clearly influenced the foundation dimensions (Table 1). CFAPs DFs had a similar percentage of steel and

concrete towers to the wind turbine foundation database, which considered all wind turbines foundations (Figure 4a). Root piles DFs, concrete driven piles DFs and MAAPs DFs are present mainly steel tower, while steel driven piles are presented mainly in concrete towers.

The average pile cap diameter is 16.5 meters, ranging from 13.0 to 19.0 meters, which is like SFs. CFAP DFs exhibited similar pile cap diameter statistical distribution of SFs. In turn, root piles DFs had a lower statistical distribution of pile cap diameter than CFAP DFs and SFs. Steel driven piles DFs had the highest statistical distribution of pile cap diameter, while MAAPs DFs exhibited the lowest pile caps diameters, with a maximum diameter of 11.3 meters. In general, DFs pile cap diameters were higher for concrete towers than for steel towers. For example, root piles DFs, used mainly in steel towers, had a maximum pile cap diameter of 17.0 meters, while steel driven piles DFs, which had mainly steel towers, had a minimum pile cap diameter of 16.5 meters. CFAPs DFs, used in steel and concrete towers, had a wide range of pile cap diameters. The average pile cap height was around 2.80 meters, ranging mainly from 2.50 to 3.25 meters. No significant difference on the pile cap height between deep foundations was noticed. Additionally, SFs had similar values of pile cap height as deep foundations.

A wide range of concrete volume values were observed, ranging from 172.0 to 700.0 m³. The steel amount required for DFs also had a wide statistical distribution, ranging from 12.690 to 56.685 t. CFAPs DFs had a similar statistical distribution of concrete volume and steel amount of SFs. Root piles DFs and MAAPs DFs had the lowest statistical distribution of concrete volume and steel amount of the pile cap, while steel driven piles had the highest statistical distribution of material amount. For example, DFs that exhibited a great share in concrete towers, e.g., steel driven piles DFs and CFAPs DFs, had a superior statistical distribution of foundation diameter and, as a result, great material amount. Figure 11a shows the influence of the pile cap diameter on concrete volume and steel amount of wind turbines DFs. Great concrete volume and steel amount are required as the pile cap diameter increased. Therefore, steel driven piles DFs, which used large pile cap diameter, required great material amount, while root piles DFs and MAAPs DFs, which had low pile cap diameter, used less material amount (Figure 11a). Additionally, the material amount required for the pile caps DFs was slightly superior to those observed for SFs, while a similar trend was observed; however, it was identified a notable difference when considering the total material amount, pile cap plus pile group. For example, CFAPs DFs had median increase of 26.9% of the concrete volume when considering the pile cap and pile group, with this value ranging from 14 to 86%.

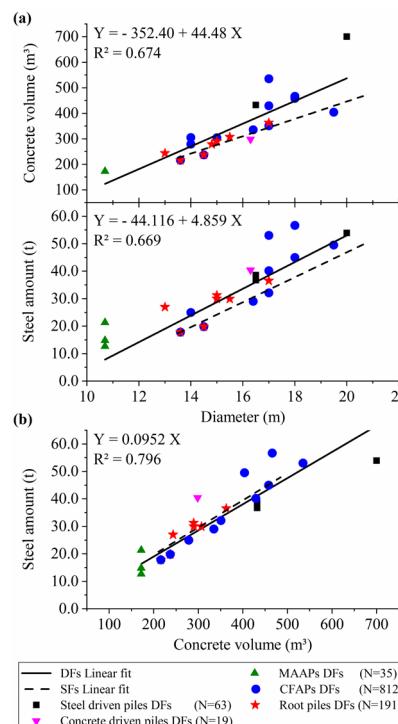


Figure 11. Influence of the pile cap diameter on (a) concrete volume and steel amount of wind turbines DFs. Additionally, (b) reinforcement ratio of DFs.

Figure 11b shows the concrete volume and steel amount relationship of the pile cap DFs. It can be noticed that as the concrete volume increased, the steel amount increased. The reinforcement ratio was like all DFs types, with an average value of 95.2 kg of steel per m^3 of concrete. This value was near the same of SFs, which had an average value of 98.6 kg of steel per m^3 of concrete. The pile cap reinforcement ratio values were around these values, with exception of steel and concrete driven piles DFs, which had inferior and superior values, respectively.

Backfill weight of DFs ranged 1,300 to 6,800 kN, which is like SFs. CFAPs DFs had a wide statistical distribution of backfill weight as great amount of data was available. MAAPs DFs, which had the lowest pile cap diameter, exhibited the lowest backfill weight among deep and shallow foundations. Root piles DFs and steel driven piles DFs exhibited a median backfill weight around 4,000 kN.

DFs used between 14 to 48 piles per foundation. CFAPs DFs and root piles DFs exhibited in average approximately 30 piles per foundation, with an average pile diameter of 60 and 40 centimeters, respectively. Steel and concrete driven piles DFs and MAAPs DFs had in average around 38 piles per foundation. Steel driven piles DFs used structural H shape piles, while concrete driven piles DFs and MAAPs DFs exhibited piles diameter of 50 and 30 centimeters, respectively. The piles of all types of foundations were vertically installed, with exception of MAAPs which were 12 degrees inclined with the vertical.

Figure 12 shows the statistical results of the pile length, pile toe depth and SPT impenetrable depth for all types of pile foundations. Different amount of data was available for piles length, piles toes depths and SPT impenetrable depths (Figure 12). The median piles lengths of DFs ranged from 11.0 to 15.0 meters. CFAPs had a medium pile length of 12.8 meters. Steel and concrete driven piles exhibited a medium pile length of 15.0 and 13.5 meters, respectively. Root piles had the lowest median pile length of 11.0 meters. MAAPs had a median pile length of 14 meters. CFAPs, MAAPs and steel and concrete driven piles exhibited similar spread of pile lengths, ranging mainly between 10.0 to 20.0 meters. Root piles, in turn, had a narrow statistical distribution, ranging mainly from 10.0 to 12.0 meters. Approximately 23 steel driven piles DFs and 11 concrete driven piles DFs had information about the difference of maximum and minimum piles length in the same foundation. The median difference of driven piles length for the same DF was around 2.5 to 3.5 meters with a standard deviation of 1.60 meters, ranging from 1.0 to 7.0 meters.

Figure 12b displays the piles toes depths of CFAPs, root piles and driven piles. In general, the piles toes depths were equal to the piles length plus 2.0 to 3.0 meters, as the pile cap bases were set 2.0 to 3.0 meters under the ground level, usually. Figure 12c shows the SPT impenetrable depths of CFAPs, root piles and driven piles. As previous mentioned, the SPT impenetrable depth is usually related to the presence of weathered rock or rock layers. The medium SPT impenetrable depth of CFAPs were 16.0 meters and ranged mostly from 8.0 to 24.0 meters. The CFAPs lengths were restricted by the SPT impenetrable depth since the piles toes depths were inferior to the SPT impenetrable depth. This result was expected since the drilling process by the continuous flight hollow stem auger is limited by high strength layers. Root piles, in turn, exhibited a medium SPT impenetrable depth of 5.0 meters, ranging mostly from 0.0 to 13.0 meters. Root piles were used when the SPT impenetrable depth was close to the ground level, which inhibited the use of CFAPs; therefore, root piles were installed through weak rock and rock layers. Steel driven piles exhibited a wide statistical distribution of SPT impenetrable depths, while concrete driven piles had a narrow statistical distribution due the amount of data (Figure 12c). Clearly, driven piles had a high SPT impenetrable depth, with a median value of approximately 35.0 meters.

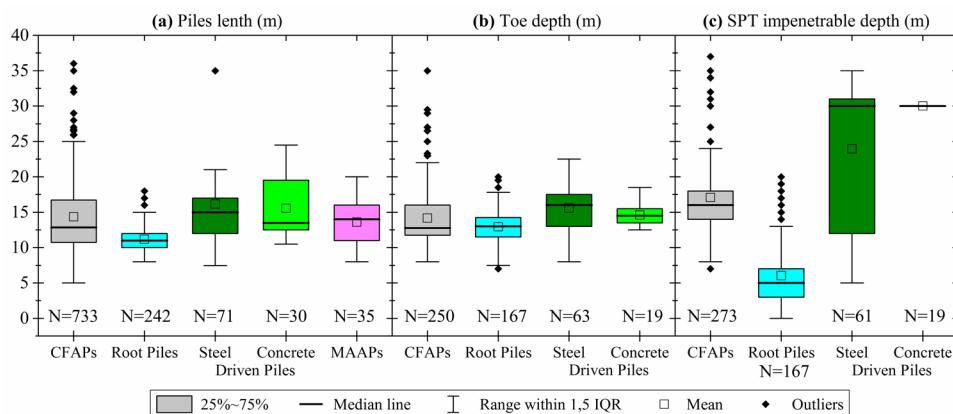


Figure 12. Statistical results of pile length, toe depth and SPT impenetrable depth for wind turbine DFs.

Figure 13 shows the percentage of soil investigations that had identified the presence of a water level. Additionally, Figure 13 displays the water level depth of wind turbines sites from which the water level was identified. In general, the presence of water level or not was similar to all wind turbines on a wind farm site.

Almost no soil investigation had identified the presence of water level for SFs and root piles DFs (Figure 13). In turn, for CFAPs DFs, approximately 68.3% of the soil investigation had identified the presence of a water level, which exhibited a median depth of 3.1 meters, with 50% of the values between 1.8 and 4.8 meters. For driven piles DFs, almost all soil investigations had identified the presence of a water level, which had a median depth of 1.25 meter. The presence and depth of water level clearly limited the pile cap base depth. CFAPs DFs had a median pile cap base depth of 2.0 meters, ranging from 1.3 meters above the ground level to 3.8 meters depth. Driven piles DFs exhibited a median pile cap base depth of 1.5 meters and ranged mostly from 1.0 meter to 2.5 meters.

The underground types were analyzed, i.e., soil, weathered rock or rock, in relation to the pile top, pile shaft and pile toe. Concerning the pile shaft, the length of subsoil layers was analyzed in relation to the pile shaft of each DFs. The database acquired geotechnical investigation data of 556 wind turbines DFs. The geotechnical investigation data was mainly composed by 307 CFAPs DFs, which represents 25.6% of the CFAPs DFs sample, and 167 root piles DFs, which represents 65.7% of the root piles DFs sample. Steel and concrete driven piles DFs had geotechnical investigation data of 63 and 19 wind turbines, respectively.

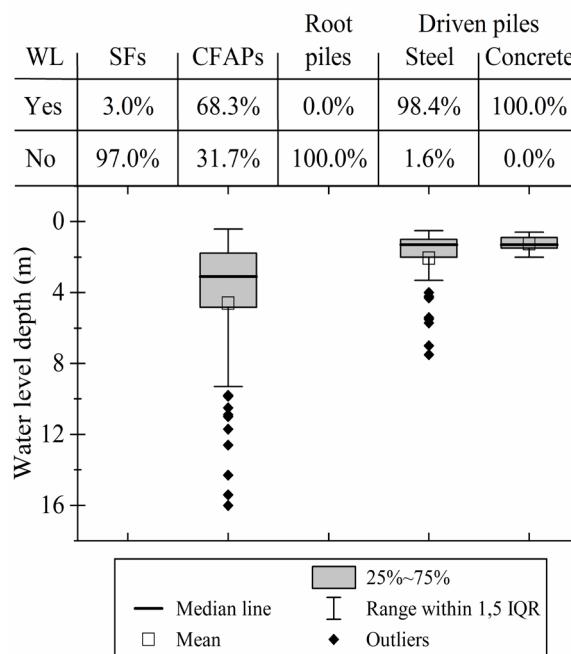


Figure 13. Water level (WL) depths of wind turbines foundations.

The results indicate that the piles tops were mostly embedded in soil layers, which were identified in more than 85.0% of the wind turbines DFs. The pile tops were mainly in contact with sandy soils. CFAPs had a minor share of piles tops embedded in clayey soil layers (29.0%). Root pile DFs exhibited a minor percentage of pile tops settled at silty soils (21.0%), backfill (14.3%) and rock layers (11.4%). The results obtained for the pile tops, which are equivalent to the piles cap bases, were significantly different from SFs, which had a significant share of SFs settled above rock layers (36.5%) and weather rock layers (21.3%).

The pile shafts were mostly embedded in soil layers, except for root piles DFs. The pile shafts of CFAPs, steel and concrete driven piles were more than 85.0% in contact with sandy soil layers. Steel driven piles had a minor share of piles shafts embedded in weather rock layers (13.4%). Root piles shafts, in turn, were mostly embedded in rock layers (58.8%), especially sandstone, phyllite and migmatite, followed by soil layers (30.9%) near the ground level.

The piles toes of CFAPs DFs and steel and concrete driven piles DFs were mostly embedded in soil layers, especially sandy soils. CFAPs DFs exhibited 24.8% of the pile toes embedded in rock or weathered rock layers, mostly sandstone.

CFAPs toes were limited by the drilling process of these layers. Steel concrete driven pile toes were 36.5% of the cases embedded in sandstone rock layers. The root pile toes, in turn, were 89.2% of the cases embedded in rock layers, especially sandstone, phyllite and migmatite.

Figure 14 shows the box chart of the N_{SPT} and RQD values of the pile tops, pile shafts and pile toes for wind turbines DFs. For clarity, the N_{SPT} values showed for the pile shaft refer to the average shaft value for each DF. CFAPs and driven piles exhibited significant low pile top N_{SPT} values (Figure 14 a, c and d), with 75% of the N_{SPT} values lower than 14. CFAPs and steel driven piles had a median N_{SPT} value of 9, while concrete driven piles exhibited a median N_{SPT} value of 11. These values were lower than the pile cap of SFs with SRTs, which had a 75% of the N_{SPT} values higher than 13 (Figure 10a). In turn, root pile tops exhibited a median N_{SPT} value of 18, ranging mostly from 10 to 28 (Figure 14b). When the root pile tops were settled above a rock layer, a median RQD value of 0%, with 75% of the RQD values under 20%, was obtained (Figure 14b). The statistical distribution of root pile tops N_{SPT} and RQD values were similar to SFs with SRTs settled above soil and rock layers (Figure 10a and 11a). The average pile shafts N_{SPT} values for CFAPs and driven piles are shown in Figure 14 as well. These DFs usually exhibited a linear increase of the N_{SPT} values with depth. The median pile shafts N_{SPT} average value for CFAPs and concrete driven piles were 30, while steel driven piles DFs exhibited a median value of 27. Additionally, a narrow statistical distribution was observed in the average pile shaft N_{SPT} values, ranging mostly from 25 to 35 (Figure 14 a, c and d). The root piles shafts were usually embedded in initial layers of soil, which had N_{SPT} values data, and then weathered rock and rock layers, which had RQD values data. Therefore, the averages pile shafts N_{SPT} or RQD values were not determined.

Additionally, Figure 14 shows the N_{SPT} and RQD values of DFs pile toes. When the pile toes were embedded in soil layers, CFAPs and steel driven pile toes had a median N_{SPT} value of around 43, with 75% of N_{SPT} values superior to 35 (Figure 14 a and d). Concrete driven pile toes had most N_{SPT} values around 50 (Figure 14c). When CFAPs toes were embedded in weathered rock or rock layers, the N_{SPT} and RQD values were 50 and 0%, respectively (Figure 14a). Steel driven pile toes, when embedded in rock layers, had median RQD value of 50, with 50% of the RQD values between 20% and 70% (Figure 14d). The root pile toes were usually embedded in rock layers which had a median RQD value of 35% with a wide statistical distribution of the RQD values, exhibiting 50% of the RQD values between 0% and 75% (Figure 14b).

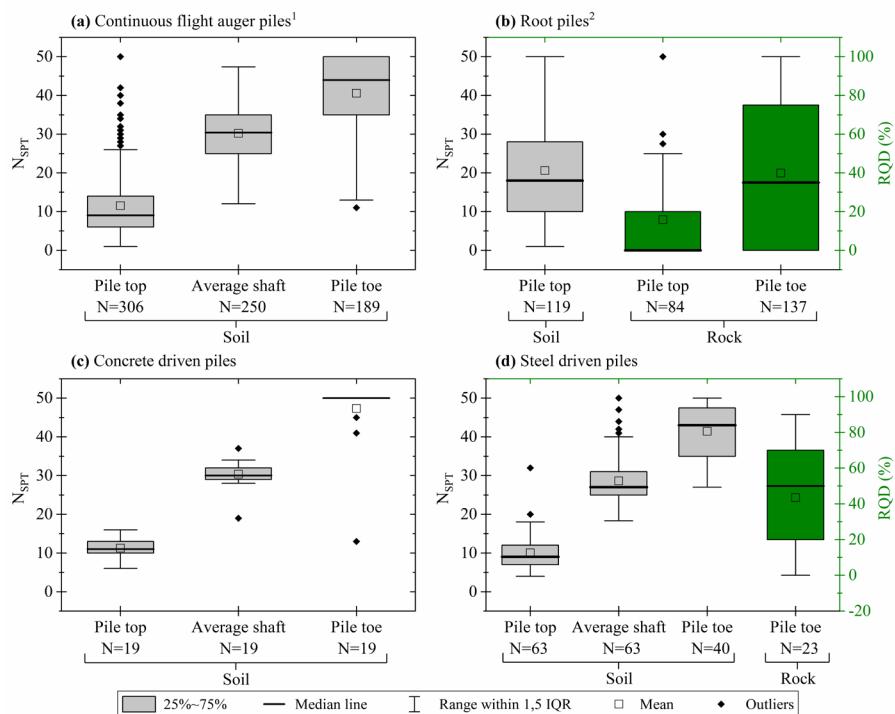


Figure 14. The N_{SPT} and RQD results of pile top, average pile shaft and pile toe for: (a) CFAP DFs; (b) root piles; (c) concrete driven piles; and (d) steel driven piles. Notes: ¹ CFAPs toes embedded in weather rock and rock had N_{SPT} and RQD values of 50 and 0%, respectively; root piles toes embedded in soil and weather rock had N_{SPT} value of 50.

6 DISCUSSION

The results indicated that different types of foundations are used according to several subsoil factors (water level depth, N_{SPT} value, quality of rock, for example), and not only the soil type. These underground conditions determine the feasibility of the wind turbine foundation in terms of design and executability.

Approximately 43% of the onshore wind turbines in Brazil used a shallow foundation. Shallow foundations were mainly used when subsoil conditions provided appropriate geotechnical properties near the ground level. Geotechnical conditions were usually characterized by no water table presence and appropriate soil resistance near the ground level, increased with depth. The subsoil strength and type, such as soil, weathered rock or rock, and the SPT impenetrable depth determined with soil improvements or rock anchors were required. Soil improvement techniques were used to improve the strength of thin porous layers near the ground level. Soil-cement stabilization was mainly used for soil improvement, while stabilization grouting was mainly used for weathered rock improvement. When the bed rock was near the ground level, rock anchors were usually used.

Deep foundations were used in 57% of the onshore wind turbines in Brazil. Different types of piles were used depending on the geotechnical conditions. Continuous flight auger piles were usually used upon certain conditions, which were characterized by the presence of water table and very poorly soil resistances near the ground level, which slowly increased with depth through the pile length of around 13 meters. Root piles deep foundations were used upon different underground conditions, which were characterized by the absence of water table and the presence of weak weather rock and rock layers near the ground level, within 5 meters depth. Therefore, the root piles shafts were mostly in contact with weathered rock or rock layers, differently of CFAPs. Concrete and steel driven piles deep foundations were characterized by the presence of water table near the ground level and the presence of porous soil layers, whose resistance slowly increased with depth through the pile length of around 13 to 15 meters. All piles were vertically installed, except the micro alluvial anker piles which were 12 degrees inclined with the vertical.

Continuous flight auger and driven piles lengths were usually restricted by the presence of strong layers, such as weathered rock and rock layers, due to drilling and driven process restriction. In turn, root piles were used when weathered rock and rock layers were close to the ground level. This result was expected since root piles are small diameter bored piles whose resistance is mainly due to shaft-rock friction. The geotechnical conditions and pile installation process clearly influenced in a certain pile preference. Additionally, a great share of wind turbines used continuous flight auger piles DFs due the great local acceptance to this type of piled foundation.

Several geotechnical conditions influenced the foundation type, including ground type, water level depth, soil layers resistance, extent of porous soil layers and bed rock depth. However, occasionally, there was an intersection between similar geotechnical conditions and different types of foundations. For example, shallow foundations, rock anchored shallow foundations and root piles deep foundations occasionally had similar geotechnical conditions. Two main reasons are identified: a certain type of foundation prevailed among others on a wind farm as the same foundation is used for several wind turbines; and a certain foundation type was preferred according to the local foundation expertise.

7 CONCLUSION

The status of onshore wind turbine foundations in Brazil was investigated. The main aspects concerned were the technology status of wind turbines, including rated power, rotor diameter and hub height, and the characteristics of the foundations, such as types, loading, dimensions and geotechnical aspects. The following conclusions were drawn.

- The technology status analyses identified that Brazilian wind turbines have similar characteristics, i.e., wind turbines rated power, rotor diameter and hub height, of most worldwide wind turbines. New wind farms tend to use larger wind turbines rated power and rotor diameter, while a moderate increase in the wind turbine hub height is expected. Concrete towers, which represented 26.4% of wind turbines in Brazil, were used when the hub height exceed 100 meters.
- Foundation loading, i.e., the overturning moment at the base, directly influenced the size of the wind turbine foundation, while the foundation type was not affected. Foundation loading was significantly influenced by the tower material, concrete or steel, and the wind turbine IEC Class. Concrete towers or Class II wind turbines exhibited higher overturning moment at the base than steel towers or Class III wind turbines, respectively. The wind turbine rated power, rotor diameter and hub height had relative effect on the foundation loading. As these characteristics increased, it was expected that the foundation loading increases due to stronger wind and large swept area; however, a marked spread of foundation loading for different wind turbines characteristics was observed.
- As concrete towers increased the foundation loading, the tower type influenced the shallow and deep foundations dimensions and material amount. Concrete towers required greater foundation diameter and material amount than steel towers. Additionally, deep foundations required a greater number of piles when concrete towers were used.

- The types of foundations used in onshore wind turbines differ in each country. In Brazil, for example, there is a large use of deep foundations, especially continuous flight auger piles and root piles. The type of onshore wind turbine foundation is chosen according to several factors. The geotechnical conditions, including soil type, water table level, soil layers resistance, the extent of porous soil layers and bedrock depth, had a major role on the foundation type. Additionally, the local foundation expertise and acceptance clearly influenced the definition of the foundation type. For example, it was noticed that a great share of wind turbines used continuous flight auger piles DFs, which are widely used for conventional structures in Brazil.
- Usually, a unique foundation type was chosen for all wind turbines in a wind farm. However, the wind turbines can be relatively far from each other; therefore, considerable variability of the geotechnical aspects were noticed and, in a few cases, more than one type of foundation was required.
- Unexpectedly, no significant difference in raft diameter and material amount was noticed between shallow and deep foundations. Root piles and micro alluvial anker piles deep foundations, in turn, used smaller pile cap diameters and materials amount than the other types. However, no significant difference in the reinforcement ratio of shallow and deep foundations was observed.

Commonly, wind farm construction sites are geotechnical unfavorable. Further responses in the literature on onshore wind turbine foundations are required, especially because: limited data of actual situation and conditions have been published; wind energy has recently advanced in underdevelopment countries, such as Brazil; distinct geotechnical conditions; and different local foundation expertise and acceptance. Additionally, future research should address numerical analysis, risk and reliability and life-cycle assessments of these different wind turbine foundation types.

The paper presents the status of the wind turbine in Brazil. The information that there is no correlation between overturning moment and rated power, rotor diameter, hub height show that the design criteria to calculate overturning moment is not standard. Therefore, it cannot identify correlation between foundation diameter, concrete volume steel amount with rated power, rotor diameter and tower height.

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