International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.2, Issue.4, July-Aug. 2012 pp-2680-2686 ISSN: 2249-6645

Effect of the Supporting Strata on Design of Windmill Tower

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Abstract : *Windmill, machine that converts wind into useful energy. This energy is derived from the force of wind acting on oblique blades or sails that radiate from a shaft. The turning shaft may be connected to machinery used to generate electricity. The present paper makes an attempt to show the effect of wind and earthquake load on tubular type windmill and its foundation considering hard, medium and soft soil strata. The modeling of windmill tower was done in computer software by finite element modeling technique. In that windmill tower was subjected to wind and earthquake forces and check bending stresses, mode Shape, base shear comparison, stability, safety of windmill for hard, medium and soft strata. Also check stability, safety of windmill foundation and design of reinforcement required in the foundation for hard, medium and soft strata. Based on the analytical investigation and design it has been concluded that the effect of wind on windmill is significant as compare to earthquake, hence stability of windmill is thoroughly check for this load. Soil strata also play a major role in deciding its safety and stability. The normalized base shear, seismic moments, natural time period, bending stresses in tower and sizes and reinforcement of foundation increases from hard strata to soft strata.*

Keywords - *Wind load, Earthquake load, stability of tower and foundation, soil strata.*

I. Introduction

The world of wind power is growing at a very faster rate. This projection put the average growth of the industry at 24% for the next five years.Therotically wind could produce enough energy to meet global demand. Growth will be driven by rapidly developing countries, such as India, Brazil, and China. Improving efficiency and falling cost of turbine production and installation will make wind power more price competitive. The amount of wind energy generated depends mostly on the size, height, type and location of a wind turbine. Windmill although are structurally simple, their behavior under the operating condition is quit complex due to the static and dynamic effect of wind. Due to the operation of the windmill during high wind makes the behavior still more complex. If these windmills are founded on relatively soft foundation soil, structural stability during dynamic loads can be one more matter of concern.

The main components of windmill are windmill tower, nacelle, hub, and blade. The windmill basically divided into Horizontal axis machines and Vertical axis machines, based on their axis of rotation. For more electric energy generation Vertical axis Windmill i.e. tubular type windmill and lattice type of tower windmill is mostly used. Foundations for windmill are rectangular, square, and circular of a similar configuration. Very high requirements are imposed on windmill foundation with respect to durability and strength. This uneven loading also has effects on the strength of the reinforcement structure provided in the concrete main part. With the windmill foundation, the reinforcement structure generally consists of the known reinforcing bar or reinforcing steel mesh.

For the analysis we have taken the 74 meter height tubular type windmill with three blade of each 32 meter length. The total weight of windmill was 184 ton. The power generation capacity of this windmill was 1250 KW.This windmill were analyzed in computer software for different load such as dead load, wind and earthquake loads. The main objectives of this paper was to determine the most vulnerable combination of windmill structure and foundation under the action of dynamic load for different soil strata such as hard,medium,soft strata. So that suitable remedial measures can be taken during the design. According to that deign of circular foundation was done in order to achieve economy, stability, safety of foundation, so that windmill is withstand safely.

II. Methodology

Windmill structures are relatively flexible and have a longer fundamental period. If such structures are founded on rigid foundation such as rock or hard soil, seismic force may not govern the design as wind force become more critical, but many times due to non availability of hard rock it may be necessary to construct such structures on soft soil. This is especially true near the sea shore, where most of the area consists of reclaimed soil and mostly windmills are constructed at the sea shore as wind is much effective in this area and availability of land is easily accessible. As a result of this soft layer of soil the earthquake ground motion gets modified and have relatively longer predominant period. Due to this it is essential to analyze and design of windmill for soft, medium, and hard soil strata.

2.1 Wind Analysis

Wind speed in the atmospheric boundary layer increases with height from zero at ground level to a maximum height called the gradient height. As the windmill is of grater height and normally situated in open terrain category the wind load is major affecting factor. This effect of wind on structure as a hole was determined by the combined action of external and internal pressure acting on it. The Wind analysis was done by using IS-875(Part-3) code. As per code wind speed considered for proposed site was 39 m/s. Due to the high rise of the structure the wind speeds also increasing. So the greater effect produced on the Windmill. Therefore wind load (F) on windmill structure acting in a direction normal to the individual structural element was calculated by:

$F = C_f A P_z$ (1)

Where, C_f = Force coefficient; A = surface area of structural or cladding unit; P_z = design wind pressure.

The windmill experiences both compression and a bending moment about its footing. The compression is due to the weight of the nacelle and rotor whilst the bending moment is induced by the thrust caused by drag forces on the blade of windmill. The tower itself also experiences an unevenly distributed force due to the drag forces created by the oncoming wind. This drag force or thrust due to wind was calculated as per IS-875 Part-3 as below:

$F = C_f A P_z$ (2)

2.2 Earthquake Analysis

The dynamic response of a structure against an earthquake vibration is an important structural aspect which directly affects structural resistance and consequently the hazard level. For analysis for earthquake loads, it is necessary to find out characteristics of structure as well as earthquake. Characteristics of the windmill were determined by Response Spectrum method analysis. In Response Spectrum method analysis the fundamental time period and mode shapes of the structure can be found out. The main objective of this analysis was to understand the overall behavior of windmill structures founded on soil strata. Response Spectrum method analysis of the different windmill towers was carried out by considering tower as a continuous system. By considering tower as cantilever beam fixed at one end and free at the other, natural time period can be computed from the Equation:

$W_n = C_n\sqrt{EI/ml^4}$ & $C_n = a_n L^2$ (3)

Where, W_n = Natural frequency of the system in n^{th} mode; C_n= Constant for boundary conditions; $a_n = 4\sqrt{mw^2/EI}$; E= Modulus of elasticity; I=Moment of inertia of the given system; m=Mass per unit length of the system; L=Total length of the system

III. Performance Analysys

Selection of windmill is depending upon the availability of wind speed, power generation capacity. Windmill can be best analyzed as tall cylindrical tower of uniform cross section because they produce minimal lift as they display no surfaces that with an angle of attack that can produce a significant pressure difference.

3.1 Modeling of Windmill Tower

The modeling of windmill tower was done by using Finite element modeling technique. Tower of the windmill was modeled with 4-noded tetrahedral elements in computer software which is shown in Figure 1. All elements were connected to each other with proper boundary condition. The support condition considered for this structure was pinned because of load transfer from tower to foundation is through anchor bolt.

Total number of 4-noded tetrahedral elements = 2700

Figure1. Modeling of windmill Tower

3.2 Loading

The windmill is mainly subjected to Dead load, Wind load and Earthquake load. In that Wind load is the major governing factor for changing behavior of windmill.

3.2.1 Dead load

The nacelle, hub and blades were mounted on windmill tower. So weights of these components were taken to be considered for the analysis. And also considered self weight of tower.

Dead load of nacelle = 52 Ton = 510 KN
Dead load of hub = 12 Ton = 120 KN
Dead load of 3 blade = 130 KN

3.2.2 Live load

In this case there was not any type of Live load acting on windmill tower; so live load considered should be zero.

3.2.3 Wind load

Windmills are cylindrical and high rise structure, so the wind analysis of this structure is important and shall be done by using IS-875 (Part-3) method.

i) Design wind Pressure (P_z)

The wind pressure on plates of windmill tower was given by:

$P_z = 0.6 V_z^2$ (4)

Where, $V_z = k_1 k_2 k_3 V_b$; $k_1 = 0.92$; $k_2 = 0.93$ for 10 m height; $k_2 = 0.97$ m for 15 m height; $k_2 = 1.0$ m for 20 m height; $k_2 = 1.04$ m for 30 m height; $k_2 = 1.10$ m for 50 m height; $k_2 = 1.17$ m for 100 m height; $k_3 = 1$; $V_b = 39$ m/s

Table 1 Design wind pressure (P_z)

Height of tower (M)	Vz (m/s)	P_Z (KN/m^2)
10	33.37	0.67
15	34.80	0.73
20	35.88	0.77
25	36.60	0.81
30	37.32	0.84
35	37.86	0.86
40	38.40	0.89
45	38.93	0.91
50	39.47	0.93
55	39.72	0.94
60	39.97	0.96
65	40.22	0.97
70	40.47	0.98
75	40.73	1.00

ii) Wind forces on windmill tower

The wind load, F acting as a pressure load on the individual plate element was given by;

$F = C_f A P_z$ (5)

Where, C_f = 1 for H/B ratio = 18.50 & Circular shaped element… (Table No.23, Page No.40); A = surface area of four nodded rectangular plate; P_z = design wind pressure.

Table 2 Wind force (F)

Height of tower (m)	$F = C_f A P_z$ (KN/m^2)

10	0.67
15	0.73
20	0.77
25	0.81
30	0.84
35	0.86
40	0.89
45	0.91
50	0.93
55	0.94
60	0.96
65	0.97
70	0.98
75	1.00

This wind load are applied on plate of windmill tower as a pressure load along positive X-direction(WLX+), negative X-direction(WLX-), positive Z-direction(WLZ+), negative Z-directive (WLZ-) in computer software which is shown in Fig.2

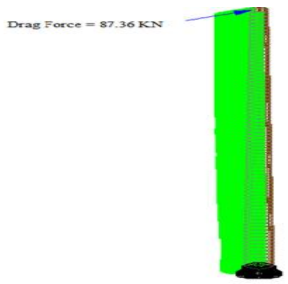

Figure 2.Wind load on windmill tower

iii) Drag force on blade of windmill due to wind pressure
The tower itself also experiences an unevenly distributed force due to the drag forces created by the oncoming wind on blades .This drag force or thrust due to wind was calculated as per IS-875 Part-3 as below;

$F= C_f A P_z$ (6)

Where, C_f = 0.6 …for ellipse shape element.……. (Table No.23, Page No.40); A = Average area of one blade = 32*((2.75+1.5+0.3)/3) = 48.53 m^2; P_z = 1 KN/m^2

Therefore, F = 0.6*1*48.53*3 = 87.36 KN

This drag force applied at top of tower horizontally which is as shown in Fig.3

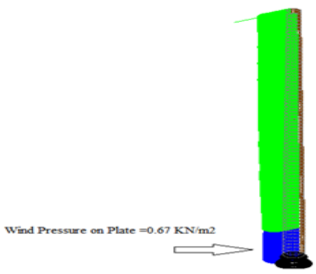

Figure 3. Drag force on windmill

3.2.4 Earthquake load

In computer software the earthquake analysis of windmill was done by using response spectrum method. The analysis gives result such as seismic base shear, seismic moment at C.G.of tower due to seismic forces, seismic moment at bottom of tower due to seismic shear, deflection of tower, bending stresses in plate due to seismic forces.

The total design lateral force or design seismic base shear (V_B) along any principal direction shall be determined by the following expression;

$V_B = A_h W$ (7)

Where, $A_h = Z/2*I/R*S_a/g$; W =seismic weight of structure

The basic parameters required for the analysis of earthquake as per code IS-1893-2002 are:
Zone factor (Z) = 0.16 for Pune (India) region
Importance factor = 1
Response reduction factor = 5
Damping factor = 0.02
Frequency (ZPA) = 33
S_a/g = Average response acceleration coefficient and depend on natural period of vibration and damping of the structure.

The seismic load applied in X, Y & Z direction as shown in Fig.4

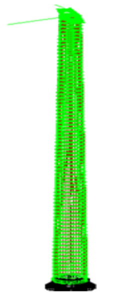

Figure 4.Earthquake load on windmill

3.3 Load Combinations

The load combinations for Design of RCC foundation and analysis and design of steel structure shall be taken as per IS-456-2002, IS-800-1984, and IS-1893-2002.

Load combinations for Foundation design:
1. (DL+LL)
2. DL+LL± (WLX+)
3. DL+LL± (WLZ+)
4. DL±EQX
5. DL±EQZ
6. DL±EQY
7. DL± (WLX+)
8. DL± (WLZ+)

Load combinations for Windmill tower:
1. DL+LL
2. 0.75[DL+0.5LL±EQX]
3. 0.75[DL+0.5LL±EQZ]
4. 0.75[DL+0.5LL±EQY]
5. 0.75[DL+LL± (WLX+)]
6. 0.75[DL+LL± (WLZ+)]
7. 0.75[DL±EQX]
8. 0.75[DL±EQZ]
9. 0.75[DL±EQY]
10. 0.75[DL± (WLX+)]
11. 0.75[DL± (WLZ+)]
12. 0.75[0.9DL±EQX]
13. 0.75[0.9DL±EQZ]
14. 0.75[0.9DL±EQY]
15. 0.75[0.9DL± (WLX+)]
16. 0.75[0.9DL± (WLZ+)]

IV. Design of Circular Foundation

The function of foundation is to transmit the load from the structure to underlying soil. If these loads are to be properly transmitted, footing must be designed to limit the total settlement of the structure to a tolerably small amount and to eliminate as nearly as possible the differential settlement or rotation of the various part of the structure and to provide adequate safety against overturning and sliding. The choice of suitable type of footing for a structure depends on the depth at which the bearing strata lies, the soil condition and the type of superstructure.

For this structure we used circular type foundation with pedestal. The general dimensions of the circular foundation are shown in Figure 5. The size of foundation is depending upon the total load from tower to foundation and bearing capacity of soil. The foundation was checked for one way shear, two way shears. The foundation was design for soft, medium and hard strata. The net safe bearing capacity of hard, medium and soft strata soil was considered as 350.00 KN/m^2, 200.00 KN/m2, and 115.00 KN/m2 respectively. The design of pedestal and footing for different soil strata are listed in Table 3

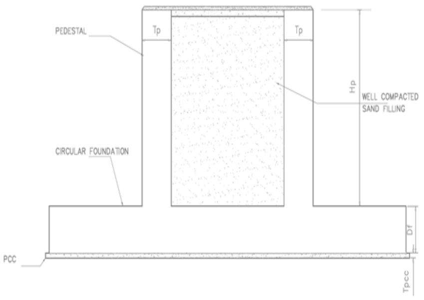

Figure 5.Circular Foundation

Table 3 Design of Foundation for hard, medium and soft strata

Sr. No.	Item	Hard strata	Medium strata	Soft strata
	A)Pedestal			
1	Outer dia of pedestal(mm)	4300	4300	4300
2	Inner dia of pedestal(mm)	3700	3700	3700
3	Ht of pedestal(mm)	2700	2700	2700
4	Ht of pedestal above FFL(mm)	500	500	500
5	T.O.G.Elevation(mm)	700	700	700
6	Vertical R/F@ outer face	74 nos-25Ø	74 nos-25Ø	74 nos-25Ø
7	Vertical R/F@ inner face	84 nos-25Ø	84 nos-25Ø	84 nos-25Ø
8	lateral ties	10Ø @ 150 c/c	10Ø @ 150 c/c	10Ø @ 150 c/c
	B)Footing			
1	Outer dia of footing (mm)	18000	19000	21500
2	Thickness of footing (mm)	1100	1100	1100
3	R/F @ bottom face	20Ø @ 100 c/c both way	20Ø @ 100 c/c both way	20Ø @ 100 c/c both way
4	R/F @ top face	16Ø @ 120 c/c both way	16Ø @ 140 c/c both way	20Ø @ 300 c/c both way
5	lateral ties	12Ø @ 250 c/c side face	12Ø @ 250 c/c side face	12Ø @ 250 c/c side face

V. Result and Disscussion

5.1 *Deflection of tower*

It was observed that the deflection is maximum for wind load as compare to seismic load for different soil strata. So in this case the windmill tower is more critical for wind load as compare to seismic load. The deflection of tower increasing from hard strata to soft strata. The deflection of tower for different soil strata are presented in Table 4, 5&6.

Table 4 Maximum deflection of windmill tower for hard strata

Node	Load combinations	Horizontal deflection in X-Dir(mm)	Horizontal deflection in Z-Dir(mm)	Remark
3540	0.75[DL+LL+(WLX+VE)]	178.546	0	Wind Load
3567	0.75[DL+LL+(WLZ+VE)]	3.547	90.314	
3558	0.75[DL+0.5LL+EQX]	10.472	0	EQ Load
3565	0.75[DL+0.5LL+EQZ]	3.682	6.581	

Table 5 Maximum deflection of windmill tower for medium strata

Node	Load combinations	Horizontal deflection in X-Dir(mm)	Horizontal deflection in Z-Dir(mm)	Remark
3540	0.75[DL+LL+(WLX+VE)]	178.546	0	Wind Load
3567	0.75[DL+LL+(WLZ+VE)]	3.547	90.314	
3558	0.75[DL+0.5LL+E	12.796	0	EQ Load

	QX]			
3564	0.75[DL+0.5LL+EQZ]	3.733	9.597	

Table 6 Maximum deflection of windmill tower for soft strata

Node	Load combinations	Horizontal deflection in X-Dir(mm)	Horizontal deflection in Z-Dir(mm)	Remark
3540	0.75[DL+LL+(WLX+VE)]	178.546	0	Wind Load
3567	0.75[DL+LL+(WLZ+VE)]	3.547	90.314	
3558	0.75[DL+0.5LL+EQX]	14.895	0	EQ Load
3564	0.75[DL+0.5LL+EQZ]	3.746	10.845	

5.2 Stability of windmill tower

It was observed from the analysis that bending stresses are maximum at the bottom level plates of the tower. There was tensile and bending stresses are developed in the tower of windmill. The bending stresses developed in the bottom plate of windmill tower were maximum for wind load as compared to seismic load for different strata.

The permissible bending stress in tension and compression=σ_{bt} = 0.66*f_y , where, f_y =yield stress of steel. For steel of yield strength 250 N/mm^2, σ_{bt} = 0.66*250 = 165 N/mm^2.From Table 7 it is observed that no bending stresses are exceeding the value of permissible stresses hence windmill tower structure is safe for the bending.

Table 7 Bending stress in tower

Sr.No.	Soil Strata	Bending Stress(Kn/m2)	Loading
1	Hard strata	151	Wind Load
		15.8	Earthquake load
2	Medium strata	151	Wind Load
		17.2	Earthquake load
3	Soft strata	151	Wind Load
		18.8	Earthquake load

5.3 Base shears comparison

It was observed from the seismic analysis that absolute base shear for soft soil strata are maximum as compared to hard soil strata. It is obvious when soil becomes softer, stiffness of soil goes on decrease and as result of this there is maximum vibration in the structure. The absolute base shear for different soil strata is listed in Table 8

Table 8 Base Shear

Earthquake Load	Base Shear (KN)		
	Hard Strata	Medium Strata	Soft Strata
EQX	40.96	44.32	47.36
EQZ	40.91	44.39	47.55
EQY	27.18	27.18	27.18

5.4 Safety of foundation

It was observed that the actual bearing pressure on the soil for design size of footing is less than the permissible safe bearing capacity for hard, medium and soft strata which is shown in Table 9, 10&11. So foundation is Safe.

Table 9 Pressure intensities for hard strata

Load combination	Net pressure intensities (KN/m2)		Gross pressure intensities (KN/m2)		Allowable SBC for hard strata(KN/m2)
	Max	Min	Max	Min	
DL of foundation +VW of windmill	35.92	35.92	75.47	75.47	
DL of foundation +Vertical weight +Wind	69.49	2.34	142.63	8.31	350.00
DL of foundation+ Vertical weight+Seismic	37.67	34.16	78.99	71.95	

Table 10 Pressure intensities for medium strata

Load combination	Net pressure intensities (KN/m2)		Gross pressure intensities (KN/m2)		Allowable SBC for hard strata(KN/m2)
	Max	Min	Max	Min	
DL of foundation +Vertical weight of windmill	35.00	35.00	74.61	74.61	
DL of foundation +Vertical weight +Wind	63.6	6.5	131.71	17.51	200.00
DL of foundation+ Vertical weight +Seismic	36.91	33.19	78.33	70.89	

Table 11 Pressure intensities for soft strata

Load combination	Net pressure intensities (KN/m2)		Gross pressure intensities (KN/m2)		Allowable SBC for soft strata(KN/m2)
	Max	Min	Max	Min	
DL of foundation	33.40	33.40	72.97	72.97	

+Vertical weight of windmill					
DL of foundation+ Vertical weight +Wind	53.11	13.70	112.38	33.56	115.0
DL of foundation+ Vertical weight +Seismic	34.97	31.83	76.11	69.83	

5.5 Stability of foundation

For stability of foundation the soil must be capable of carrying the loads from any engineered structure placed upon it without a shear failure and with resulting settlements being tolerable for that structure. Excessive settlements can result in structural damage to a building frame, and excessive wear or settlements. So it is necessary to check windmill for sliding and overturning. From Table 12, 13&14 it is observed that the windmill for different soil strata is safe for sliding and overturning. The factor of safety against sliding and overturning is greater than 1.5

Table 12 Check for stability of foundation for hard strata

Checks	Parameters	Load case	
		DL+Wind	DL+Seismic
Check For sliding	Fs	407.64	553.03
	Fr	6914.09	6914.09
	FSs	16.96	12.50
	SAFE / UNSAFE	SAFE	SAFE
Check For overturning	Mo	19799.03	1036.60
	Mr	155566.97	155566.97
	FSo	7.86	150.07
	SAFE / UNSAFE	SAFE	SAFE

Table 13 Check for stability of foundation for medium strata

Checks	Parameters	Load case	
		DL+Wind	DL+Seismic
Check For sliding	Fs	407.64	614.77
	Fr	7616.06	7616.06
	FSs	18.68	12.39
	SAFE / UNSAFE	SAFE	SAFE
Check For overturning	Mo	19799.03	1290.04
	Mr	180881.33	180881.33
	FSo	9.14	140.21
	SAFE / UNSAFE	SAFE	SAFE

Table 14 Check for stability of foundation for soft strata

Checks	Parameters	Load case	
		DL+Wind	DL+Seismic
Check	Fs	407.64	777.52
For Sliding	Fr	9536.98	9536.98
	FSs	23.40	12.27
	SAFE / UNSAFE	SAFE	SAFE
Check for overturning	Mo	19799.03	1578.82
	Mr	256306.43	256306.43
	FSo	12.95	162.34
	SAFE / UNSAFE	SAFE	SAFE

5.6 Reinforcement details of foundation

The reinforcement for foundation was increases from hard strata to soft strata which are presented in Table 15.So the cost of foundation is increases with respect to increasing reinforcement in foundation.

Table 15 Reinforcement details of Foundation

Sr.No.	Item	Hard strata	Medium strata	Soft strata
	A)Pedestal			
1	Vertical R/F@outer face	74 nos-25Ø	74 nos-25Ø	74 nos-25Ø
2	Vertical R/F@inner face	84 nos-25Ø	84 nos-25Ø	84 nos-25Ø
3	lateral ties	10Ø @ 150 c/c	10Ø @ 150 c/c	10Ø @ 150 c/c
	B)Footing			
1	R/F @ bottom face	20Ø @ 100 c/c both way	20Ø @ 100 c/c both way	20Ø @ 100 c/c both way
2	R/F @ top face	16Ø @ 120 c/c both way	16Ø @ 140 c/c both way	20Ø @ 300 c/c both way
3	lateral ties	12Ø @ 250 c/c side face	12Ø @ 250 c/c side face	12Ø @ 250 c/c side face

VI. Conclusion

In this work attempt was made to critically study the behavior of windmill tower and foundation system subjected to wind load and earthquake load for different supporting condition such as hard, medium and soft strata.

Based on this analysis and design following conclusion were made:

1. The effect of wind is significant as compared to earthquake and has to be considered in the analysis of windmill.
2. When effects of wind are considered the stability of windmill has to be thoroughly checked.
3. Soil strata play a major role in safety and stability of windmill.
4. The effect of wind on blade i.e. drag force is more critical in the analysis of windmill and its make more drastic changed in the structure.
5. In earthquake analysis, the normalized base shear, moment due to shear is increasing with respective to hard, medium and soft soil strata.

6. The foundation sizes, concrete material, reinforcement material shall be increasing with respect to hard, medium and soft Strata. So cost of structure also increased.

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