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Instrumentation and monitoring of an onshore wind turbine piled-raft foundation

Hendrik LOUW[1], Elsabe KEARSLEY[1]

[1]Department of Civil Engineering, University of Pretoria, Pretoria, South Africa
Corresponding author: Hendrik Louw (henilouw@gmail.com)

Abstract

With a rapidly growing population, South Africa has experienced a significant increase in electricity demand over the past few decades. The majority of the current electricity demand is satisfied through coal-fired power generation units, with the rest generated from other sources such as nuclear power plants and renewable energy generation, including onshore wind farms. As South Africa has a high level of renewable energy potential, with generation capacity largely centred around wind, more wind farms are being erected with the focus on fewer, but taller structures to deliver the same electricity output. The increase in both the vertical and especially the horizontal loads acting on these taller structures needs to be accounted for, resulting in the size of the foundations supporting these structures increasing significantly. Due to limited research available, and the lack of full-scale instrumentation and testing on these foundations, designs of these support structures tend to be conservative resulting in uneconomical structures that are not sustainable.

This paper gives background on the instrumentation and monitoring system of an onshore wind turbine piled-raft foundation on a newly constructed wind farm near Wesley in South Africa. Various instruments were installed within the piles and the raft of the turbine foundation, supporting a turbine with a hub height of approximately 120 m. This allowed monitoring of the foundation's response to both self-weight and horizontal loading caused by the wind. Preliminary strain and temperature results obtained during the construction of the foundation are presented and discussed, highlighting concrete shrinkage and thermal effects. Strains measured inside the piles during turbine installation before operation and commissioning are also presented.

Keywords: Onshore wind turbines, Piled-raft foundation, Soil-structure interaction, Structural health monitoring

1. Introduction

In many civil engineering structures, the governing force driving the design, selection and size of most structural foundations is vertical loading, largely caused by the self-weight of the structure and imposed live loads, with little to no consideration typically given to potential horizontal forces that might act on the external structure. Horizontal loading normally only becomes critical in areas where winds of significant magnitude and duration are present, resulting in mentionable horizontal shear forces and overturning moments at foundation level that cannot be ignored, with the self-weight of the structure generally assisting in reducing its impact.

Renewable energy power generation is a fast-growing industry that strives towards environmentally friendly solutions to combat climate change challenges. With a rapidly growing population, South Africa has experienced a notable increase in electricity demand over the past few decades. The majority of the current electricity demand is satisfied through coal-fired power generation units, with the rest generated from other sources such as nuclear power plants and renewable energy generation, including onshore wind farms. As South Africa has a high level of renewable energy potential, with generation capacity largely centred around wind, more wind farms are being erected in an attempt to meet carbon dioxide reduction targets. Focus on these wind farms is drawn towards taller wind turbine structures, erecting fewer turbines to deliver the same energy output. The increase in both the vertical and especially the horizontal loads and overturning moments acting on these taller structures needs to be accounted for, resulting in the size of foundations increasing significantly.

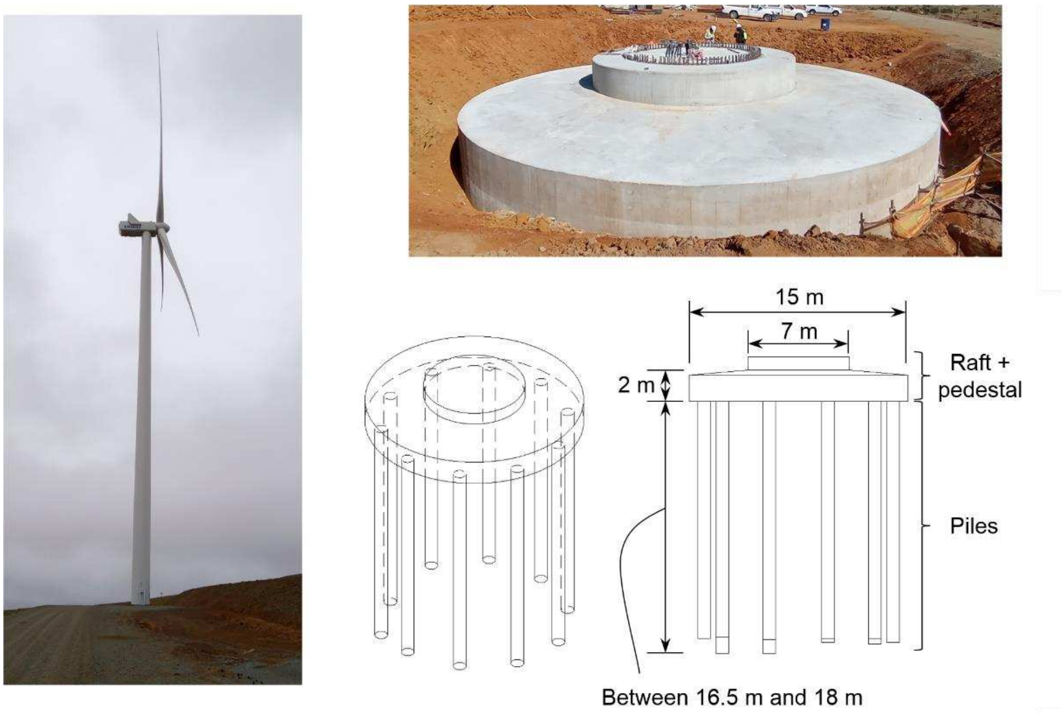
Typically foundations supporting these structures vary between the conventional gravity-based (raft) foundation or piled-raft foundation depending on the properties and depth of the supporting soil, with the response dominated by the interaction between the foundation and the soil (Poulos & Davis, 1980; Randolph, 1983; Tomlinson, 1986; Clancy & Randolph, 1993). Limited research and instrumentation have been conducted on full-scale onshore wind turbine foundations, resulting in the designs of these support structures being conservative, relying on simplified models that were not originally developed for wind turbine application, where the impact of the vertical self-weight of the turbine on the underlying foundation is smaller than that caused by the horizontal wind forces. Available research (Currie et al., 2013; Currie et al., 2015; McAlorum et al., 2018; He et al., 2019), however, only considered gravity-based reinforced-concrete foundations, all of which focused on the region where the turbine tower connects to the concrete foundation, either through an embedded steel can or an anchor cage. This was deemed critical to the stability of the overall turbine tower and was thus investigated by the researchers concentrating on vertical tower movement, crack deterioration and foundation rotation due to the large overturning moments caused by the wind, with little to no consideration given to soil-structure interaction effects.

Thus, in an attempt to investigate and better understand the soil-foundation interaction mechanisms involved, particularly for a foundation subjected to large horizontal loads and overturning moments, a full-scale piled-raft foundation of a newly constructed onshore wind turbine on a wind farm near Wesley in South Africa was instrumented. This paper gives background on the instrumentation and structural health monitoring system, highlighting the various instruments that were installed within the piles and the raft of the turbine foundation, supporting a turbine with a hub height of approximately 120 m. This allowed monitoring of the foundation's response to both self-weight and horizontal loading caused by the wind. Preliminary strain and temperature results obtained during the first 14 days after the construction of the raft part of the foundation are presented and discussed, highlighting concrete shrinkage and thermal effects. Strains measured inside the piles during turbine installation before operation and commissioning are also presented.

2. Foundation instrumentation and monitoring

2.1 Wind turbine and foundation description

The instrumented foundation is a piled-raft foundation and the supporting structure of one of ten newly constructed Vestas V126-3.45 MW wind turbines on the Wesley-Ciskei Wind Farm located near Wesley in the Eastern Cape Province, South Africa. Each turbine has a hub height of about 120 m, a rotor diameter of approximately 126 m and a generating capacity of 3.45 MW, giving the entire wind farm a combined capacity of 34.5 MW. Figure 1(a) indicates the turbine installed on the instrumented foundation. The instrumented foundation had a raft with a base diameter of approximately 15 m and a minimum thickness of 2 m. A pedestal of about 7 m in diameter and 1 m thick extended from the top of the raft to which the turbine was connected through an anchor cage.



(a) (b)

Figure 1: Instrumented wind turbine: (a) wind turbine; (b) reinforced-concrete foundation.

Ten 900 mm augered reinforced-concrete piles, positioned along a perimeter with a radius of about 6.5 m from the centre of the raft, extended to bedrock from the bottom of the raft and were connected to the raft through reinforcing bars extending from the top of the cast piles. The depth of bedrock fluctuated at the position of the instrumented foundation resulting in the lengths of the piles varying between 16.5 m and 18 m, respectively. Figure 1(b) shows the completed raft after being cast as well as a schematic of the whole piled-raft foundation.

2.2 Site conditions

The instrumented foundation is situated on a hill at an elevation of 130 m above sea level, with a thick layer of aeolian silty sands present to depths of about 22 m obtained from borehole data summarised in the site geotechnical report. According to the Unified Soil Classification System the soil was classified as clayey sand (SC) with plastic fines. Standard Penetration Test (SPT) results taken on-site indicate medium dense to dense soil conditions, with Dynamic Probe Super Heavy (DPSH) testing showing a proportional relationship between soil density and depth. The groundwater table was located at a depth of 25 m below the soil surface.

2.3 Instrumentation placement and sensors

A total of 17 concrete embedment vibrating wire strain gauges (VWSGs), with built-in thermistors, were installed. A VWSG was located in each pile at a depth of 2.5 m below the bottom surface of the raft (see Figure 2(a)), attached to the main reinforcing bars. Each pile in Figure 2(a) is labelled as indicated in black, with "P" referring to "Pile" and the accompanied number corresponding to the position of the pile from the centre of the raft, relative to North expressed in degrees. For the piles located within the prevailing wind direction (54 P and 198 P) additional VWSGs were placed at depths of 0.5 m and 4.5 m, respectively, to assess axial and bending stresses with depth. Red markers visible in each pile indicate the position of the VWSG relative to the centre of each pile.

Figure 2(b) presents the position of the VWSG installed within the raft of the piled-raft foundation, with the position label relative to North, similar to that with the piles, with the accompanied "R" referring to "Raft". A total of 14 additional concrete embedded VWSGs were installed in the top (T) and bottom (B) of the raft (see Figure 2(b)), either in the radial (Ra) or transverse (Tr) direction, allowing the measurement of bending stresses. Figure 3(a) indicates an example of a VWSG installed within a pile, attached to the main reinforcing bars.

2.4 Construction sequence and monitoring system

Construction of the foundation commenced in February 2020 with the casting of the piles, followed by the installation of the anchor cage and construction of the raft in July 2020. Installation of the wind turbine took place in February 2021, after which the turbine was commissioned in August 2021.

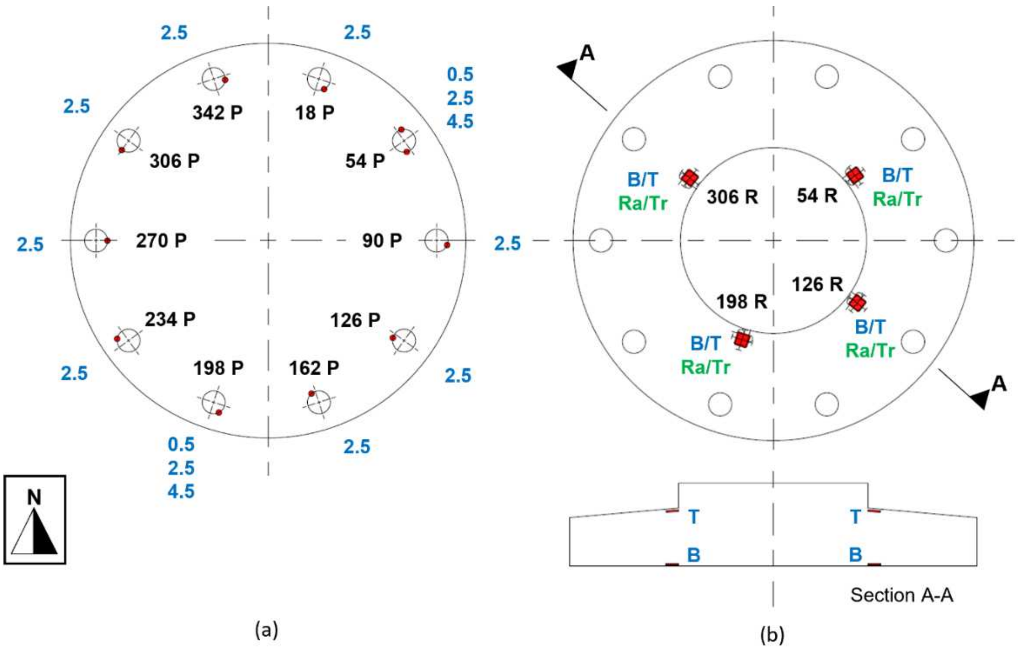


Figure 2: Instrumentation placement: (a) piles; (b) raft.

(a) (b)

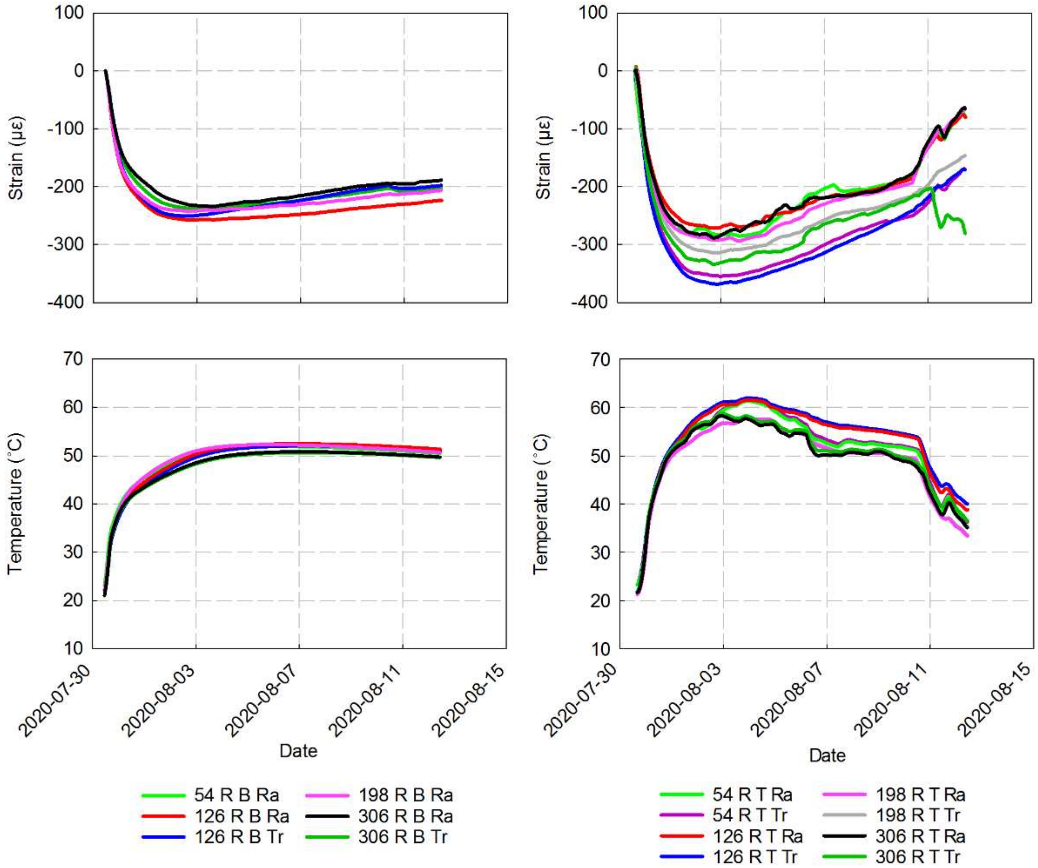
Figure 3: Instrumentation: (a) pile example; (b) datalogger and remote monitoring system.

Measurements were taken throughout the construction process of the foundation, however only where construction activity allowed, as well as during turbine installation and after commissioning to assess the response of the foundation under working load conditions. All measurements were taken using a Campbell Scientific CR6 measurement and control datalogger (see Figure 3(b)), accompanied by two AM16/32B multiplexers to increase the number of channels available to log simultaneously, with measurements taken at 15-minute time intervals. After turbine installation, the datalogger was placed within the wind turbine mast and data were monitored and downloaded remotely using a cellular modem connected to the datalogger.

3. Results and discussions

3.1 Raft cast

Strain and temperature data from the VWSGs were measured continuously for the first 14 days after the raft was cast and is indicated in Figures 4(a) and 4(b) for the bottom and the top of the raft, respectively.



(a) (b)

Figure 4: Total strain and temperature in raft: (a) bottom; (b) top.

The presented strain data represents the total strain measured in the concrete after the vibrating steel wire was temperature compensated using the built-in sensor thermistor. The total strain is a combination of both the mechanical and thermal strain experienced by the concrete, with the total and mechanical strain calculated using Equation 1 and Equation 2:

$$\mu_{total} = (R_1 - R_0) + (T_1 - T_0)(C_1) \quad (1)$$

$$\mu_{mechanical} = (R_1 - R_0) + (T_1 - T_0)(C_1 - C_2) \quad (2)$$

where R_0 = initial strain, R_1 = final strain, T_0 = initial temperature, T_1 = final temperature, C_1 = coefficient of thermal expansion of the VWSG steel wire (assumed as 12.20 με/°C) and C_2 = coefficient of thermal expansion of the surrounding concrete (measured as 8.46 με/°C).

From Figures 4(a) and 4(b) it can be seen that the maximum temperature caused by the heat of hydration only occurred after approximately five days from cast, with the maximum temperature towards the top of the raft being 10°C higher than that experienced at the bottom. This results in a slight thermal gradient existing within the concrete section potentially causing premature cracking of the concrete if not controlled. Consideration should thus be given when casting even larger foundations. The rate at which the top of the raft started cooling was significantly higher in comparison to that of the bottom as well, especially after the removal of both the shuttering and thermal blanket.

Within the first few days, the total strain measured was dominated by the thermal effects due to the exothermic reaction caused by the heat of hydration of the concrete causing tensile (negative) strains. When the thermal effects are removed (see Figure 5) it can be seen that mechanical strains were still present after two weeks from the start of the cast, even though no external loads were applied to the raft, and were caused by either shrinkage or differences between the thermal strains at the top and bottom of the raft. Figures 5(a) and 5(b) presents the mechanical strains measured at the bottom and top of the raft, respectively.

The casting of the raft had little effect on the existing piles cast earlier as indicated in Figure 6(a) for Pile 54 P, having a total of six VWSGs, three at different depths on opposite sides of the pile. A slight increase in strain (positive equals compressive) was observed due to the presence of the wet concrete from casting the raft, however, as the concrete started to cool and cure, a reversal of strains (becoming more negative) indicated the influence of concrete shrinkage on the piles through the steel bars extending and binding the raft to the piles. The fact that the strains at the same depth but opposite sides of the pile differ significantly, indicates the presence of bending moments, with the largest measured bending moment observed at 2.5 m below the bottom of the raft. As presented in Figure 6(b), it is interesting to note that only the top of the pile (0.5 m below the bottom of the raft) experienced an increase in temperature due to the exothermic reaction from the heat of the hydration process.

3.2 Shrinkage measurements – reference cylinders

Apart from taking concrete samples from the raft mix to obtain the 28-day compressive strength, two 250 mm diameter, 500 mm high cylinders were cast, each containing a VWSG (see Figure 7(a)).

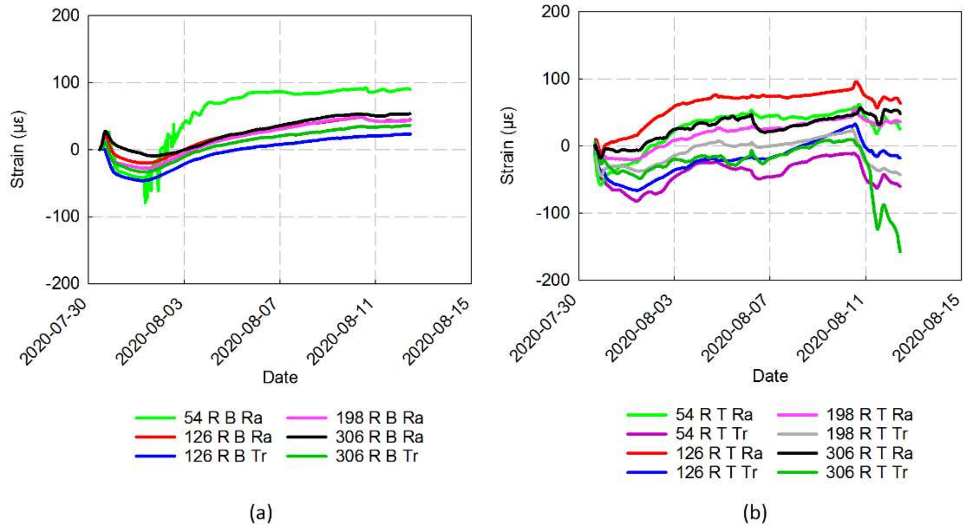


Figure 5: Mechanical strain in raft: (a) bottom; (b) top.

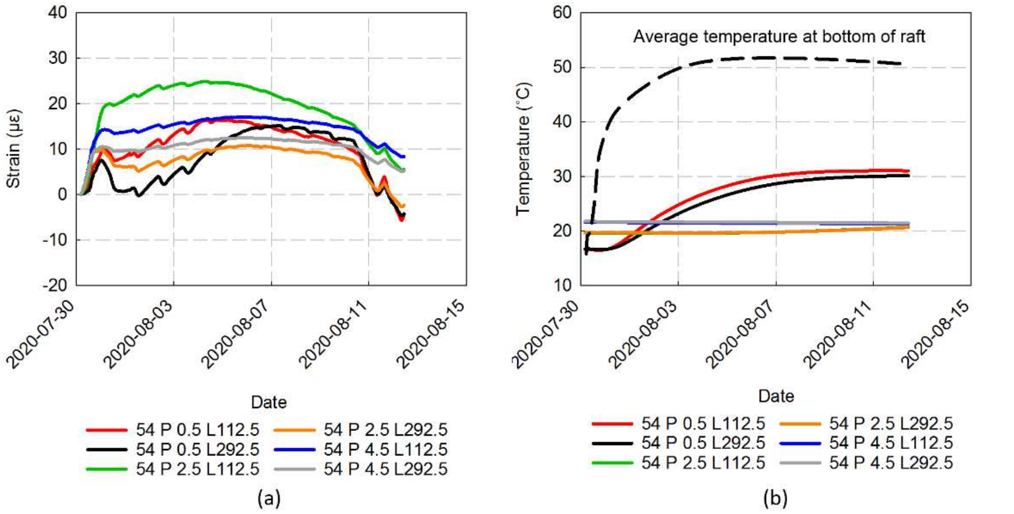


Figure 6: Pile response (54 P): (a) mechanical strain; (b) temperature.

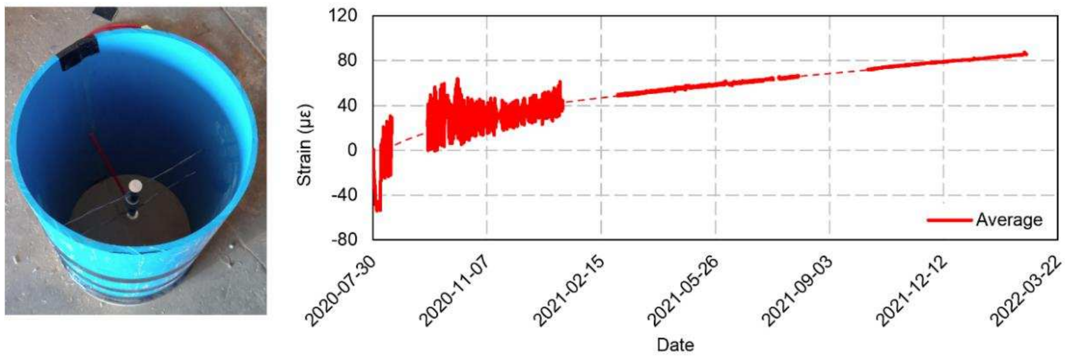
This allowed for the monitoring of the shrinkage of the concrete used to cast the raft, enabling its influence to be subtracted from the measured mechanical strain data obtained from the foundation. Figure 7(b) presents the average concrete shrinkage data obtained from the two cylinders, measured from the start of cast, including the most recent data. After nearly two years from casting it can be seen that concrete shrinkage could contribute approximately 80 με to the measured mechanical strain.

3.3 Pile strain data – turbine installation before commissioning

Figure 8 indicates the mechanical strain measurements for Pile 54 P during turbine installation, followed by a few days thereafter. The turbine was not yet operational, thus fluctuating strains were potentially due to the wind acting on the turbine tower and stationary blades. It should be noted that strain measurements were not zeroed since the casting of the raft, thus, measured data suggests a potential built-in bending moment already present within the pile caused by the shrinkage of the raft before turbine installation. As the turbine and the mast have known own weights and eccentricities, the strain increments recorded during turbine installation can be used to calibrate the system, making it possible to quantify the magnitude of the forces and moments induced in the piled-raft foundation during future storm wind conditions.

4. Conclusions

The results presented show the strains and temperatures obtained from embedded sensors during the first 14 days after the raft was cast, highlighting the influence and importance of concrete shrinkage and thermal effects on not only the response of the foundations' raft and piles during the construction period, but also over time. Preliminary strain results measured during turbine structure installation showed the possibility of calibrating the foundation system measured strains against the turbine's known own weight and gives an indication of the bending moment distribution in the piled raft.



(a) (b)

Figure 7: Shrinkage measurement (a) reference cylinder; (b) measured mechanical strain.

This would not only allow for the estimation of load sharing between the raft and the piles, but also the quantification of forces and overturning moments caused by the wind on the external turbine under normal working conditions. The effect of wind speed and wind direction on the bending moment response of the raft and piles will also be investigated. This paper demonstrated the successful installation of a structural health monitoring system for a wind turbine piled-raft foundation in South Africa. This set-up is currently being used to investigate the soil-foundation interaction mechanisms of onshore wind turbine foundations.

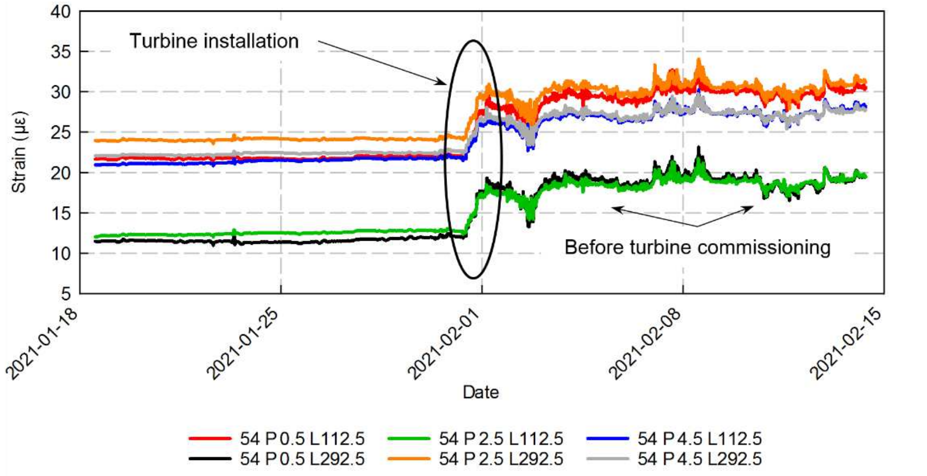


Figure 8: Pile mechanical strain measurements (54 P) – turbine installation.

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