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Foundations of onshore Wind turbines: current situation and trends

Cimentaciones de aerogeneradores terrestres: situación actual y tendencias

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ABSTRACT

The commitments by the governments for the net zero emissions for the coming decades will be a huge challenge for the renewable sector all over the planet. Wind energy will play a significant role in this transition and scale-up, in both offshore and onshore, is a crucial step to move forward. The quick development of the new onshore wind turbine models in the race for the most powerful machine, the gradual increase in the hub height, and the unitary power of the new onshore wind turbines are producing modifications in different components of the turbines. This work presents a review of the onshore wind turbines foundations, especially about the different foundation design concepts available in the onshore business, the analysis of some of them and the trends.

Keywords: onshore wind turbine; onshore foundations; shallow foundations; wind turbine tower; foundation typologies; sustainability.

RESUMEN

Los compromisos de los gobiernos para las próximas décadas respecto a las cero emisiones representarán un reto enorme para el sector renovable en todo el mundo. La energía eólica jugará un papel fundamental en esta transición y el crecimiento de las turbinas, tanto en el sector offshore como en el onshore, está siendo un paso crucial. El rápido desarrollo de las nuevas turbinas en la carrera por la maquina más potente, el incremento gradual en altura de buje, y la potencia unitaria de los nuevos aerogeneradores onshore está provocando numerosas modificaciones en diferentes componentes de dichos aerogeneradores. Este trabajo presenta una revisión de las cimentaciones de aerogeneradores onshore, especialmente sobre los diferentes conceptos de diseños disponibles en el sector, el análisis de algunos de ellos y las tendencias.

P*alabras clave:* aerogeneradores terrestres, cimentaciones terrestres, cimentaciones superficiales, torres de aerogeneradores, tipologías de cimentaciones, sostenibilidad.

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1. INTRODUCTION

The United Nations (UN) requested an urgent action to achieve net zero greenhouse gas (GHG) emissions by 2050 (1). The European Union (EU) has committed to reach climate neutrality in 2050 and, as intermediate step, to cut GHG emissions by 55% compared to 1990 by 2030. In total more than 120 countries, representing approximately half of global gross domestic product, have joined to the initiative (1).

The challenges for the wind energy sector considering the objective of the European Union to achieve climate neutrality by 2050 are not less great than the opportunities. Cost reduction is key for the growth of the wind energy sector and to meet the commitments as expected by the governments and the society. Levelized cost of energy (LCOE) reductions have been one of the key factors when designing a new wind turbine generator (WTG) model, and it will continue being a crucial factor in the future. The prices in the energy auctions all over the world are decreasing drastically (2).

For the cost reduction scale-up is needed, both in onshore and offshore, there is no discussion about the fact that the more powerful wind turbines (per MW) are, the less development, manufacturing, installation, and maintenance cost. The most powerful onshore wind turbines in the European market are at the moment close to 7MW, with maximum hub heights around 150m and rotor diameters between 140-180m and these power and sizes will be surpassed quickly in the coming years.

Plus, something important is that the smaller number of wind turbines in a windfarm are, the less environmental impact, therefore optimizing the land use and integrating in the agricultural and farming areas is key for the progress of the onshore wind energy sector. Because of this, repowering onshore projects will be one of the trends for the future (1,2), to take opportunity of the best wind sites with the current technology and to generate more power with a smaller number of wind turbines.

In this context of quick change of the WTG models into more powerful and bigger machines with significant opportunities for the future, the objective of this work is to bring light on the current situation of the onshore wind turbine foundations, as well as to show the influence of scaling-up in this component, and the main trends that are to come and how to face the challenges ahead.

2. EVOLUTION OF WIND TURBINE FOUNDATIONS

At the beginning of the proliferation of the windfarms, between the last decades of the XX century and the first decade of the XXI century (3), one of the most used solutions for some of the original equipment manufacturers (OEMs) for the foundation of wind turbines was the square shaped foundation with a "steel ring". The "steel ring" consists of a short steel tower section that is directly embedded into the concrete, the lower flange of this steel ring is the one responsible for the load transfer from the tower to the foundation.

The dimensions of these old foundations were quite small (between 8-10m) and the market was growing at that time, therefore there was no big interest in optimizing this component. The design drivers in this case were the simplicity and execution easiness, the market was requesting quick installation rates.

For some other OEMs and specifically in the US, circular or octagonal foundations with anchor cage were the ones to be implemented from the beginning. The interface through anchor cage for tubular steel towers, consists of a set of anchor bolts supported by an upper and lower flange, this is the interface system that nowadays is being used for most of the OEMs and it is proved to be a more robust solution than the steel ring.

Between 2005 and 2010, the WTG manufacturers that initially used the steel ring system, started the migration to the anchor cage system. Nowadays, the anchor cage system is the most used load transfer system from the conventional steel towers to the foundations.

Regarding the geometry of the foundation, the evolution was, in most of the cases, from the square shaped foundations to the variable height foundations, taking the advantage of the fact that the shear forces decrease from the centre to the outer part of the foundation. Also, the circular/conical shaped was proved to be more economical than any other geometry, as described and explained in the bibliography (4). In some countries the octagonal shaped foundation is used because the difference in cost with the circular one is very small, and the execution of the steel reinforcement and the formworks may be simpler.

After that, the reduction of the LCOE as a real design driver came into play, the capital expenditures (CAPEX) needed to be decreased and all the WTG components were revised and updated to optimize the cost of the machine as much as possible. Therefore, more complex geometries were designed, and they will be analysed as follows.

3. FOUNDATION DESIGN

The main distinguishing factors of the WTG foundation from any foundation from other structure, are the following:

1. The bending moment is the prevailing load and therefore there is a high eccentricity of the load.
2. The dynamic behaviour of the structure and the influence on the loads through the minimum dynamic rotational stiffness requirement to the soil-foundation interaction, to avoid the resonance with the excitation frequencies coming from the rotor rotation.
3. Gapping control requirement to ensure that the operation of the foundation will not be compromised due to the repeated gapping cycles and the potential soil degradation.

Geotechnical and seismic aspects are of course key for the design, but not so much a differentiating factor from any other foundation.

3.1. Dynamic Rotational Stiffness

The rotational stiffness is measured in N*m/rad, therefore it is a bending moment divided by a rotation, depending on the WTG model and for a conventional steel tower the range of values can be from 3.0 E+10 N*m/rad to 2 E+11 N*m/rad.

As the WTG tower height and weight increases the minimum rotational stiffness requirement is higher.

The dynamic rotational stiffness is calculated to avoid specific tower vibration frequencies that could enter into resonances with the vibration frequencies of the rotor (5). If those resonances occur, this could lead to the collapse of the structure, therefore it is an important verification to be done in the foundation design of the WTGs, as indicated in reference (6).

There are different stiffness values to consider: vertical, horizontal, rotational, and torsional, but when it comes to the WTG foundation design, the most important requirements are the dynamic rotational stiffness and the horizontal stiffness especially for deep foundations, it must be verified that the raft, piles, and supporting soil account for the minimum dynamic rotational and horizontal stiffness.

One methodology to calculate the dynamic rotational stiffness can be found in the reference (7). The rotational stiffness indicated as Rocking (mode of motion) in Equation [1]:

$$[1] \quad K_R = \frac{8GR^3}{3(1-\nu)}(1+\frac{R}{6H})(1+2\frac{D}{R})(1+0.7\frac{D}{H})$$

And the simplified version in Equation 2, and most used version of the formulae, is as follows:

$$[2] \quad K_R = \frac{8 \cdot G \cdot R^3}{3 \cdot (1-\nu)}$$

R is the radius of the foundation
G is the shear modulus of the soil
v is the Poisson ratio
D is the total embedment depth of the foundation
H is the height of the stratum in which the foundation is embedded over the bedrock.

This is the classical and simplified calculation method of the dynamic rotational stiffness. As it can be observed in the equation, the rotational stiffness depends on the shear modulus of the soil, the Poisson ratio, and geometrical parameters of the foundation. It is a quick and simple way to calculate it if the needed data is available, especially the dynamic geotechnical parameters.

According to the previous simplified formulae, the dynamic rotational stiffness is directly proportional to the cube of the foundation radius (for circular shaped foundations), what means that the dynamic rotational stiffness can be increased if the foundation diameter is increased.

The problems of the calculation methodology, especially for the WTG foundations currently designed, are as follows:

- It is only applicable for rigid foundations while the sector is using nowadays flexible foundations in the range of 20-25m.
- It only accounts for the static stiffness while the requirement is a minimum dynamic rotational stiffness.
- The methodology considers that the foundation is always in contact with the soil.

Therefore, it is convenient to be careful when using this calculation methodology as indicated in (8), since the conditions for its use can be seldom fulfilled in the current WTG foundations. When there are different conditions, the other calculation methods are the following:

- Classical finite element model, using “compression only” supports and using the subgrade modulus based on the dynamic young modulus of the soil.
- Soil-structure interaction study (9) using a geotechnical engineering finite element software, such as Plaxis 3D, Midas, etc...

In the most complex cases, where there are doubts about the rotational stiffness verification due to the challenging geotechnical conditions, it is strongly recommended to do a soil-structure interaction study, since the calculation using the formulae in the reference (7) can result in a significant deviation from the reality.

3.2. No gapping requirement between foundation and soil

The purpose of this requirement is to avoid that repeated gapping cycles may cause a degradation of the subgrade. The shape of the subgrade right underneath the foundation must remain stable over the whole operational life of the structure. The criteria to avoid this effect, is an important part in the design of WTG foundations, the criteria that must be applied is as follows:

- No gapping shall occur between the foundation and the subgrade under operational loads combination (quasipermanent load), as indicated in reference (6).
- Gapping is permitted for the characteristic extreme load up to the centre of gravity of the bottom area of the foundation.

These requirements are included in the reference (10) DNVGL-ST-0126 in the chapters 7.5.5.3 and 7.5.5.4 respectively. Both are important and must be verified, but especially the no gapping requirement under operational loads is the one that normally drives the design in the shallow foundations.

4. FOUNDATION COST

As it can be seen in the reference (11), the balance of plant weight of a wind project (civil and electrical infrastructure works) can mean between 25-33% of the cost depending on the project size and the electrical infrastructures needed to transport the energy produced by the windfarm.

Within the Balance of plant (BOP) of the windfarm, the following scopes are included: wind turbines foundations, roads and platforms of the windfarm, medium voltage lines for the connection of the wind turbines, substations and transmission lines.

Among all these scopes, the one that is more expensive within the BOP scope, is in most of the cases the WTG foundation. The variability of the foundation cost in the reference projects according to the reference (11) is around 16-33% of the BOP cost, which implies that in the total cost of the wind project, it will mean between 4-10% of the cost. This is in line with the reference (12) but in the lower range (4%), meaning a standard foundation designed for favourable geotechnical conditions. Additionally, within the BOP scope, the higher optimization potential is in the civil works.

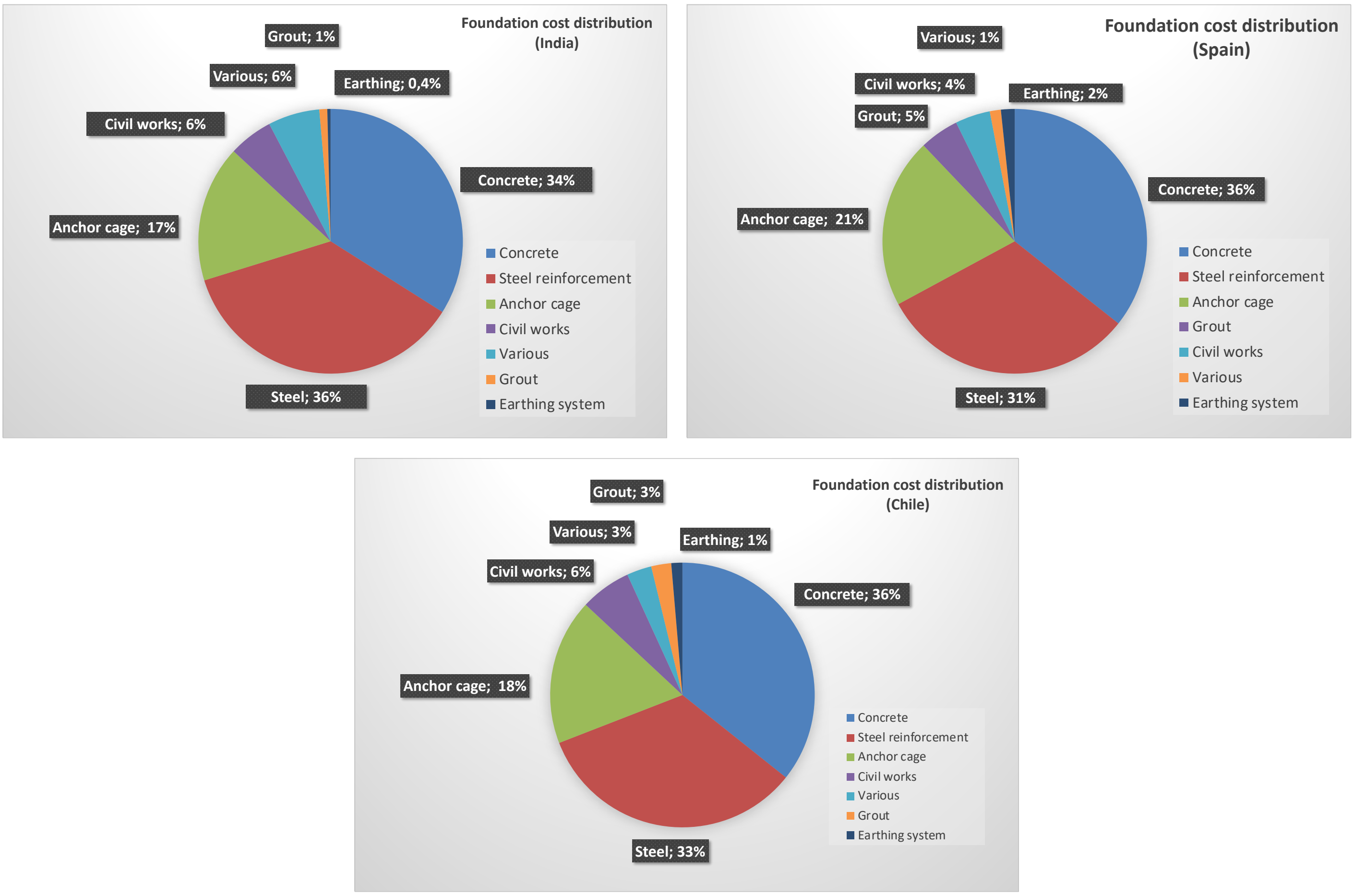

Figure 1. Example of the foundation main cost distribution for a Wind Project in India, Chile, and Spain.

Focusing on the WTG foundation only, the biggest portion of the cost is in the supply and execution of the main materials, which are the following:

- Interface between the tower and foundation, currently the above-mentioned anchor cage system.
- Concrete: normally there are different strength classes for the blinding concrete, slab concrete and plinth concrete. The local norms and regulations in every region/country define the specifications for the concrete.
- Steel reinforcement: the most used are the ones with a yield strength: 500 MPa, 450 MPa and 400 MPa. The local norms and regulations in every region/country define the specifications for the steel reinforcement depending on the materials availability.

The cost distribution is quite variable depending on the foundation design and the material quantities, and specifically the foundation typology. The labour costs and the cost of the materials is extremely variable depending on the geographic area where the project is located.

In this article a small, but representative, sample of this variability is shown in the figure 1, where a rough estimation of the cost distribution for the main materials and civil activities can be compared in projects built in Chile (high materials cost), Spain (medium materials cost) and India (low labour and materials cost). This exercise was done for a standard foundation (circular shaped and variable height foundation with anchor cage interface) for a WTG with conventional steel tower.

5. INFLUENCE OF SCALING-UP IN FOUNDATION EXECUTION

The level of loads of the new WTGs in the European market, that have reached around 5-7MW of unitary power, means that the dimensions of the foundations are much bigger than their predecessors of 2-3MW (13). The new foundations require a much more quantity of concrete and steel reinforcement, what results in some complexities during the execution of the foundation:

- Higher concrete specifications, which in some countries it is not standard and easy to find or manufacture.
- Higher complexity in the steel reinforcement works, due to the congestion in specific areas and the number of rebars required in the design.
- Higher complexity in the anchor cage installation, due to the weight increase of the elements, sectorization, needed tooling, transportation costs, etc...
- Higher complexity in the concrete casting process of the foundations. Due to the concrete volume to be casted in a daytime, the following resources may be needed:
  - ◇ At least 2 concrete plants ready to supply concrete 2-3 in situ concrete pumps.
  - ◇ A significant number of concrete trucks to keep a continuous supply of concrete and to mitigate the risk of casting interruptions.
- These additional resources require a very strict coordination and planning to avoid issues in the most critical phase of the foundation execution.
- Given the large dimensions of the current foundations and depending on the project location and the ambient tempe-

rature, in some projects it is needed to monitor the temperature in the core of the foundation (installing sensors connected to a data logger before the concrete casting) in order to ensure that the temperature in the core and the gradient between core and surface temperatures are within the limits (14).

All these complexity adders indicate that the standard solution for foundation (variable height foundation with anchor cage), that is currently being used by most of the developers and WTG manufacturers, could reach its operating limitation in the short term. Therefore, new solutions are arising that reduce the concrete and steel quantities, also new precasted solutions are being launched and tested these days.

6. FOUNDATIONS TYPOLOGIES

Regarding the different typologies of foundations for conventional steel towers, focusing on the shallow foundations with anchor cage interface, the following ones would be the most used according to the author's humble opinion:

Circular shaped foundation, variable height: it is the most widespread foundation typology (hereinafter called standard foundation), the circular shaped geometry has been proved to be the most competitive solution by means of steel reinforcement and concrete quantities. The geometry is a combination among a wide cylinder in the lower part of the foundation, a conical shape in the variable height portion, and a new cylinder at the top in the pedestal (as it can be seen in the figure 2). The execution consists of an excavation until the required depth, then a lean concrete layer is poured at the bottom of the excavation. After that, the construction of the foundation takes place, normally the concrete casting is done in a single phase in this foundation type and finally backfilled.

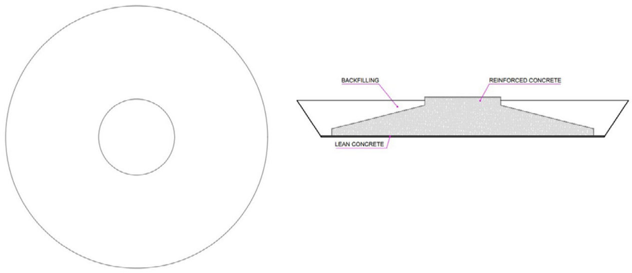

Figure 2. Sketch of standard foundation: plan view (left side) and section (right side).

Octagonal shaped foundation, variable height: it is commonly used in projects located in Australia and in the US, despite in terms of quantities the circular shaped is more competitive, the difference is quite low, therefore the execution of the steel reinforcement (avoiding the circular rebars) can be easier and slightly quicker.

EPS layer: this is an improvement method for any concept that includes a slab. Comparing it with the standard foundation, the only difference is that it requires to place a plate of expanded polystyrene (EPS) between the foundation and the supporting soil, to modify the stress distribution. The behaviour of the foundation with this EPS layer is like an annular foundation, the main benefit of using it is that the gapping verification improves significantly. The foundation diameter can be reduced and therefore there is a slight concrete volume reduction. CTE Wind developed a solution called soft-spot with this system (15).

Walls's foundation: this foundation consists of a cylindrical lower slab with a height between 0.5-1m, over the lower slab there is a smaller central cylinder, the height of this cylinder is up to the pedestal height (between 2-4m). The number of walls is selected by the designer the most common are: 4, 6 and 8 walls. This solution may obtain important savings, especially in the concrete volume, where in some cases compared to the standard solution the need of concrete volume is 50%.

The anchor cage and the steel reinforcement related to the interface are embedded into the central cylinder, as it can be seen in Figure 3. Although there were some previous concepts and preliminary experiences, the first WTG manufacturer who developed, designed, prototyped, and built this solution was Siemens Gamesa, in the 8-walls version. Currently, there are other developers and OEMs that are using this solution.

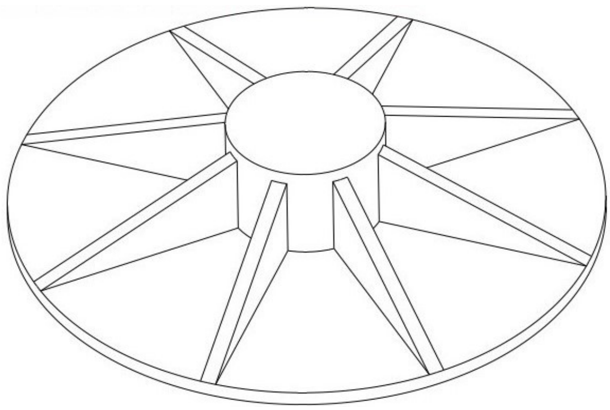

Figure 3. 3D view of the 8 walls foundation (Siemens Gamesa).

Braced foundation (Esteyco): more sophisticated foundation that includes an interior posttensioning of the braces that connect the lower slab to the central cylinder, a 3D view can be seen in Figure 4. The anchor cage system is shorter than usual. It is likely one of the most competitive solutions in terms of design, with one of the higher reductions of concrete and steel quantities compared to the standard foundations (16).

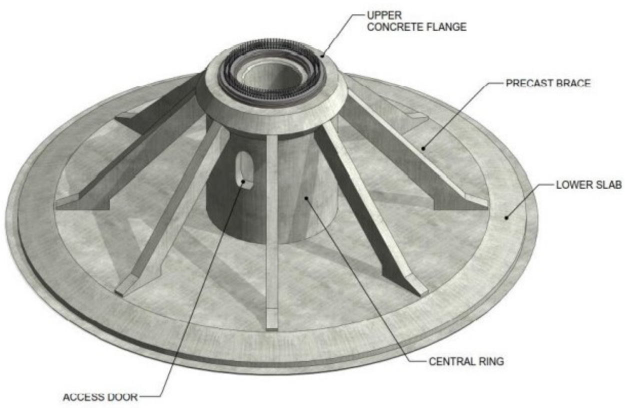

Figure 4. 3D view of a braced foundation (Esteyco).

On the other hand, the execution of the braced foundation implies to set up an industrial process on site, with a strict program for the sequence of activities and a detailed planning that is not always possible to implement in some international projects. It also requires a learning curve depending on the experience of the civil contractor, so it is more suitable for large windfarms.

It is also an adequate solution when it comes to increase the foundation height some meters (up to 10m) to obtain a higher hub height using the same conventional tower design and increasing the annual energy production (AEP).

<u>Precast foundation</u>: there are some precast foundation solutions for onshore WTGs, mainly they have been developed by traditional precast companies like for example Artepref in Spain, reference (17) and Figure 5. The most used design is based on the foundation walls solution but adapted to the precast technology. Other companies are developing similar solutions in other parts of the globe.

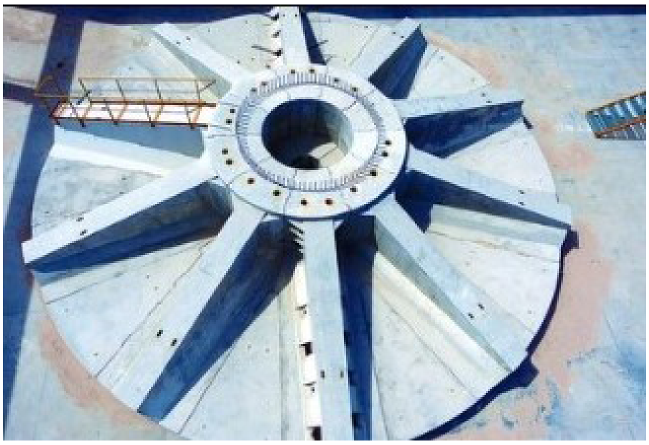

Figure 5. Picture of the Artepref precast foundation prototype (Artepref).

<u>Patrick & Henderson foundation (Tensionless pier)</u>: the solution consists of a hollow monopile that is executed using two concentric cylindrical permanent formworks in the inner and outer part of the monopile. The depth of the monopile is around 8-10m depending on the WTG loads and the geotechnical conditions. Inside the formwork system the anchor cage is embedded into the concrete monopile, for the inner backfilling the existing soil is normally used and the gap between the excavation and the outer formwork is filled by slurry backfilling according to Patrick and Henderson (P&H) specifications. The P&H foundation system is very widespread in the US and Mexico.

It is likely the most competitive solution in terms of design, with the highest reductions of concrete and steel quantities compared to the standard foundations. But it is more suitable for small wind turbines, for large wind turbines and depending on the geotechnical conditions, the required foundation depth of the monopile becomes significant, which could reduce the cost effectiveness due to the excavation depth (18).

<u>Rock anchored foundation</u>: depending on the rock quality on the project site, the rock anchor foundation will be a slab or just a plinth (also called rock adapter). In the best-case scenario, it is sufficient with a plinth of 1m depth and around 7 m in diameter. In any case, posttensioned rock anchors are needed to transfer the loads from the tower to the bedrock, it is required normally both vertical and inclined rock anchors. This is a common solution in places where there is a high-quality rock at a shallow depth (like for example Norway, Sweden, and Finland).

These solutions, among others, are the ones that have been used for conventional steel towers and with the range of loads of the current WTG models. However, the speed of the WTG development and the increase in height and weight of the new models, will step up the load range and the tower technology may change in the short to medium term. Therefore, new foundation concepts will be needed to respond to the challenges to come.

Hereunder, a comparative analysis is done comparing the most used foundation solutions for conventional steel towers. The key factors that have been selected for the comparison are as follows:

1. Pros and cons, according to the following aspects:
   a. The ease or difficulty in the execution
   b. The execution lead-time
   c. Need of special resources
   d. Materials optimization
   e. Execution risks
2. Geotechnical conditions: some foundation typologies before-mentioned, require a specific geotechnical condition for their application, which is limiting the applicability of the solution.
3. Resources and auxiliary means: some typologies require,
   a. Especial formwork system
   b. Posttensioning systems to joint different elements
   c. Cranes for the assembly of the elements (not including the one needed for the anchor cage installation).
   d. In situ Precasting systems
   e. Special excavations machinery.
4. Certified or patented system: this is an important information since in some projects the financing entity requires that the foundation design is certified by a third party, therefore it is important to know if the system was certified before. Also, some design concepts are patented, for others a patent has been requested.
5. Applicability: it is important to know in which conditions it is more suitable to use one solution or the other. And in which situations, there is no point in considering a solution at all, for the reasons that will be tackled eventually in the article.

Following, it is included the Table 1 that can serve as a portfolio of foundation design solutions for onshore WTG with conventional steel towers.

There are other foundation concepts for WTGs with conventional steel towers, but the ones analysed in this article, are the most used and promising for the onshore market.

7. INFLUENCE OF NEW TOWER TECHNOLOGIES

There are different solutions being used and under development, among others: the full concrete tower, the hybrid tower (concrete and steel), the guyed tower, steel sectorized tower and the lattice-tubular tower.

Table 1. Comparative analysis of the most used foundation solutions for conventional steel towers.

Founda-tion design concept	Pros	Cons	Geotechnical conditions	Resources and especial means	Patented / certified system	Applicability
Circular shaped variable height (standard)	Easy and quick execution.	Not optimized when it comes to material quantities	Geotechnical conditions needed for a direct foun-dation, no special limitations.	Not required, well known by civil contractors.	Certified system, very widespread.	Any situation of direct foundation.
Octagonal shaped variable height	Easy and quick execution.	Not optimized when it comes to material quantities, less optimized than circular.	Geotechnical conditions needed for a direct foun-dation, no special limitations.	Not required, well known by civil contractors. Slightly easier exe-cution of the steel reinforcement.	Certified system, very widespread.	Any situation of direct foundation. Commonly used in Australia and in the US.
Wall's foundation	Concrete volume reduction compared to standard of around 50% with 8 walls solution.	Sequence of ac-tivities, minimum 2 casting phases, higher execution Leadtime. The steel quantities maybe higher with this solution vs stand-ard, around 35% higher.	Geotechnical conditions needed for a direct foun-dation, no special limitations.	Requires special formwork system and medium spe-cialization of the civil contractor.	Certified system, very widespread.	Any situation of direct foundation, but it re-quires special formwork system that need to be foreseen before the con-struction and medium specialization of the civil contractor.
Braced foundation	An important con-crete volume reduc-tion. Compared to standard, reduction of 40% in concrete volume and 20% in steel quantities. Advantages when foundation elevation is needed.	Execution diffi-culty, it requires special means, higher execution time and industri-alized process.	Geotechnical conditions needed for a direct foun-dation, no special limitations.	In situ precast Special formwork Posttensioning Industrialized process Experienced civil contractor (spe-cialized personnel)	Patented and certified system. International patent in force by Esteyco, reference (19).	It obtains an important reduction of the mate-rials. For the execution it is needed to imple-ment an industrialized process on site. More adequate for large WFs in developed countries.
EPS layer foundation	Easy and quick execution. Concrete volume optimization: 5-15%.	Small material optimization compared to other design concepts.	Bearing capacity requirements are slightly higher than in an equi-valent standard foundation.	Not required, the installation of the EPS is simple. The execution process is almost the same as in the standard.	Certifiable sys-tem and patent granted in France to CTE Wind, reference (20).	Any situation of direct foundation. Smaller savings, but the execu-tion process is almost the same. Balance between design savings/execution.
Precast foundation	-Quickest on-site ex-ecution lead-time. -Mitigation of exe-cution risk. -If 8 walls type, concrete volume reduction of 50% vs standard.	-It requires a pre-cast plant close to the site. -Special means for the precast tech-nology.	Geotechnical conditions needed for a direct foun-dation, no special limitations.	Posttensioning of the foundation elements. Cranes for the lifting and po-sitioning of the elements.	Patented sys-tems. Various patents, among others, Europe-an patent grant-ed to Artepref/ Stefano Knisel, reference (21).	-For sites where a pre-cast plant is relatively close. -Easy and quick execu-tion on site. -Synergies with con-crete or hybrid towers, site precast plant.
Patrick & Henderson	-Very significant re-duction of materials. -Small amount of concrete (approx. 1/3 compared to the standard founda-tion). -Besides the anchor bolts, there is no steel reinforcement needed.	-Special means, special excavations, and formworks, sometimes it may require blasting.	-In case of soils, it is advisable a soil-structure interaction study during the design phase.	-It requires special machinery and specialized personnel for deep excavations. -Blasting may be needed, depending on the geotechni-cal conditions.	Patented and certified system. US patent ex-pired in 2019.	-More suitable for small WTGs, depending on geotechnical conditions (18). -It requires special means for the execution and specialized per-sonnel. -If feasible, this design concept can obtain a very significant material optimization.
Rock anchored foundation	Very significant ma-terial optimization. The material opti-mization depends on the solution: concrete cap or adaptor slab.	-Very specific geotechnical con-ditions. -Special means.	It is required a high capacity and high-quality rock for the feasibility of this solution compared to other options.	Special means and specialized personnel for the anchors (verti-cal and inclined anchors).	Certified sys-tem. Various patents, among others, the reference (22).	High quality rock is required for the appli-cation of this design concept, especially suitable for sites located in Finland, Sweden and Norway with the above-mentioned geote-chnical conditions.

There is no clear consensus as to the solution that will be most used in the future, but what it is clear is that the conventional tower won't be the best solution for hub heights over 130-140m which is being reached in some of the current projects. Some of the WTG manufacturers are working in different solutions, others have developed their existing solutions and there are also specific tower designers working on their own solutions. The solution that is being used at the moment when high hub heights are required seems to be the hybrid solution reference (23), it can be a trend or maybe the other design concepts are yet to be developed.

Obviously, the imminent evolution in the tower technology of the onshore WTGs will directly affect their foundations, the design of the foundation for a steel tower is quite different than one for a concrete tower. Some concrete towers are designed to do the posttensioning at the bottom, therefore the foundation geometry is completely affected, since they are normally hollow at the centre, and they must provide enough space to do the posttensioning in the inside of the structure.

8. LIFE EXTENSION

The number of WTGs that are reaching the design limit of 20 years of operation is increasing more and more, therefore the need of extending the life of the WTG components is one of the focus areas for the operators and WTG manufacturers, as indicated in the reference (24). This is especially important for the foundations where the periodic inspections can be done only above-ground, and when a major retrofit is needed it is too late to avoid massive excavations and interrupting the wind generation.

In the reference (25), a long-term monitoring system can help predict the fatigue safety of the tower and foundation as well as the crack width evolution in the concrete of the foundations. This will be an important information for the windfarm's operators to take decisions about the asset life extension.

There is also extensive research related to the embedded steel ring (26) from the study of the failure mode to monitoring the degradation and cumulative damage of the compressive zone of the concrete (27) and strengthening systems to improve the fatigue life of the foundation (28).

Final, DNV-GL has developed different guidelines for the lifetime extension of wind turbines, the references (29) and (30), as well as a certification service based on different lifetime extension assessment methods. This is a useful system to confirm if the wind turbine is suitable for the life extension, and the time in which this lifetime can be extended.

9. REPOWERING

One of the lifecycle strategies can be the repowering of some or all the wind turbines of a windfarm when they reach their design lifetime. Regarding the foundation, there are different options:

1. Repowering can consist only of the blades upgrading for example, in that case a verification of the foundation with the new loads at tower base will be performed, the foundation may remain the same if the verification is positive, or it may require a small retrofit if the foundation cannot withstand the new loads.
2. A completely new wind turbine in the exact same location as the original, then there is the option of analysing if the existing foundation or part of it, can be reused for the new wind turbine as the reference (31) proposes.
3. A new wind turbine located in other location; therefore, the existing wind turbines will be decommissioned, and the new ones will be installed and connected. Likely, only the roads and hardstands, some parts of the cabling and the substation (that may require further upgrading) will be reused from the original windfarm.

As it is explained the repowering will affect differently the wind turbine foundation, but it may mean the concept of reuse or to give a second life to the foundation in case the repowering concept allows it. Additionally, in case the existing foundations are demolished, the recycled aggregate resulting from the demolition maybe reused for roads and hardstands construction and to manufacture new concrete for: blinding concrete for foundations and concrete for pavements or ditches.

In the reference (32) a reusable foundation solution for onshore wind turbines is described, it uses an active stabilization system that moves the movable load around the foundation depending on the load direction. It is a smart idea when it comes to reducing the CO_2 emissions since the solution can be upgraded to taller and more powerful wind turbines, but, the challenge of this solution is to connect the wind turbine control system with the active stabilization system which is needed for the feasibility of this solution.

10. SUSTAINABILITY

Due to the expectations of wind turbine installations in the future it is crucial to ensure that sustainable wind turbine foundations are designed and built. Besides, a foundation for a wind turbine may require at least 400 m^3 of concrete and 50t of steel reinforcement (depending on the wind turbine model), which means a significant environmental impact in the manufacturing of the materials to build some foundations for a wind project. The document in reference (33) proposes an interesting approach that has been used in different countries, that is the use of a concrete design mix replacing 50% of the cement weight by blast furnace slag or fly ash or a combination of both.

This measure will not only reduce the environmental, energy and CO_2 impact of the wind turbine foundation, but it may reduce its cost in some countries. Therefore, it is very interesting to investigate this option when performing the concrete mix design. Most of the foundation optimizations will reduce the environmental impact because the quantities of concrete and/or steel to be used will be less compared with the standard solution, but if combined with this sustainable concrete design mix whenever possible, the reduction of the environmental impact will be higher.

11. CONCLUSIONS

One of the main conclusions of this document, after analysing various foundation concepts for onshore WTGs and conventional steel towers, is the fact that it does not exist an optimal solution for any load level and any geotechnical conditions. It is necessary to do a technical and economic study to select the best solution for a specific site with a specific WTG model and considering the detailed geotechnical conditions.

The advantage in this case, is that there is a wide range of options for most of the situations that can occur, therefore it is just to select the most cost-effective solution for the project considering not only the design but also the construction cost and lead-time. It is crucial to do the assessment in the right way, the balance between material savings in the design vs the execution complexity, and how feasible it is to solve these complexities on site.

One of the new challenges ahead is the fact that the conventional steel tower is reaching its utilization limit for high hub heights and therefore it won't be competitive vs other tower technologies in the future. Other tower design concepts have been used for a long time now (by some OEMs), but this technology change will imply for sure an important change in the way the foundations are designed and executed, and new opportunities for the optimization not only from design but also from manufacturing and construction point of view.

The fact that the foundations for the new generation of onshore WTGs (between 5-7MW in the European market) have a considerable size due to the justified increase in the load level, means that the use of the standard foundation solution (widely selected for most of the developers) implies some complexities in the execution. For example, the concrete casting process of quite large concrete volumes in remote areas or the need of monitoring the concrete temperature at the core of the foundation, that must be taken into consideration in the selection of the design concept for a specific project.

The rotational stiffness is one of the differentiating requirements between a WTG foundation and a foundation for other structure. The calculation of this parameter may be challenging, especially when there are complex geotechnical conditions and if the calculation methods are not adequate. The formulae of the reference (7) DNV Riso, has some limitations that make it suitable only for very specific situations that are not meet by most of the current foundation designs. Therefore, it is strongly recommended a FEM model to ensure that the requirement of the minimum dynamic rotational stiffness is satisfied.

Finally, sustainability is key for the design and operation of the wind turbine foundations, the use of a concrete mix design that reduces the environmental impact as well as, potentially, its cost is a very interesting option. The combination of a foundation optimization with a sustainable concrete design mix would be a good strategy to significantly reduce the environmental impact. Besides, lifetime extension and repowering strategies are focus areas for operators and wind turbine manufacturers and they will continue developing steadily in the future.

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