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Development of a Numerical Model to Predict Wear in Grouted Connections for Offshore Wind Turbine Generators

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***Abstract*—**In order to better understand the long term implications of the grout wear failure mode in large-diameter plain-sided grouted connections, a numerical model has been developed and calibrated that can take advantage of existing operational plant data to predict the wear accumulation for the actual load conditions experienced over a given period, thus limiting the requirement for expensive monitoring systems. This model has been derived and calibrated based on site structural condition monitoring (SCM) data and supervisory control and data acquisition systems (SCADA) data for two operational wind turbine generator substructures afflicted with this challenge, along with experimentally derived wear rates.

***Keywords*—**Grouted Connection, Numerical Model, Offshore Structure, Wear, Wind Energy.

I. Introduction

HISTORICALLY, straight sided grouted connections without shear keys have been extensively used across the offshore wind industry to transfer loads from the bottom of the wind turbine tower to the top of the monopile (MP), via a transition piece (TP). Typically the TP is a large diameter steel circular section, which is placed over the smaller diameter circular section of the MP with overlap of about 1.5 diameters of the MP. The resulting annulus is then filled with high strength grout, which allows any piling verticality tolerances of the MP to be accommodated to ensure the verticality of the wind turbine generator (WTG) tower is within acceptable limits of 0.25° [1]. A typical arrangement is shown in Fig. 1.

Unexpected settlements of the TP relative to the MP in many of the offshore wind farms substructures reported since 2009, have resulted in existing grouted connections requiring extensive ongoing remedial works to relieve them from fatigue damage accumulation, while providing sufficient axial capacity. Subsequent investigation of the grouted connection behaviour [2] and through structural condition monitoring and site investigations [3] have shown that significant relative vertical displacements between the inner surface of the grout annulus and outer steel surface of the MP are occurring. Historical experimental testing undertaken as part of development of design standards for plain-sided, and shear keyed grouted connections for jacket substructures, has also shown relative movement is required for the mobilisation of axial capacity of the connection [4]-[6] and summarised in "submitted for publication" [7]. This displacement, in combination with compressive stress and the presence of water, has been shown by experimental testing to result in loss of thickness of both the steel and the grout [8].

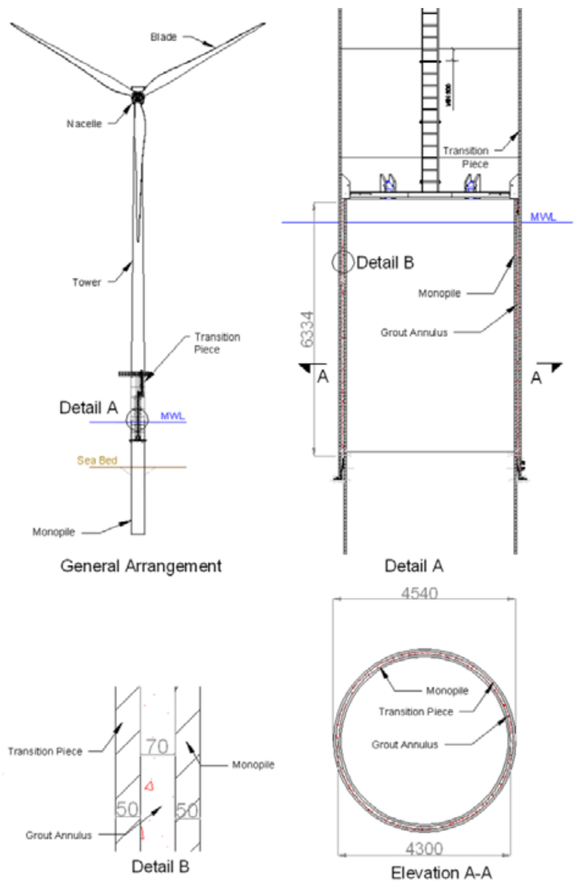

Fig. 1 Typical general arrangement of WTG monopile grouted connection substructure

To determine how significant this loss of thickness is over the lifetime of the plant, a numerical model has been

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developed to apply the wear rates derived from this experimental testing to the loading regime experienced by typical offshore wind turbine structures. The model provides an indication of the distribution of wear around the circumference and depth of the grouted connection, which will help to determine if further remediation of the existing grouted connection is going to be required within the remaining operational life of the wind turbine. It also provides the methodology for future designers and current operators of grouted connections to check designs against wear failure for their particular application, with their case-specific details.

This paper will describe the development and calibration against site structural condition monitoring of this numerical model.

II. Model Development

A review of the literature [7] and experimentation [8] undertaken previously as part of this research project, as well as research by [9], have indicated that wear is a function of the material properties, accumulated relative displacements and pressure applied to the surfaces. These factors will be directly influenced by the grouted connections specifications and the loads applied to them. By the very nature of a WTG, the loads experienced by the substructures will vary both spatially and temporally due to the variation of wind speed, direction and turbine operation, on a macro-scale between different sites, and micro-scale around the wind farm. As a result, the compressive stress and relative displacements experienced by each grouted connection will also vary. Ideally direct measurements of these stresses and displacements at various locations around individual grouted connections throughout a wind farm would be taken to provide the inputs to predict wear, but the cost of such extensive structural monitoring over the scale of a typical commercial wind farm with 100 such structures [10] would be prohibitive from a commercial perspective. The model has therefore been developed to take advantage of existing data collection on wind speed, direction and WTG power output through the WTG's supervisory control and data acquisition (SCADA) system, which is used to provide control and information on the status of the WTG.

To determine wear at circumferential locations and depths of the grouted connection, inputs from the WTG's SCADA system in the form of ten minute average data on wind speed, wind direction and power production from two full scale offshore WTG substructures, identified as H4 and K1, have been used. The model combines this time series information, with relationships derived from analysis of H4 and K1 structural condition monitoring (SCM) and SCADA data systems, to determine the values of the key factors for wear (displacement and compressive stress) through appropriate transfer functions. These transfer functions are required as the SCM was installed to understand the fatigue implications on the primary steel, as a result of the unexpected load transfer between jacking bracket and top of the MP caused by the settlement of the TP. Therefore some of the measured responses are not in locations relevant to determining wear in the grouted connection. These values of displacement and compressive stress are then used to determine the wear based on the experimental testing wear rates for the appropriate foundation conditions. The architecture of the model is shown in Fig. 2.

A. Inputs

In order to develop the relationships between the environmental inputs determined from the WTG's SCADA system and the structural response determined by the substructure's SCM system, a comparison of the two systems' outputs has been made. Details of the two systems are shown in Table I, with the layout of the SCM system, in relation to jacking bracket locations in the substructure, shown in Fig. 3.

The first steps in the data analysis was to synchronize the SCM and SCADA data time stamps and remove any periods of invalid data, due to system unavailability. Based on initial analysis of the SCADA and SCM systems data, a period of three months was chosen (January to March 2012) to derive the relationships, where limited drift in the data was apparent. This ensured that changes in substructure, such as gradual settlement of the TP relative to the MP would not influence the relationships derived. The initial analysis of the data also the relationships derived. The initial analysis of the data also highlighted that the vertical strain (SGA-V) outputs did not align with the structural response (Fig. 4).

This was due to the datum setting for the data not being practical to be set when the wind speed was exactly 0m/s, but instead was set at 0600, 01/09/2011, 2.6m/s and 174° and at 2150, 25/10/11 3.5m/s and 109° for K1 and H4 respectively. All strain gauge data therefore had to be corrected before any relationships were derived.

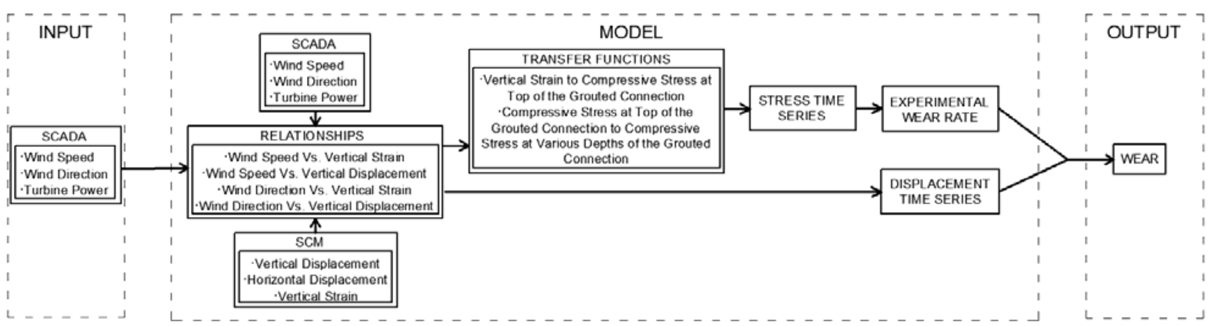


Fig. 2 Grout wear numerical model architecture

TABLE I
DATA ACQUISITION SYSTEM DETAILS

System	SCM			SCADA	
Acquisition frequency	20Hz			20Hz	
Periods of data analysis	01/2012 - 01/2013				
Instrumentation location	Top of grouted connection			Hub height	
Instrumentation abbreviations	**W-SX-Y-Z**			WS	Wind speed
	W	Foundation location	H4	AP	Active power
			K1		
	X	Bracket location	1-6	WD	Wind direction
			SGA-Axial strain		
	Y	Gauge type	RD-Radial displacement		
			VD Vertical displacement		
	Z	Orientation	V – Vertical displacement		

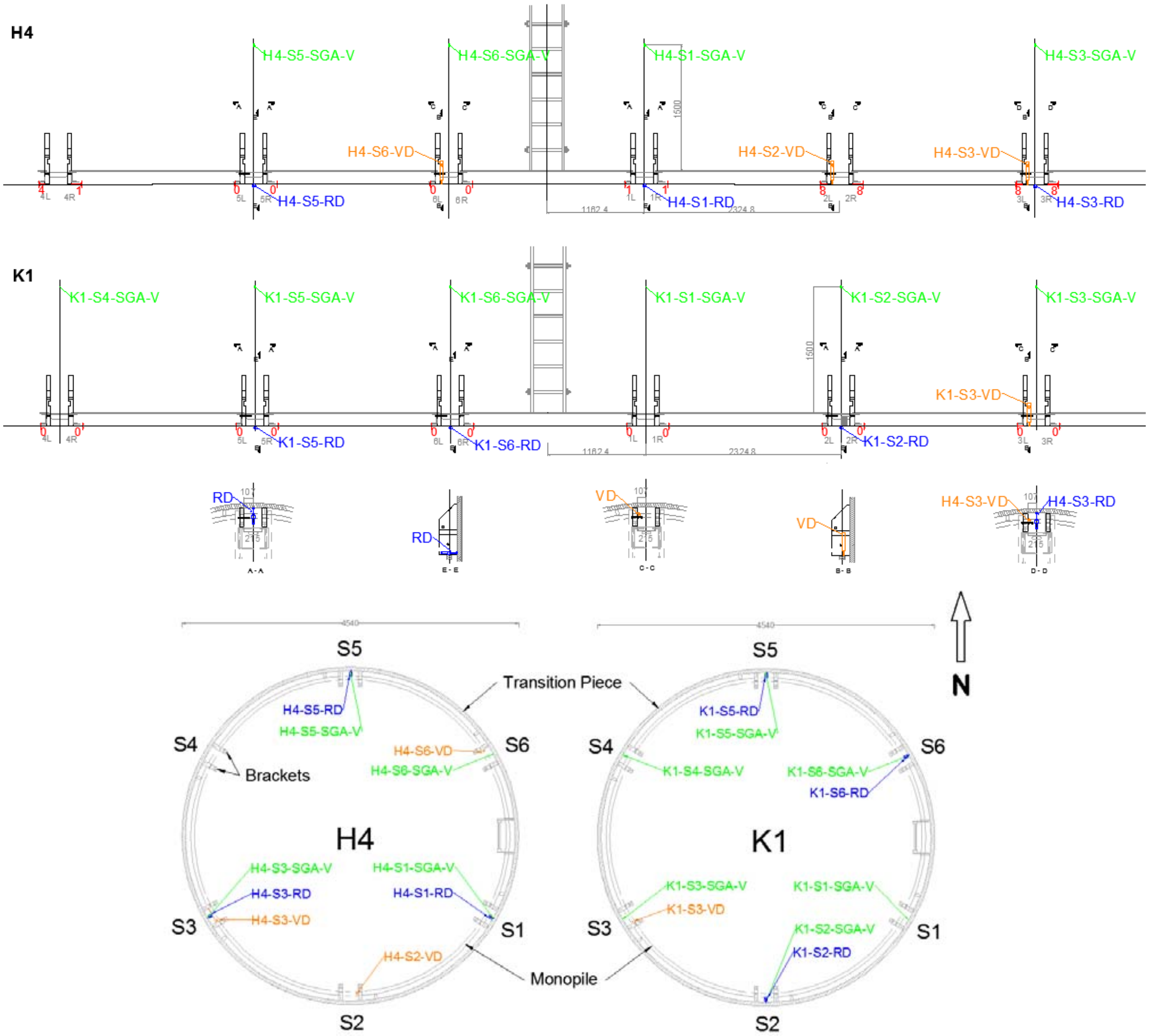


Fig. 3 SCM layout

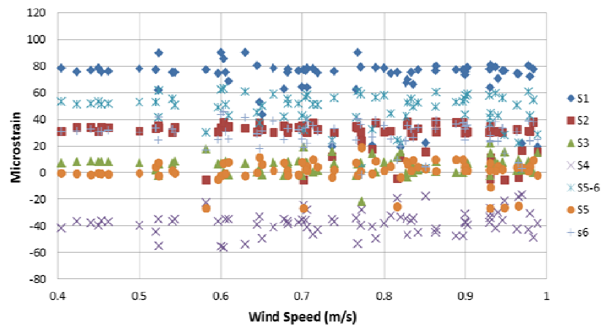
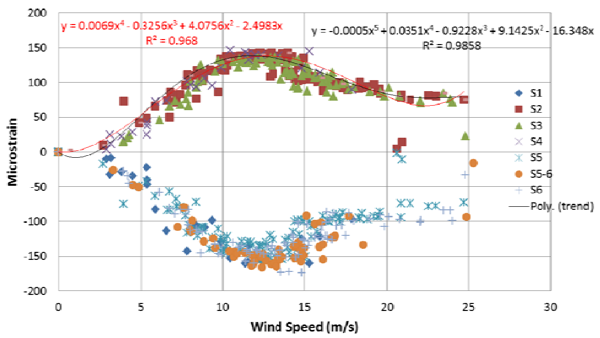


Fig. 4 Strain responses (SGA-V) of K1 at low wind speeds to derive correction factor

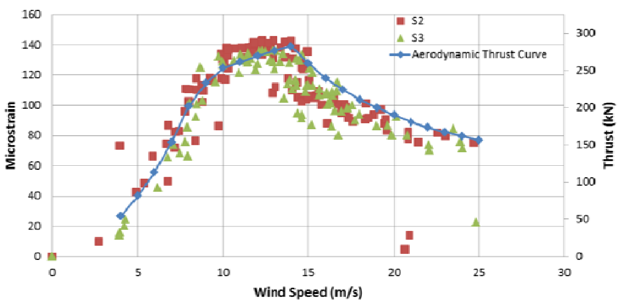
B. Relationships

1. Wind Speed and Vertical Strain

To derive the relationship between the wind speed and the corrected vertical strain at 1.5m above the top of the monopile (SGA-V), the date from the three month derivation period was screened for events when the wind direction was within ±1° of the strain gauge orientation, with the resultant strain and wind speed plotted. This resulted in the relationship depicted in Fig. 5, with the grey trend line and associated equation used for wind speeds less than 6m/s and black for greater than 6m/s.



(a)



(b)

Fig. 5 (a) Strain 1.5m above top of the MP (SGA-V) and wind speed at the nacelle and (b) comparison with WTG specified thrust curve

It is evident that there is a strong trend between vertical strain, 1.5m above the top of the monopile, and wind speed from a direction aligned to the strain gauge. Positive (tensile) values were taken for upwind locations and negative values downwind locations, as limited tensile strain events occur for SGA-V gauges S5 and 6 because they are located on the prominently downwind side of the foundation. This derived response aligns well with the WTG thrust curve, also shown in Fig. 5.

2. Wind Speed and Vertical Displacement

The same methodology was used to derive the relationship between wind speed and vertical displacement (VD) between the MP and TP, Fig. 6, where the derived grey trend line is used for wind speeds less than 6m/s and the black, greater than 6m/s.

C. Transfer Functions

Functions have been developed to determine the stress and displacement distributions around the circumference and down the depth of the grouted connection.

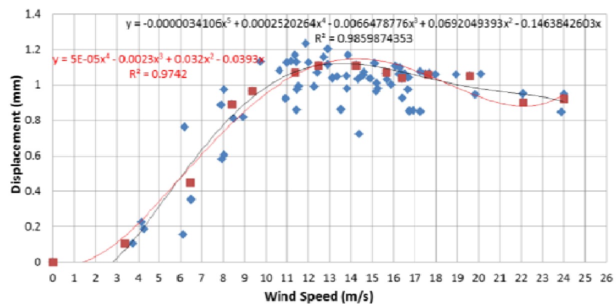


Fig. 6 Variation in vertical displacement between the monopile and transition piece at the top of the grouted connection with wind speed

1. Stress Distribution

To transform the TP strain at 1.5m above the top of the MP (SGA-V) to the radial stress within the top of the grouted connection directly below the gauge location, a transfer function has been derived based on bending of hollow circular sections and recommendations provided for the design of grouted connections within the Det Norske Veritas (DNV) offshore standard [1].

DNV OS J101 Section 9B 103 states:

$$p_{nom} = \frac{3\pi M}{R_p L_g^2(\pi+3\mu)+3\pi\mu R_p^2 L_g} \quad (1)$$

where p_{nom} is the normal stress, R_p is the radius of the pile, L_g is the grout length, μ is the coefficient of friction between steel and grout and M the applied moment. Therefore:

$$p_{nomtg} = \frac{3\pi M_{tg}}{R_p L_g^2(\pi+3\mu)+3\pi\mu R_p^2 L_g} \quad (2)$$

where subscripts tg denote the top of the grouted connection.

For simple beam bending:

$$\frac{M}{I} = \frac{\sigma}{y} \quad (3)$$

where I is the second moment of area, σ is the stress, and y is the distance from the neutral axis. For a hollow section:

$$I = \frac{\pi(R_{tp}^4 - R_{tpi}^4)}{4} \quad (4)$$

For the WTG TP:

$$y = R_{tpi} \quad (5)$$

Therefore if it is assumed that section modulus and radius of the TP are constant between 1.5m above the grouted connection and the top of the grout, the ratio of vertical stress is equivalent to the ratio of moment between the two points:

$$\sigma_{vtp} = \frac{M_{tp1.5}\sigma_{vtp1.5}}{M_{tg}} \quad (5)$$

where the subscript *i* denotes the inner surface. Therefore:

$$p_{nomtg} = \frac{3\pi M_{tp1.5}\sigma_{vtp1.5} I}{M_{tp} R_{tpi}(R_p L_g^2(\pi+3\mu)+3\pi\mu R_p^2 L_g)} \quad (6)$$

where *v* denotes vertical orientation, *tp* the transition piece at top of the grouted connection and *tp1.5* the transition piece 1.5m above the top of the grouted connection.

Based on specifications of a typical offshore WTG MP substructure, the ratio of M_{tp} and $M_{tp1.5}$ is fixed and dependent on the length of the structure above the grouted connection to the zero moment point at hub height of the WTG (79.4m) and the 1.5m above the grouted connection to zero moment at hub height. Therefore, based on the foundation specifications below and since:

$$\frac{M_{tp1.5}}{M_{tp}} = 0.9811 \quad (7)$$

$$\sigma = E\varepsilon \quad (8)$$

$R_{tpi} = 2.22m, R_{tpo} = 2.27m, L_g = 6.45m, R_p = 2.15m, I_{tp} = 1.63m^4, \mu = 0.7$ and $E = 210GPa.$

where *E* is the Young's modulus of steel, ε is the strain.

$$p_{nomtg} = \frac{3\pi(0.9811)(210x10^9)\varepsilon_{vtp1.5}(1.64)}{(2.22)((2.15)(6.45)^2(\pi+3(0.7)) + 3\pi(0.7)(2.15)^2(6.45))}$$

To determine the distribution of normal stress vertically throughout the grouted connection length:

$$p_{nomy} = \frac{M_y p_{nomtg}}{M_{tg}}$$

where:

$$\frac{M_y}{M_{tg}} = \frac{(79.4 + y)}{79.4}$$

y is the depth below the top of the grouted connection.

To account for the discontinuity of the end of the connection, a Stress Concentration Factor (SCF) is included so that:

$$p_{local} = SCF p_{nom}$$

Based on DNV-OS-J101 B105:

$$SCF = 1 + 0.025(\frac{R}{t})^{1.5}$$

where *R* is the radius and *t* is the thickness.

This relationship along with outputs from the FEM design of the grouted connection has been used to derive the vertical relationship of radial stress with depth of connection as shown in Fig. 7.

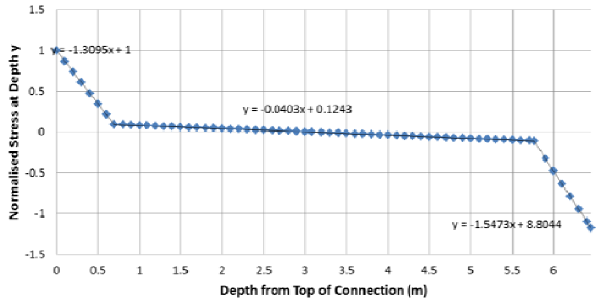


Fig. 7 Variation of radial stress with depth of the grouted connection including SCF

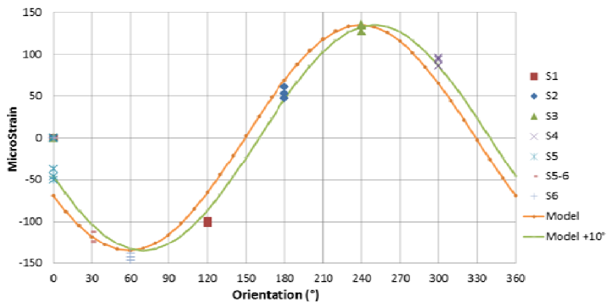


Fig. 8 Variation of measured strain (SGA-V) around the circumference of the TP wall compared with the cosine distribution assumed in the model

For a given wind direction the resulting moment transferred through the grouted connection will result in a variation of radial stress in the grout around its circumference. This will be at a maximum at the top of the grouted connection on the upwind side of the grouted connection, reducing to zero in the perpendicular orientation to the prevailing wind direction, before tension is experienced on the downwind side of the connection. This distribution has been represented by a cosine function, which when compared to the circumferential variation of the vertical strain detected by the SCM for a fixed wind speed and wind direction, Fig. 8, shows good agreement for a 240° prevailing wind direction. However, a shift of +10° in the model prediction would result in less error between the predicted and measured circumferential strain distribution, Fig. 8. This variation is partly due to the misalignment between the WTG nacelle and wind direction, which has been indicated to be typically ±5°. There is also likely to be an inaccuracy due to the installation methodology of the SCM gauges, with their orientation being based on reference to the internal ladder, which along with TP will vary to the reference to true north due to installation tolerances.

2. Vertical Displacement Distribution

A cosine distribution for the variation in vertical displacement with circumferential orientation was also assumed. As only a couple of vertical displacement transducers (VD) were installed per foundation, a "virtual" response has been created by plotting wind direction against vertical displacement for a fixed wind speed. During the period used for derivation of the relationships, prevailing winds were from the 160–330° direction and so an alternative period has also been included, where significant periods of other wind directions were experienced to validate the 0 – 160° part of the curve. From Fig. 9 it can be seen that the cosine distribution provides a good approximation.

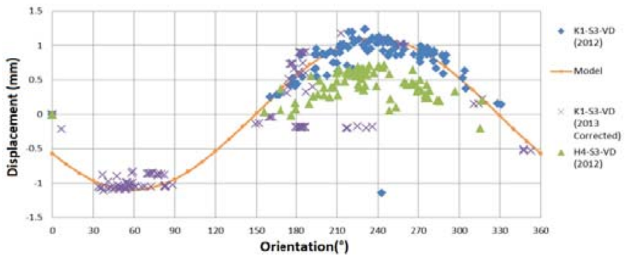


Fig. 9 Comparison of measured and predicted variation of vertical displacement around the circumference of the grouted connection

As the accumulated relative vertical displacement will be an important factor on the total wear, a factor to account for the influence of only using the available ten minute average SCADA data needed to be incorporated. Investigation of the higher frequency SCM data indicated a significant increase in accumulated displacement for a given period with increasing averaging frequency, Fig. 10. Based on this relationship the time averaging period was varied until the magnitude of the model matched that of the SCM.

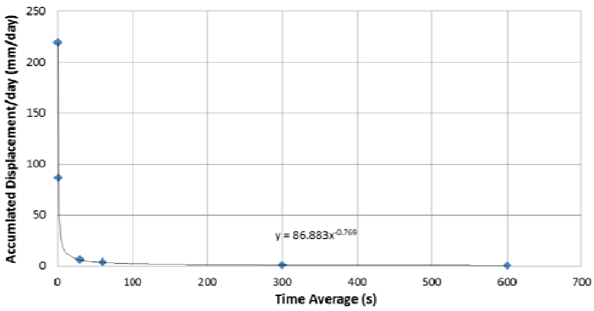


Fig. 10 Variation of accumulated displacement with data time average period

D. Wear Rate

For a given radial stress applied to the grouted connection the rate of wear has been shown to vary for a given relative displacement amplitude [8]. Based on this experimentation a wear rate for wet corroded conditions, similar to those indicated by inspections [3], have been used based on the linear relationship shown in Fig. 11.

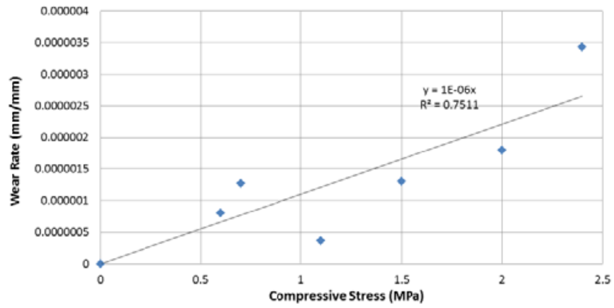


Fig. 11 Variation of wear with compressive stress for wet corroded conditions [8]

Experimental testing was only undertaken for compressive stress conditions, due to the nature of the test arrangement. However, SCM indicates that that under prolonged periods of the wind heading from the non-predominant direction, upon return to the predominant direction the upwind distance between the TP and MP had increased, suggesting that deposition of wear material is occurring and therefore a negative wear rate should be applied. However, experimental testing did not investigate this rate and it is likely to be strongly influenced by the ability of the wear debris particles to migrate from the compressive side, where it is formed, to the opposite side where the area of gapping is occurring. A linear wear rate was therefore applied, which aligned with the indication by the SCM.

E. Wear Output

The model takes the ten minute average SCADA data input, uses the relationships derived to estimate the vertical strain in the TP wall 1.5m above the MP and transforms this input into an equivalent compressive stress at various locations around the grouted connection. The wear rate based on this stress is then applied from Fig. 11.

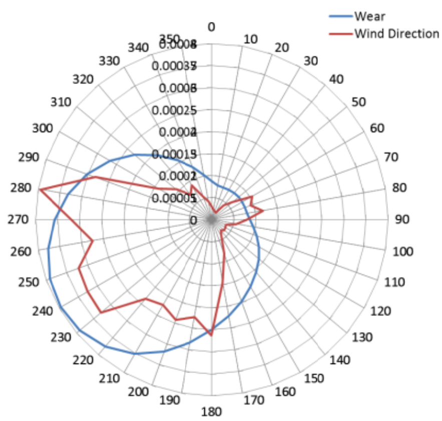


Fig. 12 Comparison of wind direction and wear distribution at the top of the grouted connection

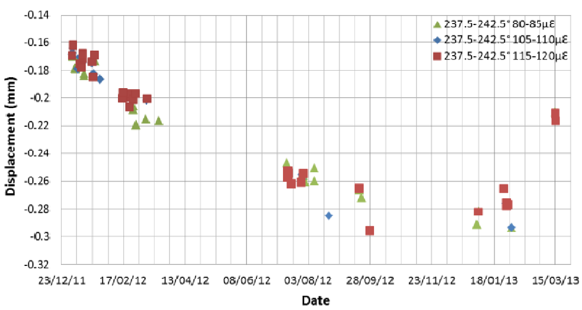
The wear rates are then averaged over the entire inputted period and multiplied by the sum of the accumulated displacement differences between the ten minute average absolute displacements computed from the previously derived relationship. Based on this, the circumferential wear distribution at the top of the grouted connection, indicated in Fig. 12, is outputted. It can be seen that it shows good agreement with the wind direction distribution for the period of inputted SCADA data.

III. Calibration

In order to validate and calibrate the predictive model developed, measured loss in thickness of the two foundations based on SCM data has been determined for comparison with the model's predicted losses. This has been achieved by analyzing the ten minute average data from the horizontal displacement transducers at foundations H4, bracket pairs S1 (H4-S1-HD) and S3 (H4-S3-HD) and K1, bracket pairs 2 (K1-S2-HD), 5 (K1-S5-HD) and 6 (K1-S6-HD), as indicated in Fig. 3. Data was taken for three different magnitude loading events within ± 5με, 1.5m above the displacement transducers and within ± 5° wind direction to the bracket pair. This has been based on the assumption that for a given axial strain at the 1.5m level and particular wind direction, the load conditions experienced by the grouted connection are constant. Therefore any change in horizontal displacement caused by a change in deflection of the materials should be the same, resulting in any change in displacement detected over time indicating loss of material thickness.

Fig. 13 shows the resultant data points, which show a strong negative correlation on some of the bracket locations for some of the investigated periods, indicating wear is occurring. Unfortunately some of the periods had insufficient occurrences of similar events to be able to significantly determine any trends, but enough existed to enable the gradients of these trends to be used to determine an indicated wear rate by the SCM, to then compare with the numerical models output.

From Fig. 13 it can be seen that the circumferential locations on the predominantly upwind side of the substructure show the largest magnitude of indicated wear and in particular K1-S2. This was therefore chosen as the calibration value, as it is likely to represent the worst case and so the model will provide a conservative prediction.



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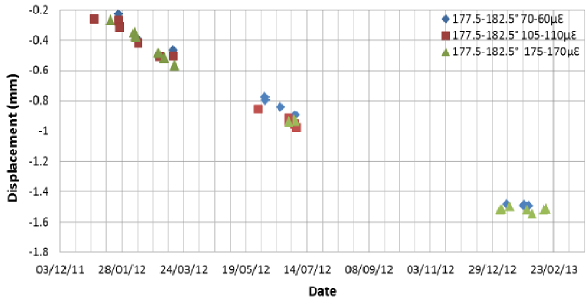

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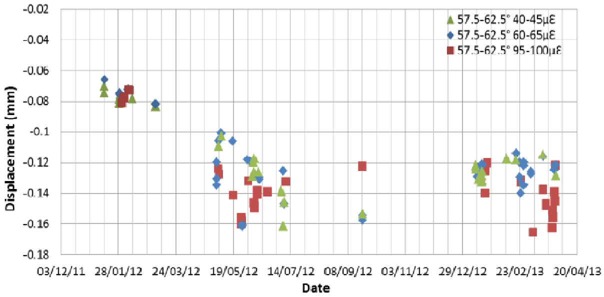


(c)

Fig. 13 Examples of detected loss in thickness between MP and TP based on change in horizontal displacement readings over time for constant strain and wind direction (a) H4-S3-HD (b) K1-S2-HD (c) K1-S6-HD

When the model outputs, based solely on the ten minute average data with no correction for the accumulation of walked displacement, as discussed earlier, are analysed, it can be seen in Fig. 14 that the distribution of wear aligns well with the SCM, but the magnitude of wear is a factor of 570 out.

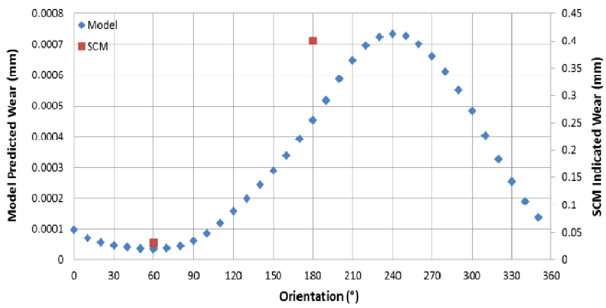


Fig. 14 Comparison of model predicted wear and SCM detected wear

A correction factor was then applied, based on incorporation of accumulation of relative displacements dependent on frequency of data analysed, and variation of negative wear rate, that resulted in the model outputs matching the worst case K1 SCM indicated wear for the January to March 2012 period, Fig. 15.

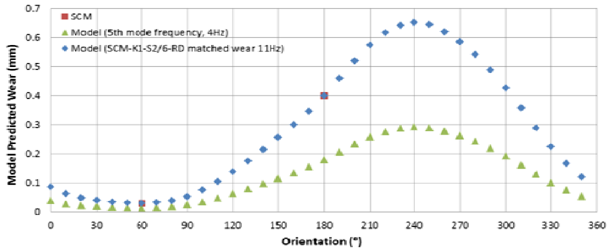
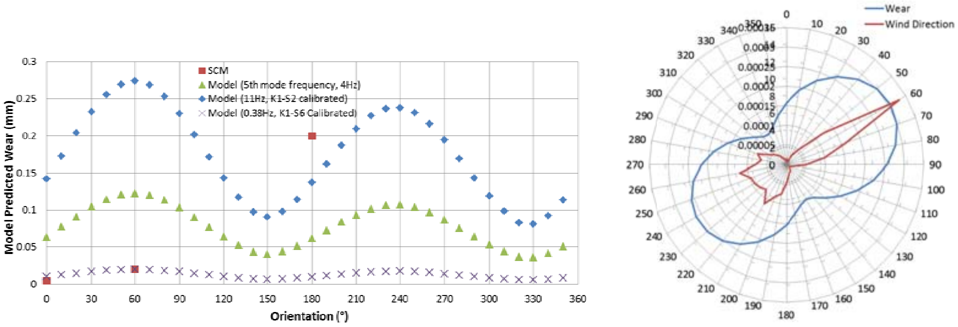


Fig. 15 Model calibrated against SCM

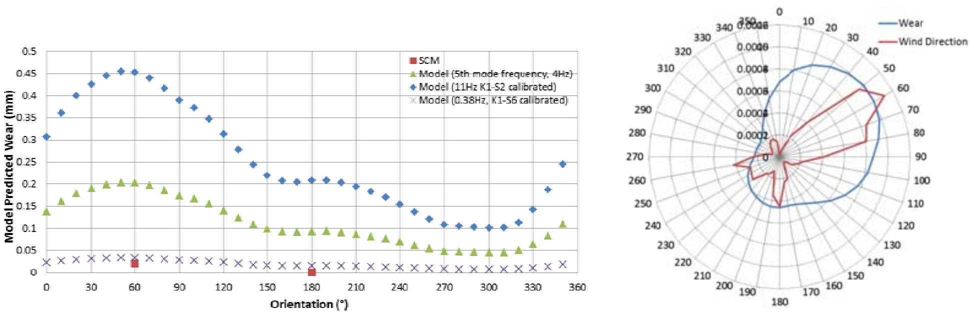
It is evident from Fig. 15 that in order to produce a model output that matches the indicated wear from the SCM the equivalent frequency response is 11Hz, which is over 2.5 times higher than the WTG substructures 5th mode (4Hz) response and so is unlikely to represent actual behaviour. The 4Hz equivalent response has been included to represent a likely structural response predicted wear and can be considered as the model's lower bound. The 11Hz equivalent response has been included to represent a model response that minimises the error between model predicted and the K1 SCM detected wear between January and March 2012, and can be considered the upper bound prediction.

Based on this calibration and to demonstrate the validity of the model, wear has been modelled for the other two SCM periods for K1 and the three periods for the H4 foundation.

It can be seen from the responses shown in Fig. 16 that for the majority of the periods, the K1-S2-HD calibrated model response significantly overestimates the SCM detected wear by around a factor of 10, but the wear distribution shows strong correlation to the wind direction distribution for the inputted period. However, the included 0.38Hz equivalent model's, calibrated against K1-S6-HD indicated wear, response shows good agreement with the majority of the SCM indicated wear for both the K1 and H4 foundations. This frequency coincides with the first mode of the dynamic response of the substructures at 0.29-0.33Hz, and the 1P and 3P driving frequencies from the WTG at 0.14-0.31Hz and 0.43-0.92Hz. The disproportionately high wear rates indicated by K1-S2-RD, possibly suggest that the wear indicted by K1-S2-RD may not be a true reflection of the wear experienced by the grouted connection. It is therefore recommended that site inspections are undertaken to validate the accuracy of this and the other onsite SCM instrumentation and on a larger sample of the wind turbine foundations to improve the significance of the results.



(a)



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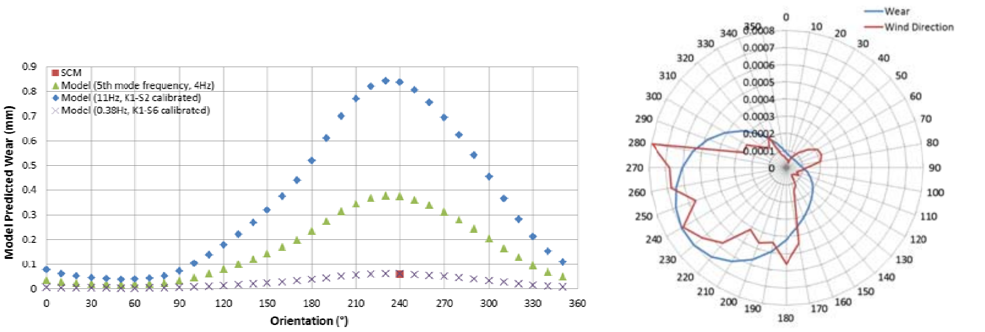

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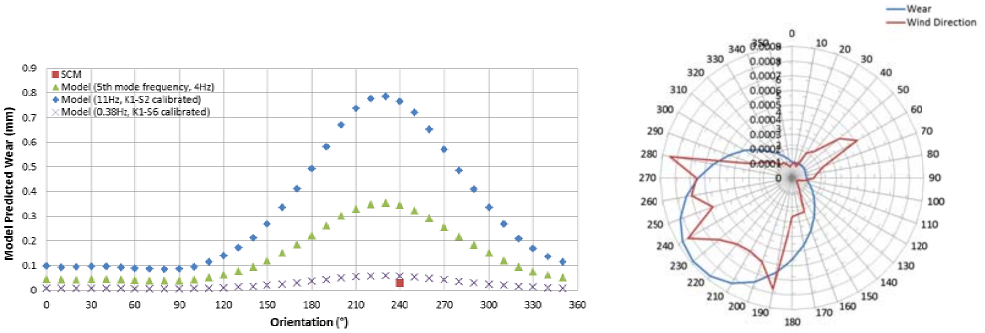

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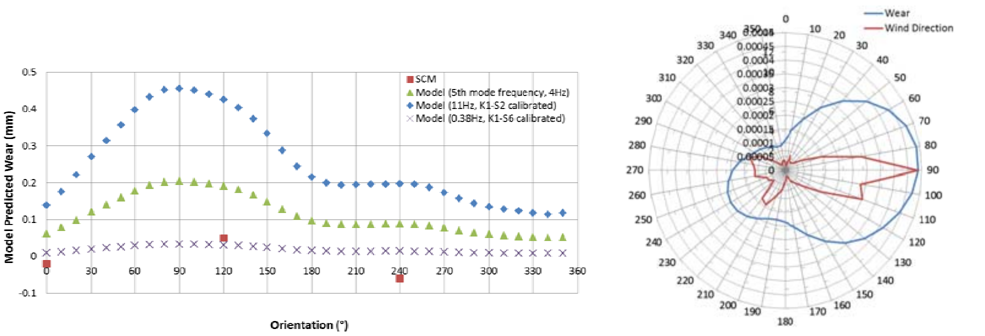

(e)

Fig. 16 Comparison of numerical wear model outputs with SCM indicated wear for (a) K1 05-06/2012, (b) K1 01-03/2013, (c) H4 01-03/2012, (d) H4 07-09/2013 and (e) H4 01-03/2013

IV. Conclusions

In order to understand the long term implications of the grout wear failure mode in large-diameter plain-sided grouted connections, a numerical model has been developed to predict the accumulation of wear in the grouted connection for the actual load conditions experienced over a given period, limiting the need for expensive SCM (structural condition monitoring). This model has been derived and calibrated based on limited site SCM and SCADA (supervisory control and data acquisition) data of two operational WTG (wind turbine generator) substructures afflicted with this challenge, along with experimentally derived wear rates, to determine the wear for a given period of data. Good agreement has been shown between the model's predictions and SCM detected wear for all the instrumentation locations except one and for all the periods screened. Although the model is specific to the structural performance and specifications of the substructures used in this case study, the devised methodology can be applied to other situations by replacing the case-specific details.

Ongoing work involves onsite inspections of a sample of the population of the wind turbines, in order to provide validation of the SCM findings, that has occurred in the four years since the WTG have been operational, which will help to further validate the proposed model.

It is also hoped to incorporate statistical analysis of the inputted period of data, so to enable comparison with historical wind statistics for the site. This will allow the model outputted wear to be appropriately scaled to provide a prediction of the expected wear over the design life of the plant. By modelling each WTG substructure location, this will enable a better understanding of the significance of the wear at each location due to the variance in wind loading. This can then be used to indicate if further remediation may be required to specific substructures in the future and if so allow for better planning for the remediation works helping to minimize financial costs. It will also allow for a reduction in site inspections by determination of the structures experiencing the most significant loading conditions for wear.

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