SITE SPECIFIC WIND TURBINE FOUNDATION CERTIFICATION

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ABSTRACT

Site specific wind turbine foundation certification is an important part of the complete certification process of wind turbines. Certification helps in ensuring safety of the wind turbine. A wind turbine tower structure and its foundation receive a considerably high fatigue loading during the turbine's 20 year expected life span. The foundations of wind turbines are subjected to highly dynamic loading and these loads are extremely eccentric in nature. It must be able to resist the large concentrated force resulting at the tower base due to the wind's aerodynamic and mechanical forces. As wind turbine foundation failure can cause complete failure of wind turbine system, site specific foundation certification becomes necessary and essential for continuous and safe functioning of wind turbine. Moreover, the foundations should also suit the Indian site conditions. This paper focuses on the complete process of certification of site-specific wind turbine foundation considering various parameters.

Keywords: Wind turbine, Foundation, Site-specific, Certification

1. Introduction

Certification of wind turbines has a history of more than thirty years. It has been applied differently in scope, requirements and depth in different countries. India is one of the top five wind turbine markets in the world. In order to streamline the growth of the industry in India, the Ministry for New and Renewable Energy (MNRE) made the requirement for Type Certification of wind turbines mandatory in India. The Centre for Wind Energy Technology (C-WET) which is under MNRE prepares and issues the “Revised List of Models and Manufacturers (RLMM)” of wind turbines periodically. Certification as per GL RC is widely recognized by C-WET. To suit the Indian conditions, some type-certified wind turbines may undergo major/minor changes. Especially in case of wind turbine foundations which are designed site-specifically, they need to suit the Indian conditions. Many wind turbines in India are coming up in areas of high seismic zones. Therefore, safety level of such foundations is an important requirement to be followed. This criteria makes the certification of wind turbine foundations in India very important in the present scenario.

Certification of wind turbines has its own benefits. It helps in ensuring safety of the wind turbine. It also improves product confidence and reduces the risk on the investment. It also influences customers in the selection of Original Equipment Manufacturers (OEM’s). Certification of wind turbines helps successful market entry and market growth through increased competitive advantage.

Site specific wind turbine foundation certification is an important and compulsory part of Site-Specific Design Assessment module in Project Certification. As most foundations in
India are designed site-specifically, site specific foundation certification becomes important and can be done independently from a Project Certification.

2. Wind Turbine Foundations and Their Importance

Foundation is needed to support and absorb loads from the wind turbine. The choice of foundation type is entirely dependent on soil conditions and water table location prevailing at the planned site of a wind turbine. A safe and economic foundation design is an important part of all construction projects. Wind turbines are usually supported by either a slab foundation when competent material exists within a few meters of the surface, or a pile foundation in cases of weaker ground. This further, depends on geotechnical conditions and foundation method of developing resistance to overturning forces. The groundwater conditions along with the water table location below the foundation base should also be considered while determining the load carrying capacity of the top soil for the wind turbine foundation. Some other types of wind turbine foundations may include slab foundation held down by rock anchors and concrete monopile foundations which consist of a single large diameter concrete cylinder, which resists overturning by mobilising soil lateral loads alone.

3. Certification of Wind Turbine Foundations

Generally certification of wind turbine foundations can be performed in the following cases:
1. As part of the Type Certification of the wind turbine which includes design assessment and manufacturing evaluation of the foundation.
2. As part of the Project Certification of a wind farm as site-specific foundation examination.
3. Site-specific foundation design assessment in addition to an existing type certificate of a turbine, without applying for a complete project certificate.

4. Site Specific Wind Turbine Foundation Certification

Sometimes the type certification of a wind turbine does not include the foundation certification (optional according to GL RC’s guideline GL Guideline for Wind Turbines (GL-IV-1)) and, type certification ends at the tower bottom. The reason is that often standard type foundations are not planned by the designer but only site specific solutions are planned. The foundation designs for the specific sites are based on site conditions and local requirements. In India, the local site-specific requirements considering the type of soil, seismic zone shall be evaluated while designing the foundation of a wind turbine. Other factor such as quality of available workmanship is also considered which may lead to an increase in cost by delays during the construction phase. Figure 1 shows a picture of Wind turbine foundation construction in India.

The wind turbine foundation is critical as the loads from the tower are transferred to the soil by the foundation. Hence, it is important for wind turbine manufacturers and financiers to obtain site specific certification of the foundation. However in India in many cases, the site-specific foundation design is not certified by an accredited certification body.
5. Process of Site Specific Foundation Certification

The process of certification of a site-specific wind turbine foundation is described below as shown in Figure 2. The manufacturer submits the complete documentation related to the foundation design which will be required for the certification process. This documentation is then assessed by the certification body by a parallel assessment. During the assessment, it will be verified that the wind turbine foundation is suitable for the intended site, soil conditions and that the requirements for the structural integrity of the foundation are met with due consideration of the external conditions.

![Figure 2: Modules of Site Specific Foundation Certification](image)

5a. Load Assumptions

The load assumptions required for site-specific foundation certification could be the following: a) in case where the site is covered by the type certified load assumptions, the tower bottom loads from the already certified load assumptions can be used and b) in cases when the site is not covered by the type certificate loads, a new load calculation must be done.

If necessary or if the load calculation is not clear in some cases, a load calculation (with reduced scope) is done for the comparison of the site with the type class loads. The load assumptions must include all loads required for the analysis of the foundation for the ultimate and serviceability limit state. Both the characteristic loads and the design loads adapted by partial safety factors are required at the tower/foundation interface. This includes both the
extreme and fatigue loads. In addition, the loads for the foundation also include loads required for the analysis of the gaping joint, etc.

Additionally for Indian site conditions, earthquake loads are also considered in areas with risk of occurrence of earthquake. As a requirement for C-WET to consider earthquake loads for sites in India, GL RC also has provision to consider the same. For estimating the earthquake loads, locally applicable regulations can be applied. In India, the design standard for earthquake resistant design for buildings is IS 1893(Part1):2002. The general approach requires calculation of a representative horizontal seismic load using local building code procedures and superimposing the load with the wind turbine design loads. GL-IV-1 also recommends use of procedure as per Eurocode 8 and/or API, in the absence of any locally applicable regulations.

Several procedures are available for evaluation of seismic loading of buildings and other structures. The recommended analysis procedures can generally be categorized as consisting of modal response spectrum procedures and time history analysis procedures. Evaluation of the various modes of vibration of a structure typically requires the use of a computer program for processing the input data and performing the computations required to solve the equations of motion. Modal analysis of wind turbine seismic loading can be performed using software such as GH Bladed, an industry standard software package by GL Garrad Hassan used in the design and certification of wind turbines. In GH Bladed, the analysis is accomplished through an iterative procedure to compute the response spectrum for a reference motion.

5b. Documentation

The set of documents that the manufacturer submits for certification of foundation could include drawings, site specific geotechnical investigation report along with detailed design calculations, load calculation report, and construction instructions.

The design drawings contain all the necessary information and technical requirements for the construction of the foundation. These drawings include the representation of the foundation, geometry, along with detailed presentation of the reinforcement (reinforcement drawings). The material specifications and soil requirements for the intended site are also mentioned in the drawings. The specification of turbine type and type class on the drawings is recommended.

For site-specific certifications, a soil investigation report is very important. The report shall contain statements on the ground with strata, faults, disturbances and inclusions. The groundwater conditions along with soil and rock properties and their parameters are included in the soil investigation report. The boundaries of the investigated areas and their boundary conditions are also mentioned in a soil investigation report. The dynamic properties of soil such as the dynamic shear modulus are provided in the soil investigation report in order to calculate the rotational spring stiffness.

The detailed design documentation of the foundation submitted includes all the loads for which the foundation was designed and the material parameters and relevant verifications. The load assumptions are clearly stated in the documentation. An instruction for construction could also be provided, specifying all steps and procedures for construction. The scope of documentation for certification may differ depending on the case.
5c. Design assessment of foundation

The loads on the foundation are determined considering the different load cases as described in GL-IV-1 which is based on IEC-61400-1. The analysis is performed with the least favourable of all combinations of actions according to GL-IV-1. For the analyses in the ultimate and serviceability limit states, both the characteristic loads and the design loads adapted by partial safety factors are needed at the tower/foundation interface. The design resistance is determined with due consideration of the partial safety factors $\gamma_M$ according to Table 1, taken from GL-IV-1.

Table 1: Partial safety factors for the material $\gamma_M$

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate limit state</th>
<th>Serviceability limit state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fracture and stability failure</td>
<td>Fatigue</td>
</tr>
<tr>
<td>Concrete</td>
<td>$1.5$ $^1$ $(1.2)$ $^2$</td>
<td>$1.5$</td>
</tr>
<tr>
<td>Spun concrete</td>
<td>$1.4$ $^1$ $(1.2)$ $^2$</td>
<td>$1.4$</td>
</tr>
<tr>
<td>Reinforcing and prestressing steel</td>
<td>$1.15$ $^1$</td>
<td>$1.15$</td>
</tr>
</tbody>
</table>

$^1$ For unusual design situations, e.g., earthquake calculations, $\gamma_M = 1.3$ can be set for concrete and spun concrete and $\gamma_M = 1.0$ for reinforcing steel and prestressing steel.

$^2$ For the calculation of deformations when taking account of non-linearities of the geometry and/or the material, $\gamma_M = 1.2$ may be taken (value in brackets).

$^3$ For precast concrete elements, a reduction of the partial safety factor for concrete $\gamma_M$ is allowable if this reduction is given in the recognized design code used (EC 2 or DIN 1045-1). In this case, the conditions of the code for the reduction shall be fulfilled. Required measures shall be specified in consultation with GL. Mixing of the two codes is not permitted.

Additional loads resulting from imperfections and tilting of tower and foundation are also considered as 3 mm/m tilting of the foundation for consideration of unevenly subsidence of ground.

For the dynamic analysis, the distance of the natural frequency for the overall structure from the excitation frequencies is decisive in avoiding resonance. In the assessment of the expected natural frequencies, a parameter study is needed for the dynamic soil parameters; this is defined so that a range of possible soil types and soil properties is covered. The required minimum values for the shear modulus G of the soil could be specified as dynamic values in relation to the Poisson’s ratio $\nu$.

The assessment of foundation rotational stiffness is an important part of the design assessment process because of the effect it has on tower natural frequency, and hence on fatigue loading. A minimum foundation rotational stiffness is normally specified by the manufacturer to ensure that the tower natural frequency is high enough for the fatigue loadings on which the tower design is based to be valid. Based on this, later the foundation footprint is ensured that it is sufficiently large to achieve this rotational stiffness.

Static strength analysis and fatigue analysis of the structural steel components and reinforced concrete are performed in order to assess the foundation design. A finite element
(FE) model of the foundation can be developed and used for the analysis. An example of the FE model of a slab foundation created using a FE program has been shown in Figure 3. The design is verified applying the safety concept as described in GL-IV-1. Generally for the analysis of reinforced concrete and pre-stressed concrete, Eurocode 2 EN 1992 is applied. For the components of steel in the foundation such as the embedded steel section in foundation, the relevant parts are verified according to Eurocode 3 EN 1993. In India, the reinforced concrete designs for the foundations are done as per IS 456:2000.

Figure 3: An example of a Finite Element model of a Foundation showing the elements

Fatigue assessment is important during the design assessment of foundation. Fatigue damage occurs through repeated applications or variations of loads. Ultimate limit states of fatigue may be associated with the failure of reinforcing steel, of prestressing steel or of concrete. Concrete can be calculated for fatigue using the Palmgren-Miner cumulative damage law. Unlike steel, the fatigue strength of concrete is very sensitive to the mean stress.

For components of reinforced concrete or pre-stressed concrete, detailed fatigue analysis is provided for the concrete, the reinforcing steel and the pre-stressing steel as described in GL-IV-1. The load spectra and corresponding mean values or Markov matrices are used for verification of the fatigue strength. CEB-FIP Model Code 1990 or equivalent could be applied for fatigue verification.

The following describes briefly the procedure described in GL-IV-1, Section 5.4.2.2 para (2) for the fatigue analysis of concrete. For wind turbines with a nominal number of operational load cycles

\[ N_{nom} = r \cdot n_r \cdot T \leq 2 \cdot 10^9 \]
where: \( r \) = number of rotor blades; \( n_R \) = rated rotor speed; \( T \) = intended service life,
a detailed analysis for concrete under compressive loading is not required, if the condition
expressed in the following equation is met:

\[
S_{cd,\text{max}} \leq 0.40 + 0.46 \cdot S_{cd,\text{min}}
\]

with:

\[
S_{cd,\text{min}} = \frac{\gamma_{sd} \cdot \sigma_{e,\text{min}} \cdot \eta_c}{f_{cd,\text{fat}}}
\]

\[
S_{cd,\text{max}} = \frac{\gamma_{sd} \cdot \sigma_{e,\text{max}} \cdot \eta_c}{f_{cd,\text{fat}}}
\]
as explained further in Section 5.4.2.2 of GL-IV-1.

Slab foundations are verified against tilting (eccentricity of load / gaping joint),
bearing capacity failure, sliding, buoyancy and settlement of the soil. The foundation is
designed such that there is no ground gap for the permanent loads with a probability of
exceedance of \( p_T = 10^{-2} \) (equivalent to 1750 h in 20 years), as described in GL-IV-1.
Furthermore, the forces resulting from the characteristic loads of load case 1, 2 and 3
according to GL-IV-1 are only permitted to cause a ground gap up to the centre of gravity of
the bottom area of the foundation. An example of the results of FE analysis in the form of soil
stresses for verification for gaping joint is shown in Figure 4 and that of the bending moment
plot from FE analysis is shown in Figure 5.

Figure 4: An example of soil stresses for verification of gaping joint (Gaping for
permanent loads permitted only up to half of C.G. of bottom area of foundation)
In pile foundations analysis of the external bearing capacity of piles is performed for all loads as described in GL-IV-1. The maximum static pile loads are determined and verified with the pile capacity. The different types of pile foundations for wind turbines may include monopiles, multi-pile foundation, anchored pile foundation, etc.

6. Conclusions

Wind turbine foundations are very important for the safe operation of the complete wind turbine. These foundations are designed for significant dynamic loads compared to building foundations. The design of wind turbine foundation is quite complex as the loading direction changes with wind direction and nacelle orientation. Vertical and shear forces along with significant overturning moments must be resisted within tolerances for foundation settlement and tilt. This further increases the complexity in wind turbine foundation design. The foundations have to be analysed for the ultimate limit states of extreme and fatigue loads. Earthquake loads shall also be considered for earthquake prone sites. Certification of foundation thus ensures safety and safe operation of the wind turbine. In cases of site-specific foundation certification, it is important and necessary to meet Indian site conditions. Thus the process of certification of a site-specific wind turbine foundation should be followed properly for continuous and safe functioning of the wind turbine for its expected life span.

7. References

