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Evaluation of Wind Power Plants from the Aspect of Earthquake Design

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ABSTRACT

Türkiye in recent years, consequently, their share in the total generation of energy within the country is also increasing every year. Considering the cost of wind power plants, together with the targeted amount of energy generation, earthquake planning for these systems becomes crucial. Earthquakes are one of the principal risks of wind energy investments, especially when considering the earthquake hazard level in a large portion of the country. Under the present circumstances, the companies producing wind turbines conduct the analysis and planning they deem necessary and forward these to the investors in our country. The extent to which manufacturers consider earthquake parameters and analysis methods in the design of wind turbines for earthquake resistance is not well-defined. The lack of clarity makes it difficult for investors to accurately evaluate the suitability of wind turbine tower and foundation designs for the specific conditions of the country.

This study evaluates earthquake design methods by looking into the regulations used in the design of wind turbines around the world. The magnitude of ground motion considered in the earthquake design, the method of analysis used, the load combinations on which the designs are based, and the criteria for the designs have been inspected. Moreover, the design documents for a wind turbine that is being constructed has been examined in detail, with the earthquake design stage being especially scrutinized.

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Assessments and recommendations have been made regarding the design specifications, analysis methods and criteria used in the analysis and design of the wind turbines currently being built in our country. Subsequently, obtained recommendations have been taken into consideration to propose an earthquake design procedure for the earthquake design of wind turbines.

Keywords: Wind power, seismic design, design criteria.

1. INTRODUCTION

The implementation of wind power plants has been continuously increasing in Türkiye in recent years, consequently, their share in the total generation of energy within the country is also increasing every year. Considering the cost of wind power plants, together with the targeted amount of energy generation, earthquake planning for these systems becomes crucial. Earthquakes are one of the principal risks of wind energy investments, especially when considering the earthquake hazard in a large portion of the country. Under the present circumstances, the companies producing wind turbines conduct the analysis and planning they deem necessary and forward these to the investors in our country. The extent to which manufacturers consider earthquake parameters and analysis methods in the design of wind turbines for earthquake resistance is not well-defined. The lack of clarity makes it difficult for investors to accurately evaluate the suitability of wind turbine tower and foundation designs for the specific conditions of the country.

This study evaluates earthquake design methods by looking into the regulations used in the design of wind turbines around the world. The magnitude of ground motion considered in the earthquake design, the method of analysis used, the load combinations on which the designs are based, and the criteria for the designs have been inspected. Moreover, the design documents for a wind turbine that is being constructed has been examined in detail, with the earthquake design stage being especially scrutinized.

Assessments and recommendations have been made regarding the design specifications, analysis methods and criteria used in the analysis and design of the wind turbines currently being built in our country. Subsequently, obtained recommendations have been taken into consideration to propose an earthquake design procedure for the earthquake design of wind turbines.

2. TYPES OF DAMAGE IN WIND POWER PLANTS (WPP) DUE TO EARTHQUAKE

The current literature does not contain any information on damages caused by earthquakes to WPPs. The primary reason for this is that the average period in which earthquakes of a certain high magnitude are repeated is quite long, while at the same time, the number and geographic distribution of the relevant systems have only begun to increase in the last twenty years.

However, considering the geometric and construction specifications of WPP-type structures, the locations and types of damage expected due to the impact of an earthquake can be listed as follows:

i. Tower - Crushing and cracking in the concrete at the connection of the tower to the foundation.

ii. Tower - Local bending and buckling in the tower components at the connection of the tower to the foundation.

iii. Tower - Shear and bending damages in the tower components at the connection of the tower to the foundation

iv. Bending and shear damage in the flanges and bolts at the joints of the tower components

v. Bending damage in the reinforced concrete component of the foundation

vi. Damage to the load-bearing system due to excessive deformation on the ground under the foundation

vii. Damage to the moving mechanisms of the nacelle due to a high degree of horizontal ground motion and acceleration.

Figure 1 - Damage at the connection of the tower and the foundation of the WPP

Figure 2 - Possible damaged of WWP due to earthquake (REF)

After the site visits of existing WPPs Kahramanmaras Earthquakes occurred on 6 February 2023, it has been observed that the most common structural problems in turbines in Türkiye occur at the foundation and/or the tower and at the foundation connections. The sources of these problems encountered in the foundations are primarily related to the quality of reinforced concrete construction, reinforcement layout and arrangement, reinforcement concrete covers, and concrete curing. The most common problem among them is the separation of the base-tower connection over time. Problems that may arise in the tower-base connection are mostly because of bending. In some cases, permanent bending deformations may also occur in the tower. Moreover, general internal-external foundation controls that are primarily evaluated by visual inspection and conducted rapidly pose significant risks. Microcracks that may occur can be a precursor to a serious problem in the future.

The problems in the foundation generally stem from design errors and workmanship issues in the application. In particular, the lack of sufficient inspection in Türkiye, coupled with rapid manufacturing processes, results in problems in the foundation.

To identify the types of damage mentioned above, a systematic examination and observation is the most appropriate approach. To this end, the following activities are recommended:

i. Monitor and compare horizontal displacement and acceleration values in the support system of the WPP with the design parameters.

ii. Continuously measure the tilt and deformations occurring at the transition between the tower and the foundation of the WPP tower.

iii. In the event of an earthquake occurred within 30 km of the WPP, torque control should be performed on the foundation connection bolts.

iv. Inspect the foundation concrete, including the transition between the tower and the concrete, both inside and outside the tower, for cracks resulting from crushing, as well as possible deformations on the concrete surface.

v. Inspect non-structural elements inside the tower.

3. DESIGN REGULATIONS FOR WIND POWER PLANTS (WPPS)

The main regulations and specifications widely accepted and used worldwide for the design of WPPs that form the basis of this study have been examined. The main components of the analysis include the loads considered in the structural design, load combinations, structural analysis methods, structural modeling rules, design criteria, and methods. In the examination, the latest versions of the regulations that are widely used both in our country and in the world have been considered. These regulations are as follows:

i. Turkish Standards, TS EN 61400 -1 (April 2006), Wind Turbines - Part 1: Design requirements (Wind Turbines - Part 1: Wind turbine generator systems, Safety requirements, (IEC 61400-1:1999, modified)

ii. INTERNATIONAL STANDARD IEC 61400-1, Wind turbines – Part 1: Design requirements 2005

iii. ACP 61400-1-202x, Wind Energy Generation Systems – Part 1: Design requirements – Modified Adoption of IEC 61400-1

iv. SASO IEC 61400-3-1: 2020, IEC 61400-3-1: 2019, Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines

v. Germanischer Lloyd: Guideline for the Certification of Wind Turbines, Basic Principles for Design and Construction, 2010

vi. DNVGL-ST-0437 Edition November 2016, Loads and site conditions for wind turbines

vii. ASCE/AWEA RP2011, Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures

viii. DNV GL AS, DNVGL-ST-0437 Edition, November 2016, Loads and site conditions for wind turbines

ix. ASCE/AWEA RP2011, Recommended Practice for Compliance of Large Land-based Wind Turbine Support Structures

Some of the regulations comprise expanded versions of some main regulations and others compromise modified versions consistent with the dissimilar conditions of various countries.

The most important point to be emphasized here is that, since these regulations are used all over the world, it is necessary to refer to the specifications and guidelines in local regulations and engineering practices both in analysis and design processes, or to leave the relevant design decisions to the approach of the engineer responsible for the design.

The earthquake design approaches in the examined regulations contain quite general expressions and approaches, and parameters to be used in WPP seismic design are left to countries' local regulations.

In the light of the above-mentioned issues, in the design of WPP in regions where earthquake risk is high in Türkiye, the most rational, the most current data and methods focused on practical implementation have been determined by conducting a detailed evaluation of the most used documents (i), (iii) and (viii) from these regulations, with the aim of establishing a more rational design approach.

3.1. Turkish Standards, TS EN 61400 -1 (April 2006)

This regulation, *Turkish Standards, TS EN 61400-1 (April 2006), Wind turbines - Part 1: Design requirements, Wind turbine generator systems, Part 1: Safety requirements, (IEC 61400-1:1999, modified)*, has been accepted as a Turkish Standard by the Turkish Standards Institute, based on the relevant European standard.

In the section related to definition of seismic input definition of the relevant regulation, it is clearly stated that "*there are no earthquake resistance requirements for standard class turbines*". However, the regulation also stated that in regions with high earthquake risk, the section referred to as "*Annex C*" can be used. It is noted here that earthquake loads can be considered together with significant and frequently occurring operating loads. The ground movement sets, and response spectrums set out in the local regulations may be used in the determination of the earthquake loads. For the determination of earthquake loads, the ground motion level with a 10% probability of exceedance within a 50-year period (average recurrence period of 475 years) is considered. Earthquake loads are combined with (a) normal operating loads and (b) the larger of the loading that occurs during emergency shutdowns. In addition, the load factors for design are considered as 1.0 in load combinations where earthquake loading is considered. When considering earthquake loading in the time domain, enough ground motions are required to be taken into account and combined with operating loads. For the determination of the resistance under earthquake loading, the structure should exhibit limited ductile and elastic behavior.

3.2. ACP 61400-1-202x, Wind Energy Generation Systems – Part 1: Design requirements – Modified Adoption of IEC 61400-1

The document is one of the most current documents used for wind turbine design and was created through the updating of IEC 61400-1 document. This document primarily proposes 2 approaches for ensuring the safety and integrity of the support structure:

- Verifying the safety of the system by considering the largest expected impacts during the operational process of the WPP design
- Verifying the structural integrity by considering the largest values of the effects in the region where the system is located

The document does not specifically mention the design of WPPs under earthquake effects. It is noted that earthquake hazards should be considered in the design stages in the regions where seismic activity is high, and the design steps are explained. The fundamental approach in the earthquake design is to combine seismic loads with significant and frequent operating loads arise during the wind turbine operation period.

3.3. DNV GL AS, DNVGL-ST-0437 Edition, November 2016, Loads and Site Conditions for Wind Turbines

The DNV - GL document is a standard where the design principles, technical requirements, loads to be considered and site conditions of the wind turbines are fundamentally set out. The principal purpose of this standard is to specify the loads that are to be considered in the design of wind turbines under an acceptable level of safety, as well as to determine the principles of design under different load conditions, for designers, manufacturers and administrators. Taking into consideration the standards in practice and engineering practices, the document also serves as a guide for the design of wind turbines.

The earthquake effect in the document is referenced to the latest version of IEC 61400-1 regulation [1]. It is stated that local earthquake codes should be considered in regions where earthquake hazard is high, and in the absence of appropriate local codes, Eurocode 8 [2] and/or API 2RP [3] documents can be used. Combining the earthquake loads corresponding to ground motion level with an average recurrence period of 475 years and wind loads in the earthquake design of wind turbines is recommended.

The rules required for the determination of the design loads to be used during structural analysis are defined in this document. It is stated that linear calculation methods are to be used in the structural analysis, but that non-linear methods may also be used where the ground conditions may result in excessive deformations. It is emphasized that it is important for the structural model to be used, both in linear and non-linear analyses, to be established in a manner to reflect the dynamic behavior in the most rational way possible. The definitions of the load components to be used under all these loading conditions and the design are set out in the form of tables.

4. EVALUATION OF THE REGULATIONS IN OPERATION FROM THE ASPECT OF EARTHQUAKE DESIGN APPROACHES

The highlighted aspects compiled from evaluations made within the framework of analysis and design rules specified for the design of wind turbines in the examined regulations are presented below in bullet points.

- Due to the application of WPPs in many different regions of the world, earthquake effect is not initially considered as a priority in the relevant design codes.
- The conditions regarding the earthquake loading are specified in the sections of the regulations referred to as "extreme loading".
- For the WPPs which are installed in the regions where the earthquake risk is high, it is indicated that the effect of earthquakes should be considered.
- No specific limit parameter has been defined for the criteria of high earthquake hazard, and the local regulations that are applicable in the relevant region has been referenced.
- The regulations recommend that in case of considering the earthquake effect in the design, the earthquake loads should be considered along with operation, emergency stop, restart, and extreme wind loads.
- Considering an earthquake ground motion with a 10% probability of exceedance in 50 years is recommended in the earthquake design.
- Although a specific target is not given for the earthquake performance level, definitions such as maintaining the integrity and stability of the system under operational loads during the earthquake are provided, and no specific value is given for performance criteria. However, it is required to ensure that the units comprising the structural system remain within elastic limits.
- The recommended analysis methods include the time-domain analysis and mode combination methods, which are specified in all regulations, and the mathematical model of the structural system is considered using the packed mass approach.
- Particularly in the current regulations, emphasis is placed on the need for more detailed modeling and analysis approaches for the earthquake analysis and design, as well as the control of the system integrity and verification of the structural elements' behavior remains within elastic limits.
- It is recommended to perform structural analysis to obtain the displacement and acceleration values generated in the rotor and other moving components on the tower during the earthquake effect, and to compare them with the limit values defined by

the manufacturer for the safe operation of the system. However, there is no control or suggestion mechanism regarding whether these elements exhibit nonlinear behavior under the design earthquake level.

- In earthquake analysis, it is recommended to use a structural damping ratio of 1%.
- It is stated that for the design of the foundation system of WPPs under the earthquake effect, not only the stress distribution that will occur at the foundation but also the deformations in the soil should be determined. For this purpose, it is stated that experiments and analyses should be carried out to determine the dynamic properties of the soil within the scope of local soil investigations.
- In only one regulation [7], it is stated that the acceleration values affecting the non-structural elements of a WPP should be determined and possible negative effects on the integrity and operation of the system under the occurring displacements should be controlled.

5. THE EVALUATION OF WPP DESIGN APPLICATION PRACTICE IN TÜRKIYE

After reviewing analysis reports of a WPP currently being applied to evaluate the analysis and design stages of wind turbine applications constructed in Türkiye, the following points have emerged:

5.1. Soil Investigation Practices

Geotechnical investigation studies carried out in the scope of the earthquake design mainly intend to determine the soil bearing capacity. The soil investigation and analysis activities specified in Section 16 of the Turkish Building Seismic Code (2018) are not adequately carried out within the scope of soil investigation studies. Insufficient number and depth of drilling and geophysical surveys are being carried out to determine the distribution of the shear wave velocity (V_{s30}) that is required to determine the parameters for the earthquake design, and this prevents the correct determination of the soil class as stated in the earthquake regulation.

5.2. The Determination of the Earthquake Parameters

In the earthquake design of WPPs, the earthquake parameters taken into consideration in practice are based on the Türkiye Seismic Hazard Map (TSHM) published in 2018. As known, during the preparation phase of the aforementioned map, effects such as "*effect of near-fault*", "*directional effect*", "*orientation effect*" and "*topographic conditions*" were not taken into account in determining the earthquake parameters.

Additionally, another important point is that the high natural frequencies of WPPs require a specific examination of the earthquake spectrum provided within the scope of TSHM (2018) for high-period systems.

5.3. The Modelling of the Structural System

The mathematical models considered in the seismic analysis of WPPs in practice are greatly simplified models. The support systems of WPP-type structures are quite simple, and the packed mass modeling approach with the mass concentrated at the top point provides a sufficient modeling in the seismic analysis. However, this simple approach is not used in practice and the structural analysis is only used to determine stress distribution occurring below the foundation system. In practice, the tower system is not considered in the mathematical model, and fictitious forces provided by the WPP manufacturer at a certain height in the superstructure are used for the foundation analysis and design. In determining the stresses on the foundation, no special or detailed modeling work related to the soil is performed, and simple support approaches are applied.

Existing literature regarding modeling wind turbines for seismic loading is divided between two types of models; models that focus on the tower by accounting for the mass of the nacelle and rotor as a point mass at the top of the tower; and models that describe the full turbine including the nacelle and rotor with some level of detail. Simplified models are preferable since they remove the complexity of modeling the rotor. But it should be emphasized that the simplified approach in which the turbine is considered as a SDOF system and may be unreliable for modeling behavior that arises from modes other than the first tower mode.

5.4. The Methods of Earthquake Response Analysis

In practice, no calculation or analysis is carried out to determine the cross-sectional forces occurring in WPPs under the effect of earthquakes. In the design phase, the cross-sectional forces resulting from earthquake effects are provided by the manufacturer, and the earthquake parameters and analysis methods used to obtain these values are not specified.

The analysis methods used in the earthquake design of structures, namely "*equivalent earthquake load* ", "*mode superposition*", and "*time-domain analysis*" methods, can also be applied to WPPs. In case the performance-based design approach is applied as an advanced earthquake analysis method, then "*the non-linear analysis*" can also be used in the earthquake design. In practice, the rational approach from an engineering standpoint is to obtain the cross-sectional forces related to the earthquake loading by considering all the characteristics of the structure by the design engineer, rather than receiving them from the manufacturers and using without analysis. These values should then be compared with those provided by the manufacturer before being utilized.

In terms of consistency in design, conducting an earthquake analysis using the locally applicable earthquake parameters and monitoring the displacements and deformations occur in the event of an earthquake is recommended.

5.5. The Analysis and Design of The Foundation

During the foundation analysis and design phase of WPPs, simple approaches are used for soil modeling to determine the tensions and cross-sectional forces that emerge at the foundation base. To determine the tension distribution occurring on the foundation in the most rational way, modeling the soil behavior efficiently is required. Especially due to the occurrence of tensile stresses in the stress distribution that will occur under the foundation, the calculation of the primary loads that form the basis of tension distribution and soil modeling are of great importance.

In practice, the approaches used for the analysis and design of the soil and the foundation system contain inadequacies in determining both the soil tension distribution and the internal forces and soil deformations essential to the design. Adopting a more feasible modeling approach for the soil characteristics to determine the stress distribution of soil, deformation, and cross-sectional forces is required.

The reinforced concrete calculation of foundation section shall be performed within the framework of the TS500 rules in effect in Türkiye, while the ACI-318 and EC 2 reinforced concrete design regulations accepted in the international arena may also be used.

5.6. Recommendations for Earthquake Analysis and Design Practice for WPP Systems

Distinctively different approaches and design procedures can be seen when the stages of the analysis and design of wind turbines in practice in Türkiye are examined. One of the main reasons for this situation is the lack of regulations for existing designs that can be followed in Türkiye.

Certain approaches and criteria for a more rational consideration of the impact of earthquakes at the analysis and design stages are recommended because of the investigations and evaluations which have been conducted. These recommendations are as follows:

- Evaluating the behavior of the WPP support system under the effect of the earthquakes (*limiting the relative displacement*)
- Analyzing and evaluating the effect of horizontal displacement and acceleration limits occurring in the system during the power production stage of WPP systems on operational efficiency
- Controlling the behavior of the non-structural systems in the WPP systems under the effect of earthquakes (*detecting the displacement and acceleration levels of the systems that can affect production)*
- The realization of the design of the WPP support system considering the post-elastic behavior *(including the determination of the deformations occurring at the tower and connection points by considering the material-based and geometrical post-elasticity situations)* under the effect of earthquakes.
- Defining a specific performance criterion to be determined by the manufacturer at different earthquake levels for the design of WPP support systems *(determining economic and labor loss within the framework of performance-based design)*

6. AN ALTERNATIVE APPROACH TO THE EARTHQUAKE DESIGN OF WIND TURBINES

The adequacy of the designs created by WPP manufacturers under the effect of earthquakes should be reviewed based on the latest data, adopting the most up-to-date approaches. Considering the costs of these investments and the benefits they will provide throughout their service life, the importance of the earthquake design of these systems becomes evident once again.

In case of constructing such systems in areas with high earthquake hazard, it is recommended that the designer, manufacturer, and investor come together to determine the expected performance under the effect of earthquakes and establish the necessary design criteria to achieve this performance. Potential economic losses and operational continuity must also be considered during the performance assessment.

It is recommended that the following factors should be included within the scope of these special technical specifications:

- Conducting a site-specific earthquake hazard analysis and preparing the design acceleration spectrum of the design and ground motion records to be used in analysis for the relevant magnitudes of earthquake.
- Conducting a sufficient soil investigation and analysis to determine the aerodynamic characteristics of the soil.
- The use of mathematical models that consider the system behavior more appropriately according to the soil and earthquake conditions in which the system is located (soil, superstructure, and soil-structure interaction)
- Realization of nonlinear analysis in the time domain to demonstrate that the behavior of the system's current section, size, and connection details exhibit linear elastic behavior under the effect of earthquakes.
- The definition of required checks for non-structural elements for earthquake safety in the systems
- The checking of the deformations expected to occur in the foundation during the operating lifespan of the systems by conducting structure - soil interaction analyses which consider soil deformations as well as the tension distribution in the soil
- Taking into consideration the second degree (P-□) effects occurring as a result of the high level of horizontal displacements in the elements of the system.

For the WPPs which are designed with the knowledge that the risk of earthquakes in Türkiye is high in a large portion of the country, the most rational approach is determining the behavior of the wind turbine systems during operation and under the impact of earthquakes compatible with the conditions of the country and the expectations of investors.

All strategies recommended for every step throughout the design phase, including their scope, are summarized below.

6.1. The Determination of the Parameters for Soil Exploration and Design

Exploration of the soil characteristics of the region where the WPP systems are located, directly impacts determining the earthquake parameters and the foundation design. Even though these systems are not classed as buildings, it will be appropriate for the scope of Part 16 of the Building Earthquake Regulations of Türkiye (2018) to be used to determine the framework of the soil explorations to be conducted in the relevant areas and the parameters which are of the essence for the design.

When design soil surveys, the characteristics related to the special conditions of the project, the local soil structure, the seismicity of the region and the environmental conditions should be considered. The collection, recording and reporting of the data concerning the soil survey should be conducted in accordance with the relevant national and/or generally accepted international legislation, norms and standards.

6.2. Site-specific Earthquake Risk Assessment

When the importance of these structures within the power generation system and their operational continuity is considered, the use of the parameters set out in the Earthquake Hazard Map of Türkiye published in 2018 in determining the parameters which will constitute a basis for earthquake design is not sufficient. The principal reason for this has been set out below in the form of main headings.

- The Near-Fault Directionality Effect
- The Directivity Effect
- Topographical Features
- High WPP natural vibration period

Near-fault and directionality effects, which are among the principal inputs in calculation of the earthquake risk, have not been considered when creating the Earthquake Hazard Map of Türkiye. Similarly, the current Seismic Code does not include the evaluation of the inadequate topographical conditions. Additionally, due to significant free vibration periods of the WPP structures, the spectral acceleration rates stated in the current Seismic Code need to be examined. Lastly, the average renewal period (of earthquake levels), which is considered for the design of WPP structures, may vary from those provided within the scope of the earthquake regulations.

6.3. Structural Modeling Approaches

Horizontal-axis wind turbines consist of three main components: the tower, the nacelle, and the hub. (Figure 3) The tower supports the nacelles and raises the hub to the desired height. The nacelle contains the generator, gearbox, and the other mechanical components of the turbine, essential to supporting the hub. A typical structure used in a WPP is shown in Figure 3.

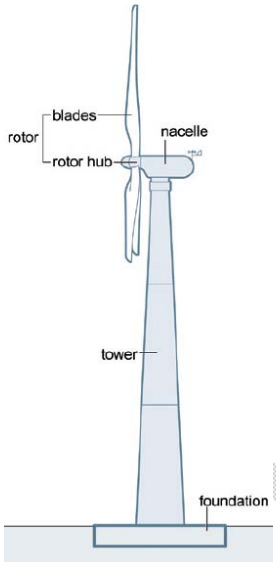

Figure 3 - The main components of the wind turbine

Two models are practiced in analyzing the reaction of wind turbines, the components of which are stated above, under external loads. The first one is the simplified model in which the mass of the nacelle and rotor is regarded as a mass stacked on the top of the tower. This first modeling approach is called a single degree of freedom system, which only considers the tower to determine the behavior of wind turbines under the external effects by regarding the nacelle and rotor as a stacked mass on top of the tower. Simplified models are the most preferred models due to the complexity of the components at the top of the wind turbine.

The other approach, on the other hand, is a more complex and advanced modelling approach where all the parts constituting the turbine are modeled in a more detailed manner.

6.4. Design Loading and Load Combinations

The behavior of the turbine under different operating conditions, under wind and earthquake loads, is considered at the stage of the analysis of the wind turbines. Different effects occurring under different circumstances, including where the ground movement has an effect while the turbine is operating, where the ground movement has an effect while the turbine is parked and where the ground movement does and does not have an effect while the turbine is in idle mode, under the normal operational state of the turbine, are taken into consideration.

It is recommended that the earthquake loads equivalent to the ground movement levels in earthquakes recurred around every 475 years and the wind loads are combined in the earthquake design of wind turbines. There are two principal loading conditions to be considered to ensure the integrity and safety of the wind turbines such as "Normal Loading Case which consists of the loadings affected by the design wind loads occurring under normal operating conditions between the periods where the wind turbine is operating, and it is shut down and "Maximum Loading Case that consists of loading conditions with an expected repetition period of 1 (one) and 50 (fifty) years during the operating life of the wind turbine.

6.5. Earthquake Analysis Methods

Either the equivalent earthquake load method, the response spectrum method or the time domain analysis shall be used as the earthquake analysis method. It is necessary for the "nacelle" effective mass to be packed together in the center of gravity of the wind turbine and for all the systems (stairs, platform, etc.) connected to the tower to be considered when calculating the effective earthquake mass in the model to be used for the earthquake analysis.

The earthquake behavior of the structural systems of WPP systems display a "reverse pendulum" type of behavior. With this behavior, the biggest cross-sectional effects and deformation motions form at the foundation section level. Even if a value for the wind turbine has not been implicitly defined for R values, the "seismic load reduction coefficient" which is to be used at the earthquake analysis and design stage in line with this behavior, R value is accepted as 1.5 - 2.5 for these types of structures, in practice (for the design).

It should be stated that linear methods of calculation are to be used in the structural analysis of these systems, but that non-linear methods may also be used under circumstances where the soil conditions may cause excessive deformations. The importance of establishing the structural model to be used in a manner which will reflect the dynamic behavior in the most rational way possible, in both linear and non-linear analyses, should be emphasized.

In practice, two methods are mostly used in the earthquake analysis of wind turbines as; Mode Superposition Analysis and Time Domain Analysis.

6.6. Earthquake Performance Targets and Criteria

The shutdown of WPPs and damages at a level which can be repaired economically under the effect of a design earthquake are permitted.

While the permitted damage should not pose a threat to human life, depending on the number of WPPs in the field, it should also be noted that the direct or indirect economic loss caused by the damage may reach an unacceptable level for the operator.

Due to the second case mentioned above, the objective of maintaining operational continuity under a higher level of design earthquake is an approach that can be determined because of the investor's requests. However, the difference between the conditions required for "life safety", which is the minimum performance objective specified in the regulations, and the high-performance level should be clearly defined.

The current design philosophy in the effective regulations define the two performance levels set out below:

- The occurrence of very little damage and disruption in normal operations under the Design Earthquake Level (with a mean recurrence period of 475 years).

- The occurrence of no severe Health, Safety and Environmental issues in rare earthquakes which are referred to as the Biggest Earthquake Level, even if they do cause irreparable and economic damage to the WPP.

Deformation tolerances are generally expressed in terms of the permanent rotation angle allowed to occur at the base of the turbine, and it is recommended that earthquake-induced permanent slope should not exceed 0.5°. Considering this performance criterion, detailed analysis tools will be required to estimate the permanent slope of the foundation during design earthquake.

6.7. Limiting Horizontal Displacement in Application

No limit has been defined for the relative displacement value used in earthquake design for wind turbine systems. The determination of the value should be decided through the joint evaluation of the wind turbine manufacturer and the designer in accordance with the effective operation of the system and the targeted earthquake performance. On the other hand, it is more appropriate to determine this value by consulting with the manufacturer instead of using the limits given in the regulations for similar types of structures used in the relevant region.

6.8. Design of the Foundation System

International regulations are used in the design of the foundations of these towers as the rules and limits set out in the regulations for local structures are not sufficient in the design of the foundations of wind turbines. However, in practice, the use of local regulations in the foundations of wind turbines is only possible were approved by an entity which issues certifications.

The following parameters need to be examined for the analysis and design of the foundation:

- Tension stress in soil
- Load-bearing capacity of soil
- Deformation of soil
- Rotation of foundation

Tensile stress that occurs during the diagnosis of ground tension is allowed up to 50% of the foundation ground.

7. GENERAL EVALUATION AND CONCLUSION

This study presented investigated the current status of consideration of seismic loads for wind turbines. This subject is attracting more interest as the use of wind power grows, particularly in seismic regions.

A preliminary analysis based on existing guidelines has been conducted to understand how tower moment demand scales with rated power. The literature shows a development from simple models that focus on predicting tower loads to full system models that illuminate loads for other components. The published analyses show that seismic loading may impact more than just the tower and suggest that full system models are important in analyzing seismic demand for turbines.

The important points revealed because of an assessment of the regulations and guidelines on the design of WPP systems in the world and an investigation into the design documents for the real practices in Türkiye have been set out in detail in the above sections.

The most fundamental conclusion which emerges in the light of these assessments is that the preparation of regulations or guidelines for the earthquake analysis and design stages of WPP systems shall be a rational approach.

Due to the reasons listed in the study, it is extremely important in a country like Türkiye, where the risk of earthquakes is high, that regulations based on the consensus that the size and power production of the investment to be undertaken should be high, that the parameters of the WPP systems to be used in earthquake design need to be determined and that the use of appropriate design procedures is the rational approach, are prepared, in order that the wind energy investments throughout the country can be realized in a consistent manner and in line with the current technical rules.

Approaches to design and criteria which should be prepared within the scope of "the earthquake design regulations for wind energy systems" as a result of activities to be conducted in this area in cooperation with investors in Wind Energy Systems and the authorities and institutions leading the sector, will thus become more suitable for implementation.

Lastly, it is considered that this document, which is to be referenced in the investments to be undertaken by investors, who hold an important position and share in the sector, will be an important step towards ensuring a certain standard within the sector and earthquake safety.

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