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MEASURED CHANGES IN THE NATURAL FREQUENCY OF OFFSHORE WIND TURBINES WITH MONOPILE FOUNDATIONS

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Abstract:

Offshore wind turbine monopiles have no redundancy in the primary foundation. The fatigue life of the welded connections is therefore of upmost importance. Fatigue loads are caused by the dynamic response of the foundation, which is dominated by the first modal response at the natural frequency. One area of concern for monopile foundations is whether significant changes in natural frequency can occur over time as a result of changes in the soil stiffness.

Natural frequency data based on nacelle mounted accelerometers has been collected on 102 offshore monopile foundations over a period of over six years at the Greater Gabbard offshore wind farm. This data set demonstrates the long-term trends in natural frequency in a real operating environment over a significant proportion of the structural design life.

Time histories of the natural frequency on each foundation demonstrate a significant difference in the behaviour of foundations with and without "rock dump" scour protection. Foundations with scour protection increase in natural frequency over time which is believed to be caused by the settlement of the aggregate.

Foundations without scour protection reduce in frequency over time. Measured scour at each location suggests that scour may be a significant contributor to the overall reduction in natural frequency. The measured change in natural frequency is small, with the majority of the foundations having a change in natural frequency of 1% or less. This corresponds to a small increase in measured fatigue loads.

Introduction

Offshore wind turbine monopile foundations consist of a single large diameter steel pile. Often the monopile is then grouted or bolted to a transition piece which is in turn bolted to the turbine. Given that there is only a single pile supporting the turbine, the fatigue life of the welded connections is of upmost importance. The fatigue loads in the welds are caused by the dynamic response of the foundation which is dominated by the first mode of the foundation at the natural frequency. Figure 1 shows the layout of the wind turbine monopile foundations of the Greater Gabbard offshore wind farm. The natural frequency has been monitored on all 102 foundations over a period of over six years to determine whether significant changes in natural frequency have occurred which might result in a change in fatigue loads.

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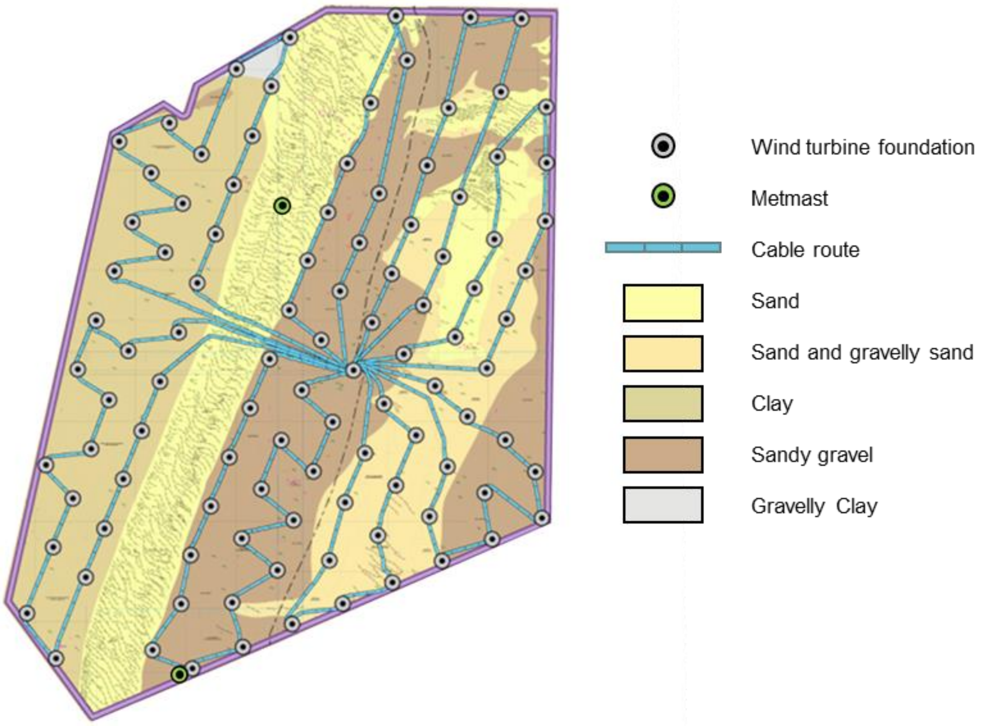

Figure 1. Layout of the wind turbine monopile foundations at the Greater Gabbard wind farm.

Natural frequency time histories

The natural frequencies of the foundations are calculated by Siemens Gamesa, the turbine manufacturer, using acceleration data measured using accelerometers in the nacelle of each wind turbine generator. The natural frequency data collected gives a natural frequency value every ten minutes for each of the 102 wind turbine foundations.

A moving average filter has been applied to the natural frequency time histories in order to visualise trends over time. The filter takes the average of 144 ten-minute measurements, equivalent to one day of consecutive data. Example natural frequency time histories are shown in Figure 2 and Figure 3. The foundations in Figure 3 have had scour protection installed.

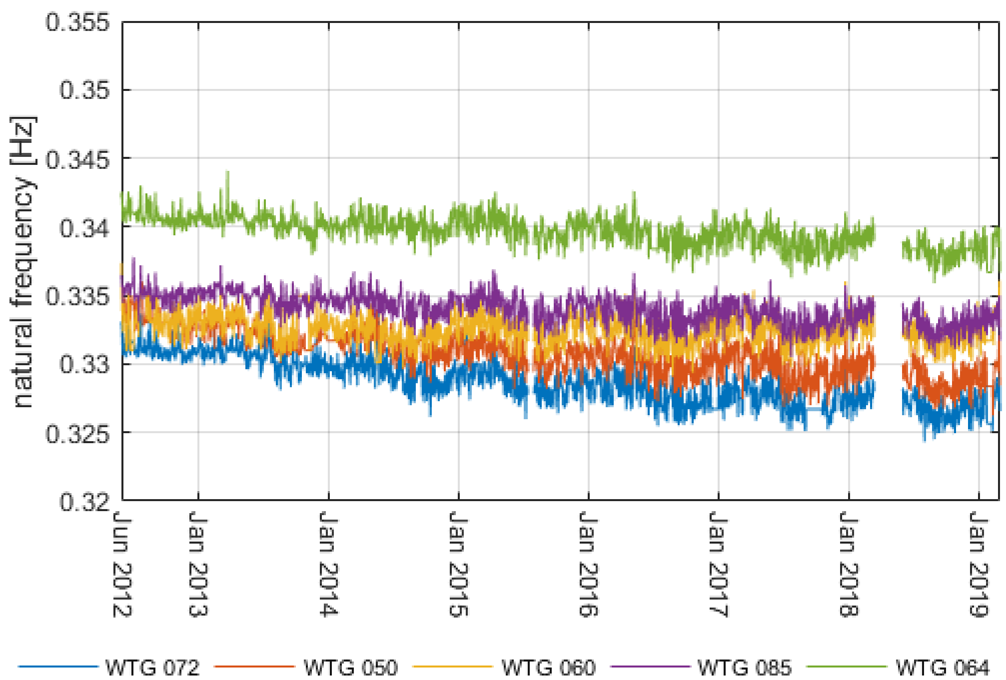

Figure 2. Example natural frequency time histories for foundations without scour protection.

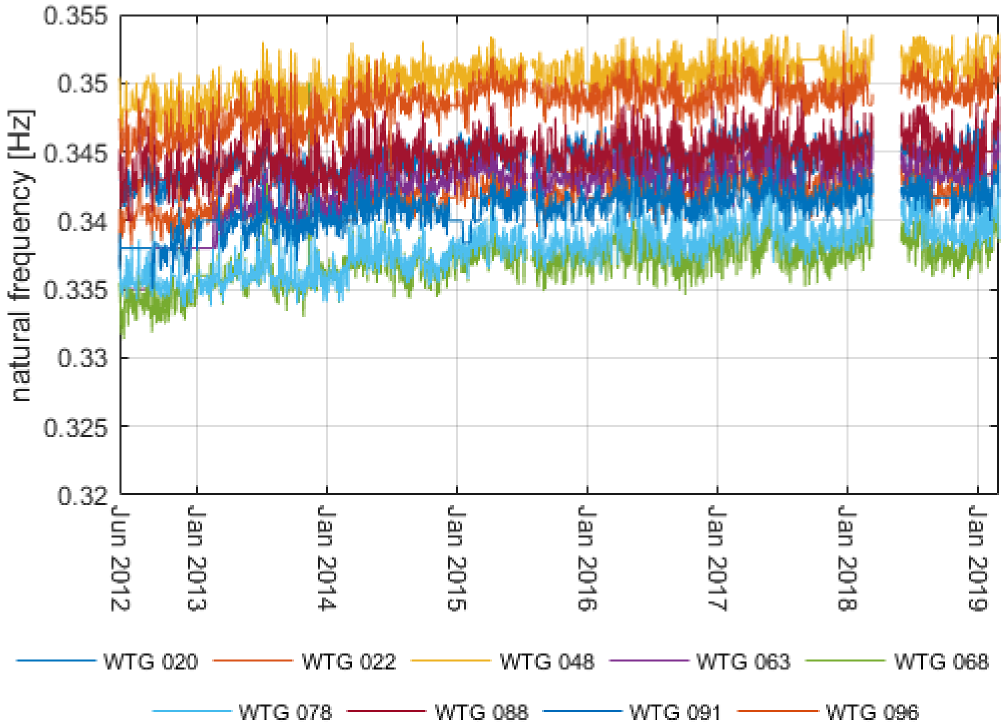

Figure 3. Example natural frequency time histories for foundations with scour protection.

A number of features can be seen in Figure 2 and Figure 3 which are of interest:

- There is an apparent reduction in frequency for the majority of the foundations. A selection of these time histories is shown in Figure 2. The change in natural frequency from the start of the monitoring period to the end of the monitoring period is relatively small, with the majority of foundations showing a reduction in frequency of less than 1%.
- There are however a number of foundations which show a slight increase in natural frequency over time, with an average increase of 1.12%. These foundations tend to have scour protection installed, which are shown in Figure 3.
- There is evidence of a seasonal variation in natural frequency which tends to be higher in the winter and lower in the summer. The difference between the maximum and minimum values in each year is significant and is of a similar magnitude as the apparent change in natural frequency from the start of monitoring.

Comparison between measured and design natural frequencies

The natural frequencies for each foundation were predicted at the design stage. These predicted natural frequencies are fundamental to the design simulations run to calculate the loading on the foundations.

Figure 4 shows how the predicted and measured natural frequencies vary in relation to the water depth of each of the 102 foundations. The predicted natural frequency during design is shown in red and it is evident that the foundations in deeper water have lower design natural frequencies.

The natural frequencies of each foundation measured in June 2012, soon after the wind turbines began power generation, is shown in blue. The reduction in natural frequency with the increase in water depth predicted during design is again evident in the measured natural frequencies. However, the measured natural frequencies are consistently higher than the design values by 7 to 14%, with a mean of 9%. This underprediction of foundation natural frequency in design at Greater Gabbard is comparable to that reported for other wind farms, such as those reported by Kallehave et al (2012).

During design the soil was modelled as a series of non-linear p-y springs representing the relationship between lateral resistance and displacement. The p-y formulations used were those presented in DNV-OS-J101, which originate from limited pile lateral load tests on long slender piles undertaken in the 1950s through to 1970s and are aimed principally at the prevention of collapse. They generally tend to under-predict the stiffness of large diameter monopiles with a relatively short embedment, such as those used at the Greater Gabbard wind farm. New design approaches have since been developed for monopiles, notably those recommended by the PISA joint industry project, Byrne et al (2017), which lead to a better modelling of the soil response and, generally, a marked increase in stiffness. It is considered that a significant proportion of the difference between the measured natural frequency and the frequency predicted during design for the Greater Gabbard wind farm can be attributed to the use of standard p-y curves to model the soil response.

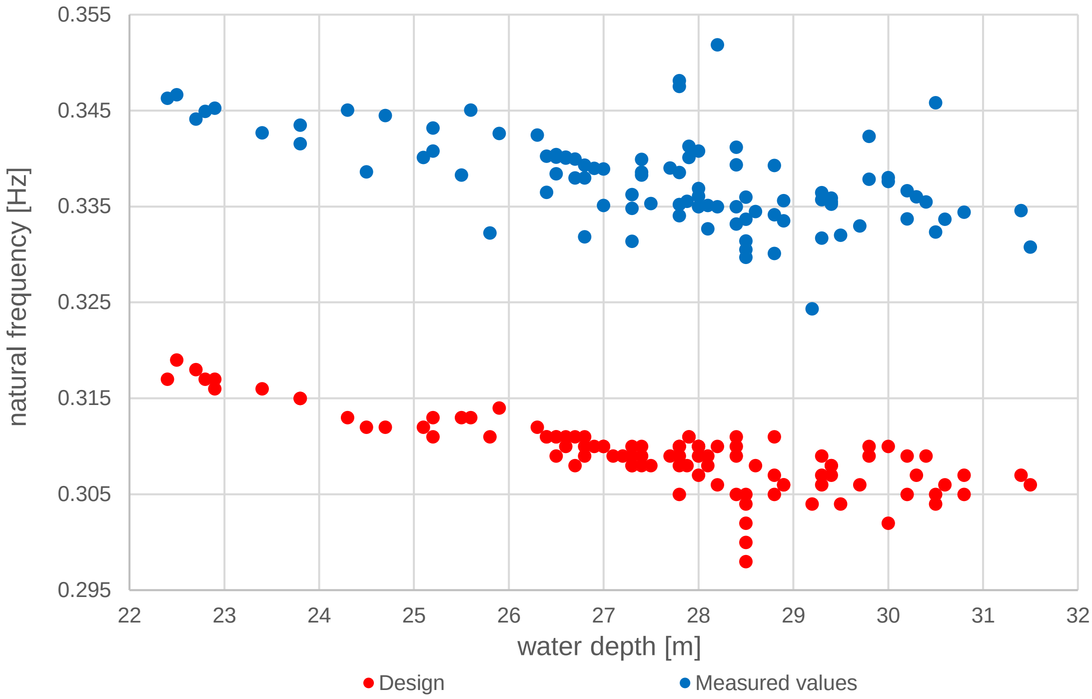

Figure 4. Comparison of design natural frequencies with initial measured natural frequencies (June 2012)

Change in natural frequency

Additional insight can be gained by visualisation of the overall change in natural frequency over time for all foundations in the wind farm. Figure 5 below summarises the change in natural frequency recorded for each turbine, reported in order of water depth. The overall change in natural frequency is represented using an arrow starting at the initial natural frequency measured in June 2012, soon after all of the wind turbines had been commissioned and ending at the natural frequency measured over six years later in February 2019. The initial and final natural frequency are calculated as monthly mean values.

Foundations with a reducing natural frequency have been plotted with a blue arrow while foundations with an increasing natural frequency are plotted with a red arrow.

Nine foundations have been identified as having soil conditions which make them prone to scour. Scour can occur around a monopile through erosion of the top layers of the seabed caused by vortices as sea water flows past the monopile. This results in a loss of soil restraint which reduces the foundation stiffness and in turn the natural frequency. These foundations have therefore been protected by building up aggregate around the ground penetration, known as a ‘rock dump’. Foundations that have had a rock dump carried out for scour protection are highlighted in yellow.

The majority of the foundations show a reduction in natural frequency over the measurement period. Foundations with deeper water depths are more likely to have lower natural frequencies. However there does not appear to be a trend between the water depth and the magnitude of the change in natural frequency.

The most significant observation is that there is a strong relationship between the foundations that have had scour protection installed and the foundations that have seen an overall increase in natural frequency since the start of operation.

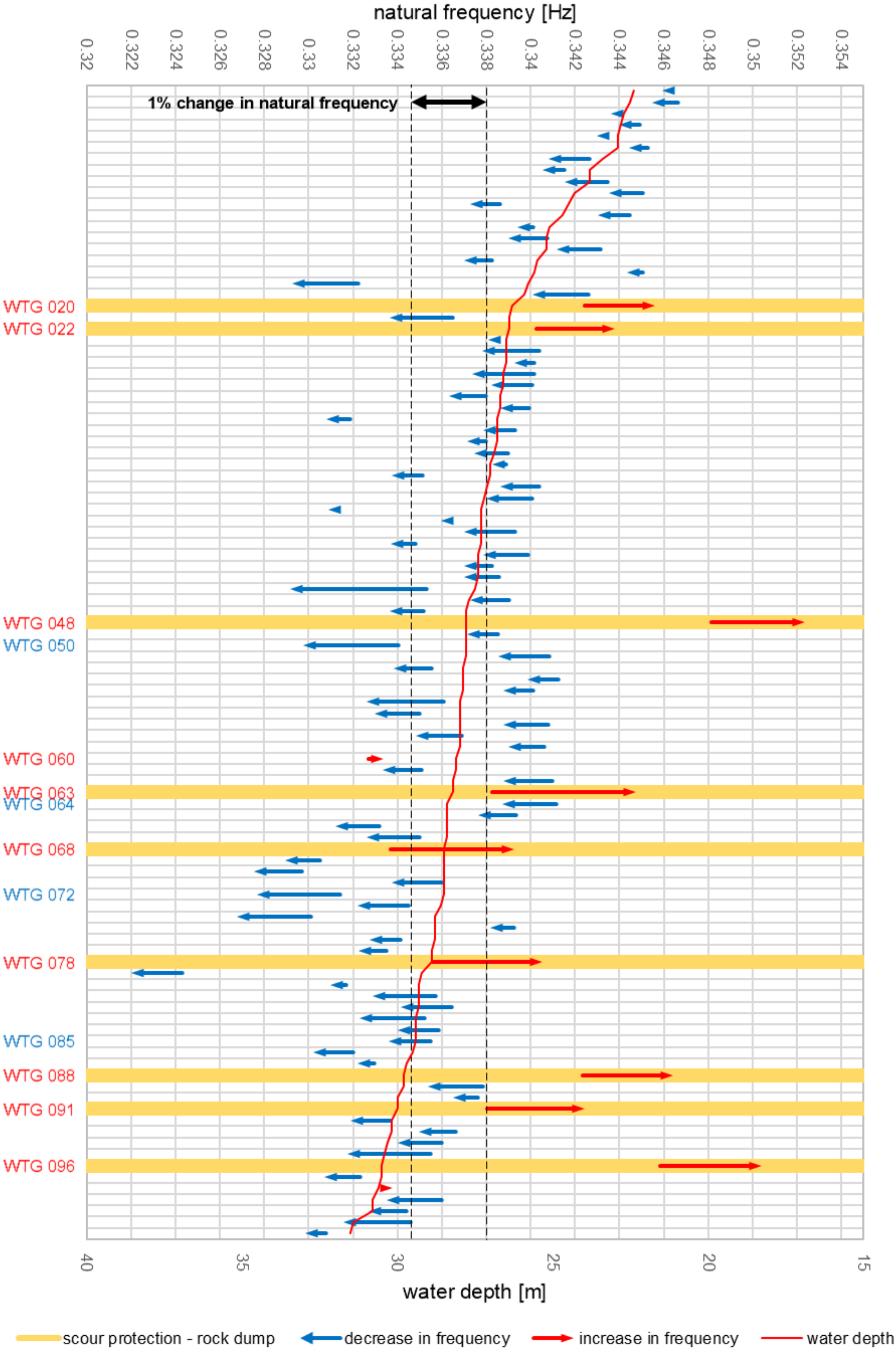

Figure 5. Change in measured natural frequency from July 2012 to February 2019.

Scour protected foundations

Figure 5 showed that the foundations that have scour protection have an increasing natural frequency over time, with an average increase of 1.34% over the 81-month measurement period. This value is dependent on the time of year at the end of the measurement period due to seasonal variation. Only two foundations have experienced an increase in frequency without scour protection, and in both cases the increase is small.

The natural frequency time histories for the foundations that have scour protection have been plotted together in Figure 3. These foundations show a steady increase in natural frequency from the start of monitoring before levelling off. This is likely to be caused by settlement and densification of the rock aggregate over time. As the aggregate settles the soil restraint becomes stiffer.

The scour protection was installed in late summer 2011, before turbine operation and before monitoring of the natural frequency across the farm. It is therefore not possible to determine if there is a change in behaviour from the period before scour protection installation and after.

Non-scour protected foundations

The change in natural frequency across the farm can be visualised as a probability distribution such as the plot shown in Figure 6. In this figure the foundations with scour protection have been excluded as they are demonstrating different behaviour.

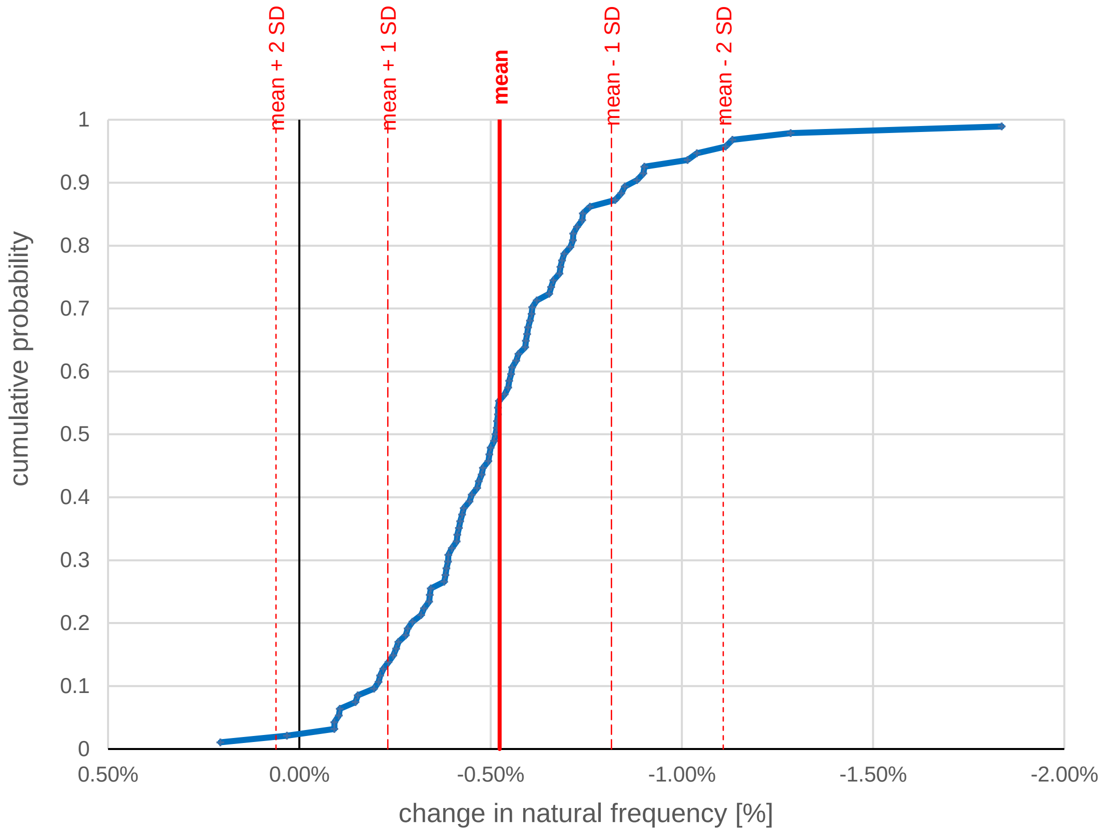

Figure 6. Probability distribution of the change in natural frequency between June 2012 and February 2019 for foundations without scour protection.

There is a mean reduction in natural frequency of 0.52% for foundations without scour protection, with a standard deviation of 0.29%. While the spread of results is relatively even about the mean. Approximately 93% of foundations have seen a change in frequency of less than 1%.

It is suspected that a significant contributor to the change in natural frequency is scour. The potential for scour to cause a reduction in stiffness has led to the commissioning of a number of scour surveys across the wind farm. The most recent survey carried out in 2015 provides illustrative scour measurements for each foundation.

The scour survey was completed between the 1st July and 18th September 2015 and therefore the change in natural frequency should be based on the same period. However, given that natural frequency measurements were not available for all foundations until June 2012, the change in natural frequency shown in Figure 7 is based on the period from June 2012 to August 2015, rather than the most recent natural frequency measurements.

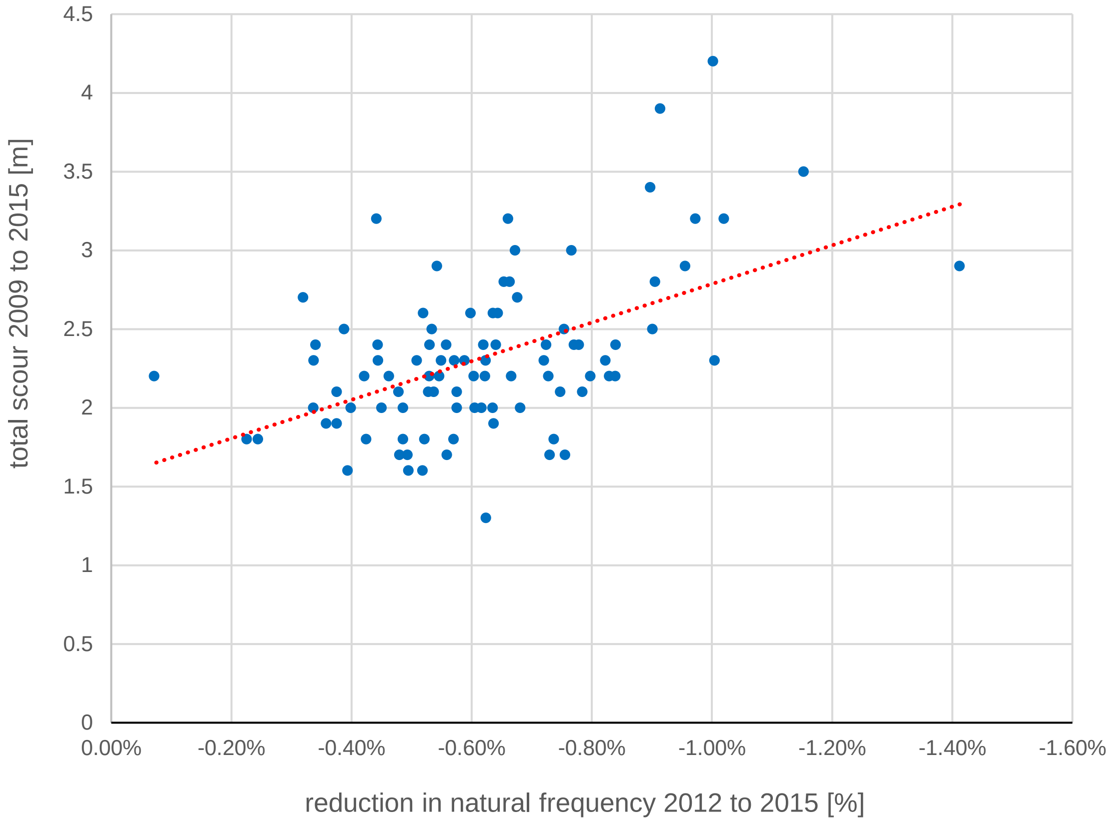

Figure 7. Relationship between change in natural frequency and total scour

While there is no definitive relationship between change in natural frequency and the total scour, there is a trend that the change in natural frequency increases as total scour increases.

An analytical model of one of the monopile foundations was used to model the measured scour and the resulting change in natural frequency. The modelled change in natural frequency was consistent with the change in natural frequency measured. However, the difference between the measurement period of the change in scour (2009 to 2015) and the measurement period of the change in natural frequency (2012 to 2015) means that there is insufficient data to determine with certainty whether scour is the primary cause of the change in natural frequency.

Seasonal variation

All of the foundations demonstrate a seasonal variation in natural frequency. A peak in natural frequency occurs during the winter months and the lowest frequencies occur during the summer.

The majority of the foundations experience a seasonal variation in natural frequency of approximately 0.5% each year. This variation in natural frequency is comparable in magnitude to the overall change in natural frequency.

A number of mechanisms were considered when investigating the possible causes of the seasonal variation such as thermal expansion, tidal effects, water level and turbine operation. However, based on the limited investigations carried out so far, it has not been possible to identify the main cause of the seasonal variation. However, given that the variation is similar on all foundations and appears to have a period of one year, it can be assumed that the cause is likely to be environmental.

Impact on fatigue load

The change in natural frequency is of particular interest as it is the dynamic loads experienced by the foundation which cause fatigue damage. Therefore, if the natural frequency of the foundation is changed such that there is a change in dynamic behaviour, then there will also be a change in fatigue load on the foundation.

Therefore, a comparison between the observed change in natural frequency and the observed change in fatigue load is of interest. Strain monitoring systems have been installed on multiple foundations at discrete circumferential locations in the transition piece. The fatigue load at these locations can be quantified by calculating a bending moment range histogram, which is calculated in accordance with ASTM E 1049-85. A Damage Equivalent Moment (DEM) is then calculated from this range histogram based on equations provided in IEC 61400-13. This gives a measure of the fatigue load on the foundation.

Using this method, the fatigue load has been estimated at the beginning and the end of the measurement period on two foundations. The fatigue load is seen to fractionally increase from the beginning to the end of the measurement period. However, the observed changes in both natural frequency and fatigue load are small in comparison to the scatter in the fatigue load data. It is therefore difficult to determine any clear conclusions from this data at this stage.

The fatigue loads discussed above are based on measurements made at an elevation within the transition piece, 5.04 m above the mean sea level. The changes in fatigue loads do not appear to be changing significantly over time at this elevation. However as scour has been observed at a number of locations, the loss of soil stiffness in the top layers of the soil could result in changes in the fatigue loads experienced near the mudline. This is illustrated in Figure 8.

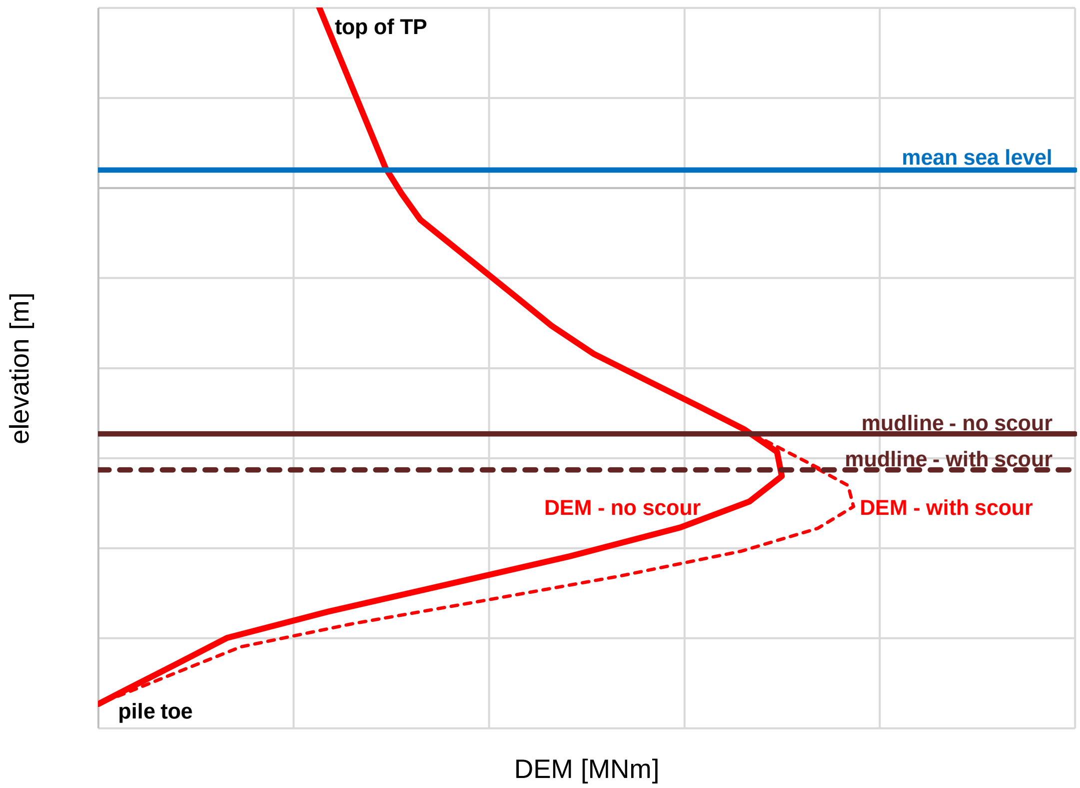

Figure 8. Postulated changes in fatigue loads near mudline as a result of scour.

The DEM profile shown in Figure 8 shows how DEM increases from the top of the tower to near the peak at mudline. The DEM only begins to reduce below mudline as the soil resists the applied moment. However, in the case where there is significant scour the DEM will continue to increase at elevations between the original mudline and the bottom of the scour, as there is no soil to resist the applied moment. This effect could result in increases in fatigue loads in the area local to the scour, as illustrated in Figure 8.

Conclusions

Natural frequencies have been measured by the turbine manufacturer on all wind turbine foundations across the Greater Gabbard offshore wind farm, using accelerometers in the nacelle of each of the 102 turbines. The following conclusions have been derived from further assessment of the measured natural frequencies:

- The measured natural frequencies are consistently higher than the design natural frequencies, with a mean percentage difference of 9%. The range is 7% to 14%. This is believed to be predominantly a result of the design codes used to calculate the stiffness of non-linear soil springs. These are based on the assumption that the piles are slender. Therefore, the spring stiffnesses calculated using this standard tend to under-predict the stiffness of large diameter monopiles.
- There are 11 locations that demonstrate an increase in frequency, with an average increase of 1.12% over the 81-month during measurement period. This is dependent on the time of year at the end of the measurement period due to seasonal variation. Given that all nine of the rock dump scour protected foundations show an increase in natural frequency, there is strong evidence that the rock dump has resulted in an increase in natural frequency. The natural frequency at these locations is still observed to be increasing. This is likely caused by settlement and densification of the rock dump aggregate, increasing the stiffness of the soil restraint.
- The foundations that have not been scour protected generally show a reduction in natural frequency over the measurement period. This reduction is on average 0.52% over the 81-month measurement period. Approximately 93% of the foundations have seen a reduction in frequency of less an 1%. These values are dependent on the time of year at the end of the measurement period due to the seasonal variation in natural frequency.
- There is some correlation between the change in natural frequency and levels of total scour observed. This would be expected given that scour is likely to reduce the soil stiffness significantly in the top layer of the soil. An analytical model of one of the foundations has been used to demonstrate that the level of scour observed could be responsible for the observed change in natural frequency. Scour could therefore be the primary cause of the change in natural frequency over time, rather than soil degradation.
- There is evidence of a seasonal variation in natural frequency. Many of the foundations reach a yearly peak in natural frequency in winter and a minimum in summer. The average annual variation of 0.5% is of a similar magnitude to the change in natural frequency over the whole measurement period. Given that the variation is similar on all foundations and appears to have a period of 1 year, the cause is likely to be environmental.
- Numerous mechanisms have been investigated to determine what causes this seasonal variation. These include thermal expansion, tidal effects, water level and turbine operation. However, based on the limited investigations carried out so far, none of these mechanisms appear to be the cause of the seasonal variation.
- A comparison of the fatigue loads measured using strain gauges installed in the transition piece on a pair of wind turbine foundations has shown that there is a small increase in measured fatigue loads from the beginning of the measurement period to the end. The observed changes in fatigue load and natural frequency imply that there may be an increase in fatigue load with a reduction in natural frequency. However, the changes are small in comparison to the scatter in the fatigue load data. It is therefore difficult to determine any clear conclusions from this data at this stage.
- Given that there is some significant scour observed on the foundations, it has been noted that there is a possibility that fatigue loads could increase at elevations local to the scour due to a reduction in soil restraint. It is recommended that this is investigated further.

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