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Improving pile foundation models for use in bottom-fixed offshore wind turbine applications

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Abstract

Performing a dynamic analysis of an offshore wind turbine with an aero-elastic solver relies on the inclusion of a model to represent the behavior of the piled foundations. The most commonly used solution is the p-y method, which was developed for offshore oil and gas applications and has been extended to the offshore wind energy industry. There are several shortcomings with this method, however, which can affect the accuracy of wind turbine simulations. These shortcomings are identified and explained in this work. More advanced pile foundations models which account for many nonlinear behaviors ignored by the traditional p-y method have been developed in the past for applications unrelated to offshore wind turbines. These models can nevertheless be applied to offshore wind turbine simulations and are discussed herein. A proposed method for incorporating these so called 'dynamic p-y' models into wind turbine simulations is laid out and discussed.

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Keywords: Pile foundation modelling; dynamic p-y curves

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1. Introduction

As offshore wind turbines move into deeper and less protected waters, with the upcoming Dogger Bank site in the North Sea as an example, the need for more cost-effective support structures grows ever greater. One of the most significant contributors to the CAPEX of bottom-fixed support structures - the expected dominant support structure topology for the near to medium-term future - is the fabrication and installation of the piled foundations which affix the structures to the seafloor [1,2]. In these first two decades of the offshore wind energy industry, much of the support structure technology has been borrowed from offshore oil and gas applications, including the primary design and analysis method for piled foundations [3]. This decades old design practice, known as the 'p-y method', was developed with offshore oil and gas applications in mind and is not well suited to the dimensions and highly dynamic behaviors which characterize offshore wind turbine systems [4]. In order to more accurately predict the performance and response of a bottom-fixed offshore wind turbine, more comprehensive design and analysis methods for piled foundations are needed; methods which are specifically developed for the offshore wind energy industry.

2. Offshore wind turbine support structures

A number of various offshore wind turbine support structures have been installed or proposed over the years, including monopiles, tripods, lattice towers, and floating structures. In the next five to ten years, as water depths extend to the 30-50 meter range and turbine sizes increase past 5 MW, the most likely support structure topology to be used is the lattice tower. While lattice towers have been used extensively in the oil and gas industry, the loading applied to an offshore wind turbine lattice tower is quite different than for an oil platform [5].

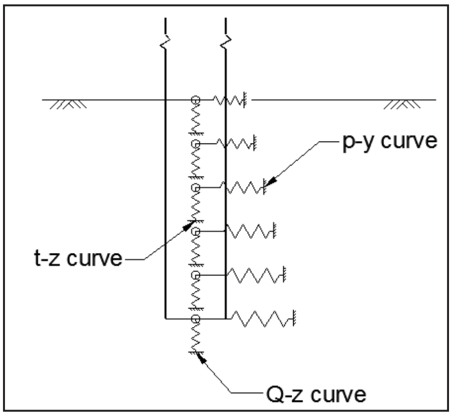
To begin with, oil platforms place extremely large, mostly static vertical loads on the support structure, while a wind turbine support structure experiences a much higher ratio of lateral loads and overturning moments. The load on a wind turbine support structure is additionally more highly dynamic due to the 1P and 3P turbine rotor vibrations, as well as from fluctuations in the thrust force due to wind turbulence. Wave loading on a wind turbine support structure is also more critical than for an oil platform thanks to the significantly lower total mass which places the natural frequency of the structure much closer to the wave loading frequency. Typically, offshore wind turbine support structures are designed so that the natural frequency lies between the frequency of the wave loading and the frequency of rotor vibration, a so called 'soft-stiff' design.

These characteristics make it much more imperative to have an accurate model of the dynamic performance of the foundation for an offshore wind turbine, as was shown by Van Buren in a comparison of wind turbine support structures with fixed foundation conditions to the same structures with foundations described by p-y curve models [6]. Because the natural frequency of the support structure lies close to the frequency of loading, even small deviations from the actual natural frequency in the calculations can have detrimental effects on the estimation of the fatigue life of the structure. Simply using a static or pseudo-static analysis method cannot guarantee a proper design, as a conservative design from static analyses may lead to an un-conservative dynamic design. As the design of wind turbine support structures is dominated by the fatigue limit state, the dynamic characteristics of the system are more important than the ultimate static capacity.

While minimizing support structure costs in the oil and gas industry was of minimal importance compared to robustness and safety due to huge profit margins from oil production, costs in the wind industry must be significantly lowered to make offshore wind power competitive in the energy marketplace [7]. Thus far, the dominating pile design and analysis tool in the offshore wind energy continues to be the p-y method. While the method has so far proved to be useful, having more accurate foundation models will reduce uncertainties in the design of the support structure and allow for a more accurate prediction of the fatigue life, potentially leading to lower overall costs for the structure.

3. P-y curve method

The p-y method for designing offshore piled foundations has been utilized by the offshore oil and gas industry for decades and is based largely on work performed in the early 1970s [5,8]. This method has subsequently been adopted into offshore wind turbine design standards, including those by API, GL, DNV, and IEC [9-12]. The method approximates the stiffness of the soil-pile system with a discrete number of nonlinear soil springs arranged along the length of the pile. These springs act independently of one another and therefore do not affect the displacement of neighboring springs. The lateral resistance of the pile is handled by p-y curves, with 'p' representing the lateral resistance and 'y' representing the lateral displacement of the pile. Similarly, vertical resistance is treated with 't-z' and 'Q-z' curves; t-z curves for the vertical resistance due to skin friction along the pile, and Q-z curves for the end bearing resistance at the tip of the pile. A visual representation of this system can be seen below in figure 1.



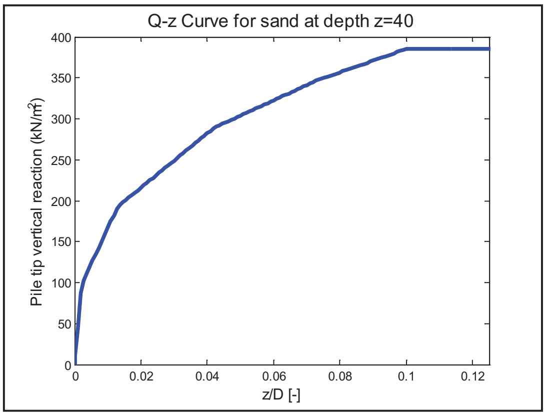


Fig 1. (a) visul representation of p-y method; (b) typical Q-z curve for sand

For a specific soil, the stiffness profiles of these springs are dependent only on the depth below the mudline at each spring location and the displacement of the pile at that depth. A unique curve for each spring is determined at every depth, save for the Q-z spring which is only located at the pile tip. The shapes of these curves are predetermined in the design standards and are defined through set relationships between pile displacement and the ratio of reaction force to the maximum possible resistance. One must simply calculate the ultimate resistance of the pile for lateral bearing, skin friction, and end bearing at each depth, and follow the given displacement-force relationship to determine the nonlinear spring profiles. The soil resistance is assumed to be equally distributed across the diameter of the pile.

3.1. Models for lateral dynamic behavior

The lateral resistance p-y curves are based on the Winkler hypothesis of an idealized beam on an elastic foundation. The ultimate resistance in lateral loading used in the design standards is derived from theoretical earth pressure models which have been calibrated by field tests. The failure model for sand follows a hyperbolic function which is a function of the internal friction angle of the soil and the depth below the mudline. The failure mode for clay is a linear function, dependent on the undrained shear strength and overburden pressure at each given depth.

3.2. Models for axial dynamic behavior

The t-z curves, which represent the vertical shaft friction along the length of pile, are determined by a total stress method for clays and an effective stress method for sands. The shaft friction force in clays is dependent on the undrained shear strength and overburden stress, while the friction in sands is determined using a dimensionless skin friction factor based on the soil classification. Similarly, the end bearing resistance, which is represented by Q-z curves, is determined from the undrained shear strength in clay soils and from a dimensionless bearing factor in sands.

While this manner of designing and analyzing piles has been used successfully in the past, a number of behaviors of the soil pile system are ignored by the p-y curve method. Many of these factors were of little importance for the oil and gas industry, but could have significant impacts on offshore wind turbines systems due to the greater importance of dynamic behaviors in a wind turbine system.

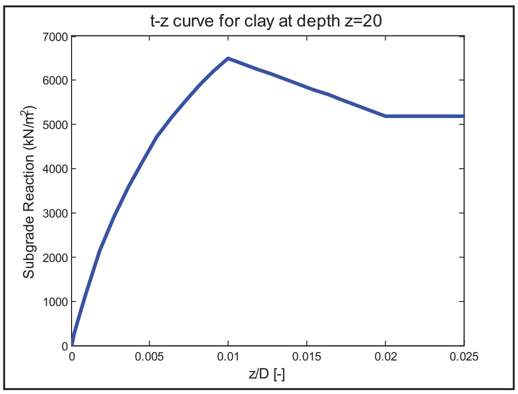
4. Dynamic behavior of piles

The interaction between piled foundations and the soil in which they are installed is a highly complex relationship. A proper analysis of this system must account for a number of nonlinearities which arise from material properties, geometry, and interaction effects [13]. The most notable of these is the nonlinear material behavior of the soil with regards to both stiffness and damping.

According to El Naggar and Bentley, the stiffness of the soil exhibits non-linear behaviors with respect to depth, strain magnitude, stress history, and the frequency of loading [14]. This nonlinear stress-strain relationship makes it very difficult to establish a rigorous solution for soil stiffness using continuum theory and led to the original development of the Winkler hypothesis and the p-y curve method. However, because the p-y method was developed using a pseudo-static approach, only the stiffness nonlinearities arising from depth and strain magnitude are properly dealt with, while the effects from stress history and loading frequency are not considered. These ignored effects can have significant consequences on the accuracy of the model, as large changes in soil stiffness can occur due to hardening, softening and pore-pressure accumulations, all of which are stress history and loading frequency dependent processes. Stress history nonlinearities also arise from time dependent phenomena such as permanent (plastic) deformations in the soil, and cyclic degradation of the soil strength due to plastic creep [15]. P-y curves do provide a provision for cyclic soil strength degradation in both the vertical and lateral directions when the pile is embedded in soft clay, but there is some debate as to whether this is appropriately handled [4].

Another important behavior of the soil pile system is soil damping, which can be divided into two main categories. The first of these is material (hysteretic) damping, which occurs due to the aforementioned softening and hardening of the soil during cyclic loading. The hysteretic nature of these softening and hardening processes is apparent, as the main mechanism for both is “damage” to the structure of the soil by a rearranging of the soil particle layout and changes in the soil particle contact interaction. The second form of soil damping is radiation (geometric) damping, which takes the form of wave propagation through the soil [16]. This process is highly dependent on the frequency of loading and to a lesser extent the stress history. The pseudo-static approach used in the development of p-y curves means that the damping from the soil is largely ignored by p-y curves. While soil damping is relatively minimal, it can nevertheless provide an important contribution in a wind turbine structure, particularly when the turbine is parked and provides very little aerodynamic damping.

Some additional significant nonlinear behaviors occur at the contact interface between the soil and the pile. This takes place in the form of slippage between the soil and pile in the vertical direction [17], and through the formation of gaps between the soil and pile when loading is in the lateral direction [18]. Both of these phenomena lead to discontinuities in the stress-strain relationship and must be carefully accounted for. Slippage is partially dealt with by t-z curves through the presence of a plastic strength profile above a given strain level as seen in Figure 2a, but this is a rather unsophisticated way to deal with a complex interaction and completely ignores any damping that may occur from such behavior [19]. Similarly, provisions for gapping in the p-y curve method are included in a simplistic manner for clay soils by introducing a strength degradation above a given strain level as is seen in Figure 2b. This degradation, however, arises more due to plastic deformations and cyclic creep in the soil and thus only deals with the permanent opening of a gap. A provision for a gap which repeatedly opens and closes due to cyclic actions, as can often occur with sands, is not considered by traditional p-y curves.



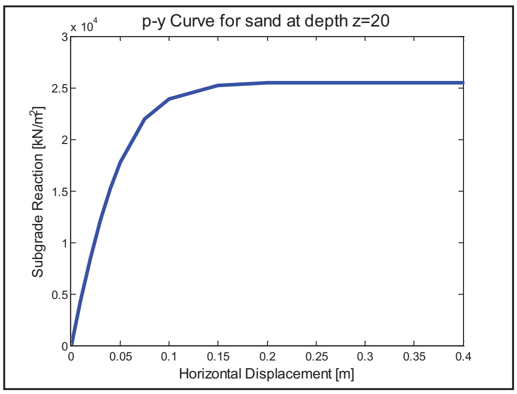


Fig. 2. (a) typical t-z curve for clay; (b) typical p-y curve for sand

Lastly, in a support structure with multiple legs such as a lattice tower, interaction effects between the piles must be included when the spacing to pile diameter ratio is less than approximately 9 [20]. Depending on the depth and soil conditions, many offshore wind support structures could fit within this zone. The close proximity of the piles can affect the stiffness and damping levels due to interactions with wave propagation and pore-pressure build up and dissipation. None of these effects are properly dealt with in the p-y method. When considering all of the shortcomings of the p-y method, it becomes clear that a more comprehensive technique is needed.

5. Dynamic p-y curves

5.1. Models for lateral dynamic behavior

Dou and Byrne (1995) highlighted the need for improved methods to determine the dynamic lateral behavior of piles by performing shaking tests on model piles and comparing the results with existing analysis methods [13]. The experimental data from the model tests was used to develop dynamic p-y curves derived from the measured bending moment distribution along the pile. The resulting curves showed the response to be highly nonlinear and hysteretic, particularly during strong shaking events. These derived dynamic p-y curves were then compared against p-y curves found in the API design standard and it was shown that the API curves underestimated the lateral soil resistance and damping levels during strong shaking events. This comparison demonstrated the need for improved dynamic soil-pile interaction models that could more accurately predict the behavior of piles to dynamic loading.

In effort to address this need, several models were proposed which utilize a number of nonlinear springs and dashpots placed together in a variety of series and parallel layouts to describe the soil-pile behavior. El Naggar and Bentley (2000) proposed a model in which the soil is separated into two distinct regions, the near-field and far-field as is seen in Figure 3a [14]. The near-field region adjacent to the pile utilizes a nonlinear spring and a dashpot in parallel to account for nonlinear soil stiffness and hysteretic damping. The far-field element consists of a linear spring and dashpot in parallel to allow for the propagation of waves to infinity to model radiation damping. This model improves upon traditional p-y models as it allows for hysteretic and velocity dependent (viscous) damping to be included in an analysis.

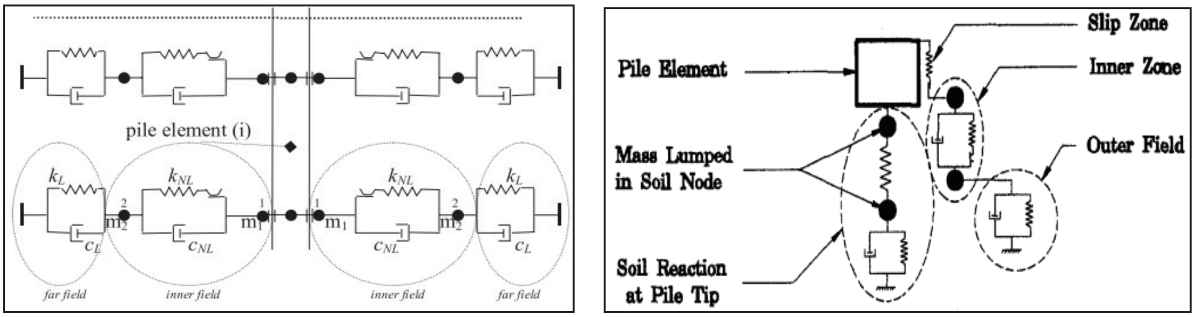


Fig 3. (a) dynamic p-y model representation: Adapted from [14]; (b) dynamic t-z and Q-z model representation: Adapted from [23]

Boulanger et. al. (1999) proposed a system which utilizes four springs and a dashpot in lieu of a single nonlinear spring [21]. This model accounts for gapping through use of a drag spring and closure spring in parallel, a plastic spring to account for permanent deformations in the soil, an elastic spring similar to traditional p-y curves, and a damper to account for radiation damping. This model was compared to centrifuge experiment results for earthquake motion and showed reasonably consistent results. This proposal adds capabilities for handling nonlinearities due to gapping and plastic deformations, in addition to accounting for hysteretic and radiation damping.

While both of these models provide improved capabilities over the traditional p-y curves found in the design standards, they were developed with an application in mind much different than an offshore wind turbine. These models were designed to analyze the response of a pile to motion inputs from the soil during an earthquake, whereas analysis of the piles in an offshore wind turbine system will require the opposite: motion inputs from the pile into the soil and the subsequent response of the soil-pile system.

5.2. Models for axial dynamic behavior

As mentioned previously, the need for models to predict the axial behavior of piles due to dynamic loading arose from studying pile driving. According to Rausche, et.al. [22], the study of pile driving is more than 100 years old and was traditionally calculated using an energy approach. With the advent of computing technology, more robust techniques became possible and many approaches have been proposed which account for nonlinear soil stiffness and damping characteristics.

Although a number of various solutions have been proposed, one in particular stands out as it utilizes the familiar and useful Winkler hypothesis and proposes a similar layout of springs and dashpots as those discussed for dynamic lateral behavior. This model, proposed by El Naggar and Novak [23], separates the soil into near and far field regions in the same manner as the work on lateral deformations by El Nagger and Bentley which was previously discussed. The inner region again is used to model the nonlinear stiffness and hysteretic damping provided by the soil, while the far-field elements are used to model wave propagation away from the pile. A rigid plastic sliding element is placed between the near field element and the pile to account for sliding. This model also provides a solution for the dynamic behavior of the end bearing resistance at the pile tip through the use of a nonlinear spring and a dashpot. A graphic representation of this model is seen in figure 3b on the previous page. Additional provisions in the model are included to account for group effects, a very important aspect when considering lattice or jacket support structures.

6. Model application to wind turbine analysis

Applying these dynamic p-y curve models to the investigation of an offshore wind turbine will enable the analysis to account for many of the nonlinearities not properly handled by traditional p-y curves, as was discussed in section 4. The added ability of these methods to account for damping in the soil will allow the simulation to predict the amount of energy from the rotor, wind, and wave loading which is dissipated through the foundation in the real system. This will potentially increase the estimated fatigue life of the support structure and bring the estimate from aero-elastic analysis closer to the true fatigue life of the real structure. Capabilities to more accurately handle gapping and slippage will provide a more complete picture of the displacement-stiffness relationship in the soil-pile system and will also provide an estimate of further energy dissipation ignored by simpler models but present in the real structure. Plastic deformation springs allow for the simulated soil stiffness to change over time according to the soil stress history, and will allow the overall pile stiffness to change accordingly, potentially altering the estimated fatigue life of the structure due to a change in natural frequency of the full support structure system during the simulation. Finally, the ability of the dynamic p-y methods to model interaction effects between adjacent piles will allow for a more accurate analysis of a lattice tower. Unfortunately, due to the nature of wind turbine analyses, simulations must be carried out in the time domain, inhibiting the ability to measure effects of the loading frequency in the soil-pile system.

In order to develop this model, a three dimensional finite element simulation of the foundation of a lattice tower for an offshore wind turbine must be carried out in effort to tune the parameters of the dynamic p-y model (i.e. the springs and dampers). Such a finite element analysis is currently under development which utilizes 4 distinct zones in concentric rings around the pile. The zone farthest from the pile consists of infinite elements which allow energy to radiate away from the system without being reflected back. The amount and rate of energy which is measured leaving the system in the FE analysis will be referenced in tuning the radiation damping dashpot in the dynamic p-y model. The next zone inward consists of an elasto-plastic medium from which output data will be utilized to tune the non-linear soil stiffness springs. The next zone consists of small strain elements which can be utilized in setting the parameters on the slip springs and the hysteretic damping dashpot. Finally, contact criterion between the pile and the small-strain elements in the FE model will be called upon to help determine the gapping spring parameters.

This finite element analysis model will be used in conjunction with an aero-servo-hydro-elastic simulation of a 10MW reference turbine currently being developed by The Norwegian Research Centre for Offshore Wind Technology (NOWITECH). This concept utilizes a lattice tower support structure which continues from the sea floor to the nacelle with no transition to a tubular tower as is often seen. The piles for this tower were designed using a MATLAB algorithm, developed by the author, which optimizes the piles according to mass through use of the pile capacity and structural requirement equations found in the IEC 61400:2007 design standard for offshore wind turbines. A diagram of this concept is seen on the next page in Figure 4. Time-domain simulations of this reference turbine with traditional p-y curve models for the pile foundations are performed using the software FEDEM, resulting in time-series data of displacements and rotations of the pile head. These time-series will be imposed on the piles in the FE simulation of the four pile-soil system and the resulting output from the simulation will be used to develop the dynamic p-y curve model by fitting the parameters of the springs and dampers to best match the output from the FE model.

A drawback to this type of more advanced soil-pile model is that current wind turbine solvers do not have the capacity to handle the added complexity and are only built to utilize traditional p-y curves. Therefore, a dynamic p-y model must be implemented into the simulation of a wind turbine through the use of an external dynamic soil model library in the form of a dynamic link library (DLL) or similar structure. Using this format will allow the model to be coupled with any aero-elastic solver that allows for the use of DLLs, with some minor changes to the structure to fit each given program.

7. Conclusions and further work

The use of traditional p-y curves in analyzing an offshore wind turbine does not account for many of the nonlinear behaviors of the foundation. By excluding from the simulation hysteretic and radiation damping, slippage and gapping at the soil-pile interface, interaction effects between the piles, and changes in stiffness due to stress history, an inaccurate picture of the damping and stiffness levels in the foundation is given. This can lead to an incorrect approximation of the fatigue life of the structure as the overall natural frequency of the structure may change over time, and energy dissipated out of the system through the soil is not accounted for in the simulation. Through the use of aero-servo-hydro-elastic simulations of a large offshore wind turbine and finite element modeling of the piles, an external dynamic soil model library which can be incorporated in the time domain simulations of offshore wind turbines will be developed.

Once this external library file for the foundation behavior is developed and implemented into wind turbine analysis software, the next step will be to investigate the effects of the added capabilities on the performance of the wind turbine and the support structure. Of particular importance will be the effects on the fatigue life of the support structure. Performing a structural optimization of the support structure, both with and without the use of the soil model library will give an indication at potential cost savings arising from the expected longer fatigue life when soil damping is included.

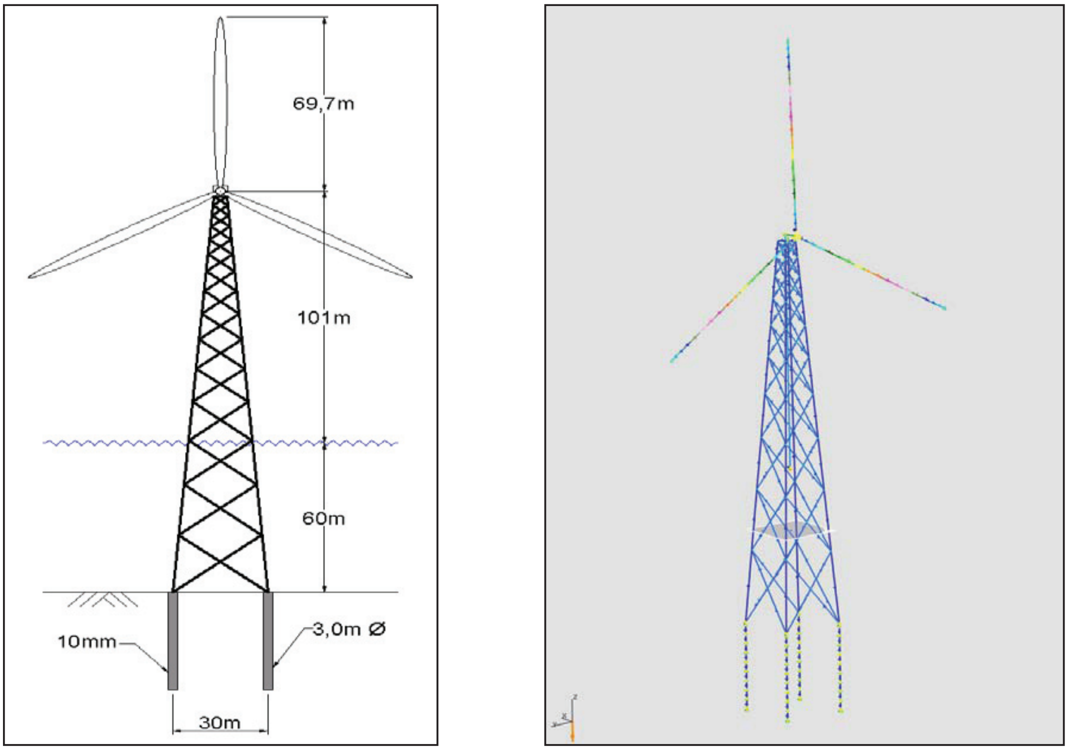


Fig 4. (a) Layout of NOWITECH 10MW reference turbine; (b) FEDEM model of reference turbine

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