Loading and Dynamic Response Considerations for the Design of Wind Turbine Foundations on South African Soils

Byron Mawer[1], Denis Kalumba[2] Charles Warren-Codrington[3]
[1]*Jeffares & Green, Pinelands, Cape Town, South Africa*
[2]*Department of Civil Engineering, University of Cape Town, Cape Town, 7701 Rondebosch, South Africa*
[3]*SMEC, Westway Office Park, 3629 Westville, South Africa*
E-mail: denis.kalumba@uct.ac.za

ABSTRACT: Wind energy has been selected an appropriate means of diversifying South Africa's energy mix and improving its electricity capacity in view of growing socio-economic and environmental pressures. However, this comes with engineering challenges, one being designing efficient foundations for wind turbine structures. This discussion was centred on the sources of loading that wind turbines experience and the consequences of this on the geotechnical design of gravity footings. Rotational stiffness of the foundation was shown to have an important effect on the dynamic response of the wind turbine tower, and thus, on the assumptions surrounding the calculation of the natural frequency of the global system. Means of assessing the rotational and lateral stiffness as well as models investigating soil stiffness inclusion in natural frequency assumptions were evaluated in the context of a South African case study, specific to the South Eastern city of Port Elizabeth. Soils of this region were dominated by weathered silty fine sands and varying degrees of pedogenic calcrete, creating unique challenges in design. Soil stiffness effects on natural frequency assumptions were found to be more critical than the minimum stiffness requirements applied by design guidelines and had a notable effect on dynamic amplification for an undamped system.

KEYWORDS: Natural frequency; Rotational stiffness; Cyclic loading; Pedocretes; Wind turbines, Gravity foundations

1. INTRODUCTION

1.1 Background

Two major themes underpin any discussion on energy in South Africa. The first relates to an electricity capacity deficit and poor service delivery, and the second is South Africa's dependency on fossil fuels for electricity production. Wind energy has been placed at the centre of South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in view of increasing and diversifying South Africa's electricity capacity amidst growing environmental and natural resource constraints. An important engineering challenge of today is to provide foundations for the wind turbine structures safely and efficiently based on site-specific geological conditions.

1.2 Foundation Engineering: the Challenge for Wind Turbine Structures

Much of the knowledge and experience of foundation behaviour, design and construction for wind turbines is derived from projects in the Northern Hemisphere, due to prolific wind farm development in countries such as, The United Kingdom (UK), United States of America (USA), Denmark, Germany and the Netherlands. Similarly, temperate zone transported soils of the Northern Hemisphere form the origin of modern principles of soil mechanics, soil classification and experience with regard to soil and rock behaviour. Soils of tropical areas, that were not subjected to the glaciations of the Pleistocene era, are, in contrast, characterised by deep weathering and advanced pedogenesis (Netterberg, 1994). This has resulted in the founding conditions of much of Southern Africa, and other semi-arid areas of the world, being characterised by variably cemented soils called duricrusts or pedocretes.

Similarly, the current trend within the wind energy industry is not to optimise wind turbine structures for specific sites, but rather to produce a selection of standard wind turbine super-structures in order to keep manufacturing costs low. The task then is to choose a standard wind turbine from this selection and verify that it is capable of withstanding the required limit states for the given location (DNV/Risø, 2002). Conversely, foundation design is a process which should be site specific in order to account for material variability across the significant area on which wind farms are generally constructed. Therefore, in order to achieve a safe and efficient design, the engineer should:

- have a sound understanding of the structure to be supported, the loading and the dynamic structural response that will be experienced in conjunction with,
- Knowledge of the local soil and rock conditions prevalent on site as well as the geotechnical practises of the respective area or country.

The interaction between structural and geotechnical engineering is therefore vital, and is a theme which is threaded through each of the following sections, covering topics including the loading and operational states of wind turbine structures, the dynamic response of tower-foundation systems and an overview of critical aspects pertaining to design checks. This is presented with respect to the behaviour and characteristics of a South African case study close to the South East city of Port Elizabeth. Figure 1 presents an overview of these major themes.

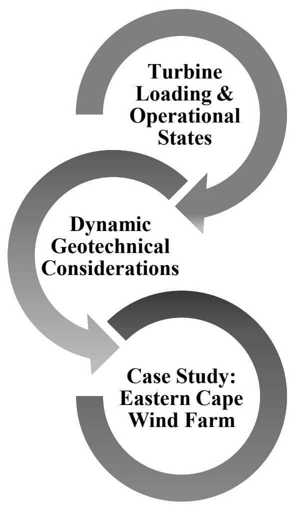

Figure 1 Overview of Themes (Warren-Codrington, 2013)

2. WIND TURBINE MECHANICS AND DYNAMICS

The term *load* refers to forces or moments that may act upon the wind turbine structure as a result of (1) its external conditions and (2) the dynamic response of the structure through its mechanical operation and response to time-varying external loads. All of the loads acting on a wind turbine must ultimately be transferred to the ground through the tower and foundation. This section of the paper, firstly presents an overview of the wind turbine loads and how they are affected by the operational state of the turbine. This is then followed by an explanation of how these key aspects affect the dynamic response of the foundation soil.

2.1 Loading Standards

Environmental conditions govern wind turbine loading, with wind characteristics such as speed and turbulence playing the greatest role. Lightning, snow, frost, fire and rain are also key loading considerations, but mainly affect the durability of the structure. The wind turbine should be designed according to the anticipated external conditions with respect to the IEC 61400 standard in conjunction with local design and construction standards. The International Electrotechnical Commission (IEC) is a non-profit, non-governmental international standards organisation that prepares and publishes codes for electrical, electronic and related technologies – collectively known as "electrotechnology". Additionally, guidelines such as DNV/Risø (2002) should also be observed. These standards and guidelines will be alluded to in the following discussion, but not explored in detail as they are well established and accessible to any wind turbine designer.

2.2 Source of Loading

Wind turbine structures are subjected to a number of forces and moments based on the airflow characteristics of the area in which they are erected. Using the forces of drag and lift, wind turbine systems manipulate the energy of the head wind they are exposed too, and generate their own wind tangentially to the direction of rotation of the rotor blades, causing the system to oscillate. Most modern wind turbine mechanisms make use of primarily lift forces to generate this rotation, as the speed of revolution is not limited by the wind speed of the area, in contrast with those powered by drag.

The resultant loading for these systems is modelled using complex software packages that predict the stresses and strains experienced by the structural elements through the actions of the turbulent fluid flow. This is generally investigated specific to the turbine model that is being considered, with the resulting loading data being provided by the turbine manufacturer. The manufacturer considers all the critical design load cases identified by the IEC 61 400 and provides those critical for the ULS and SLS foundation design checks for both structural and geotechnical applications. This is presented as force and moment values along the x, y, and z directions of the turbine as shown in Figure 2. The loads in the x and y directions are often combined in to resultant force and moment acting in some direction parallel to the base of footing, and manufacturers including Siemens and Vestas provide the forces in this format.

Table 1 highlights the loads for a Vestas V112 3 MW 1540rpm HH 94 IEC2A turbine which was used in the study by Mawer (2015), when conducting design checks on gravity footings using soil data from wind project sites in South Africa. In this research, the two extreme wind load cases found during normal and abnormal operating conditions respectively were used for all ULS design checks such as bearing capacity and overall structural stability. Normal wind load cases under normal operating conditions were used for SLS design checks such as that of settlement. The final load considered in gravity foundation design would be that of the self-weight of the footing acting vertically down in z-direction or the weight and lateral earth forces when considering a piled solution.

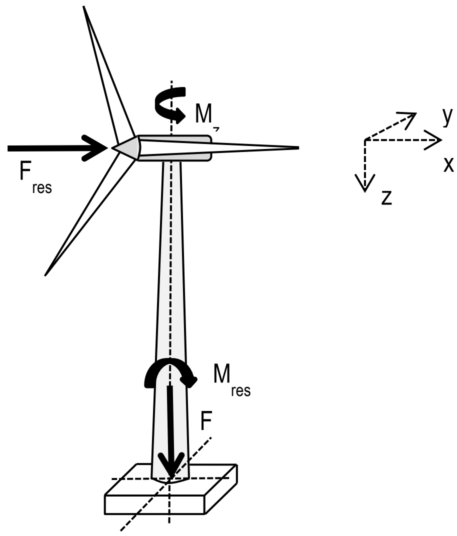

Figure 2 Forces and Moments applied to wind turbine structures (Mawer, 2015)

Table 1 Loading for Vestas V112 3 MW 1540rpm HH 94 IEC 2A

EXTREME LOADS
Normal Operation

DLC	M_{res} (kNm)	M_z (kN)	F_{res} (kN)	M_z (kNm)	**PLF**
3.2	66700	-353	695	-4590	1.35

Abnormal Operation

DLC	M_{res} (kNm)	M_z (kN)	F_{res} (kN)	M_z (kNm)	**PLF**
6.2	85100	1551	1031	-4500	1.35

NORMAL LOADS
Normal Operation

DLC	M_{res} (kNm)	M_z (kN)	F_{res} (kN)	M_z (kNm)	**PLF**
1.1	49100	731	554	-4620	1.35

2.3 Wind Turbine Operational States

The operational states of a wind turbine rotor are central to the unique loading experienced by wind turbine foundations. Three rotor control philosophies are traditionally used to manage energy production, including: (1) passive stall, (2) active stall and (3) pitch regulation. The former two methods of power regulation are classified as stall regulated. Each of these control systems conveys different implications for the dynamic response of the soil-turbine system.

2.3.1 Passive Stall Regulation

Passive stall is defined by the blade angle relative to the hub being fixed, therefore, as the wind velocity increases, the angle of attack,α, will also increase until it reaches approximately, 14^0 at which point stall is induced. Stall in terms of wind turbines, is the point at which the angle of attack of the wind has surpassed that of the critical angle (14^0). Drag, or the resistance experienced as the blades try and pass through the flow of air, increases as stall occurs, resulting in extreme loading on the rotor, which is in turn transferred to the tower and foundation. Furthermore, the cross-sectional area of passively controlled rotors is fixed, and thus when parked no shedding of load may occur.

2.3.2 Active Stall Regulation

The active stall mechanism also uses a fixed blade-hub angle until the rated power is reached. At this point the angle of the blades relative to the hub is adjusted to optimise the lift and drag forces acting on the blades. This allows the rated power to be maintained through fluctuations in wind velocity and improves the load shedding of the structure. In a parked state the blades are pitched with the trailing edge into the wind which reduces the load on the rotor and the tower.

2.3.3 Pitch Regulation

Pitch regulated rotors are automatically controlled to reduce the angle of attack on the rotor blade and maintain the power producing capacity of the rotor by optimising the lift and drag forces. This is done by reducing lift rather than increasing drag, as in the previous cases. As the rotor can shed loads more efficiently, the advantage of this control mechanism is that their is reduced thrust on the rotor with increasing wind velocity.

The tower base moment is directly influenced by the rotor operational mode of the turbine due to shedding, or lack thereof in the case of stall controlled machines. That is, the thrust of stall-regulated machines tends to increase up to the cut out speed, opposed to the reduction in thrust associated with pitch-regulated rotors after the rated power has been reached (Bonnett, 2005). Figure 3 is indicative of this relationship, and shows the ability of pitch regulated machines to maintain the rated power while shedding load. The parked loading curves follow a simple squared relationship with respect to wind velocity, where the difference in magnitude between the two philosophies is based on passive regulated machines having greater cross-sectional area and drag forces when parked.

Therefore, the dynamic nature of wind turbine structures results in significantly higher loading during operation than what would be expected from a static structure of equal cross-sectional area. In addition, the rotor regulation philosophy has a significant influence on the tower and foundation loading, especially in the wind velocity range between 15 m/s and 25 m/s.

Typically, the control mechanisms discussed can be adapted for any turbine model based on the Client and turbine operators' preference although manufacturers often suggest the best operation mechanism for a particular model. In the case of the loads provided in the Vestas V112 3 MW system investigated by Mawer (2015), normal operating conditions considered a pitch-regulated philosophy. Under extreme wind conditions (>25m/s) and subsequently for ULS design, the turbine is parked to avoid damage to the mechanical constituents housed in the turbines nacelle.

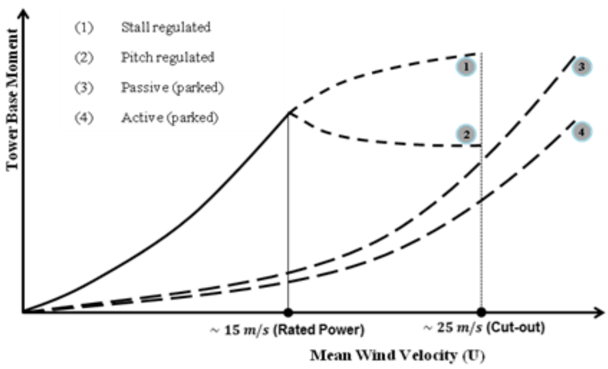

Figure 3 Loading Curves for pitch and stall regulated machines (Warren-Codrington, 2013)

2.4 Effect of Dynamic Nature of Loading on Soils

The natural variations in aerodynamic forces caused by wind require the foundation to resist various dynamic loads transferred via the turbines structural response. Dynamic soil loads can be defined in three main categories, including: (1) Impulse loads – a once-off dynamic wave moving through a soil medium, (2) Vibrations or cyclic loads – repetitive loading occurring at frequencies between 1-100 Hz for 10-100 cycles (Priest, 2012), and (3) Fatigue related loads – including those of very small frequency but at thousands or hundreds of thousands of load cycles. In wind turbine systems, fatigue related loads are the most common experienced in the supporting soils.

Additionally, to understating the type of load applied, an important parameter for ensuring foundation stability throughout the service life of a turbine structure is predicting the expected stress-strain response. The level of shear strain imposed on the foundation-soil system may be assumed to lie within the elastic threshold, at shear strains of approximately 10^{-3}. However, the excessive number of loading cycles experienced by these foundations leads to stiffness degradation over time being the primary concern. Figure 4 illustrates this schematically, where $N_4 > N_3 > N_2 > N_1$. These may be broadly termed "fatigue effects". Critically, the degradation of soil stiffness over time bears consequences on the super-structure as well, mainly in the form of changes in natural frequency due to stress redistributions. This is the subject of the investigation for South African pedocrete soils of the Eastern Cape.

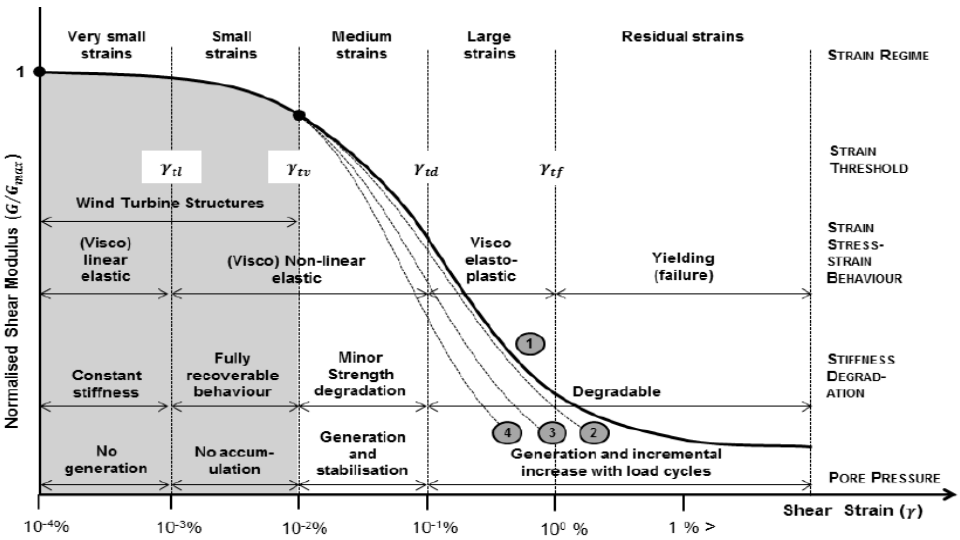

Figure 4 Loading Curves for pitch and stall regulated machines (Warren-Codrington, 2013)

3. DYNAMIC GEOTECHNICAL CONSIDERATIONS

3.1 Mass-Stiffness Relations of Gravity Footings

Wind turbine towers are slender structures, with low material stiffness and a rotating mass at the free-end. Turbines, if classified as typical engineering structures would be considered *isolated columns* in foundation-engineering terms (see Figure 5), which is an important consideration when assessing the way in which a turbine system will respond to dynamic loading. The ability of cyclic loads to amplify static stresses and strains experienced within the body of the structure is based on the idea of resonance. Resonance, in a structural sense, is the phenomenon in which a structural element tends to oscillate or vibrate at high amplitude when subjected to a vibration at a specific frequency or natural frequency as it is commonly referred.

For wind turbine systems, the effects of resonance can be avoided by designing the tower-foundation-soil system via one of two methods. Firstly, the dynamic amplification of loads can be reduced with damping systems that allow the resonant energy to dissipate quickly, not allowing the system to vibrate to the point where stresses and strains become dangerous. Damping systems are typically employed by using materials that have naturally high-energy dissipation properties like rubber, however for structures like wind turbines that are constructed from steel and concrete, this is not always possible. Consequently, the second and more favoured technique is planning the system so that the frequency at which the structure operates, is not within the range of the natural frequency of the structure. The natural frequency (f_n) of the structure is, very simply, a product of two main elements: the structures mass as well as its stiffness shown in Equation 1. The stiffness (k) in this sense is the combined stiffness of each of the systems constituents: the nacelle, tower, foundation and supporting soils and the mass (m) is the total mass of turbine and footing.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

The inherent natural frequencies that require avoiding in the design of wind turbines are based on the rotational rate of the rotor blades. The controlled frequency of rotation of the turbine mechanism housed in the nacelle is the first frequency that must be avoided and is commonly referred to as the 1P, mechanical working frequency. Secondly, depending on the number of blades that the turbine model possess, the second natural frequency is often referred to as the 2P (for a 2 blade system) and 3P (for a 3 blade system) blade passing frequencies. As a result, turbines can be designed in one of three ranges: (1) the soft-soft range where the natural frequency of the system is below the 1P frequency, (2) the soft-stiff range between the 1P and 2P/3P range, and (3) the stiff-stiff range, above the 2P/3P value. The natural frequency of efficiently designed tower-foundation systems exists between the 1P and 3P frequencies. Designing below the 1P natural frequency is irrational as it would result in inadequate structural stiffness to resist static loads effectively, and designing above the 3P range (stiff-stiff), although not uncommon, may result in highly-overdesigned systems (Bonnet, 2005). The working frequencies of the turbine are obtained from the range of operation design speeds that is then compared with these values in order to find safe design stiffness for which the foundation is designed. The dark grey area of the Campbell diagram in Figure 6, shows the narrow range of soft-stiff natural frequencies available for a safe design. This is consequently the reason for many wind turbine systems being designed in the stiff-stiff range, although the soft-stiff is more efficient.

To design the turbine system to lie within this range, the global stiffness of the structure must be calculated accurately. This is planned for by considering a simple isolated column model in Figure 5, founded on a gravity footing, and predicting the tower and soil stiffness respectively.

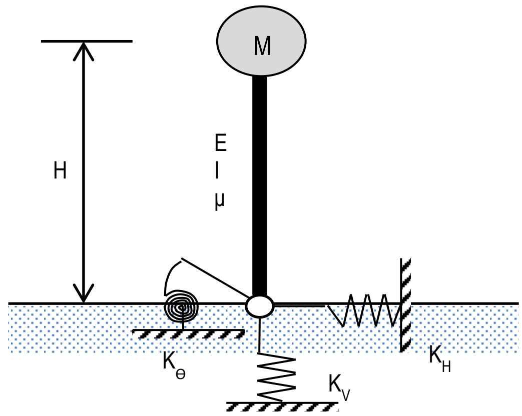

Figure 5 Idealised isolated column model of a wind turbine (Byrne, 2011)

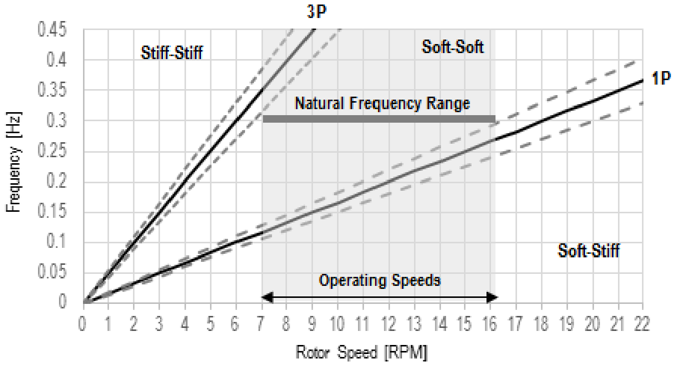

Figure 6 Campbell diagram for natural frequency design range (Von der Haar, 2014)

3.2 Soil Stiffness Assumptions

Vibrations lead to a coupled horizontal and rocking motion, a prominent aspect of the wind turbine behaviour, which strongly governs the design and is further exacerbated by the relatively low self-weight of the structure. Furthermore, vibrations coupled with the cyclic nature of the overturning and horizontal actions leads to the cyclic degradation of soil stiffness over time, making differential settlement a key concern. For this reason, the rotational and lateral stiffness of the foundation is of paramount importance. Accordingly, wind turbine manufacturers impose specific limits, as a function of hub height, on the foundation rotational and lateral stiffness. The minimum stiffness values in each of the two directions is often the limiting factor in gravity foundation design, and therefore stiffness checks are often the first of those conducted during planning of a new turbine system. Finite Element Methods are typically used to a find a minimum lateral and rocking stiffness combination, which can be used to find the minimum dimensions of a gravity footing (Wotjowitz and Vorster, 2014). DNV/Risφ (2002) provide several formulations that can be used to predict foundation stiffness in both the lateral and rotational directions. These equations are mainly dependent on radius of the footing (R), as well as the shear modulus (G) and Poisson's ratio (v) of the supporting soil. For a uniform semi-infinite soil half-space, or directly on bedrock, the following equations apply:

$$K_v = \frac{4GR}{1-v} \tag{2}$$

$$K_h = \frac{8GR}{2-v} \tag{3}$$

$$K_{\phi} = \frac{8GR^3}{3(1-\upsilon)} \tag{4}$$

The shear modulus value (G) used in these calculations must be adjusted to account for the applicable strain level imparted into the soil as well as to account for stiffness reduction over time. This is addressed using an appropriate stiffness reduction curve. There are a number of reduction methods available, although in South Africa specifically, the reduction curve suggested by Clayton & Heymann (2001) is often used in wind turbine applications:

$$\frac{G}{G_0} = \frac{E}{E_0} = \frac{1}{[1+16\gamma(1+10^{-20\gamma})]} \tag{5}$$

where G & E denotes the adjusted shear and elastic modulus, G_0 & E_0 are the small strain shear and elastic modulus, and γ is the applicable strain range for the structural application. Given the above-mentioned material characteristics the methods for determining soil stiffness parameters needs to be chosen carefully. Geophysical testing methods, such as the Continuous Surface Wave Test, have come to the fore in recent years. These methods are used to determine the shear wave velocity (ν_s) that induces distortion without volumetric strain in a material at a given density (ρ), and hence relates to the shear modulus of the soil by equation (6):

$$G_0 = \upsilon_s{}^2\rho \tag{6}$$

Geophysical testing imposes a very low level of strain on the respective material – between 10^{-6} and 10^{-3} %. This means that the shear wave velocity will travel at a speed which is a function of the very small shear strain modulus, G_0 (Clayton, 1999). Thus, advantages of seismic testing methods align well with the requirements of turbine foundation design:

- Firstly, the founding soil or rock is tested in-situ, minimising disturbances and maximising the volume of soil tested, producing a suitable and accurate range of stiffness data across the foundation breadth,
- Secondly, the strain levels imparted by geophysical methods are within the small to medium strain ranges, which is aligned with those imparted during the turbines design life.
- CSW and borehole tests are particularly useful as they allow the depth of investigation to be controlled to the zone of influence, and thus give stiffness-depth relations that are beneficial.

3.3 Modelling Natural Frequency of Wind Turbines

The natural frequency of the system is dependent on the global stiffness of the soil-foundation-turbine system, which therefore requires the soil stiffness to be taken into account when calculating the natural frequency of the system. Turbine manufacturers often quote the calculated natural frequency of their turbine models assuming the founding soils have an infinite stiffness, to exclude it from the calculation of f_n. As soils are in fact not infinitely stiff and have a finite stiffness in both the rotational and lateral directions, this assumption can often be incorrect. Typically, the stiffer the soil is, the more this assumption becomes irrelevant. DNV/Risφ (2002) suggests that the reduction in natural frequency taking into account the finite soil stiffness property is between 0-5%, and in special cases up to 20%. This can be investigated by calculating the stiffness of the turbine and combining it with the soil stiffness using the methods highlighted above. There are varying degrees of accuracy with which the tower natural frequency (f_n) may be determined. These stemmed from the single degree of freedom (SDOF) rigid models from (van der Tempel and Molenaar, 2002):

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{3EI}{(0.23m_{tower}+m_{turbine})H^3}} \tag{7}$$

where ω_n is the natural frequency in rad/s, EI denotes the flexural rigidity of the tower, H the height of the tower and m represents the mass of the respective components defined by the subscripts. Byrne (2011) additionally suggested a similar method for calculating tower natural frequency assuming a combined tower-turbine mass (M):

$$f_{ni} = \frac{1}{2\pi}\sqrt{\frac{3EI}{MH^3}} \tag{8}$$

The dynamic amplification approach is used to assess the dynamic response of a structure, whereby the dynamic magnification factor (D) is derived from the steady state response of the structure, and relates the steady state response amplitude (Y) to the equivalent static deflection that would have occurred if the respective load was static in nature (Q_0/k_y). The relationship between D and the frequency ratio $\beta = f/f_n$ is central to the dynamic control of the structure, where:

$$D = \frac{Y}{\left(\frac{Q_0}{k_y}\right)} = \frac{1}{\sqrt{\left[1-\left(\frac{f}{f_n}\right)^2\right]^2+\left(2\zeta_y\frac{f}{f_n}\right)^2}} \tag{9}$$

The reduction of the tower natural frequency due to the foundation stiffness may be accounted for by approximating the tower natural frequency using Equation 8, derived from the theory of a beam on an elastic foundation (Byrne, 2011). This was also expanded by Mawer (2015) into an equivalent global stiffness formulation based on the van der Tempel and Molenaar (2002) method, highlighted in Equation 11 below.

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{13EI}{m\left(\frac{H^3}{3EI}+\frac{H^2}{k_\varphi}\right)}} \tag{10}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{(m+0.227\mu H)\left(\frac{H^3}{3EI}+\frac{H^2}{k_\varphi}\right)}} \tag{11}$$

where k_φ denotes the rocking soil stiffness calculated in equation 4, m is the mass of the turbine nacelle, and μ is the mass per meter of the tower in kg/m. Observations of Equations 10 & 11 illustrate the effect that the soil stiffness has on the overall stiffness, where;

- a very stiff soil renders the dynamic response dependent on the tower stiffness, and
- a soft foundation-soil system renders the system unstable as the natural frequency of the system either approaches the 1P frequency (Figure 7), or becomes impractically low.

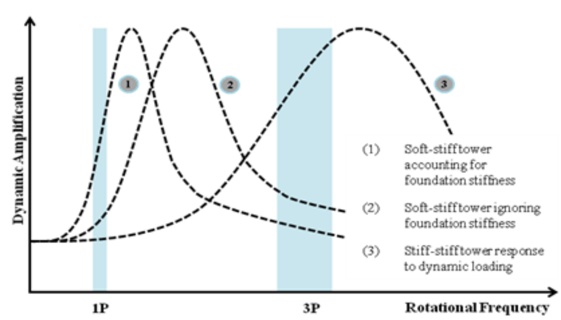

Figure 7 Effect of foundation stiffness on dynamic response of tower, schematic view of foundation stiffness effect on soft-stiff tower
(Warren-Codrington, 2013)

4. CASE STUDY: EASTERN CAPE WIND FARM

4.1 Properties of In-situ Soils

The Eastern Cape Wind Farm case study investigated by Mawer (2015) is considered representative of a large majority of potential wind energy sites along both the Eastern and Western coasts of South Africa due to the abundance of pedogenic material found in the sub-surface soil profile. The site, close to the city of Port Elizabeth, is generally underlain to varying degrees by the Algoa, Uitenhage and Gamtoos Group rocks with each group contributing to the overlying soil deposits found on the site. According to Almond (2010), Algoa group rocks are typically described as aeolian, coastal and shallow marine sediments with a large carbonate constituent due to the buried shells and marine life. After many years of deposition, solution and repreciptation of carbonate minerals; tough, white surface pedogenic calcretes form in varying degrees throughout the soil profile. Additionally, the Gamtoos group rocks typically weather into a fine red silty sand type soil with reasonable strength.

A number of boreholes conducted on the site, revealed a soil profile dominated by red silty sand to depths of up to 30m with the occasional inclusion of poorly to moderately formed hardpan calcrete lenses. These lenses usually ranged in thickness of between 0.2-1.3m in thickness, generally increasing in thickness with depth. SPT and other common laboratory testing techniques were used in order to generate soil properties for both the calcrete and silty sand material found in the vicinity of the site (see Table 2). CSW testing was also conducted in order to generate the small strain shear modulus for the site. The stiffness-depth profile (Figure 8) indicated favourable conditions for founding, with a trend of increasing stiffness with depth including an occasional spike due to a calcrete inclusion in the soil bed.

Table 2 Soil properties and descriptions of Eastern Cape Site

Soil Properties

Depth (m)	γ_{bulk} (kN/m3)	ν	LL (%)	PL (%)	Classification
1.8	18.6	0.3	19	5	Silty Sand
7.5	19.2	0.3	21	4	Silty Fine Sand
20	18.9	0.28	ND	SP	Slightly Silty Fine Sand

Calcrete Properties

Depth (m)	Thickness (m)	Point Load Index	UCS (MPa)	RQD (%)
25	1.10	0.86	19.9	9

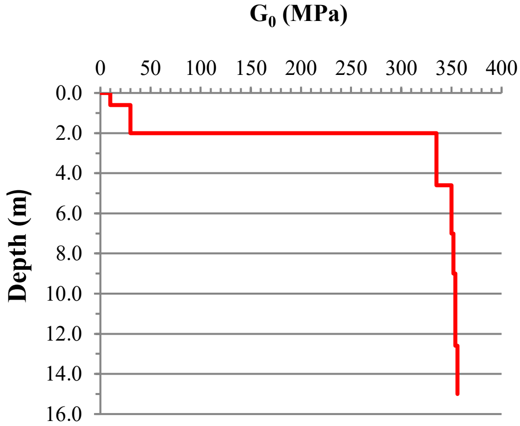

Figure 8 CSW results for Eastern Cape Wind Farm site

4.2 Stiffness Results

The stiffness reduced G value was calculated as 285 MPa after undergoing stiffness reduction, at the founding level of 3m. The results (as shown in Table 4), indicate that a footing of radius 4m or greater would be sufficient to meet the manufacturers stiffness limits for both of a General Electric 1.6 MW and Vestas V112 3 MW turbine highlighted in Table 3. Due to the fact that the sub-soil on this site was particularly strong, the minimum stiffness combination was not critical in the design. In this case, in order to maintain 0% gapping - no loss of contact area with the soil in overturning – the footing required a minimum diameter of 21m. Using this assumed design dimension in the stiffness calculations yielded values equal to 16 314 MN/m, 13 435 MN/m and 1088 GNm/rad for each of the critical resistance directions respectively. This high stiffness profile is expected for this site due to the various degrees of calcrete inclusions contained within the soil bed.

However, because calcrete in this region is commonly found in localized pockets often extending between 2 – 20m laterally, stiffness results may not be reflective over the entire foundation breadth, in which case a lower stiffness value may need to be used. Additionally, calcrete hardpans can form in thin layers with sand or finer materials - with far lower inherent stiffness and strength - trapped between each formation. This can produce localized softening of the trapped material causing differential settlement.

Table 3 Manufacturers limits on in-situ soil stiffness

	GE (1.6 MW)	Units	Vestas (3 MW)	Units
K_V	1000	MN/m	5000	MN/m
K_H	1000	MN/m	5000	MN/m
K_φ	50	GNm/rad	57*	GNm/rad

4.3 Effect on Natural Frequency of Soil-Turbine System

The natural frequency values with both a finite and infinite soil stiffness was calculated using the theory presented in Section 3 above, and the percentage difference by foundation size was compared with the predictions of the DNV/Risφ (2002). Typically, a reduction of more than 5% for the Vestas V122 3 MW turbine would take the design natural frequency within the 10% markers of the 3P range as the particular turbine considered was designed as a stiff-stiff system. The results in Table 5 show that for a Vestas 3 MW turbine, the 5 % reduction occurs with foundation radius of 6.25m, above that of the required radius for stiffness checks of 4m. As natural frequency assumptions are not commonly checked or suggested by manufacturers or design guidelines such as the DNV/Risφ (2002), this result is an important marker for future designs as it indicates that in some circumstances, natural frequency considerations can be more critical than the minimum stiffness combinations.

For the footing design dimension of 10.5m in radius, the natural frequency under the infinite stiffness assumption can be calculated as 1.048 Hz while under the finite stiffness assumption, as 1.033Hz; only a reduction of 1.43% and inside the acceptable range of stiff-stiff design frequencies. This reduction while having an insignificant effect on the value of natural frequency can still have a notable effect on the increase in dynamic stresses and strains that are experienced. As the dynamic amplification factor graphed in Figure 7 can effectively be considered a bell curve, peaking at the natural frequency value, the slight shift in natural frequency can cause an increase in dynamic amplification. In this case study, under the infinite stiffness assumption and considering an undamped system, the dynamic amplification factor was calculated as 3.89 at a frequency of 0.89 Hz (the 3P limit). Similarly, under the finite stiffness assumption this value was calculated as 4.36 due to the

Table 4 Stiffness values calculated for Vestas V112 3 MW turbine on Eastern Cape Wind Farm

	RADIUS (m)							
	3	**4**	**5**	**6.25**	**7.5**	**9**	**10**	**12.5**
K_V (MN/m)	4894	6526	8157	10196	12236	14683	16314	20393
K_H (MN/m)	4031	5374	6718	8397	10076	12092	13435	16794
K_φ (MN/m)	29366	69607	135952	265530	458837	792870	1087613	2124243
K_φ (GNm/rad)	29	70	136	266	459	793	1088	2124

- Minimum stiffness combination (radius 4 m column)
- Design stiffness combination (radius 10 m column)

Table 5 Natural Frequency reductions on Vestas V112 3 MW turbine for Eastern Cape case study

		RADIUS (m)							
		3	**4**	**5**	**6.25**	**7.5**	**9**	**10**	**12.5**
		% Reduction in Natural Frequency							
Byrne (2011)	GE 1.6 MW	11.9	5.2	2.7	1.4	0.8	0.4	0.3	0.2
	Vestas V112	45.0	20.9	11.1	5.8	3.4	1.9	1.4	0.7
	Siemens 3.2	35.5	16.2	8.5	4.4	2.6	1.5	1.1	0.5
Tempel (2002)	GE 1.6 MW	12.7	5.9	3.3	2.0	1.4	1.1	1.0	0.8
	Vestas V112	45.7	21.5	11.6	6.3	3.8	2.4	1.9	1.2
	Siemens 3.2	35.7	16.4	8.7	4.6	2.7	1.6	1.2	0.7

- Less than 5% reduction in f_n
- Between 5-20% reduction in f_n
- Greater than 20% reduction in f_n

reduction in natural frequency. This potentially increases a strain of 0.01 by 47% from that assumed under the infinite stiffness assumption.

5. CONCLUSION

Wind turbine structures are inherently dynamic. Loading from aerodynamic, rotational and inertial sources all contribute to a system dominated by high overturning moments and vertical loads. Turbine control mechanisms also significantly affect the dynamic response of the foundation leading to the necessity of considering dynamic soil response and soil-structure interaction in design.

As stiffness and mass are key parameters to the occurrence of resonance in the global system, the soil stiffness parameter and its effect on the natural frequency of the system was found to be a vital consideration in design. The natural frequency of the tower-foundation system should lie within an acceptable range, generally accepted as between the 1P and 3P range or above the 3P buffer. In order to achieve this, the rotational and lateral stiffness of the foundation are calculated by methods suggested by the DNV/Risφ (2002) using a soils inherent shear modulus obtained typically through geophysical methods and adjusting it for a soils expected level of plasticity.

To explore these effects on design, a South African case study was considered based along the South East coast of the country. This site, currently housing a wind energy project, was dominated by weathered silty fine sands of high strength and pedogenic calcrete layers. Pedocretes, as soils with highly cemented authegenic minerals, can pose specific foundation challenges, such as:

- Lateral and vertical variability, exacerbating differential settlement,
- Contain sandwiched layers of weaker materials, giving false reading of strength and high stiffness, and
- Include unpredictable discontinuous and degrees of formation that can potentially be detrimental to foundation performance.

In this case, the effect of foundation stiffness on the natural frequency of the turbine system was found to be more critical than that of the minimum combination of rocking and lateral soil stiffness often quoted in designs guidelines. Reductions in natural frequency additionally where found to have significant effects on dynamic amplification assuming an undamped turbine.

6. REFERENCES

Almond, J.E., 2010. Paleontological heritage assessment of the Coega IDZ, Eastern Cape Province, 112 pp. plus appendix. Natura Viva cc, Cape Town.

Bonnett, D., 2005. Wind Turbine Foundations – Loading, Dynamics and Design. Struct. Eng. 3, 41–45.

Byrne, B., 2011. Foundation Design for Offshore Wind Turbines, in: Géotechnique Lecture 2011. Géotechnique, London.

Clayton, C.R.I., 1999. Assessing the Stiffness of Soils and Weak Rocks, in: Wardle, G.R., Blight, G.E., Fourie, A.B. (Eds.), Geotechnics for Developing Africa. A. A. Balkema, Rotterdam, pp. 303–315.

Clayton, C. R. I. & Heymann, G., 2001. Stiffness of geomaterials at very small strains. Geotechnique 51, No. 3, 245-255.

DNV/Risø, 2002. Guidelines for Design of Wind Turbines, 2nd ed. Det Norske Veritas (DNV) & Risø National Laboratory, Copenhagen.

Mawer, B., 2015. An Introduction to the Geotechnical Design of South African Wind Turbine Gravity Foundations. MSc Dissertation. University of Cape Town, South Africa.

Netterberg, F., 1994. Engineering Geology of Pedocretes abd Other Residual Soils, in: Keynote Paper for the 7th IAEG Congress.

Van der Tempel, J., Molenaar, D.P., 2002. Wind Turbine Structural Dynamics – A Review of the Principles for Modern Power Generation , Onshore and Offshore. Wind Eng. 26, 211–220.

Von der Haar, C. 2014. Design Aspects of Concrete Towers for Wind Turbines. Proceedings of Int. Sem. On Design of Wind Turbine Support Structures. 3 September 2014. 37-46.

Warren-Codrington, C., 2013. Geotechnical Considerations for the Design of Onshore Wind Turbines – Adapting Knowledge and Experience for Founding on South African Pedocretes. MSc Dissertation. University of Cape Town, South Africa.
Wojtowitz, G, Vorster, E., 2014. The Design of Gravity Foundations for Wind Turbines for West Coast 1 Wind Farm. Proceedings of the 8th South African Young Geotechnical Engineers Conference. 17-19 September 2014. Stellenbosch, South Africa. 379-388.

Table of Notation

Symbol	Description	Units
f_n	Natural frequency of system	Hz
f	Experienced frequency of system	Hz
ω_n	Natural frequency in rad/s	rad/s
m_{tower}	Mass of turbine support tower	kg
$m_{foundation}$	Mass of turbine foundation	kg
M	Total mass of system	kg
μ	Mass per meter of tower	kg/m
EI	Flexural rigidity constants	Nm^2
k	Global structural stiffness	N/m
k_v	Vertical soil stiffness	MN/m
k_H	Lateral soil stiffness	MN/m
k_φ	Rocking soil stiffness	MN/m
k_y	Static vertical stiffness	N/m
H	Height of turbine tower	m
G_0	Small strain shear modulus	MPa
E_0	Small strain elastic modulus	MPa
G	Strain adjusted shear modulus	MPa
E	Strain adjusted elastic modulus	MPa
v	Poisson's Ratio	-
γ	Strain level experienced in soil mass	%
R	Radius of proposed footing	m
Q_0	Equivalent static load	N
Y	Steady state response amplitude	m