Seismic Vulnerability of Onshore Wind Farms

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Abstract. In recent years, more and more wind farms in China, increasing the potential for seismic vulnerability. The operation and damage status of wind turbine towers under seismic action is classified into four levels: intact, temporarily out of operation, permanently out of operation, and collapse. A finite element model is established for a 2.0 MW onshore wind turbine tower, and 25 strong earthquake records of a typical Class II site were selected for incremental dynamic analysis and Pushover analysis, and the dynamic response of the tower was obtained, and the seismic susceptibility curves of wind towers under the conditions of Class II sites were obtained after statistical analysis. And then a method was proposed to calculate the seismic susceptibility of the wind farm system based on the susceptibility of the wind tower and the booster station and the asset weights. In the context of a large onshore wind farm in Gansu, the overall susceptibility curve of a wind farm is obtained by calculation. The results show that most wind turbines operate normally during seismic activity. The probability of plasticity and collapse under a 2.0 g seismic event is less than 50%. While wind farms experience seismic action, when the PGA is 0.5g, the probability of wind farms being basically intact is 3%, the probability of minor damages occurring is about 27%, and the probability of severe damages is close to 70%. the probability of severe damages in the wind farm system increases faster in the interval of the PGA from 0.2 to 1.0 g. The probability of severe damages in the wind farm system increases faster in the interval of the PGA from 0.2 to 1.0g.

Keywords: wind turbine; wind farm; seismic vulnerability; incremental dynamic analysis; pushover analysis

B. Yuan et al. (eds.), *Proceedings of the 2024 8th International Conference on Civil Architecture and Structural Engineering (ICCASE 2024)*, Atlantis Highlights in Engineering 33,
https://doi.org/10.2991/978-94-6463-449-5_81

1 INTRODUCTION

Due to the acceleration of China's energy transition, wind power is making up a growing share of our energy sources. The wind turbine tower accounts for a large proportion of the wind turbine's mass. It has high flexibility and a long self-oscillation cycle and is more prone to seismic damage.. Thus, the seismic requirements have increased. The wind power industry specification IEC61400-1[1] states that the seismic risk of wind turbine towers must be determined based on site conditions. Therefore, it is necessary to investigate the seismic vulnerability of wind turbine towers to guide their design and perform post-earthquake damage assessment to ensure China's energy security.

The seismic hazard is high in China. Most of the country has regions with seismic intensity VI or above. Therefore, many wind farms are located in high seismic intensity areas, significantly increasing the risk of seismic damage to wind farm. Numerous studies have been conducted on the multiple risks to offshore and onshore wind turbines. All these studies have used dynamic finite element analysis. The response characteristics of onshore and offshore wind turbines under different types of loading have been studied by Dai[2-6], Mardfekri[7], etc. Asareh[8], Patil[9] analysed the seismic response of wind turbines and considered the probabilistic analysis of different damage states and corresponding susceptibility of wind towers.Kim et al.[10] investigated the seismic susceptibility of offshore wind turbines under two loading scenarios and considered the soil-structure interaction. Nuta et al.[11] et al. developed a finite element model of a 1.65 MW wind turbine and evaluated the turbine's seismic susceptibility under different damage states in two Canadian regions.

Most of the above studies on wind power towers focus on analysing the seismic response of the tower body by using dynamic finite element analysis, and there are also studies on the damage classification of wind power towers and probabilistic evaluation of seismic vulnerability by IDA method, but they are relatively few, and the methods of classifying the damage level of wind power towers are also different, and there are some irrational places. In addition, the research on the vulnerability of wind farms as a whole is almost in a blank state, and the ATC25 report in the United States[12]and Tian Deyuan[13] have only carried out vulnerability studies for thermal power plants and hydroelectric power plants. In fact, no matter the work of post-earthquake disaster assessment, or earthquake insurance, it is necessary to evaluate the overall vulnerability of such a complex system as wind farms as a whole unit.

Therefore, this paper establishes a finite element model for a typical wind tower of a wind farm in Gansu, divides the damage level of the wind tower under seismic action based on the physical parameters related to the strength and deformation of the tower, and selects 25 seismic acceleration records of a Class II site to carry out a dynamic time-course analysis of the damage state of the wind tower at all levels, and obtains the susceptibility curves of the wind tower in the soil conditions of a Class II site. Then, by taking the respective cost of wind tower and booster station as the weighting coefficients, the vulnerability calculation method of the wind farm as a whole was established by the method of full probability synthesis, and the seismic vulnerability curves of the wind farm system were calculated with the background of the basic conditions of a wind farm in Gansu.

2 SEISMIC VULNERABILITY OF WIND TURBINE TOWER

2.1 Project Overview and Finite Element Modelling

2.1.1Overview of the Model.

A 2.0 MW horizontal axis wind turbine on a large wind farm in Gansu was modelled. The peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years is 0.10 g, the period of ground vibration is 0.45 s, and the seismic intensity of the area is VII. The average wind speed at a height of 70 m is 6.19 m/s, the average wind power density is 242 w/m2, and the air density is 0.935 kg/m³.

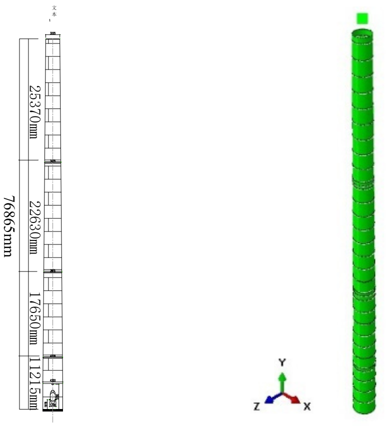
A 2.0 MW horizontal axis wind turbine with three blades was investigated. The tower has a variable cross-section and wall thickness. It consists of Q345D steel. The tower has four sections and 33 segments. The diameter ranges from 4200 mm to 3005 mm from the bottom to the top. The tower thickness ranges from 16 mm to 30 mm from the top to the bottom. The tower is 76.865 m high, and the height at the hub is 80 m. A door is located 2.268 m from the bottom of the tower. The wind turbine tower is shown in Fig. 1(a). The other parameters are listed in Table 1.

ABAQUS software was used to establish the finite element model of the tower in Fig.1(b). The upper nacelle, the hub, and the blades were simplified as mass points[2-11], and the tower segments were simulated using shell units. The segments had rigid connections. The bottom was connected to the foundation. Since the door was far from the tower's plastic hinge[14], it was not considered in the incremental dynamic analysis. Nuta et al.[11] found that a lower damping ratio provided a dynamic response of the nacelle closer to the experimental results. The industry guideline IEC suggests a 1% damping ratio for non-operating wind turbine towers, i.e., no consideration of the aerodynamic effects.[1] . Therefore, a damping ratio of 1% was used for the finite element model in this study.

Since the tower and flange consisted of Q345 steel, a bifold model was used, with a density of 7893 kg/m³, a modulus of elasticity of 6.02E12, yield strength of 345 Mpa, Poisson's ratio of 0.3, ultimate strength of 470 Mpa, and ultimate strain of 0.548.

Table 1. Main parameters of wind turbine

Component	Value	Component	Value
Blade length	51.38 m	Wheel Diameter	105 m
Blade mass	10350 kg	Rated wind speed	10.2 m/s
Wheel mass	48600 kg	Cut-in wind speed	3 m/s
Housing mass	82000 kg	Cut-out wind speed	20 m/s
Pylon mass	176000 kg		



(a) Dimensions of the tower

(b) Finite element model of the wind turbine tower

Fig. 1. Dimensions (a) and finite element model (b) of the wind turbine tower

2.1.2Modal Analysis and Measured Frequencies.

Environmental data were obtained at the wind farm to validate the model. Power spectrum analysis was conducted using the data acquisition and analysis software G01NET to obtain the first two orders of the frequency of the wind turbine tower. ABAQUS was used to carry out modal analysis of the first seven orders of modal vibration patterns. The vibration patterns are shown in Table 3. A comparison of the finite element model results and the field measurement showed errors of 3.03% and 3.52% for the first- and second-order frequencies, respectively, validating the model in Table 2.

Table 2. Comparison of frequency derived from modal analysis and field measurements (Hz)

1st order frequency			2nd order frequency		
on-site measurement	modal analysis	Error	on-site measurement	modal analysis	Error
0.32	0.33	3.03%	2.74	2.84	3.52%

Table 3. Frequency and contribution of vibration patterns to the total

vibration pattern	frequency	Contribution of vibration pattern
1st order (Z-direction bending)	0.33647	72.81%
2nd order (Z-direction bending)	2.8442	16.4%
3rd order (Z-direction bending)	8.2251	6.99%
4th order (Y-direction tension)	9.6257	3.27E-16%

5th order (X-direction twisting)	14.342	1.56E-5%
Total	--	96.21%

2.2 Classification of Wind Turbine Tower Damage and Definition of Limit State Indicators

2.2.1Damage Classification.

No codes exist for the seismic damage rating of wind turbine towers. Although these towers differ from other structures, their damage classification can be determined. Li Bo et al.[18] examined the seismic vulnerability of telecommunication towers and classified the damage level into four types: intact, slightly damaged, severely damaged, and collapsed. Mardfekri et al.[7] established a probabilistic demand model for wind turbine towers and classified the damage state into intact, temporarily out of operation, permanently out of operation, and completely damaged. They analysed the damage state during the wind turbine's operation under environmental loads (i.e., daily wind, waves, and water currents) and determined the deformation, shear, and moment. This paper performs a damage classification based on reinforced concrete frame structures in China's Standard for Classification of Seismic Damage of Buildings (GB/T 24335-2009) (2009) and Mardfekri et al.[7]. The classification scheme is listed in Table 4.

Table 4. Classification of wind turbine tower damage

Damage level	Degree of loss of functionality of wind turbine towers	Description
I	Intact: the wind turbine is operating normally and is fully functional.	The tower has no structural damage.
II	Operational warning: tower vibration causes automatic or passive shutdown of the wind turbine. Operation is resumed after maintenance.	The tower has no structural damage. The top is displaced, causing a shutdown.
III	Sabotage: the wind turbine is out of service for an extended period and requires extensive repairs.	The support structure reaches a localised plastic state. Some degree of permanent deformation of the local tower of the wind tower.
IV	Collapse: Irreversible damage to the tower, resulting in a complete loss of function. It cannot be repaired.	Severe buckling and deformation of the tower. It has collapsed or is near collapse.

2.2.2Limit State Definition

Studies on the seismic performance of wind turbine towers used parameters related to tower deformation, strength, energy, and other damage criteria[2-11]. The relative displacement of the top of the tower (RDTWT) is the most commonly used performance parameter. The first-order bending is the dominant vibration mode of wind turbine towers. The relative displacement is easy to obtain, and the computational cost is low. Therefore, we used the RDTWT as the performance parameter of the wind turbine tower.

The limit value of the tower's performance level for different damage levels was determined. When the tower is intact, the RDTWT under seismic action should not exceed 1% of the tower's height (RDT1WT = 0.8 m) according to the "Code for the Design of Tall Structures"[17]. This criterion was used as the limit value of the wind turbine in classes I and II and has been used by several studies[4,7,8].

The damage class III (permanently out of operation) occurs when the tower has yielded, i.e., stress yielding occurs at many positions. When the seismic intensity increases or rare seismic action occurs, the tower will experience more stress yielding and exhibit plastic hinges. Plastic deformation increases until the structure reaches the stress limit value of buckling, resulting in near-collapse or collapse and class IV damage.

A pushover analysis is a simplified method for assessing a structure's nonlinear seismic response. It combines a static elastic-plastic analysis with response spectra. This method has low calculation complexity and is more mature than time-range analysis. This method has been used to determine the vibration modes of towers and the limit value for tower collapse[9,11,15].It is used to apply increasing loads and examine the dynamic response of the wind turbine tower when it buckles. Pushover analysis was used in this study to determine the performance level limit value of the RDT3WT. The first three orders of vibration modes were extracted, and the mass participation coefficients were determined in Fig 2. Loads were applied to the tower to obtain the pushover curve Table 5 lists the limit values of the wind turbine tower for different classes.

Table 5. Limit values of the RDTWT for different damage levels

Damage level	I	II	III	IV
Limit value	RDT_{WT} <0.8m	0.8m≤RDT_{WT} <1.9339m	1.9339m≤RDT_{WT} <3.9775m	RDT_{WT} >3.9339 m

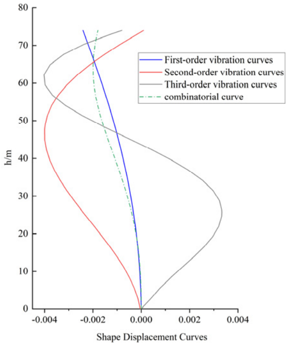


Fig. 2. Oscillation pattern combination curve

2.3 Bucklingseismic Vulnerability of Wind Turbine Tower

2.3.1Seismic Records.

We used 25 seismic records for randomly selected from the website of the Pacific Earthquake Engineering Research Centre (PEER) in the United States to conduct incremental dynamic analysis. The following selection rules were used[8]: (1) no more than two records of the same seismic event; (2) PGAs greater than or equal to 0.2 g; (3) the distance between faults is less than 20 km. The acceleration response spectra and average response spectra are shown in Fig. 3.

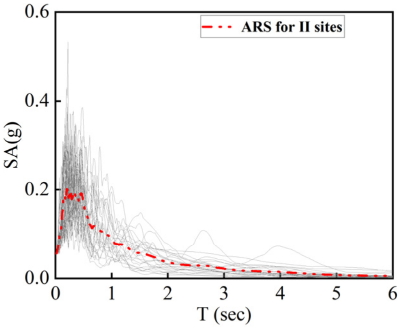


Fig. 3. Acceleration response spectrum of ground vibration recordings for class II sites

2.3.2Seismic Vulnerability Results.

Seismic susceptibility refers to the conditional probability of a structure reaching or exceeding a limit state at a given seismic intensity level x[16]. It is expressed as a functional model in Eq. (1)：

where *mR* and *βR* = *σlnR* are the median and log standard deviation (also known as the outlier) of the seismic susceptibility.

After selecting the seismic waveforms, incremental dynamic analysis was used in ABAQUS software to adjust the PGA of the seismic records several times to conduct a time-range analysis. The responses of the wind turbine towers were obtained based on the 25 seismic records for II sites with different PGAs to determine the seismic susceptibility. The main steps were as follows:

$$F_{R,IM}(x) = \Phi[\frac{ln(x/m_R)}{\beta_R}] \tag{1}$$

1. Twenty-five ground vibration records for each class were used.
2. The amplitude was adjusted according to the limit values, and dynamic analysis was performed to determine the RDTWT.
3. The exceedance probability of the damage levels was calculated using Eq. (3), assuming that the RDTWT has a lognormal distribution. The results were fitted to obtain parameters *mR* and *βR*.
4. The seismic susceptibility curves of the towers at different sites were plotted based on the parameters.

The seismic susceptibility curves are shown in Figures 4. Temporary out-of-service (TO)、Permanently out-of-service (Po)、Complete (C).The fitted parameter values are listed in Table 6.

Table 6. Fitted parameter values of the seismic susceptibility curves

Parameter	TO	PO	C
m_R	-0.0825	0.8212	1.4887
β_R	0.7065	0.7051	0.4892

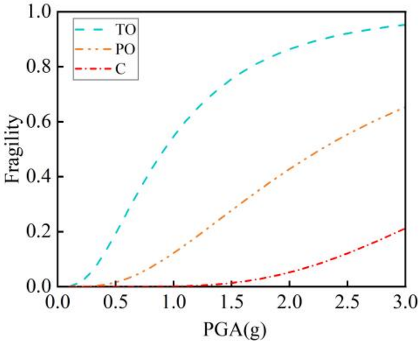


Fig. 4. Seismic susceptibility curve of the tower at the class II site

As can be seen from Fig. 4, when the local vibration PGA level reaches 0.5g, 80% of the probability of the wind tower is basically intact, the probability of the occurrence of the warning shutdown state is close to 18%, and the probability of the tower occurring a local plastic state is within 2%. When the peak acceleration of local vibration is 1.0g, the probability of basic intactness is about 48%, the probability of occurrence of early warning shutdown state of the tower is about 40%, and the probability of occurrence of local plasticity of the tower is about 12%. Under the action of 2.0g ground shaking for the wind tower barrel to reach the probability of local yielding is about 37%, to reach the probability of buckling or even collapse is about 5%. However, such levels of ground shaking are extremely rare, so overall the probability of serious damage to wind towers under general seismic effects is small.

3 SEISMIC VULNERABILITY OF WIND FARM

3.1 Methodology for Calculating the Vulnerability of Wind Farm Systems

Onshore wind farm projects are generally composed of wind turbines, booster stations, transmission lines and other parts. The wind turbine includes wind turbine foundation, wind turbine installation, tower, set transformer and so on. The booster station project includes main transformer, power distribution device, power cable, monitoring and control. The collector line is divided into overhead power line project and power cable project, the overhead power line project includes tower, foundation and wire erection, and the power cable project includes cable trench and power laying. The road works of the wind farm include approach road, station road and on-site road[19].

In this paper, in order to simplify the calculation, it can be considered to simplify the onshore wind farm into two parts, namely the wind turbine tower and the booster substation. That is, the wind farm is divided into two units: the wind turbine tower and the substation.

The susceptibility of wind turbine is expressed by the susceptibility of wind tower obtained by calculation in the above section, and the susceptibility of substation can be referred to the research results of Liu Rushan[20]. Then, the overall vulnerability of the wind farm can be calculated by the full probability method based on the vulnerability of the two units, and the value weights of the two units. In the calculation process, since the unit and system classifications are inconsistent, it is necessary to list the relationship between the seismic index and the classifications of the substation, the relationship between the seismic index and the classifications of the wind tower, and the relationship between the seismic index and the classifications of the system. As shown in Table 7. 8.9.

Table 7. Relationship between seismic indices and classifications of substations

Damage level	intact	slightly damaged	moderate damaged	severely damaged	collapsed
seismic index	$0 \le D < 0.05$	$0.05 \le D < 0.30$	$0.30 \le D < 0.55$	$0.55 \le D < 0.80$	$0.80 \le D \le 1$

Table 8. Relationship between seismic indices and classification of wind towers

Damage level	I	II	III	IV
seismic index	$0 \le D < 0.02$	$0.02 \le D < 0.1$	$0.1 \le D < 0.7$	$0.7 \le D < 1.0$

Table 9. Relationship between the system's seismic index and its rating

Damage level	intact	slightly damaged	severely damaged	collapsed
seismic index	$0 \le D < 0.02$	$0.02 \le D < 0.1$	$0.1 \le D < 0.7$	$0.7 \le D < 1.0$

For a system comprising n units, it is necessary to obtain the susceptibility matrix of the units required to make up the system, as shown in Tables 10 and 11. And the seismic damage index of the system is obtained through the seismic damage index of the units, and then the susceptibility matrix of the system is obtained. Its specific calculation process is:

1) Assume that the system has a total of n cells,each with a different number of destruction levels.

2) Assume that the number of destruction levels for each unit is Assume that the number of destruction levels for each unit is $m_1, m_2 \cdots m_n$.

3) It was also determined that the units were normalised by valueand weighted to the $\{\omega_1, \omega_2 \cdots \omega_n\}$ set,which is the cost weight.

4) At a certain seismic intensity I,the damage of the j grade occurs in unit k,which has a seismic damage index of D_{kj}^{I}. For the example of the calculation of the vulnerability of the wind farm system at the back, the median of the range of seismic indices in Tables 7 and 8 is taken into account in the calculation.

5) For the system, the number of damage combinations at intensity I is:

$$M(I) = m_1 * m_2 \cdots m_n = \prod_{l=1}^{n} m_l \tag{2}$$

6) The system has a collection of seismic indices for various combinations of units at I intensity:

$$\{D_z\} = \left\{\sum_{k=1}^{n} \omega_k \cdot D_{kj}\right\} \tag{3}$$

7) The set of probabilities corresponding:

$$\{Z\} = \left\{\prod_{k=1}^{n} P_{kj}\right\} \tag{4}$$

8) Let the system have B damage levels.The values of $\{D_z\}$ fall within the B intervals $\{b_1, b_2 \cdots b_B\}$,the set of $\{D_Z^1\}, \{D_Z^2\} \cdots \{D_Z^B\}$, respectively,and set the interval $\{D_Z^1, D_Z^2 \cdots D_Z^B\}$, then thecorresponding probability set of the summed to obtainrespective intervalsare $P_1(I), P_2(I) \cdots P_B(I)$;and $\{D_Z^1\}, \{D_Z^2\} \cdots \{D_Z^B\}$ for the average seismic index,to obtain $\overline{D_Z^1}(I), \overline{D_Z^2}(I) \cdots \overline{D_Z^B}(I)$.

9) Based on the obtained average seismic damage index $\overline{D_Z^1}(I), \overline{D_Z^2}(I) \cdots \overline{D_Z^B}(I)$ and the probability of occurrence $P_1(I), P_2(I) \cdots P_B(I)$,the sysceptibility curve is then obtained.

Table 10. Substation vulnerability matrix

PGA/g	intact	slightly damaged	moderate damaged	severely damaged	collapsed
0.05	0.7923	0.3121	0.0527	0.0007	0.0000
0.1	0.2067	0.5865	0.2382	0.0149	0.0001
0.2	0.0000	0.0891	0.6033	0.3660	0.0268
0.4	0.0010	0.0122	0.1057	0.6092	0.7778
0.8	0.0000	0.0000	0.0000	0.0091	0.1953

Table 11. Wind tower vulnerability matrix

PGA	intact	slightly damaged	severely damaged	collapsed
0.05	1.0000	0.0000	0.0000	0.0000
0.1	0.9981	0.0019	0.0000	0.0000
0.2	0.9641	0.0358	0.0001	0.0000

0.4	0.7580	0.2358	0.0062	0.0000
0.8	0.3444	0.5693	0.0848	0.0016

3.2 Calculation of Seismic Vulnerability of Wind Farms

A total capacity of 60MW wind farm as an example, assuming that the wind farm used are 2MW wind turbines, a single 2MW wind tower and equipment costs about 1100w yuan, the wind farm according to 30 wind towers, the cost of about 330 million yuan; booster station cost of about 70 million yuan, so the wind tower, the value of the boosting station weighted at 0.825, 0.175, the wind tower here for the 30 value weights of the wind tower as a whole.

Based on the seismic susceptibility curves of the wind towers already obtained in section 1.2.3 and the seismic susceptibility curves of the substations already obtained in the literature[20], the susceptibility curves of the wind farm as a whole can be obtained by adopting the susceptibility calculation method for a system constructed in section 3.1. The final seismic susceptibility curve of the wind farm is shown in Fig. 5.

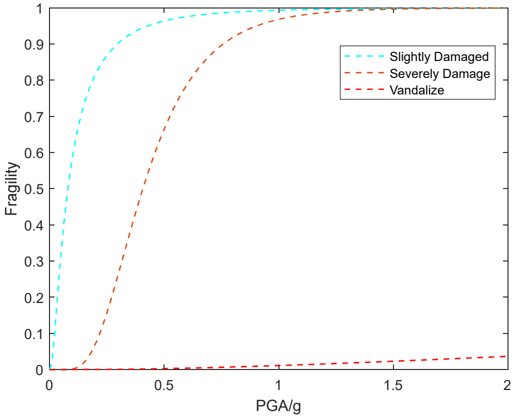


Fig. 5. Seismic susceptibility curves for wind farms

From the above results of the seismic vulnerability analysis of wind farms, it can be seen that when the PGA is 0.2g, the probability of wind farms being basically intact and slightly damaged is about 95%, and the probability of serious damage is close to 5%. When the PGA is 0.5g, the probability of the wind farm being basically intact is 3%, the probability of minor damage is about 27%, and the probability of severe damage is close to 70%. the probability of severe damage in the wind farm system increases faster in the interval of the PGA increasing from 0.2 to 1.0g, which is caused by two reasons, one is the impact caused by the too large probability of the damage of the booster station, and the other is the impact caused by the severe damage grade in the class division of the wind farm system. When classifying the wind farm system, the range of shock indices for the severe damage class is larger. In order to express the damage to the booster station and the overall power plant function affected by the earthquake, a large range of seismic damage indices was set for the severe damage class of the wind farm system. When the PGA is greater than 1g the wind farm gradually starts to show the probability of destruction, but the probability of occurrence is small.

4 CONCLUSION

Wind farms have experienced increased seismic risk in recent years. A finite element model of a 2.0 MW horizontal axis wind turbine was established. The seismic damage was classified, and incremental dynamic analysis and seismic susceptibility analysis were conducted. The seismic susceptibility curves of the wind turbine tower were obtained. Then the seismic susceptibility curve of the wind farm was then obtained by a systematic susceptibility calculation methodology.The following conclusions were drawn:

1) When the tower experienced seismic activity, plastic buckling occurred at the junction of the third and fourth sections at heights of 11.56 and 14.04 m, respectively, from the foundation. As the seismic intensity increased, buckling (plastic hinge location) occurred at greater heights.

2) Wind power towers are in the normal operation phase most of the time, and the probability of localised plasticity and collapse of the tower is very low for wind power towers, with about 2% of the peak effect of 0.5g ground shaking, and less than 10% of the effect of 1.0g seismic acceleration, and 50% of the effect of 1.0g seismic acceleration, whereas such records of ground shaking are very rare.

3) The systematic method of vulnerability calculation provides a basis for analysing the wind tower to the wind farm as a whole, and this method is verified to be reliable using the method of unit multiplication.

4) Wind farms are in a state of basic integrity and minor damage most of the time, and as the intensity of ground shaking increases, there is a probability of a portion of severe damage, at which time the unit of destruction is generally the booster station, and the probability of destruction of the wind farm is very low.

The work in this paper can provide a basis and reference for the assessment of seismic capacity of wind power towers and wind farms, as well as the assessment of seismic economic losses of wind farms. It should be noted that this paper has only studied the susceptibility of wind power towers and wind farms under class II site conditions, and the susceptibility of wind power towers and wind farms under different site conditions and considering the effect of wind speed will be carried out in the future. In addition, the delineation between the wind tower seismic damage index and the damage level needs to be further investigated. The reasonableness of the results of the vulnerability study in this paper also needs to be examined in the future based on actual seismic damage cases.

ACKNOWLEDGEMENT

This research is supported by the National Natural Science Foundation of China (U2239252) and the National Key Research and Development Programme of China (2022YFC3003603).

REFERENCE

1. IEC 61400-1, Wind turbines-Part 1: Design requirement [S]. Geneva: International Electrotechnical Commission, 2005.
2. Dai Kaoshan, Hu Hao, Mei Zhu, Liu Yang. Analysis of seismic response of wind power tower structures under long period earthquake[J]. Engineering Mechanics,2021,38(08):213-221.
3. MEI Zhu, HU Hao, DAI Kaoshan, LIU Yang. Analysis of dynamic response of wind tower under long period ground vibration-pulsating wind coupling and preliminary validation of hybrid test[J]. Engineering Mechanics,2021,38(S1):58-65.
4. Dai, Kaoshan, Zhao Zhi, Meng Jiayao. Failure probability assessment of wind towers under seismic and wind loads[J]. Engineering Science and Technology,2021,53(02):38-44.DOI:10.15961/j.jsuese.202000323.
5. Dai Kaoshan, Zhao Zhi, Mao Zhenxi. Comparative study of wind turbine tower damage under extreme dynamic loading[J]. Vibration and Shock,2019,38(15):252-257+272.DOI:10.13465/j.cnki.jvs.2019.15.035.
6. Dai Kaoshan, Yi Lida, Liu Yao, Mao Zhenxi. Performance-based seismic analysis of a wind tower structure[J]. Structural Engineer,2015,31(05):96-102.DOI:10.15935/j.cnki.jggcs.2015.05.017.
7. Mardfekri M , Gardoni P . Probabilistic demand models and fragility estimates for offshore wind turbine support structures[J]. Engineering Structures, 2013, 52:478-487.
8. Asareh M A,Schonberg W,Volz J.Fragility analysis of a 5MW NREL wind turbine considering aero-elastic and seismic interaction using finite element method[J].Finite Elements in Analysis and Design,2016,120:57-67.
9. Patil A,Jung S,Kwon O S.Structural performance of a parked wind turbine tower subjected to strong ground motions[J].Engineering Structures,2016 ,120:92-102.
10. D.H. Kim, S.G.Lee, I.K. Lee, Seismic fragility analysis of 5 MW offshore wind turbine, Renew. energy 65 (2014) 250-256.
11. Nuta E,Christopoulos C,Packer J A.Methodology for seismic risk assessment for tubular steel wind turbine towers: application to Canadian seismic environment[J].Canadian Journal of Civil Engineering,2011,38(3):293-304.
12. ATC.1991.ATC-25 Seismic vulnerability and impact of disruption of lifelines in the conterminous United States[R].Advanced Technolo gy Council.
13. Tian Deyuan, Liu Rushan, Xia Xuyi, et al. Calculation method for inferring seismic vulnerability of thermal power plants[J]. Earthquake Research,2022,45(03):379-387.DOI:10.20015/j.cnki.issn1000-0666.2022.0041.
14. ZHAO Zhi, DAI Kaoshan, MAO Zhenxi, ZHANG Caiwei. Damage analysis of wind tower under ground shaking with different spectral characteristics[J]. Engineering Mechanics,2018,35(S1):293-299.
15. Hou Aibo,Wang Mengfu,Zhou Xiyuan.Effects of different lateral load distribution methods in Pushover analysis method[J]. World Earthquake Engineering,2007(03):120-128.

16. Lv Da-Gang, Yu Xiao-Hui, Wang Guang-Yuan. Structural collapse analysis based on the IDA method for single ground vibration recordings[J]. Earthquake Engineering and Engineering Vibration,2009,29(06):33-39.DOI:10.13197/j.eeev.2009.06.012.
17. Ministry of Construction of the People's Republic of China. GB50135-2006 Design Specification for Shrugged Structures ［S］. Beijing: China Planning Publishing House, 2006.
18. Li Bo, Mao Chenxi, Guo Endong. Performance-based seismic vulnerability analysis of mobile communication towers[J]. Journal of Natural Hazards,2018,27(03):21-28.DOI:10.13577/j.jnd.2018.0303.
19. Luo Cuinan. Research on cost management of onshore wind power projects [D]. Beijing University of Chemical Technology,2024.DOI:10.26939/d.cnki.gbhgu.2023.001620.
20. Liu Rushan,Mao Chenxi,Guo Endong.2021.Vulnerability analysis model and database for lifeline systems[R]. Harbin:Institute of Engineering Mechanics, China Earthquake Administration.