Nacelle natural frequency data to assess the effectiveness of pre- and post-installation scour protection

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ABSTRACT

At the case study offshore wind farm 140 wind turbine generators were installed atop monopile foundations. At four monopiles a filter rock layer was installed before the piling operations took place, with an armor layer installed atop this layer after piling (pre-installation) and at six monopiles rock protection was installed after some scour had developed (post-installation). Accelerometers were installed in the nacelle of each wind turbine generator. Natural frequency data have been recorded for 10 years since the installation of the scour protection. The initial natural frequency for the pre-installation foundations was significantly higher (i.e. the pre-installation foundations were stiffer). The natural frequency was observed to increase with time at all locations where scour protection had been installed. It is thought that this was due to the densification of the sand within the rock matrix. These findings have implications for the pile fatigue and the management of the site.

1. INTRODUCTION

Monopile foundations have been used at 77% of European offshore windfarms (OWF) (Sánchez et al., 2019); they are favored for their ease of manufacturing and installation and are well suited to the geology and water depths of the North Sea and Baltic (BVG Associates, 2019). The current plan for most offshore windfarms is that they will be decommissioned at their end of their lifespan (typically 25 years). If there is no change of plans' over 3.5 GW of global offshore wind energy will be lost by 2035 (Spyroudi, 2021). Increasingly windfarm owners are looking to lengthen the lifespan of their assets and some early OWF are now investigating the feasibility of extending the operational life of their windfarms by repowering (upgrading parts of the old asset). The process of repowering increases utilization of the existing assets and offers a solution that requires lower maintenance costs and has environmental benefits since it delays the disposal of the assets.

Over the life of a monopile foundation the cyclic loading from the environmental forcing causes the build-up of fatigue damage (Byrne et al., 2017). If this damage becomes too severe then the foundation may become inoperable. Due to the cumulative nature of this damage and the desire to extend the asset's lifespan it is of increasing importance that the foundations are kept within the safe design ranges.

The accumulation of fatigue damage within a foundation is strongly conditioned by the dynamic performance of the system, which, in turn, depends on the stiffness of the foundation. Pile stiffness is a function of the soil strength, pile geometry (pile length and pile wall thickness), pile embedment (the length of the pile within the soil layers), water depth and the metocean forcing (wind, wave and tides) (Byrne et al., 2017). During the OWF design phase estimates of the pile stiffness are made. Traditionally this was performed using the p-y approach (where p is the soil resistance per unit length of the pile and y is the pile deflection) (DNV, 2021). The soil is modelled as a series of non-linear p-y springs to represent the relationship between lateral resistance and displacement based on pile lateral load tests. The p-y formulae are based on testing conducted on long slender piles with relatively large length to diameter ratios (~34) undertaken in the 1950's and 1960's. These tests were focused on finding the critical point of failure and so generally are found to under-predict the stiffness of larger diameter monopiles with short embedment depths (typical of those being installed in the North Sea). Approaches have since improved (Byrne et al, 2017) and research on scour/scour protection effects is ongoing (Ma & Chen, 2021; Mayall et al., 2020), but the earlier p-y approach was widely used.

As part of the assessment of pile stiffness an estimate of pile embedment is made. The pile embedment may vary over the lifespan of the assets due to the reduction in the surrounding bed-level both through general seabed lowering (e.g. through the migration of bedforms, banks and channels) and local scour. Many designs for monopile foundations may cope with a small amount of bed lowering (less than a few meters). However, when this lowering is predicted to have a detrimental impact on the pile stiffness the design may require stabilization of the surrounding bed. If stabilization or prevention of scour is required then it is likely that scour protection will be used. Scour protection typically utilizes loose rock, concrete mattresses, frond mats or rock-filled bags. Here we will be considering the impacts of rock protection, which is the dominant type of scour protection at monopile foundations. Scour protection may be installed either prior to or following the installation of the foundation. We define pre-installation scour protection as any form of scour protection that is installed fully or in part before the installation of the foundation and thus before any scour has developed. Post-installation scour protection is used to describe protection that is installed after the foundation is installed. Typically material is deposited into the developed scour pit to restore the bed level at the foundation wall to just below the level of the surrounding seabed (Mayall et al, 2020).

Use of pre- or post- installation is often guided by access constraints, costs and the predicted rate and maximum depth of scour. The two design methods have differing considerations for type and volume of rock required.

Research into the impacts of scour protection on the pile stiffness and fatigue damage is in its infancy. Kallehave et al. (2015) stated from unpublished field observations that "scour protection can have a significant effect on the fundamental frequency". Their sensitivity study showed that 1 m and 2 m thickness of scour protection could change the fundamental frequency by 1.4% to 3.1%. Mayall et al. (2019) utilized physical models to determine the impact of both pre- and post-installation scour protection on pile stiffness. However, these results have not yet been validated with measurements from the field and are still a long way from being formally incorporated into the design of the foundations. Stuyts et al. (2020) incorporated scour protection (represented as a dense sand layer) into their foundation back-analysis of sensor data for 5 m diameter monopiles. They concluded that substantial improvements of the fit of calculated and measured bending moments could be obtained taking account of actual bed levels around the foundation including the scour protection layer.

Here, utilizing a case study of field measurements, we consider how the design of scour protection may influence the pile stiffness and how this may impact the design life of the monopile foundation.

2. METHODS

2.1. Case study

At the case study windfarm 140 turbines were installed on monopile foundations. At ten monopiles scour protection was installed (Table 1). Pile diameters, D, range from 5.5 to 6.3 m increasing in increments of 0.1 m. Increasing pile diameters correspond with increasing water depths. Water depths at the monopiles range from -21 to -31 m relative to the Lowest Astronomical Tide (LAT). The pile lengths are unique to each location (range 58 to 68 m) to ensure top of pile at a fixed height relative to LAT and pile embedment, L, ranges from 28 to 32.5 m; i.e. L/D ~5.

Soils comprise mostly poorly sorted sands and gravelly sands, with median grain sizes between 0.50 and 0.75 mm. This material forms a surface veneer generally not exceeding 1 m thickness overlaying firm to stiff clay.

At the majority of locations just 0.5 m of local scour was predicted to occur, due to the presence of firm clays. However, where a thick sand layer was present at some locations, predicted scour depth was as much as 10.5 m (Table 1). Whilst only 0.5 m of scour was predicted to occur into the surficial clay layers, scour has generally removed the surface veneer and at most location continued into the underlying clay layers. Scour measured at unprotected piles in 2020 ranged between 1.7 and 4.5 m and was on average 2.7 m. In 2020 the scour was still developing at most unprotected monopiles across the site. Predicting scour in cohesive soils involves a great deal of uncertainty due to the complexity of the controlling factors. However, hybrid approaches, for instance those combining the Erodibility Index Method with targeted soil sample erosion testing, are improving estimates (Harris et al., 2022).

The general bed level at the ten scour protected monopiles remained stable (within ±0.8 m) over the observation period, i.e. limited bed level change through bedform or bank migration.

Table 1. Ambient seabed level, pile diameter and predicted scour depth at the 10 scour protected foundations

MP ID.	General seabed level at time of piling (mLAT)	Pile diameter (m)	Predicted scour depth with no scour protection installed (m)
MP01	-27.1	6.0	5.0
MP02	-29.4	6.2	6.0
MP03	-30.2	6.2	10.5
MP04	-30.8	6.3	10.5
MP05	-25.6	5.8	0.5
MP06	-27.1	5.8	0.5
MP07	-27.6	6.0	0.5
MP08	-28.6	6.1	0.5
MP09	-29.0	6.2	3.5
MP10	-29.2	6.1	1.5

2.2. Scour protection design

Two different scour protection designs were used at the ten protected monopiles. Both designs utilized a 10 – 60 kg crushed granite/gneiss with a median rock size (D_{50}) of 230 mm, a specific density of 2.76 T/m^3. The two designs differed in their order of installation and rock volume.

The post-installation rock was installed in September 2011, 1 – 2 years after the installation of the monopiles.

Pre-installation

There were four monopile locations where it was predicted that over 5 m of scour may occur due to presence of a thick sand layer (Table 1, MP1 – MP4). At these locations a pre-installation scour protection design was utilized to prevent local scour at the pile wall from developing.

At these four locations a circular pad of rock with a radius of 22 m and thickness of 0.65 m was installed on the seabed prior to any other works. Commonly this pre-piling rock installation is called a filter layer and tends to comprise smaller rock to allow for piling works. No records for the installation of the pre-piling scour protection were available and so these rock pad dimensions and volumes (988 m^3, Table 2) are estimated from the pre armor installation bathymetry.

Following the piling campaign the armor layer was installed atop the filter rock. The armor was installed to a thickness of 0.65 m (2.5D_{50}) atop the filter layer out to a distance of 13.75 m from the pile center. The design specified tolerance of ±0.25 m in the installed level. However, typically the installed level was above this and in some isolated locations the installed layer was more than 2 m thick. The installed armor volume ranged from 667 to 1093 m^3 (Table 2).

An example of the bathymetry at a monopile location where pre-installation scour protection has been installed is shown in Figure 1a.

Post-installation

At six locations scour protection was installed after the monopiles had been installed. At these locations the purpose of the scour protection was primarily to stabilize the cables.

Given that at some locations there was a two year gap between the piling and scour protection installation operations scour had developed to a depth of 1.3 to 2 m relative to the surrounding seabed (Table 2). The design was to fill the level of the seabed to a fixed level that was typically just below the level of the surrounding seabed level out to a distance of up to 22 m from the pile center. The design specified tolerance of ±0.25 m in the installed level. However, typically the level was much above this and in some small areas was more than 1 m above the specified level. The volume of rock installed varied between 308 and 644 m^3 and was dependent on the scour volume that needed to be filled.

An example of the bathymetry at a monopile where post-installation scour protection has been installed is shown in Figure 1b.

Table 2. Scour protection design and installed rock volumes

MP ID.	Scour protection design	Max scour depth prior to scour protection installation (m)	Maximum scour extent from pile center (m)	Total installed (m^3) [pre + post]
MP01	Pre-installed filter and post-installation armor	N/A	N/A	988+728
MP02	Pre-installed filter and post-installation armor	N/A	N/A	988+667
MP03	Pre-installed filter and post-installation armor	N/A	N/A	988+1093
MP04	Pre-installed filter and post-installation armor	N/A	N/A	988+714
MP05	Post-installation scour protection	1.3	11	350
MP06	Post-installation scour protection	1.3	9	308
MP07	Post-installation scour protection	1.8	16	585
MP08	Post-installation scour protection	2	18	537
MP09	Post-installation scour protection	2	15	642
MP10	Post-installation scour protection	1.9	14	644

Note: the design and installed volume for the pre-installation pad are estimated from the post filter layer installation bathymetry

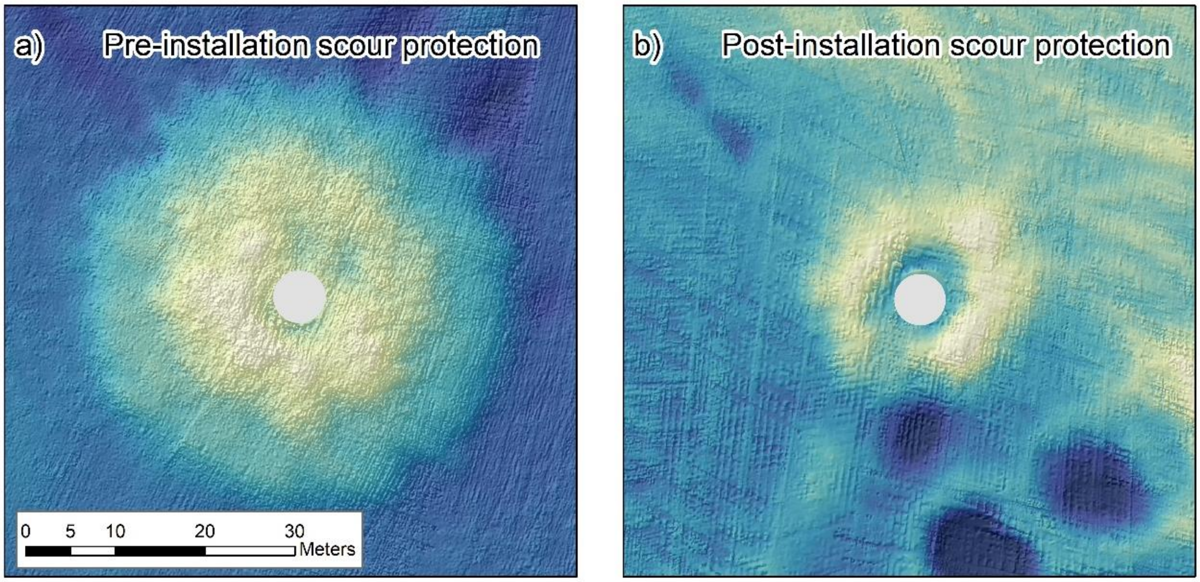

Figure 1. Multibeam bathymetry showing a foundation with a) pre-installation scour protection, and b) post-installation scour protection

2.3. Natural frequency data

Pairs of accelerometers were installed in the nacelle of each wind turbine generator. These accelerometers record 100 data points per second. The data from these has been used to quantify the natural frequencies of the foundations to a resolution of 0.0001 Hz. Natural frequency data have been recorded for just under 10 years (June 2012 through to December 2021), with a three month gap between March and May 2012 and a gap between March and May 2018. Given that the monopiles were installed from October 2009 through to August 2010 there is a 1 to 2 year gap between the pile installation and the start of the natural frequency timeseries. Data are provided as averaged 10-minute interval values, these data have been averaged further to provide a mean monthly natural frequency. The data were cleaned and any erroneous values were removed.

3. RESULTS

Figure 2 shows the monthly averaged natural frequency data for the ten scour protected monopiles (light and dark purple lines) and an example of a typical natural frequency timeseries for an unprotected monopile (green line).

Figure 3 (light purple line) shows an example of the monthly mean natural frequency data for a single monopile (MP08). The natural frequency data has a small seasonal trend, with a peak in natural frequencies during the winter months. For this reason a 12-month moving average was applied to remove the seasonal trend (dashed light purple line). The data have been portioned into nine 12-month intervals starting at June 2012 (the first month for which all scour protected monopiles have data available). A linear fit was then applied to the moving average for each of these 12-month samples (dark grey lines). The gradient of each fit describes the rate of change in natural frequency over the year sampled. These can then be compared between different monopile locations (Figure 4) to give an indication of the differences in rate of change of natural frequency. By comparing the rate of change the influence from fixed variables (such as the water depth and pile diameter) are removed, allowing comparisons to be made between monopiles with differing water depths. Positive values indicate where the natural frequency has increased over the year sampled and negative values where the natural frequency has decreased. An average has been taken of the annual trend at the 130 unprotected monopiles (dashed line). This has then been plotted on the same figure as the trends for the scour protected locations to give context to the change observed at these locations.

In the next two sections we describe the typical natural frequency responses at monopiles where scour protection was installed prior to the piling operation (pre-installation scour protection) and following the installation of the monopile (post-installation scour protection).

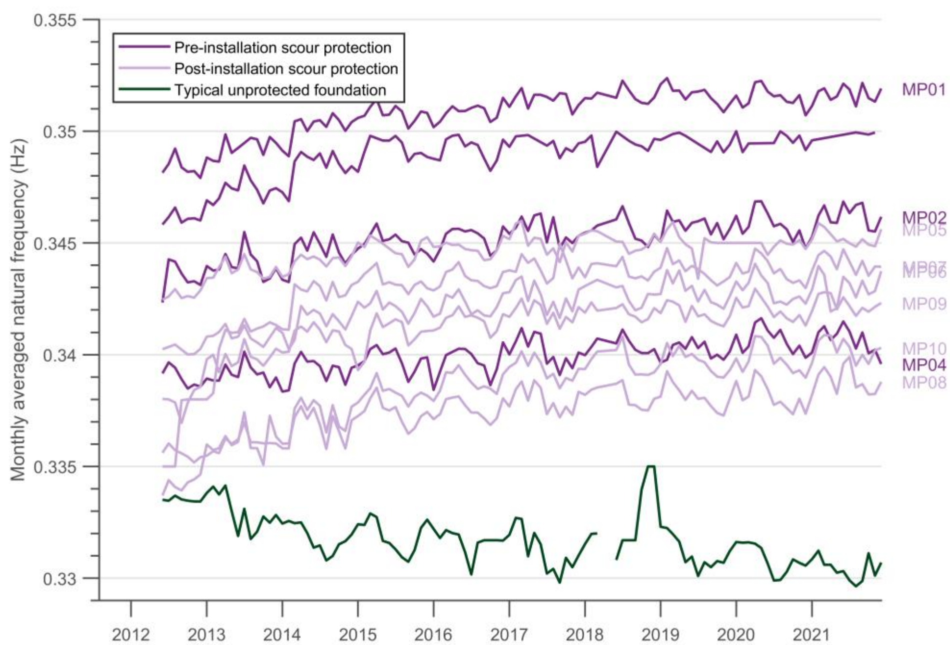

Figure 2. Timeseries of natural frequency for the ten monopiles with scour protection installed and an example of an unprotected monopile

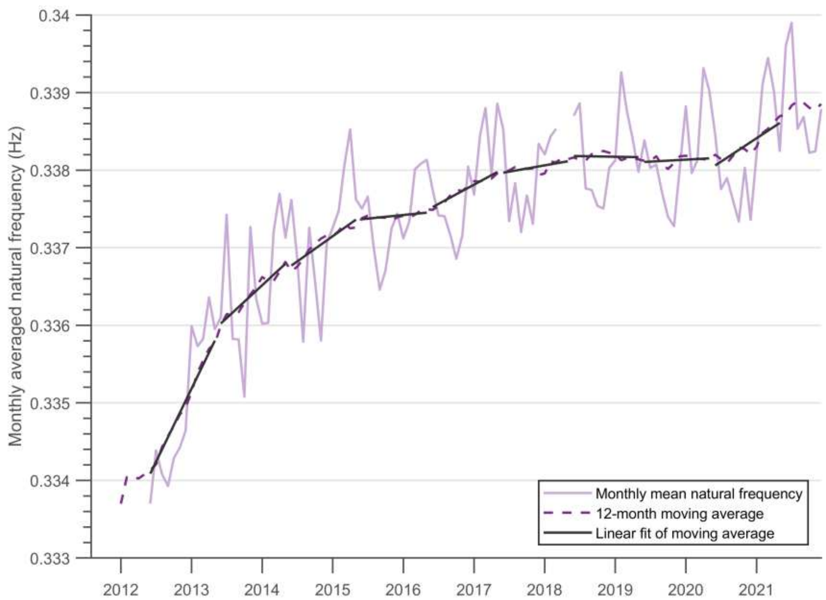

Figure 3. Example for calculating the annual average rate of change

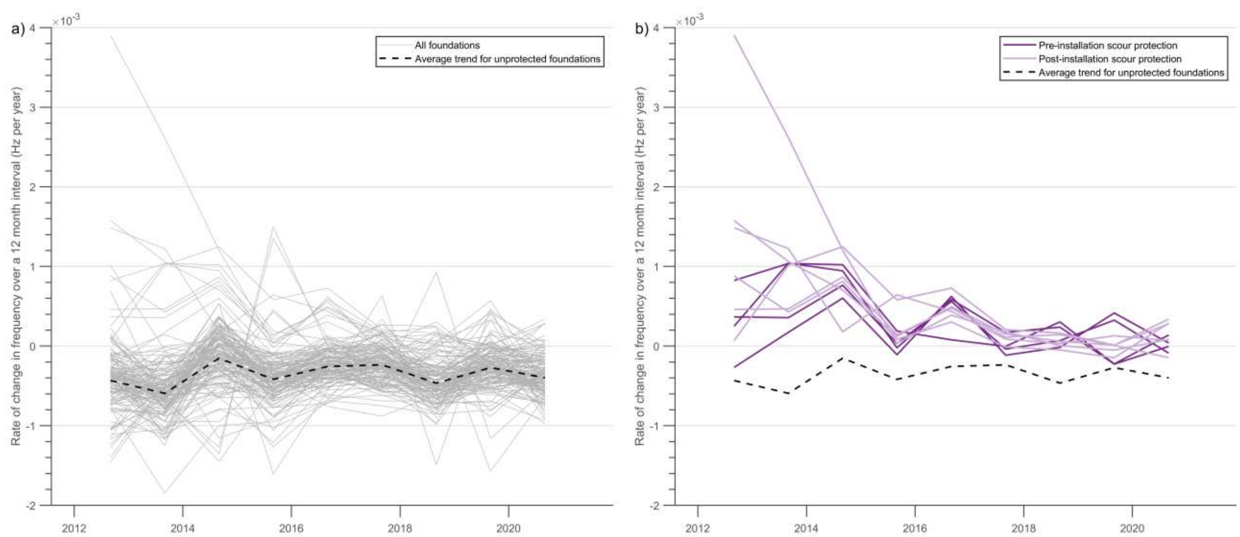

Figure 4. Rate of change in natural frequency for a) all foundations and b) for scour protected foundations

3.1. Pre-installation scour protection

Figure 2 (dark purple lines) shows the natural frequency data at the four monopiles subject to pre-installation scour protection. At these locations the data show a higher initial natural frequency and a gradual increase in the natural frequency with time. Typically the rate of increase is slightly faster over the first two years (Figure 4b).

At the start of the time series there is a larger amount of variability in the rate of change (Figure 4). At MP01 we observed a decrease in natural frequency values from June 2012 to June 2013. The cause of this variability is unclear. Across the windfarm we observed a peak in rate between June 2016 and June 2017. This is also observed at those locations with scour protection installed. Given that this is a site-wide response it is likely that a change in weather conditions caused this peak.

3.2. Post-installation scour protection

At those six foundations where the scour protection was installed after the foundation was piled Figure 2 (light purple lines) shows that the initial natural frequency was closer to that of the unprotected piles. The monthly natural frequency increased rapidly for the first 2 years at an average rate of 0.001 Hz/year (Figure 4, light purple lines). At MP10 the annual change in natural frequency between June 2012 and June 2013 was 0.0039 Hz/year. Over the rest of the timeseries the natural frequency continued to increase, but at a much slower rate, reaching near-equilibrium in 2018.

3.3. Comparison between scour protection methods

Figure 5 shows the relationship between seabed level (and thus water depth) and the average natural frequency for the last year of observations (January – December 2021) for all unprotected piles (green), those with pre-installed scour protection (dark purple) and those with post-installed scour protection (light purple). A linear trend was fitted to the natural frequency data of the unprotected piles. This demonstrates a strong relationship of increasing natural frequency with decreasing water depth (and therefore pile diameter). The ten protected piles plot above this trendline, indicating that the natural frequency with scour protection is higher than at those unprotected foundations. The unprotected foundations can be further divided into two distinct clusters, where those with post-installed scour protection plot slightly closer to the unprotected trendline than those with pre-installed scour protection.

For each protected pile using the linear relationship shown in Figure 5 we have estimated what the natural frequency would be at these locations had no scour protection installed and an average amount of scouring (~2.7 m) occurred (Table 3). These values can then be compared with the observed natural frequency data to provide an estimate of the percentage increase in natural frequency afforded by the scour protection. This difference demonstrates that the pre-installation of scour protection results in a higher natural frequency than both the unprotected foundations and those protected with post-installation scour protection. On average the pre-installed scour protection (on average 1.5 m thick at the pile wall) increased the natural frequency by 5.0%, whereas the post-installed scour protection (on average 1.75 m thick at the pile wall) increased the natural frequency on average by 2.6%. The cause of the difference in response between the two types of scour protection is discussed in the following section.

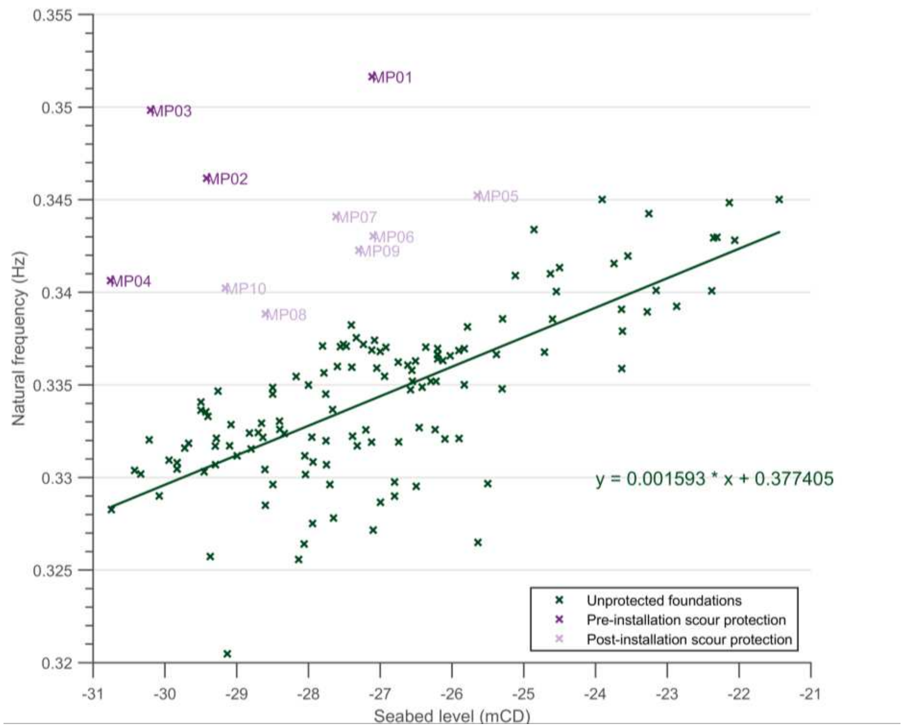

Figure 5. Relationship between seabed level and natural frequency

Table 3. Observed natural frequency at the ten scour protected monopiles and the estimated natural frequency for the same water depth without scour protection

Pile ID	Water level (mLAT)	Observed average of the last year's natural frequency data (Hz)	Estimated natural frequency for the last year with no scour protection installed (Hz)	Percentage difference (%)
MP01	-27.1	0.352	0.334	5.2
MP02	-29.4	0.346	0.331	4.7
MP03	-30.2	0.351	0.329	6.4
MP04	-30.8	0.340	0.328	3.7
MP05	-25.6	0.346	0.337	2.6
MP06	-27.1	0.344	0.334	2.6
MP07	-27.6	0.344	0.333	3.2
MP08	-28.6	0.339	0.332	2.1
MP09	-29.0	0.342	0.334	2.5
MP10	-29.2	0.340	0.331	2.8

4. DISCUSSION

Given that natural frequency data are only available 1 – 2 years after monopile installation the dataset cannot be used to indicate how the progression of scour may have influenced the natural frequency data. It is, therefore, difficult to disentangle the cause of the difference in natural frequency between those monopiles with and without scour protection, i.e.

is the difference due to the formation of scour at the unprotected monopile and/or is the difference due to the stiffening effects of the scour protection. In their physical model tests Mayall et al. (2019) observed that at the post-installation scour protection foundations the natural frequencies did not recover to the pre-scour levels. Placing the rock protection at the monopiles not only had an instant impact on the natural frequency (at the very start of the time-series those with scour protection installed already had elevated natural frequencies), but also we observed a continuing increase in the natural frequency long after the rock protection was installed. Only over the last three years (2018 to 2021) has the natural frequency at the scour protected monopiles stabilized. Mayall et al. (2019, 2020) observed in their physical model tests that after applying scour protection into a scour pit (post-installation rock, which maintains the bed level at the pile wall) the natural frequency continued to increase over the subsequent testing phases by as much as 0.7 %. This is less than observed here in the field, however, the physical model tests were only run for approximately one week at field scale. Mayall et al. (2019, 2020) hypothesized that this ongoing increase was due to the accretion of sand in the rock matrix. This was supported by their end of test observations where the rock matrix was seen to be packed with sand.

During the testing Mayall et al. (2019, 2020) also ran a pre-installation test case. During this test the natural frequency increased by 0.3 %. Similarly to the pre-installation test the rock matrix became impregnated with sand.

The infilling of the rock matrix with sand can increase the natural frequency both by increasing the friction at the pile wall, but also by the weight of the sand applying pressure on the layers of sediment below (overburden). Couldrey et al. (2020) observed that during the passage of a large solitary barchan dune the natural frequency of the foundation temporarily increased by 1 %. Through computational modelling it was shown that scour developed rapidly into the dune, therefore the dune did not provide any additional support to the pile (i.e. the pile embedment depth did not noticeably increase). Therefore, the increase in the natural frequency was due to the global overburden of the sand dune on the bed below. The infilling of the rock with sand appears to happen rapidly to begin with. But the slow (~6 year) increase in natural frequency suggests that the infilling and densification is a slow process.

Three to four times as much rock volume was used for the pre-installation design and two campaigns of installation were required. Therefore, the pre-installation design would have been considerably more expensive to install. However, given the two year gap between piling and post-installation rock protection the scour at these locations was predicted to be considerably more, and hence the design necessitated a pre-installation layer.

5. CONCLUSIONS

The following conclusions are drawn from this work:

- At monopiles where scour protection rock had been installed (pre- and post- installation) there was a year-on-year increase in the natural frequency for the first 6 years; whereas, for unprotected foundations the annual change was negative for almost all of the foundations across the whole of the ~10 year time-series. Laboratory studies (Mayall et al., 2020) indicate that the likely cause of this continued increase in natural frequency is the infilling of the rock pore spaces with sand and the compaction of the rock/sand matrix.

- The initial (~2 year) rate of change in natural frequency was faster at piles where the scour protection was installed after the monopile (post-installation) than at those where the scour protection was partially installed before piling (pre-installation).
- After this initial rapid period the rate of change slowed but was still positive at both types of scour protected monopiles, suggesting that the infilling and compaction can take over 5 years to reach near-equilibrium.
- Compared with unprotected piles from a similar water depth and with a similar pile diameter the monopiles protected with scour protection had a higher natural frequency. On average at those foundations protected with pre-installed scour protection the natural frequency was 5.0 % higher than those without scour protection, whilst at those monopiles protected with post-installation protection the natural frequency was 2.6 % higher than at the unprotected foundations. This difference in the performance of the two types of scour protection is not a surprising result since a much larger volume of rock was used for the pre-installation design and none of the soil at the pile wall will have been eroded (due to being protected by the rock).
- Our analysis confirms the impact of scour protection on pile stiffness is considerable and should be incorporated into the foundation design to ensure the lifespan of the foundations is maximized. This is in line with the earlier recommendations of Kallehave et al. (2015) and Stuyts et al. (2020).

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