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CONDITION MONITORING OF OFFSHORE WIND TURBINES WITH SCOUR AND GROUT DAMAGE IN MONOPILE FOUNDATIONS

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Abstract: Monopile foundations with grouted connections are used extensively for offshore Wind Turbine Generators. In recent years, the offshore wind industry discovered that the existing design methods for monopile to transition piece grouted connections may result in problems associated with grouted transition pieces. This has been evidenced by the settlement of the upper sections of tower structures onto the lower parts of the structures (i.e. the piles). In addition to grout damage, scour at the base of the turbine is another challenge. Excessive scour that occurs immediately adjacent to the monopiles can destabilise the turbine and affect its natural frequency. The problem of grout damage and scour can increase the likelihood of lost operation and structural failure and therefore timely detection of these problems is vital. This paper presents the derivation of a conditional monitoring strategy for detection of both issues. It has been shown that vibration monitoring of the structure alone cannot help in identifying possible scour and grout damage. It is illustrated that the forces/displacements across the new elastomeric bearings which are installed as a retrofit measure, in conjunction with long range stress/strain measurement can be used for grout damage detection as well as identification. Subsequently, vibration monitoring can be used to identify scour.

Introduction

Monopile foundations with grouted connections are used extensively for offshore Wind Turbine Generators. In recent years, the offshore wind industry discovered that the existing design methods for monopile to transition piece grouted connections (Figure 1a) may result in problems associated with grouted transition pieces. Essentially, designs have been allowed that comply with code but have relatively high degrees of ovalisation in the joint in the absence of shear keys and that these joints have been observed to fail. This problem, of major concern, is common across many operators in the UK and beyond. This has been evidenced by the settlement of the tower upper sections onto the lower parts of the structures (i.e. the piles). The design of the grouted connection has been studied by means of experimental tests and analysis by several researchers [1, 2]. Elastomeric bearings have been used as a retrofit measure to give the foundation a higher load-carrying capacity in the vertical (axial) direction, while remaining flexible in the lateral direction [3].

Another challenge associated with wind turbine foundations is the problem of scour. Scour at the base of the turbine (Figure 1b) is caused due to high levels of sand bank movement around the monopile foundations. Excessive scour that occurs immediately adjacent to the monopiles increases the unsupported length from the foundation to the nacelle and also reduces the effective fixity due to lost lateral bearing contact with the supporting soils.

The problem of grout damage and scour can increase the likelihood of lost operation and structural failure and therefore timely detection of these problems is vital. In the present work, various damage scenarios at the grouted connections and effects of scour have been

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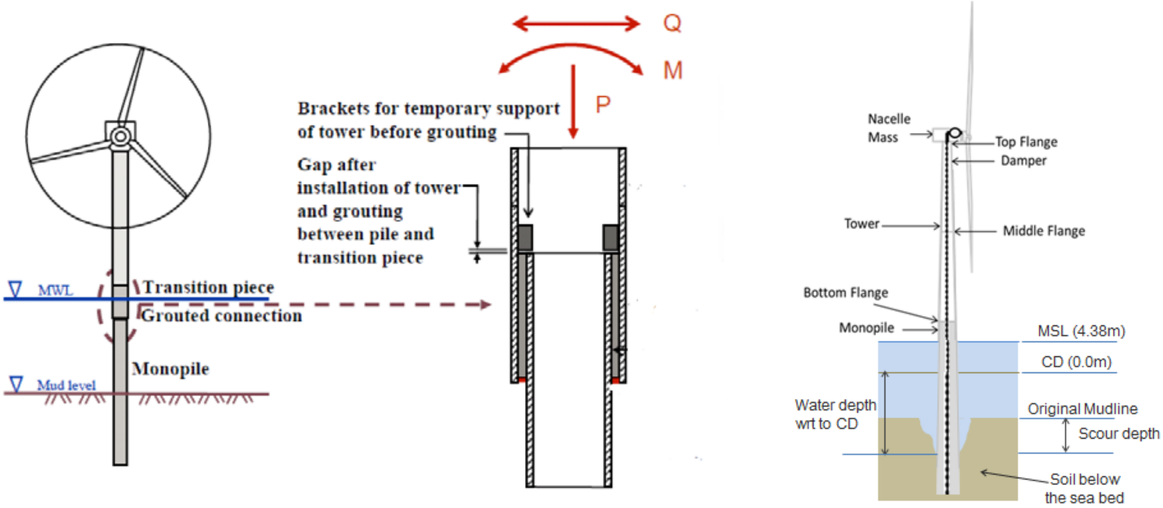
investigated using detailed FEA with a view to identifying possible continuous monitoring schemes that could be employed for the purposes of integrity assurance.



(a) (b)

Figure 1: Illustration of (a) grouted connection and (b) scour at the sea bed

Description of turbines

The turbines considered in the present study require a monopile foundation appropriate for shallow waters with typical depths of 30-40m. Figure 2 shows a generic wind turbine monopile foundation. The monopile foundation is a simple structure consisting of a steel pile driven into the sea bed. A larger diameter sleeve (transition piece) is cast to the pipe i.e. grouted, and its top rim is a flange that accommodates fixing of the turbine tower through the use of structural bolts.

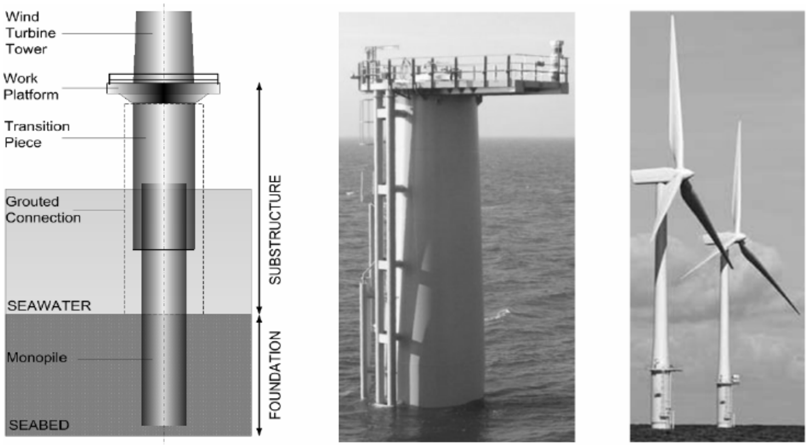


Figure 2 - Wind turbine monopile foundation

In order to make the grouted connection between the transition piece and monopile, the transition piece is first installed on top of the monopile using temporary supports (installation brackets). It is then jacked up to an acceptable degree of verticality before pumping the grout into the void. After the grout has cured, the jacks are removed, leaving a gap between the installation brackets and the monopile. The grout in the transition piece carries the shear and bending loads between the tower and the pile. The properties of the main components of the turbine associated with monopile foundations that have been considered in the analyses are summarised in Table 1.

Table 1: Properties of the main components of the wind turbine

Monopile Component	**Parameters**
Transition piece	Length: 21.84m Outer diameter = 4.54m Thickness = 50mm Material: S355 (E = 210GPa and ρ=7850kg/m^3)
Pile	Pile Length: 37.45m Outer diameter = 4.3m Thickness = 50mm Material: S355 Design embedment depth: 21.9m
Grout	Length = 6.45m Thickness = 70mm Material S5 Ducroit

Investigation of Grout damage

It has been observed in a number of cases that the insufficient axial capacity of the connection has allowed the transition piece to slip down so that the temporary installation brackets on the transition piece now rest on the monopile and carry some, or all, of the axial and bending loads from the wind turbine. The cause of the lack of axial capacity potentially stems from a number of possible failure modes which are described below.

In this study, the implications of grout damage on the global behaviour of the turbine as well as local effects have been studied in detail by performing non-linear finite element analyses. The steel shell sections have high slenderness ratios and therefore suffer from ovalisation effects which could cause loss of connectivity between either or both of the grout to steel interfaces. Furthermore, it is possible that ovalisation stresses result in crushing of the grout which can then fall out of the annulus if the wiper seal at the bottom of the Transition Piece does not perform correctly. A final consideration is that loss of adhesion between the grout and steel surfaces could result in relative shear displacements between the two materials which could result in a loss of grout stiffness and/or loss of steel thickness by abrasion of the steel by the grout. Some of these damage cases are illustrated in Figure 3.

One of the objectives of this study is to develop a strategy for monitoring grout damage based on observations/findings from the detailed analyses of various damage models.

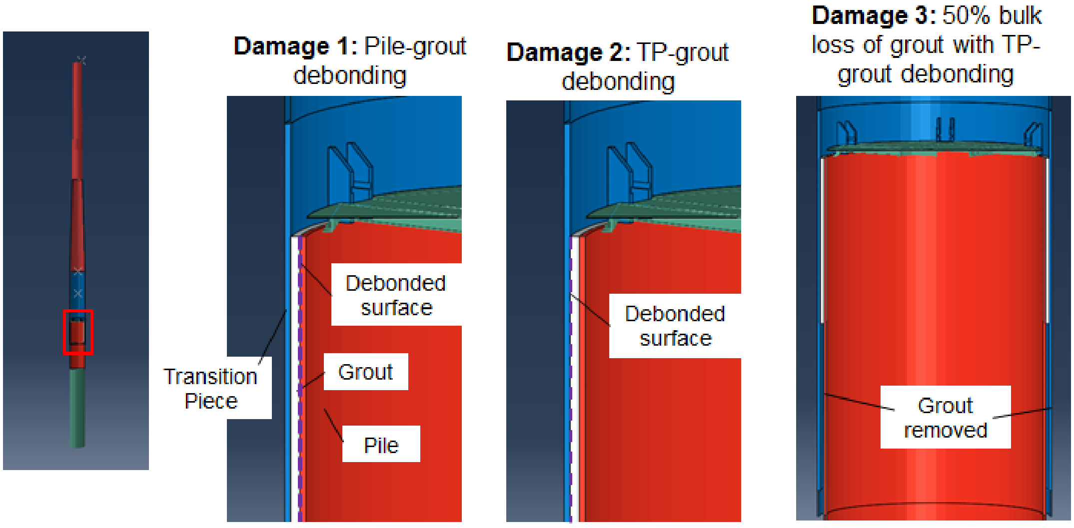


Figure 3: Representation of damage in the detailed FE model

A detailed ABAQUS model of the wind turbine was built so that various grout damage modes could be defined explicitly. The foundation of the monopile was modelled using PIPE elements connected to non-linear springs representing the foundation stiffness. The nonlinear soil spring properties were derived according to the DNV approach making use of the given soil stratification.

PIPE elements were connected to SHELL elements to represent the bulk of monopile which was connected to SOLID elements in the region of the transition piece to the monopile connection. The meshes were designed such that contact interfaces could easily be defined between the grout and steel surfaces. The installation brackets and the lower platforms were modelled explicitly using SOLID elements. The mesh of the grout was designed such that varying degrees of debonding and degradation could be applied within the same model. The detailed FE model of the turbine is shown in Figure 4.The top of the tower was represented using beam/pipe elements. All components were represented using linear elastic material models which were considered appropriate as the damage itself was represented by defining the debonded surfaces as described below.

The masses of the appurtenances and other main items such as ladders, boat landing bumpers, I-tubes were appropriately defined in the model by lumping or distributing the mass on the transition piece and tower.

Various damage modes were explicitly included in the model. For example, the debonding between the pile and the grout was modelled by defining the tangential and normal contact between the exterior surface of the pile and the interior surface of the grout. For tangential contact, the coefficient of friction μ= 0.4 was used. Similarly, debonding between the transition piece and the grout was modelled by allowing the transition piece and external surface of the grout to slide relative to each other including a coefficient of friction of 0.4. The bulk loss of grout was simulated in the FE model by reducing the height of the grout from the base.

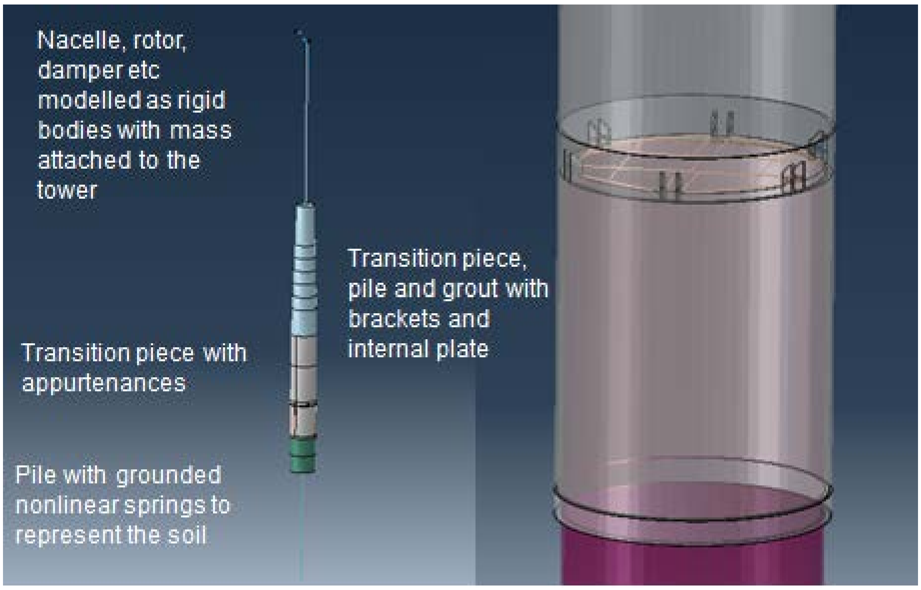


Figure 4: Finite element model of the Wind Turbine

Many wind turbines have accelerometers installed as part of the nacelle's instrumentation package and it would be advantageous to understand whether it is feasible to use the accelerometer data to diagnose any of the identified failure modes. For this reason, natural frequency of the system was calculated after representing each damage mode. The natural frequency as well as the reduction in frequency for different damage cases is summarised in Table 2. The analysis conducted here suggests that it would be possible to detect damage in the grout by monitoring the natural frequency of the structure as for all the considered damage modes the change in frequency was greater than 2%. It would, however, be impossible to distinguish between the various forms of damage just by monitoring changes in natural frequency.

Table 2:Natural frequency of the wind turbine for various damage cases.

Damage cases	Failure mode	Frequency (Hz)	% of undamaged frequency
0	Undamaged structure	0.3125	
1	De-bonding between external face of mono-pile and grout	0.2941	94%
2	De-bonding between internal face of transition piece and grout	0.2941	94%
3	10% bulk loss of grout from the base	0.2941	94%
4	50% bulk loss of grout from the base	0.2777	88.8%
5	Cone type cracking	0.2857	91.4%
6	Wear of grout by pile 1mm	0.2730	87%
7	Wear of grout by pile 2mm	0.2597	83%
8	Wear of grout by TP and pile (2mm on each side)	0.232	74%
9	Compressive failure of grout	0.294	94%

Investigation of Scour

A separate finite element model of the structure was used for investigating scour effects; this was a simplified model comprising of PIPE elements only. Non-linear soil springs were connected to the pile to represent pile embedment into the sea bed. The illustration of this concept is shown in Figure 5. The stick model was used to investigate the effect of scour by defining scour depths at 1m intervals and removing all of the soil springs above this depth as shown in Figure 5.

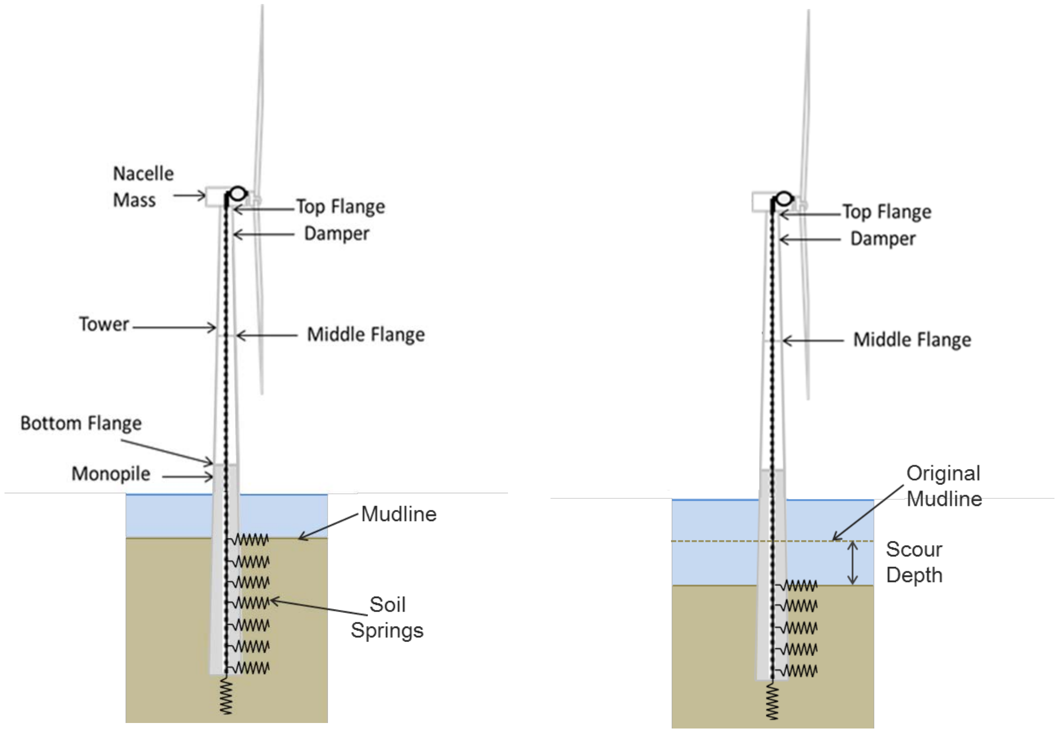


Figure 5: Scour study spring model idealisation

The fundamental natural frequency was extracted from the FE model for scour depths up to 10m. Increasing scour depth causes the length of exposed monopile to increase which reduces the natural frequency of the system. The effect of scour on the fundamental frequency is shown in Figure 6. The effect of scour on stability and utilization of the pile was also studied by consideration of overturning moments and stresses within the pile itself. It was concluded that for the example considered here, stability and utilisation criteria are of less importance up to a scour depth of 6m and natural frequency criteria governs the design.

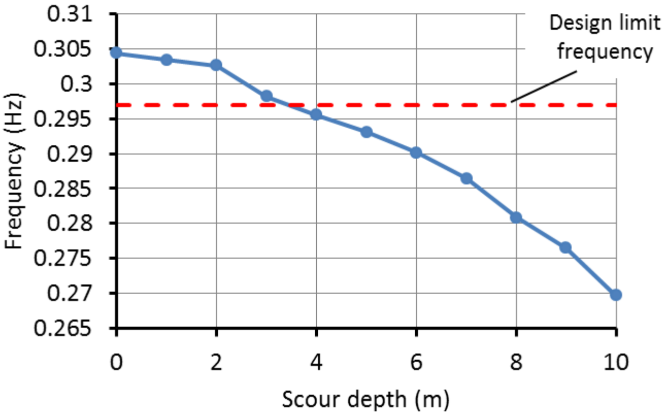


Figure 6: Natural frequency vs. scour depth

Combined grout damage and scour

The two previous investigations were then combined to investigate the potential for decoupling the two phenomena for implementation into a global monitoring and health management system.

Detailed investigation of the damaged behaviour indicated that the transition piece was able to rotate relative to the monopile. A rotational spring was therefore used to represent this damage in the stick model, located at the centre of the transition piece. The stiffness of the rotational spring was varied to allow the full range of damaged modes to be included. The rotational spring properties were calibrated for each damage mode by comparing the pushover stiffness of the detailed damaged models with the rotational spring stick model.

The effect of scour and damage on natural frequency is plotted as a function of scour and sea bed depth in Figure 7. These show that damage cases 1 and 3 cause the natural frequency to fall below the design limit at zero scour.

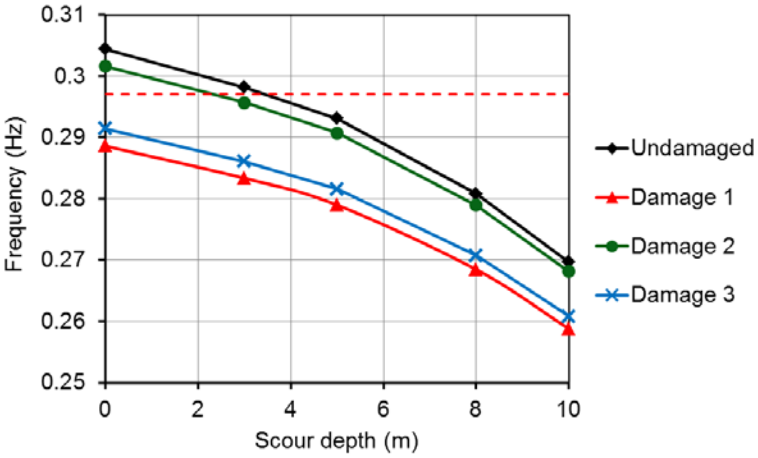


Figure 7: Effect of scour and damage on natural frequency (as a function of scour depth)

It was concluded from these analyses that the effect of scour and grout damage is to reduce the natural frequency of the turbine structure. The reduction in natural frequency caused by both scour and grout damage are in a similar range and it is therefore not possible to decouple these two phenomena simply by looking for a change in natural frequency.

Monitoring strategy

The results of the current study indicate that it is not possible to use natural frequency on its own as a method for identifying combined grout damage and scour. In order to provide a complete monitoring strategy, additional data is therefore required which can be used to identify the scour and damage levels separately.

One of the measures commonly adopted for managing grout damage is the installation of elastomeric bearings [3]. This retrofit measure gives the foundation a higher load-carrying capacity in the vertical (axial) direction, whilst retaining flexibility in the lateral directions. The bending strength of the system still relies on the grout being present in the annulus between the pile and the transition piece.

Elastomeric bearings are retrofitted by welding new brackets to the inside of the transition piece. The elastomeric bearings fit inside the bracket and rest on the monopile as shown in Figure 8. The bearings are gradually loaded as they assist the grout in supporting the weight of the transition piece and tower assembly.

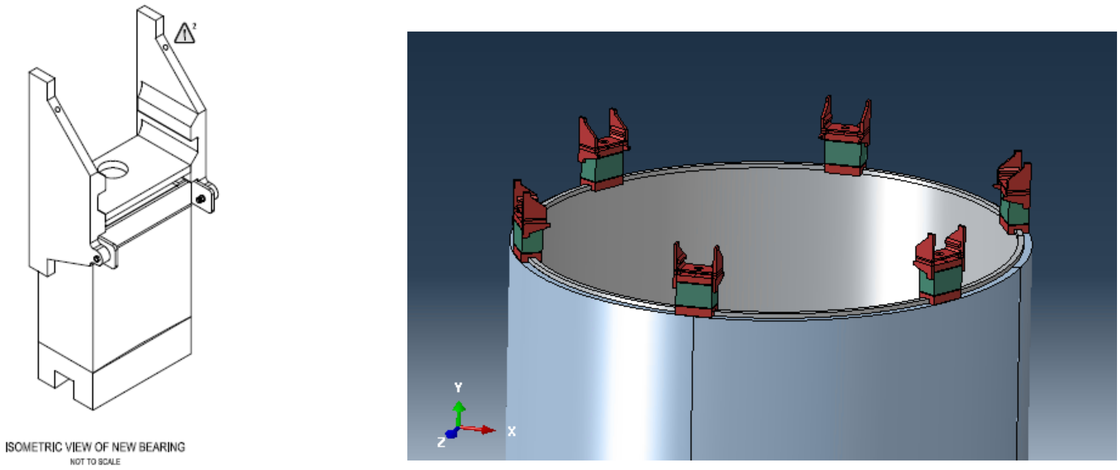


Figure 8 - The elastomeric bearings retrofit measure

The measure of force or compression in the elastomeric bearing can be used as an indicator to gauge the damage in the grouted connection. As the grout damage increases, this will be reflected by an increase in the loads carried by the bearings. This information in addition to the natural frequency data has been used to develop a monitoring strategy.

To understand the behaviour of elastomeric bearings, these were included in the FE model and the forces in them for various damage scenarios were studied. The forces in the 6 bearings considered to be installed on the monopile were combined to produce a geometric average that is direction independent. This parameter is denoted as the “equivalent force parameter”.

The magnitude of the force parameter is dependent on the magnitude of external loading and therefore cannot be used alone to identify damage. This force parameter can be normalised with long range stresses or tip displacements to remove the dependency on the applied load. Figure 9 shows this equivalent force parameter as a function of long range stress which should be measured at some distance away from the damaged grouted connection influence zone (typically 1.5-2m on the transition piece above the grouted connection).

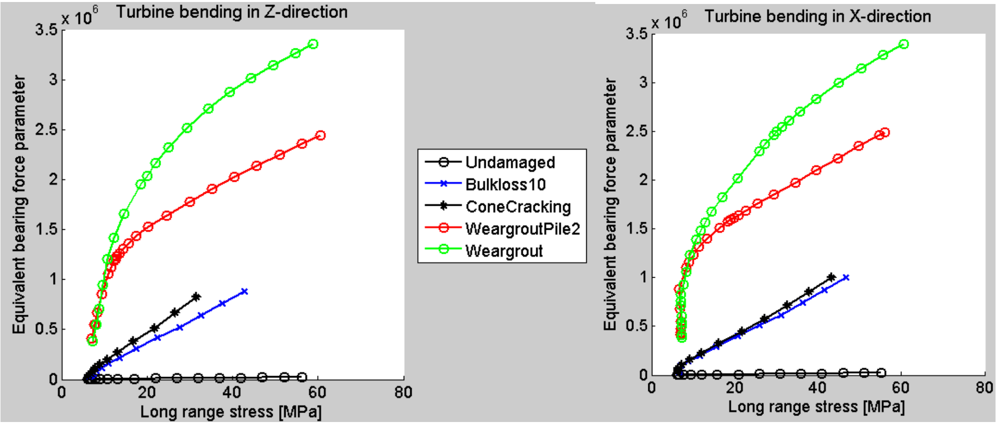
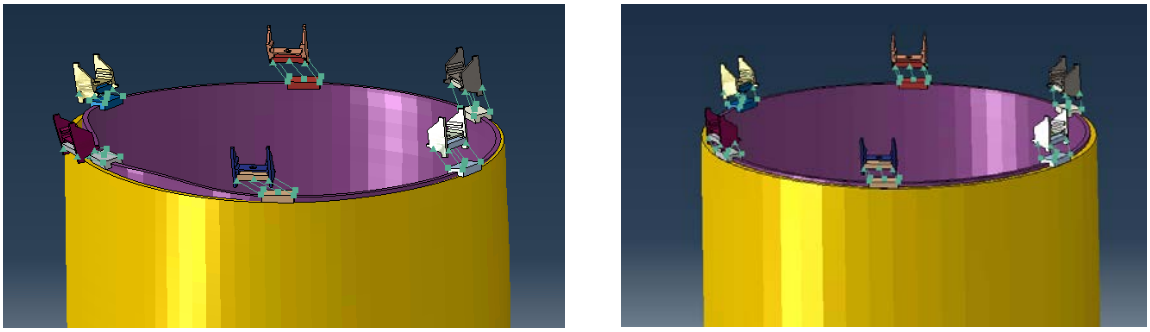


Figure 9: Equivalent force parameter and average relative horizontal displacement as function of stress on transition pile

It is noted from the plots above that for different damage modes, the shape of the curve is different. For the case of damage due to wearing away of the grout some nonlinearity is observed; whereas, for the case of damage due to grout bulk loss the plot is almost linear. This was further investigated by studying the results from the FEA analyses. The deformation plots of the pile and the brackets in the vicinity of the grouted connection for two types of damage modes (Figure 10) indicated that when there is loss of adhesion between the pile and the grout, the pile is susceptible to buckling and ovalisation due to the loss of composite action. This introduces nonlinearity in the behaviour and is reflected in the curves for the damage modes of “wear of grout by pile” plotted in Figure 9. For the other considered damage mode “bulk loss of grout”, the pile exhibits stiffer response as it continues to act compositely with the grout. The difference in the behaviour for different damage modes is depicted in the curves showing variation of bearing force with long range stresses. This information can be utilised to gain an understanding of the type of damage.



(a) Wear of grout (2mm on both pile and TP sides)-Ovalisation/buckling of the pile

(b) 10% Bulk loss of grout (with TP-grout debonding)-No ovalisation/buckling of the pile as it is stiffened due to bonding with the grout

Figure 10: Deformation of the pile due to bending of the turbine for damage modes (a) wear of grout and (b) bulk loss of grout. Displacement scale = 20

The above procedure allows for monitoring the condition of the turbine with respect to its original condition after installation of retrofit bearings. It is noted that the installation of the retrofit is due to the presence of damage within the grouted connection. The proposed strategy cannot predict the initial level of damage but can be used to estimate the damage mechanisms and observe further degradation of the grouted connection over time.

The scour study has indicated that the pile design is controlled by the natural frequency requirement and the strength and stability of the piles are not compromised for scour depths up to 5m. Monitoring of scour has to be undertaken in conjunction with monitoring of the damage level within the grouted connection. As has been shown, the natural frequency of the turbine changes in a similar manner for both grout damage and scour, and therefore these features cannot be separated easily.

Once the condition of the grout has been established based on monitoring elastomeric bearing forces, the natural frequency measurement can be used to monitor scour. For example, if the condition of the grout is found to remain unchanged over the monitoring period, then any observed change in the natural frequency of the turbine would indicate change in sea bed due to scour. Whilst damage to the grouted connection also influences the natural frequency, an estimation of the grout damage mechanism can be used in combination with the percentage reduction in natural frequency to predict the scour level using Figure 7. Where it is found that the frequency of the turbine is approaching its lower limit, then immediate inspection of the monopile is recommended and remedial action should be taken.

Conclusions

Based on the detailed analyses of a wind turbine monopile foundation, the following conclusions have been drawn:

- Natural frequency alone cannot be used to diagnose scour and grout damage modes. However when one of the scour/damage modes is well-characterised, the other may be predicted.
- It is shown that forces/displacement across the elastomeric bearings (a retrofit measure for grout damage) in conjunction with long range stresses on the transition piece could be employed to judge the degree of damage in the grout. This could be combined with frequency measurements to assess changes in the sea bed level.
- Based on above mentioned points, a strategy for monitoring scour and grout damage for the purpose of integrity assurance and safe operation of the wind turbine has been developed.

The above strategy could allow for the deduction of the severity of the damage as well as scour and would assist in deciding upon the urgency of remedial measures to be implemented.

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