Seismic Analysis of Structurally Hybrid Wind Mill Tower

Atul K. Desai, Hemal J. Shah

***Abstract*—**The tall windmill towers are designed as monopole tower or lattice tower. In the present research, a 125-meter high hybrid tower which is a combination of lattice and monopole type is proposed. The response of hybrid tower is compared with conventional monopole tower. The towers were analyzed in finite element method software considering nonlinear seismic time history load. The synthetic seismic time history for different soil is derived using the SeismoARTIF software. From the present research, it is concluded that, in the hybrid tower, we are not getting resonance condition. The base shear is less in hybrid tower compared to monopole tower for different soil conditions.

***Keywords*—**Dynamic analysis, hybrid wind mill tower, resonance condition, synthetic time history.

I. Introduction

SINCE the mid of 19th century, people have been using fossil fuels for their energy needs. But, as we are aware that there is scarcity of conventional sources of energy and it makes pollution on the earth, we must find alternative sources of energy. One of the sources without pollution is wind energy. To use the wind power, important source of power generation is the wind mills. According to details available from Government of India, the states like Gujarat, Karnataka, Kerala [10] have utilized only 3 to 5 percent of their wind power potential. All states of India have total wind power utilization of only 26777 MW which is only 8.86 percentage of the total wind power potential available in major states of India. The wide gap between the installed capacity and the assessed potential in India clearly indicates the opportunity in this field. To utilize the available wind power at any location, advancement in wind mill technology is required. As we know that at higher elevation wind velocity is higher, so by increasing the height of wind mill at any site, more energy can be generated. In the world, wind mill towers are constructed using monopole type tower or lattice type towers.

The lattice tower can be used for less loads and less height of tower, on the other hand monopoles can be used for more height. if height of monopole is higher, then more stresses are generated in wall of monopole, so it requires more wall thickness.

The lattice towers are formed by connecting the various angles or box sections by doing proper riveting at the site. The lattice towers will resist the loads by truss action of the members, so members of towers are subjected to axial forces only. As the lattice towers are open, wind will pass between the members and wind loads are reduced significantly on the towers.

The monopoles are used for lesser heights of the turbine, while the lattice tower can be used for turbines having lesser mass at the top of the tower.

By increasing the height of the wind mill tower, it becomes single degree of freedom system due to heavy mass at the top and becomes dynamically sensitive particularly in soft soils. So, in the present research, an innovative hybrid tower which is combination of monopole and lattice tower is proposed and it is analyzed for the different synthetic seismic time history obtained from SeismoARTIF software for various soil conditions. After analysis, it is found that the structurally hybrid wind mill towers can resist earthquake load more efficiently compared to the conventional monopole or lattice tower.

II. Literature Review

Gencturk et al. [1] have studied the various bracing system for 24-meter-high lattice tower, and various design alternatives are given for the wind mill lattice tower. Song and Wu [2] have studied the effects of the different earthquake on tall wind turbines and have concluded that dynamic response of structure depends on height. When the height increases to 177%, the maximum displacement in the top of the tower would increase to 231% in 8-degree rare earthquake. Lombardi et al. [3] have experimentally studied the effects of the soil structure interaction on the wind mills and have concluded that the clayey soils will make the tall structure dynamically sensitive. Negma and Maalawi [6] have done optimization of 100 kW wind mill tower using different cross-sectional areas. The authors obtained optimum design trends using the interior penalty function technique. Prowell et al. [7] have determined the dynamic properties of 52-meter-high 900 kW wind turbine considering three different types of soil and have concluded that soft soil will influence dynamic properties of tower. In another research, Prowell et al. [8] have carried out the full-scale wind turbine testing for 65 kW having 22.6 m hub height. In their work, authors have installed full scale model at simulation center and they have applied earthquake loads recommended by FEMA and various parameters such as loss of bolt torque and degradation of grout studied. Harte et al. [9] have studied the effect of dynamic soil structure interaction on wind mill towers. The authors have concluded that soil will influence the response of wind mill tower. According to the Ministry of New and Renewable Energy Government of India [10], total wind power potential of 302251 MW has been

Atul K. Desai is with the Sardar Vallabhbhai National Institute of Technology, Surat 395007 India (e-mail: atuldesai61@gmail.com).
Hemal J. Shah is with Government Engineering College, Bharuch 392002 India (e-mail: hemal3007@gmail.com).

estimated at 100-meter height In India, and only 21 percent is used by India. Hamaydeh and Hussain [11] have modelled two wind mill turbine foundations of different locations in finite element modeling software. They have modelled mat foundation. They have also modelled pile foundation with different spacings and diameters of piles. And after research, the diameter and spacing of pile is decided for different locations. Kjorlaug et al. [12] have modeled 65 kW and 5 MW wind turbine and applied wind and earthquake forces on the wind mill tower. They have also modeled soil at the foundation and have concluded that soil must be modeled to study the response of the wind mill tower.

Jerath and Austin [13] have modeled three different wind mill turbines of 65 kW, 1 MW, and 5 MW capacity in the finite element software. In their work they have applied acceleration time history of three different earthquakes and detailed dynamic analysis is carried out. They have studied the peak acceleration and deformation reponses at various levels of the tower. From the research, it was concluded that change in damping ratio will not affect response in horizontal direction, however change in damping ratio has significant effect on the vertical direction response. Subhamoy et al. [14] have studied the dynamic properties of off-shore wind turbine considering soil structure inter action and have concluded that the frequency of offshore turbines largely depends on the foundation type and soil type, therefore in analysis of turbines the effects of soil must be considered for avoiding resonance.

III. Finite Element Modelling of Tower

For the present study, 125-meter-high monopole and structurally hybrid tower which is combination of monopole and lattice tower is modelled in finite element software. For modeling 125-meter-high tower, the wind mill data are collected from research paper published by Nuta et al. [4] titled “Methodology for seismic risk assessment for tubular steel wind turbine towers, application to Canadian seismic environment” published in Canadian journal of civil engineering (2011). In his research work, authors have modeled 78-meter-high tower and the details of the material used for modeling of tower are shown in Table I.

TABLE I
Material Properties

Material	Mass Density kg/m^3	E in N/mm^2
Tower	9891	200000
Nacelle	1529	200000
Rotor	1101	210000
Blades	1101	1000

The material properties as above are inputted in the software using user defined options. The wall of the monopole tower is modeled using thin shell property given in the software. The tower is modelled using the diameter and height given in the referred paper. At the base of the tower, fixed supports are assigned. Based on the base diameter and thickness of the walls, the shell is modeled at various levels of monopole tower. At the top of tower, nacelle is provided for the generator and other parts of the wind mill. The mass of the nacelle is given by the researcher, and its point of application is also defined by the researcher. The other major mass acting at the top of tower is mass of blade. As the blades are eccentric, so mass of blade acting at lateral eccentricity forms the center of the tower. The details of mass of nacelle and blade are given in Table II. Based on details shown in Table II, the loads are applied at the top of the tower. The two joint rigid link property given in software is used to transfer the mass of nacelle and blade to tower.

TABLE II
Loads Acting on Tower

Sr no	Component	Mass	Eccentricity
1	Tower	108 ton	--
2	Nacelle	52 ton	125.6-meter level
3	Rotor	43 ton	3.447 meter from center

As discussed earlier, the structurally hybrid tower can resist seismic forces more effectively than monopole tower, so the same 125-meter tower is modeled as hybrid tower which is combination of lattice and monopole tower.

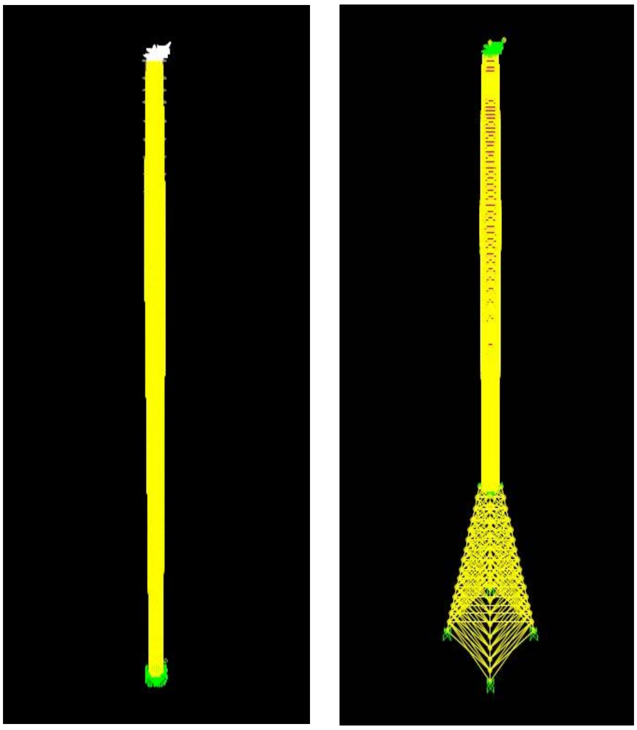

Fig. 1 Model of 125-meter-high monopole and hybrid tower

Fig. 1 shows 125-meter-high tower modelled in the finite element software. In the proposed 125-meter-high structurally hybrid tower, bottom 68-meter portion is taken as lattice tower and top 57-meter tower is modeled as monopole. As the width of the tower is increased at the base, it will provide more stability to the wind mill tower. The width of the tower at the base is taken as 16 meter which is reduced to 4.1 meter at 68-meter level of tower. The mass of nacelle and mass of rotor is also applied on the tower as mentioned in Table II.

To keep the lattice and monopole portion as single structure, proper connection between the monopole and lattice element is required. The finite element software has given the two joint link elements. This two-joint link element will connect the joints of structure rigidly. By providing such links, the loads and moments of one joint are transferred to other joint. In order to achieve the proper connection between lattice and monopole portions at 68-meter level, these two joint links are used.

In the lattice portion of the tower, M type bracing is given to increase the stiffness of the tower and to reduce the unsupported length of the tower members. In the lattice portion of the tower, the main leg members are continuous members, so leg members are modelled as frame element. The bracing system of the tower is connected by pinned connection with main members of tower, so bracing members are modelled as truss element.

IV. Dynamic Loads Acting on Tower

In the wind turbine tower, large mass of turbine is provided at the top of tower, so tower is subjected to the dynamic loads due to rotation of blade of turbines.

The lateral loads acting at the top of the tower are due to the rotating blades produced by the turbulence in the wind. The magnitude of this dynamic load depends on the turbulent wind speed.

The rotor of the turbine is provided at some distance from center of tower. Due to this mass eccentricity, the load is generated on top of tower having frequency same as rotational frequency of tower and it is known as 1Pl load. The rotating speed of the turbine depends on velocity of wind and this wind velocity varies with time, so 1P is not a single frequency but a frequency band between the frequencies associated with the lowest and the highest revolutions per minute.

Other loads in the tower are generated by the vibrations caused by blade shadowing effects which are known as 2P/3P frequency of the wind turbine. When the blades of the wind turbine pass in front of tower, it causes shadowing effect on tower structure due to which results in loss of wind load on tower. In case of two-bladed wind mill turbine, this dynamic load has frequency of two times rotational frequency. In case of three-bladed turbine dynamic, load has three times the rotational frequency of turbine. We can obtain these frequencies by multiplying 1P frequency by 2 or 3 depending on blades of turbine

In addition to rotational frequencies of turbine, natural frequencies of the tower will play important role in design of tower. The natural frequency of the tower depends on mass and stiffness of the tower. The mass and stiffness of tower are important parameter for the natural frequency of the tower. The natural frequency of tower should be such that operating frequency of turbine should not match with natural frequency of the tower.

Based on the natural frequency of tower and 1P and 3P frequency of tower, there may be three possibilities

- The natural frequency of tower is less than the 1P frequency range which is a very flexible structure known as soft- soft design and almost impossible to design for a grounded system.
- natural frequency of the tower is between 1P and 3P frequency of tower which is known as Soft-Stiff design. This is the most common in the current offshore development.
- Natural frequency of the tower is more than 3P frequency of the tower known as Stiff-Stiff design and this type of design need a very stiff support structure.

We have considered the dynamic loads form research work done by Nuta et al., [4]. In his research, they have used wind mill having 1P frequency of 0.18 to 0.24 Hz, so from this 3p frequency is 0.54 to 0.72 Hz.

V. Synthetic Accleration Time History

For seismic response analysis of buildings and other tall structures, earthquake acceleration time histories are required as inputs. The acceleration time history consists of the time and acceleration data recorded by the seismograph at any seismic station. It is not possible to install seismograph at all locations of world. So, it is not possible to get the acceleration time history to certain locations. It may be possible that the acceleration time history at any location where we want to construct our structure is not available due to non-availability of seismograph at locations. The acceleration observed by ground at location depends on its distance from the epicenter and the underlying soil conditions.

In such condition, the acceleration time history of location can be generated using synthetic accelerogram. In the present research work, the software named SeismoArtif developed by SeismoARTIF is used.

The input in the software is the acceleration time history record, location of the structure, moment magnitude of the earthquake and the location is near field or far field. In the software, the soil classification is given based on shear wave velocity. The classification of soil is shown in Table III.

TABLE III
Classification of Soil as per NEHRP

Sr no	Description of soil	Shear wave velocity m/s
1	Stiff Rock	940
2	Generic Rock	620
3	Generic Soil	310
4	Very Hard Rock	2900
5	NEHRP B-C Boundary	760
6	NEHRP B-C Boundary site amplification	700
7	Class C	520
8	Class -D	255

TABLE IV
Details of Earthquake

Sr no	Earthquake	Magnitude	Duration	Peak Ground Acceleration
1	Bhuj	7.8	46.94 sec	1.0382 m/s^2
2	Nepal	7.7	322.96 sec	1.601 m/s^2

In the present research work, the two-severe earthquakes, namely Bhuj and Nepal earthquakes, are considered. The details of earthquake considered in research are shown in Table IV.

As the location and soil type of above time history is known so based on this time histories the synthetic time history for three different soil conditions in two earthquake directions are generated. To generate the synthetic time history, three different types of soil defined in SeismoARTIF software are considered.

The generation of synthetic ground motions is illustrated in Fig. 2. For a deep profile overlaying the bedrock, the profile is divided into one soil layer.

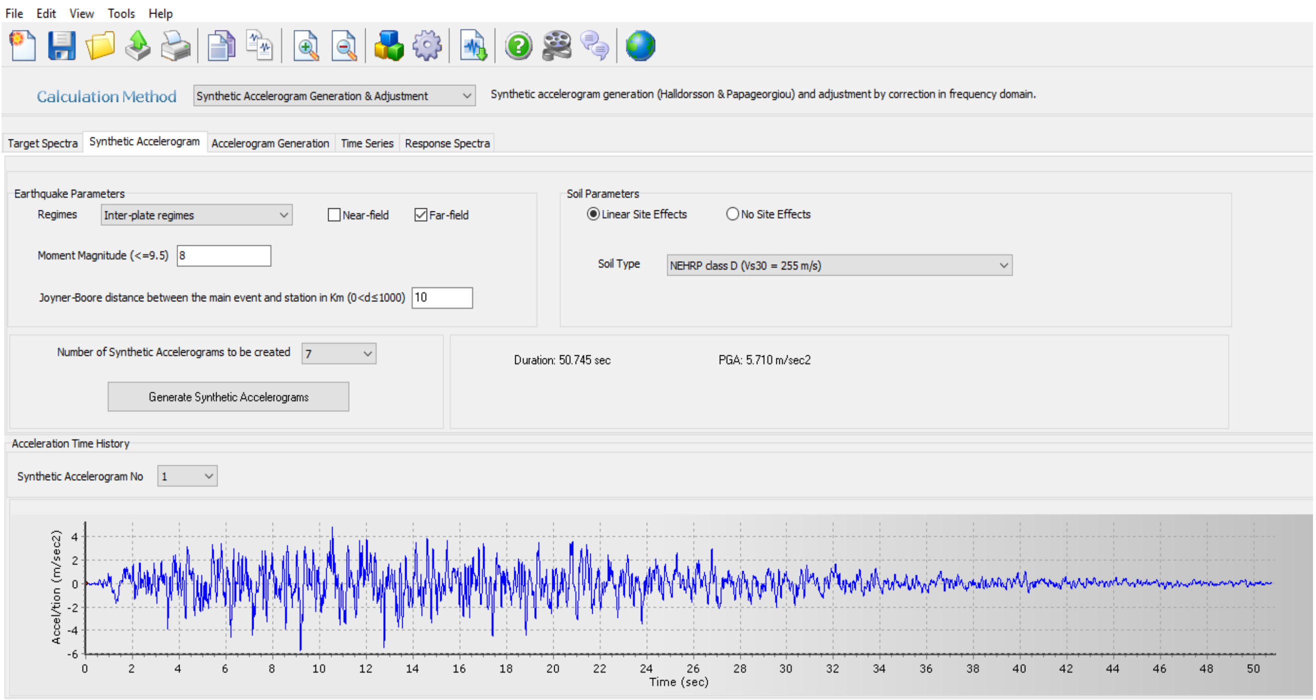

Fig. 2 Generation of synthetic acceleration time history

The input parameter for generation of synthetic time history is the acceleration record vs time for the given earthquake, moment magnitude of earthquake, near/far field description of the earthquake and type of underlying soil at the given location. Both earthquake records were analyzed in the software for three different soil conditions. The three different types of soil considered for research are as under.

1. Type 1 generic rock with shear wave velocity of 620 m/s
2. Type 2 Generic soil with shear wave velocity of 310 m/s
3. Type 3 class- D soil with shear wave velocity of 255 m/s

The soils are classified based on shear wave velocity at 30-meter depth. For the present research, it is assumed that tower is constructed on three different types of soil such as hard soil, medium soil and soft soil. The properties of the hard soil, medium soil and soft soil are considered from book *"Foundation Analysis and Design"* by J.E. Bowles [5]. The properties of three different soils considered in research are shown in Table V.

TABLE V
PROPERTIES OF SOIL

Type of soil	Shear modulus (G) kN/M^2	Elastic modulus (E) kN/M^2	Poisson's ratio
Hard	30000	72000	0.2
Medium	20000	50000	0.25
Soft	10000	26000	0.3

For the present research work, soil is assumed as homogeneous soil having isotropic properties. It is also assumed that soil behaves as elastic material. One of the methods to model such soil is 3-dimensional solid element in software. The soil properties such as shear modulus, elastic modulus and Poisson's ratio are input for the soil parameters.

The boundaries of the soil are assumed fixed at the base. To simulate the real soil conditions in the software, the horizontal displacements of all joints lying the vertical faces of the soil are prevented. The 125-meter-high tower with soil modelled at base is shown in Fig. 3.

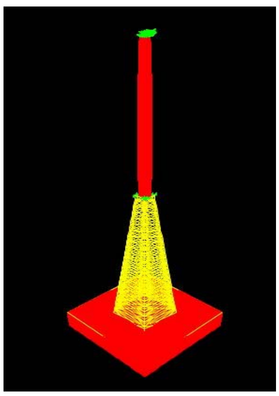

Fig. 3 Modeling of Soil For 125-meter-high hybrid tower

The synthetic time history data are obtained in two horizontal directions for three different type of soil such as type 1, type 2 and type 3 depending on soil velocity. The acceleration data so obtained for different soils are applied in two directions for 125-meter-high monopole tower. To compare the behavior of the structurally hybrid towers, the same data are applied on the 125-meter-high hybrid tower. The nonlinear time history analysis of both towers for different earthquake and different soil conditions are carried out in software.

The dynamic properties such as modal frequencies of the tower are calculated for different soil conditions. The results of the dynamic analysis are used to analyze the resonance condition in the tower during operation of the wind mills.

VI. Result and Discussion

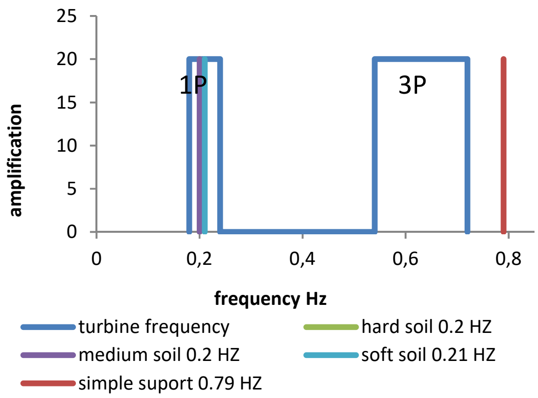

Fig. 4 (a) frequency of 125-meter-high monopole tower

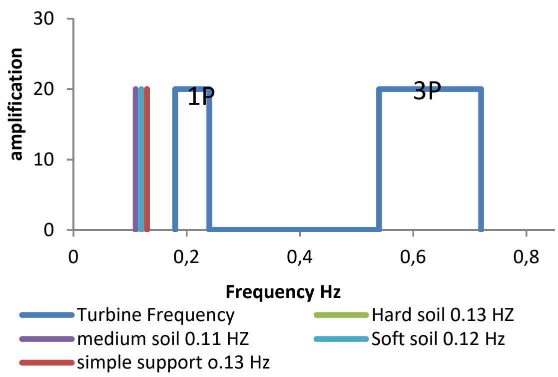

Fig. 4 (b) frequency of 125-meter-high Hybrid tower

Fig. 4 shows the 1P frequency and 3P frequency for the 125-meter-high monopole and hybrid wind mill tower. The variation of natural frequency of tower is also plotted in the graph. From this graph, we can observe that, by analyzing tower with underlying soil, the frequency changes. As we can see in the case of monopole tower, the natural frequency of tower is coinciding with 1P frequency of the wind mill turbine. This results in the resonance and large amplitude in the tower under operating conditions. On the other hand, instead of monopole tower if we use structurally hybrid tower the natural frequency of the tower will not coincide with 1P and 3P frequency of tower. So, we can say that the structurally hybrid tower will avoid the resonance conditions on different soil.

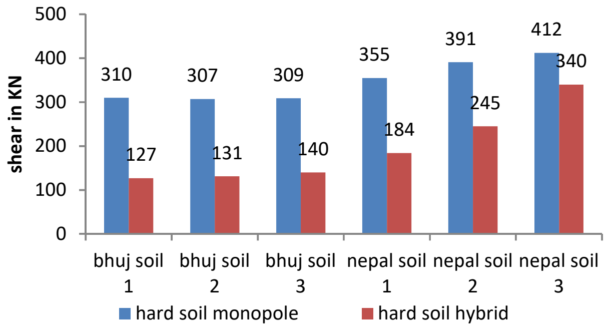

Fig. 5 Base shear for hard soil

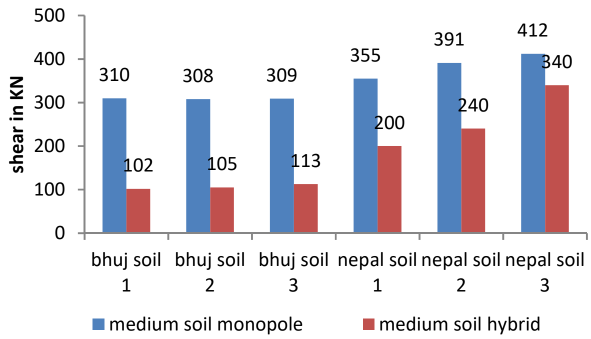

Fig. 6 Base shear for medium soil

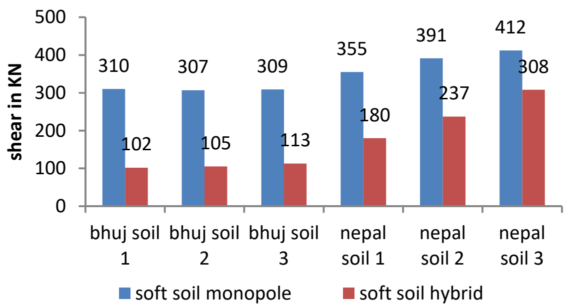

Fig. 7 Base shear for soft soil

Fig. 5 shows the base shear obtained for the tower constructed on hard soil. From the figure, we can observe that the base shear obtained for Bhuj earthquake is approximately half for the structurally hybrid tower compared to the monopole tower. For the Nepal earthquake, the base shear is 52 to 82 percent less in the hybrid tower compared to the normal monopole tower.

Fig. 6 shows the variation of the base shear when tower is constructed on the medium soil. We can observe that base shear is reduced by 66 percent for the Bhuj earthquake in different soil conditions. The base shear is 60 to 82 percent less for the Nepal earthquake when the tower is constructed on the medium soil.

Fig. 7 shows the base shear value for the monopole and hybrid tower constructed on the soft soil. We can observe that the effect of soft soil is almost the same as per the medium soil and value of base shear for hybrid tower is approximately 66 percent less in hybrid tower compared to monopole tower. In soft soil for the Bhuj earthquake, we are getting almost the same value of base shear compared to medium soil. But, there is reduction in base shear in Nepal earthquake compared to medium soil.

VII. Conclusions

From the research, we can conclude the following observations

1) The hybrid tower avoids resonance conditions in 125-meter-high wind mill tower under operating conditions of wind mill.
2) The base width of the hybrid tower is more compared to the monopole tower. Due to this, it converts single degree of freedom system of monopole tower in multiple degree of freedom system and reduces the vibrations due to operating conditions of wind turbine and reduces the resonance conditions in tower.
3) By using the structurally hybrid tower system, it is possible to provide more base width at the base which gives stability to wind mill tower which is efficient to resist the seismic forces during severe earthquakes.
4) From the research, we can deduce that the structurally hybrid tower will give lesser value of base shear compared to monopole tower of same height in different soil conditions.
5) By deriving the synthetic acceleration time history, we can get the acceleration time history for different soil conditions and it can be applied to structure and effect of soil on the structure can be studied.

Finally, we can conclude that the structurally hybrid tower is more effective for resisting dynamic forces generated by rotation of the turbine and it can resist seismic forces more effectively compared to monopole wind mill towers.

References

[1] B. Gencturk, A. Attar, and C. Tort “Design Optimization of Lattice Wind Turbine Towers Subjected to Earthquake Forces” Structures Congress ASCE (2014) pp 1694 – 1703.

[2] B. Song, and J. C. Wu “Comparative Analysis on Dynamic Response of Wind Turbine Tower in Different Sites” International Efforts in Lifeline Earthquake Engineering ASCE (2014).

[3] Domenico Lombardi, Subhamoy Bhattacharya, David Muir Wood “Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil” Soil Dynamics and Earthquake Engineering 49 (2013) ELSEVIER pp 165 – 180.

[4] Elena Nuta, Constantin Christopoulos, and Jeffrey A. Packer “Methodology for seismic risk assessment for tubular steel wind turbine towers: application to Canadian seismic environment” Canadian Journal of Civil Engineering. 38 (2011) pp 293–304.

[5] Joseph E. Bowles, “Foundation analysis and design” The McGraw-Hill Companies pp 39-45.

[6] Hani M. Negma, Karam Y. Maalawi “Structural Design Optimization Of Wind Turbine Towers” Computers and Structures Elsevier Science Ltd. 74 (2000) pp 649 – 666.

[7] Ian. Prowell, A. Elgamal, J. Lu, & J. E. Luco “Modal Properties of a Modern Wind Turbine Including SSI” Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (2009) 1989-1992.

[8] Ian Prowell, P. E., Chia Ming Uang, M., Ahmed Elgamal, M. J. Enrique Luco, and Lanhui Guo “Shake Table Testing of a Utility-Scale Wind Turbine” journal of engineering mechanics ASCE July (2012) pp 900-909.

[9] M. Harte, B. Basu, S. R. K. Nielsen “Dynamic Analysis of Wind Turbines Including Soil-Structure Interaction” Engineering Structures 45 (2012) ELSEVIER pp 509 – 518.

[10] Ministry of New and Renewable Energy, Government of India website http://mnre.gov.in.

[11] Mohammad Al Hamaydeh, Saif Hussain “Optimized Frequency-Based Foundation Design for Wind Turbine Towers Utilizing Soil–structure Interaction” science direct Journal of the Franklin Institute 348 (2011) pp 1470–1487.

[12] Remi Andre Kjørlaug, Amir M. Kaynia, Ahmed Elgamal “Seismic Response of Wind Turbines due to Earthquake and Wind Loading” Proceedings of the 9th International Conference on Structural Dynamics, EURODYN (2014).

[13] S. Jerath and S. Austin “Response of Wind Turbine Towers to Seismic Loading at Different Damping Ratios” Structures Congress 2013 © ASCE (2013) pp 1391 – 1402.

[14] Subhamoy Bhattacharya, James A. Cox, Domenico Lombardi David Muir Wood “Dynamics of offshore wind turbines supported on two foundations” ice proceedings (2012) Geotechnical Engineering Volume 166.

Atul K Desai has done his graduation in 1983 and masters in structure in 1985 from Sardar Vallabhbhai National Institute of Technology Surat. He has done PhD in structural engineering in 2008 from Sardar Vallabhbhai National Institute of Technology Surat, INDIA.

He is working as professor in Applied Mechanics Department at Sardar Vallabhbhai national institute of technology for 35 years. He is life member of 5 national and international technical institutes. He has published more than 250 research papers in national and international journals. His area of interest is Structural Dynamics; Machine Foundations; Bridge Engineering; Earthquake Engineering and Structural Forensic.

Hemal J Shah has done his graduation in 2002 and masters in structure in 2013 from Sardar Vallabhbhai National Institute of Technology Surat. He is working as assistant professor in Applied Mechanics Department at Government Engineering College, Bharuch, Gujarat, India. He is pursuing PhD from Sardar Vallabhbhai National Institute of Technology Surat.

He has teaching experience of 13 years and guided post graduate students in structural field. He has published 10 research papers in international journals. His area of interest is analysis of tall structures, dynamic analysis of structures and seismic analysis of structures.