Understanding the health of wind turbine foundations to maximize production

With the foundations of wind turbines being below ground, they are often the most overlooked when it comes to maintenance. After all, a visual inspection is limited to the above ground parts of the foundation, or requires destructive testing. Data driven non-destructive testing mechanisms, already quite common in other industries, is not yet standard practice in the wind industry. Structural health monitoring of wind turbine generator foundations and support structures can provide valuable insights into the performance of what can't be visually inspected.

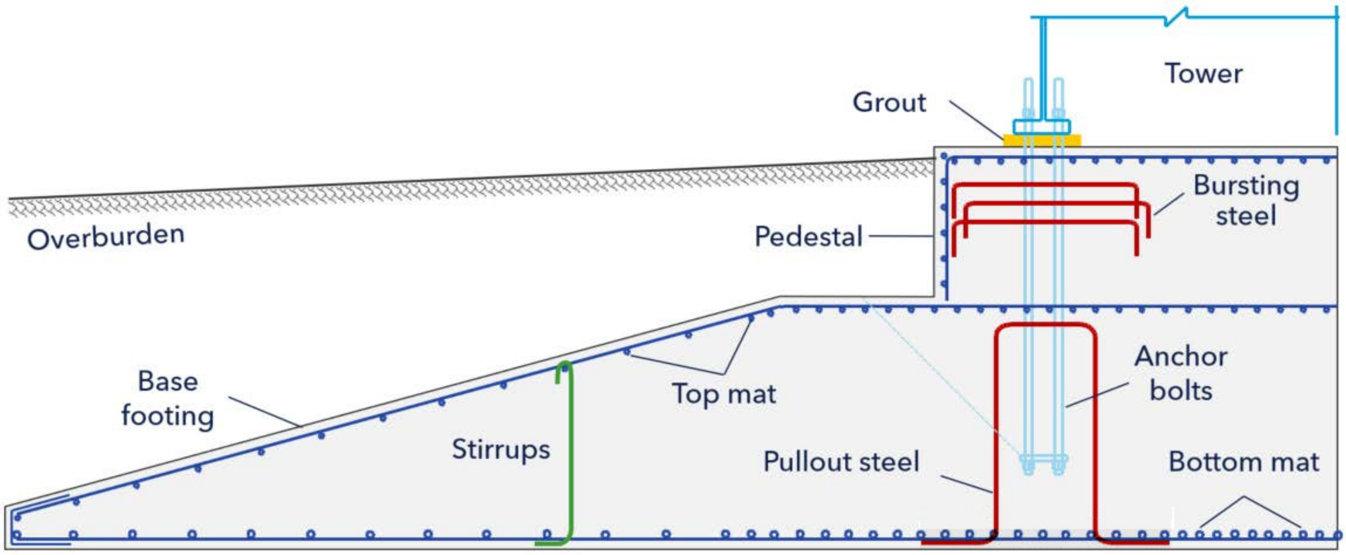

Figure 1: Cross section of a typical wind turbine foundation

The onshore wind industry has thrived since the development of the first commercial-scale wind farm. As the number and size of wind farms continue to grow, more resources are required to proactively manage operational assets. Proactive management and asset condition monitoring are critical to ensuring the long-term operation and viability of the life of onshore wind farms, particularly in the context of life extension.

Wind turbine generator (WTG) foundations are estimated to represent approximately 25% of the cost of the balance of plant (BOP) of a wind farm. This percentage is second only to that for the electrical elements of the BOP, yet the foundations are the least visible components, and consequently often receive less attention than other aspects of the wind farm. Furthermore, despite the extensive remote monitoring and sensing capabilities of modern SCADA-connected wind turbines, there is generally no, or very limited, information available pertaining to the health of WTG foundations.

Wind farm owners and operators are put in a challenging position. The foundation supports a multimillion-dollar asset, without which revenue would be impossible; yet this asset is largely invisible and its operational health unknown.

Wind turbine generator foundations

The role of a WTG foundation is to adequately support the wind turbine above-ground structure across a large range of environmental conditions. While many different types of WTG foundations are used across wind farms, one thing is common to all: typically, only a small portion of the foundation is visible, with most of this support structure being buried below the ground.

From a structural point of view, WTG foundations are significantly different from other conventional tall structures such as buildings or towers. Typically, wind loads are dominant and greater when compared with dead loads acting on a vertical cantilever beam. Also, aerodynamic and aeroelastic effects must be considered for wind turbines, unlike equivalent static wind loads on buildings. In addition,fatigue loading may govern the foundation design, as opposed to conventional buildings where wind fatigue loading is small and typically ignored.

An evolving understanding

The general goal of structural codes is to provide an acceptable probability of failure for the given design life of the structure. Considering that modern wind turbines and their foundations are a relatively new type of structure, and that their size continues to increase rapidly, understanding of their behaviour, likely damages and failure modes, and industry requirements are evolving. As such, the applicable knowledge and standards used when WTG foundations were being designed even just a few years ago are likely to be different from what applies today in the evolving understanding and standards related to foundation failure mechanisms.

Deficiencies can be, and are, identified when assessing previously constructed wind farms, often as part of a technical due diligence review or when abnormal behaviour is observed. Furthermore, analysis or inspection of the current state of an existing wind farm may result in the determination that the foundation design does not provide the level of reliability intended by the latest standards, i.e. a non-conformance with current standards is identified.

While this does not necessarily mean that the intended design life will not be achieved, it does indicate that further analysis and monitoring should be undertaken, to better understand the current health of the foundation and the risk to the asset during its lifetime.

Structural health monitoring

Structural health monitoring (SHM) refers to a system comprising of a datalogger, sensors to monitor the health of engineering structures, and analysis tools to interpret measurements. In the context of WTGs, this typically refers to the health of the tower-foundation system. As with many monitoring applications, the 'health' of a tower-foundation system cannot be directly measured, but is inferred indirectly through the measurement of other parameters. These may include, for example, the first mode frequency of the tower-foundation system, or its flexural stiffness.

Foundation monitoring recommendations from Standards

Current international standards and guidelines related to wind turbine foundation design, such as IEC 61400-6 [1], DNVGL-ST-0126 [2] and DNVGL-ST-C502 [3], provide recommendations for planning, defining inspection programmes and types of inspection, determining appropriate intervals between inspections, and documenting inspection findings. They also provide guidance on specific items to focus on during the inspection. DNVGL-ST-0126 also recommends that inspections of foundations are used in conjunction with structural health monitoring. It also references DNV-RP-C210 and DNV-RP-G101. Whilst not wind turbine specific, these standards introduce the components that comprise a risk-based inspection programme.

Why structural health monitoring is needed

Structural health monitoring of WTG foundations and support structures provides an insight into the performance of

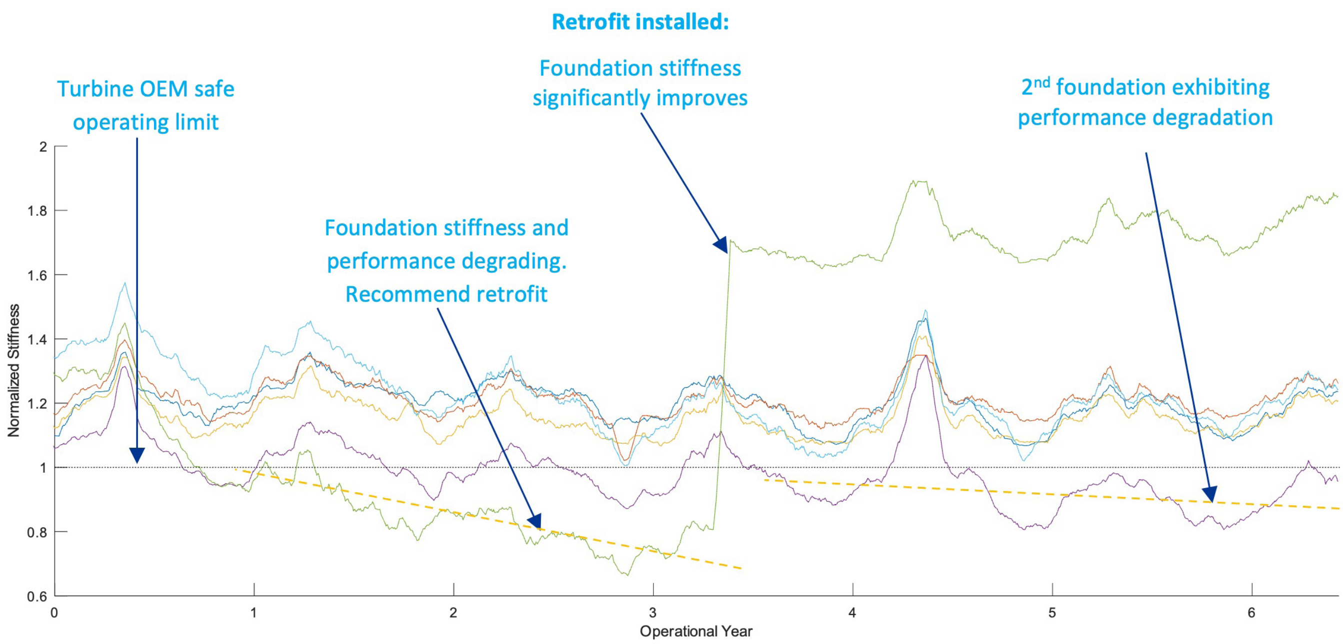

Figure 2: Real-world example of degradation in foundation stiffness and subsequent repair

what can't be visually inspected without destructive testing, such as drilling or excavation. Typically for ageing structures, such as road infrastructure, various levels of visual inspections are systematically carried out to check their serviceability and rate their condition.

Where visual inspections cannot be carried out, other non-destructive testing mechanisms or data-driven analysis may be employed. While this has been standard practice in many other industries faced with similar challenges, it is not widespread in the relatively young wind industry. As multi-megawatt scale WTGs age, it will become an important factor in maximizing the revenue from any wind asset.

In short, SHM can provide greater certainty about the health of the system and how it is changing over time. Data from long-term monitoring can not only be used to detect whether a system is deteriorating; in some cases, the monitoring can be employed to determine when intervention is required to address structural integrity degradation or performance issues. It can also provide insight into what the sources of deficiencies are, and what retrofit options may be suitable.

Often in conjunction with a threshold value, SHM can help to determine if a certain limit has been reached or, in some cases, when it might be reached. This information is particularly useful in the planning of significant investments or in taking further actions or deciding on retrofits.

Increasing certainty through structural health monitoring

In the context of refinancing, long-term operation, life extension or sale of a wind farm asset, the condition of the foundations is often one of the largest unknown factors in the equation. This is where SHM truly can provide valuable input into the analysis.

Depending on the data recorded, it can be used to infer both the current state of the foundation and its behaviour over time. This helps to understand whether there may be more margin than anticipated for the foundations to keep performing efficiently, effectively, and safely, or if prompt action is required to address any deficiencies. Either way, SHM provides critical knowledge for determining when and what to invest in for any life extension scenarios.

A purely theoretical analysis may result in a higher risk profile for the wind asset because of uncertainty in the environmental conditions. However, the presence of sufficient SHM data showing that there is no deterioration would provide a reliable basis to potentially downgrade the risk profile.

Structural health monitoring approaches

There are currently two main viable approaches to SHM of wind turbine foundations. Both are highly dependent on the aim of the monitoring campaign and the existing equipment in the WTGs, but can in general be grouped as utilization of existing measurement equipment installed in the nacelles of WTGs and installation of specific SHM monitoring equipment in the foundations, towers and/or nacelles.

While the first approach is generally more economical, its suitability is highly dependent on two main factors. Firstly, whether the existing condition monitoring equipment is suitable and accurate enough for the desired outcomes. Secondly, whether the data from the condition monitoring equipment can be made available to the asset owner / manager, on a near real-time basis, for the purposes of monitoring. This is not always the case.

In contrast, the installation of custom SHM monitoring equipment can be designed and engineered specifically for the desired outcomes. The cost of a custom SHM system is typically a tiny fraction of the value of the asset or its annual revenue, and the insights gained can be highly useful.

Structural health monitoring in the real world

At some point in the design of a monitoring system, the question will arise: how many WTGs within the wind farm should be monitored? From an engineering perspective, the answer is 'ideally all', but typically this is impractical or uneconomic. Therefore, the answer will depend on the goal of implementing an SHM system.

The priority generally is to monitor any tower-foundation systems that may be deemed at risk of not achieving their intended design life. In assessing whether particular foundations should be monitored, the following questions should be considered.

Are visual inspections detecting physical indications of deterioration in any foundations? Have there been any design reviews which have identified a particular foundation or type to be at risk of not achieving their intended design life? Have any environmental condition assumptions significantly changed since construction? Have there been any significant events occurring at any WTG location which may impact the integrity of the WTG tower-foundation system?

In the context of SHM where there are no specific foundations of concern, e.g. when SHM is utilized to inform possible life extension of an asset, it is recommended that a representative sample of foundation types and geotechnical conditions are considered for monitoring. A reference to compare against is highly desirable. This can be in the form of historical data and/or other monitored systems.

When implementing SHM on multiple WTGs within a wind farm, it is advisable that at least one of the systems monitored is on a foundation that is considered 'healthy', one of each foundation type used at the site. This provides a solid reference system with which other systems can be compared as well as against each other.

Figure 2 illustrates a real-world example of structural health monitoring of multiple WTGs within the same wind farm over six or more years. In this case, the SHM of multiple WTGs allowed the retrofit of a foundation to occur before substantial damage had occurred, with a significant improvement in the stiffness witnessed after the retrofit. It also shows that a second foundation is also degrading.

As can be seen, monitoring multiple WTGs makes identification of outliers more apparent. Also, fluctuations in the normalized stiffness curves occur due to seasonal variations in environmental conditions.

In conclusion

Structural health monitoring is a useful tool to gain insight into the condition of an asset and to help inform further decisions for its maintenance. For remote assets or assets with limited access such as wind turbine foundations, SHM can be a highly valuable and economical monitoring approach, providing continuous or frequent access to the condition of an asset.

It is important that any SHM campaign is well-designed, and that the analysis process is rigorous to ensure that the resulting information can be relied upon.

When correctly implemented, SHM can provide increased certainty about the health of a tower-foundation system and how it is changing over time. This information is incredibly useful in understanding the condition of the asset and supports making informed decisions for the ongoing operation and maintenance, refinancing, long-term operation, life extension or sale of a wind farm asset.

While there are multiple benefits to having structural health monitoring of WTG foundations, there are of course some limitations associated with it. For example, on its own, it may not detect or provide warning of abrupt or unexpected failures. However, in conjunction with other structural analysis and design reviews, potential failures may be identified beforehand, allowing time for appropriate remediation. Likewise, monitoring for a short or intermittent period does not usually provide useful information.

Given the gradual influence that environmental conditions can have on the stiffness of foundation-WTG systems, SHM provides the greatest benefit when implemented over longer periods in select environments across the wind farm.

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