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ANALYSIS AND DESIGN OF ONSHORE WIND TURBINE FOUNDATION AT KAYATHAR, TUTICORIN DISTRICT

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Abstract - *At present the life in Planet Earth requires Air, Water, Food and ENERGY. So far, the Energy is being produced from fossil fuel to meet the Global requirement. In this regard fossil fuel power plant like coal fired power plants are the largest emitter of Green House Gases and creates threatening environment for the human life and causes the depletion of Ozone layer. In addition, the availability of the coal resources is also reducing very fast all over the world. Hence the alternative is the RENEWABLE ENERGY. Renewable Energy has two major wings such as WIND and SOLAR. Kayathar in Tuticorin District plays a major role in wind energy production in Tamil Nadu. The present paper makes an attempt to show the effect of wind and earthquake load on windmill foundation considering hard, medium and soft soil strata. The modeling of windmill tower was done in computer software by finite element modeling technique. This study includes wind and earthquake forces and check for bending stress, base shear comparison, stability and safety of windmill foundation for hard medium and soft soil strata at Kayathar, Tuticorin District.*

Key Words: **Renewable Energy, Onshore Wind Turbine Foundation, Wind Analysis, Earthquake Analysis, Drag force, Stability Analysis, Critical design**

1. INTRODUCTION

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 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 analyse and design of windmill foundation for soft, medium and hard soil strata.

2. ANALYSIS

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:

$$\mathbf{F = C_f\, A\, P_z}$$

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

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:

$$\mathbf{F = C_f\, A\, P_z}$$

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 behaviour 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:

$$W_n = C_n\sqrt{EI/ml^4}\ \&\ C_n=a_nL^2$$

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

2.3 Soil Properties used for Anaysis

(As per Joseph E.Bowles Foundation Engineering reference [26]).

Table-1 Soil Properties

Soil Type	Modulus of Subgrade (KN/m³)	Poisson Ratio	Modulus of Elasticity (N/mm²)
Hard Soil Strata	96000	0.4	96
Medium Soil Strata	45000	0.4	45
Soft Soil Strata	10500	0.4	10.5

3. PERFORM ANALYSIS

3.1 Modelling 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 = 2880;
No.of Joints = 2916;
No.of Supports = 36

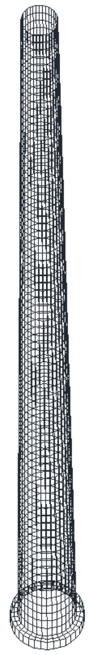

Fig.1 - Modelling of windmill tower

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 behaviour of windmill.

3.2.1 Dead Load

The nacelle and blades were mounted on windmill tower. So, weights of these components were taken to be considered for the analysis of windmill forces which includes the self-weight of the tower (GE 1.5sle) [15] also.

Dead load of nacelle = 56 Ton = 560 KN
Dead load of 3 blade = 12 x 3 = 36 Ton = 360 KN
Dead load of Tower = 71 Ton = 710 KN

3.2.2 Live Load

Since there is no live load acting on the windmill, Live load consideration is nil.

3.2.3 Wind Load

Windmill 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): 1987 method. In this code of reference wind loads are calculated by Simplified method and Random response method. As windmills are flexible structures dynamic effect of wind is also taken into account for the analysis.

3.2.3.1 Design Wind Pressure (P_z)

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

$$P_z = 0.6\, V_z^2$$

Where,
$V_z = k_1\, k_2\, k_3 V_b$;
$k_1 = 0.92$;
$k_2 = 0.93$ for 10 m height; k2 = 0.97 m for 15 m height;
k_2 =1.0 m for 20 m height; k2 = 1.04 m for 30 m height;
k_2 =1.10 m for 50 m height; k2 = 1.17 m for 100 m height;
$k_3 = 1$;
V_b = 39 m/s (Kayathar, Tuticorin)

3.2.3.2 Design Wind Speed Analysis

The calculated values of k_1, k_2 & k_3 from the analysis results are furnished in the Table 2. From the values of the design wind speed pressure (P_z) arrived from Table 3 were used to calculated wind forces on Windmill Tower and furnished in Table 3.

Ht. of tower (m)	k1	k2	k3	Vz (KN/m²)	Pz (KN/m²)
10	0.92	1.05	0.78	29.39	0.52
15	0.92	1.09	0.82	32.07	0.62
20	0.92	1.12	0.85	34.16	0.70
25	0.92	1.14	0.87	35.43	0.75
30	0.92	1.15	0.88	36.31	0.79
35	0.92	1.16	0.89	37.04	0.82
40	0.92	1.18	0.91	38.53	0.89
45	0.92	1.19	0.92	39.20	0.92
50	0.92	1.20	0.93	40.04	0.96
55	0.92	1.21	0.94	40.81	1.00
60	0.92	1.21	0.95	41.24	1.02
65	0.92	1.22	0.96	42.02	1.06
70	0.92	1.22	0.97	42.46	1.08
75	0.92	1.23	0.98	43.25	1.12
80	0.92	1.24	0.99	44.05	1.16

Table-2 Design Wind Pressure (P_Z)

3.2.3.3 Wind forces on Windmill Tower (F)

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

$$F = C_f\, A\, P_z$$

Where,
C_f = 1 for H/B ratio = 18.50 & Circular shaped element
A = surface area of four nodded rectangular plate;
P_z = design wind pressure.

Table 3 Wind force (F)

Height of tower (m)	F= C_f A P_z (KN/m²)
10	0.52
15	0.62
20	0.70
25	0.75
30	0.79
35	0.82
40	0.89
45	0.92
50	0.96
55	1.00
60	1.02
65	1.06
70	1.08
75	1.12
80	1.16

This wind load is 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

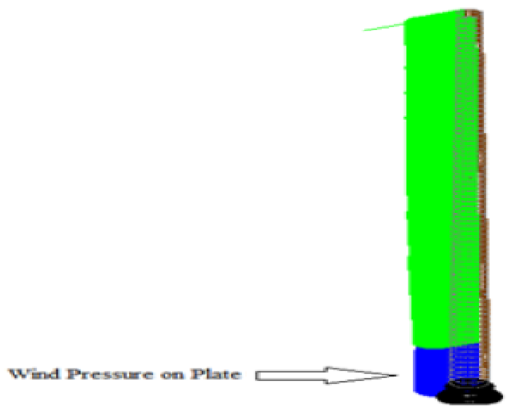

Fig. 2 Wind load on Windmill Tower

3.2.3.4 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 wind acts on blades. This drag force or thrust due to wind was calculated as per IS-875 Part-3 as below;

$$F = C_f A P_z$$

Where,

C_f = 0.6 for ellipse shape element
A = surface area of one blade
= 38.5 * ((2.75+1.5+.3)/3) = 58.39m²
P_z = 1 KN/m²

Therefore,

F = 0.6 * 1 * 58.39 * 3 = 105.10kN

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

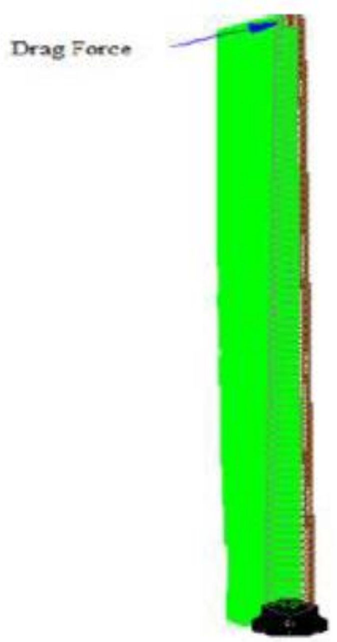

Fig. 3 Drag force on Windmill Tower

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 Centre of Gravity 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;

$$V_B = A_h W$$

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 Zone III (Kayathar, Tuticorin) region

Importance factor = 1.5
Response reduction factor = 5
Damping factor = 0.02

S_a/g = Average response acceleration coefficient and depend on natural period of vibration and damping of the structure.

3.2.5 Foundation Load

Considering the circular type of foundation with pedestal, the general dimensions of the circular foundation are shown in Figure 5.5. 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 and designed for hard, medium & soft strata. The allowable safe bearing capacity of hard, medium and soft strata soil was considered as 350kN/m², 200kN/m² & 115kN/m² respectively. The pedestal and footing size of different soil strata are with various load combinations are listed in Table 4.

Table 4 Dimensions of the pedestal and foundation

S. No	Item	Seismic load in hard strata	Seismic load in medium strata	Seismic load in soft strata	Wind load in any strata
1	**Pedestal**				
	Length (mm)	600	600	600	600
	Width (mm)	600	600	600	600
	Height (mm)	2700	2700	2700	2700
2	**Raft**				
	Diameter (mm)	18000	20000	22000	24000
	Thickness (mm)	1000	1000	1000	1000

Pedestal loads are considered as point load at every support for analysis and design purposes. Soil load between above the foundation and below the ground level is atomically calculated in the software itself.

Dimensions and load of the pedestal for any type of loading is given below.

Length of the pedestal = 600mm = 0.6m
Width of the pedestal = 600mm = 0.6m

Height of the pedestal = 2700mm = 2.7m
Unit weight of the concrete (R.C.C.) = 25kN/m2
Load from pedestal for each = 0.6 x 0.6 x 2.7 x 25 = 24.3kN

3.3 Foundation Load

Load Combinations for Foundation Design:
1. DL + (WLX± / WLZ±) + FL (Hard soil)
2. DL + (WLX± / WLZ±) + FL (Medium soil)
3. DL + (WLX± / WLZ±) + FL (Soft soil)
4. DL + (EQX± / EQZ±) + FL (Hard soil)
5. DL + (EQX± / EQZ±) + FL (Medium soil)
6. DL + (EQX± / EQZ±) + FL (Soft soil)

4. RESULT AND DISCUSSION

Windmill structure has large number of joints, elements and beams. Normally it has more than 2880 elements, 2916 joints and 5796 members. Analysis and do the design of entire elements or members only will be complication of the design of windmill foundation. Hence doing this complicated analysis and design cannot be completed manually, because it requires sufficient time limit and moreover, we can encounter with lots of human errors.

Considering the above points STAAD.Pro & STAAD.foundation software is used to complete this complicated analysis and design.

Input analysis programe used for various types of load combination.

Dead load + Foundation Load + Seismic load with Hard soil
Dead load + Foundation Load + Seismic + Medium soil
Dead load + Foundation Load + Seismic + Soft soil
Dead load + Foundation Load + Wind load with Hard soil
Dead load + Foundation Load + Wind + Medium soil
Dead load + Foundation Load + Wind + Soft soil

4.1 Base Shear Comparison

It was observed from the seismic analysis that absolute base shear for soft soil strata is 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 5.

Table 5 Base Shear

Earthquake Load	Base Shear (KN)		
	Hard Strata	Medium Strata	Soft Strata
EQX	24.22	32.94	40.45
EQZ	24.22	32.94	40.45
EQY	16.15	21.96	26.97

4.2 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 6, 7 & 8. So, foundation is Safe.

Table 6 Pressure intensities for hard strata

Load combination	Base Pressure (KN/m²)	Allowable SBC for hard strata (KN/m²)
Dead load of foundation + Vertical weight of windmill + Wind	77.96	350.00
Dead load of foundation + Vertical weight of windmill + Seismic	77.58	

Table 7 Pressure intensities for medium strata

Load combination	Base Pressure (KN/m²)	Allowable SBC for hard strata (KN/m²)
Dead load of foundation + Vertical weight of windmill + Wind	55.22	200.00
Dead load of foundation + Vertical weight of windmill + Seismic	56.09	

Table 8 Pressure intensities for soft strata

Load combination	Base Pressure (KN/m²)	Allowable SBC for hard strata (KN/m²)
Dead load of foundation + Vertical weight of windmill + Wind	29.30	115.00
Dead load of foundation + Vertical weight of windmill + Seismic	29.20	

4.2 Stability of Foundation

Stability of foundation the soil must be capable of carrying the loads 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 9, 10 & 11, it is observed that the windmill for different soil strata is safe against sliding and overturning. The factor of safety against sliding and overturning is greater than 1.5. Concrete having M30 grade and Fe500 grad steel has been used for the design of circular raft foundation.

Table 9 Check for stability of foundation for hard strata

Checks	Parameters	Load case	
		D.L. + F.L. Wind	D.L. + F.L. Seismic
Check for Sliding	F_s (KN)	512.02	306.48
	F_r (KN)	11309.73	6361.73
	FS_s	22.08	20.76
	SAFE / UNSAFE	SAFE	SAFE
Check for Overturning	M_o (KNm/m)	1234.10	583.17
	M_r (KNm/m)	3370.11	3414.21
	FS_o	2.73	5.85
	SAFE / UNSAFE	SAFE	SAFE

Table 10 Check for stability of foundation for medium strata

Checks	Parameters	Load case	
		D.L. + F.L. Wind	D.L. + F.L. Seismic
Check for Sliding	Fs (KN)	512.02	318.80
	Fr (KN)	11309.73	7853.98
	FSs	22.08	24.64
	SAFE / UNSAFE	SAFE	SAFE
Check for Overturning	Mo (KNm/m)	1233.42	632.71
	Mr (KNm/m)	3370.11	3533.22
	FSo	2.73	5.58
	SAFE / UNSAFE	SAFE	SAFE

Table 11 Check for stability of foundation for soft strata

Checks	Parameters	Load case	
		D.L. + F.L. Wind	D.L. + F.L. Seismic
Check for Sliding	512.02	512.02	329.40
	11309.73	11309.73	9503.32
	22.08	22.08	28.85
	SAFE	SAFE	SAFE
Check for Overturning	1234.82	1234.82	681.60
	3370.11	3370.11	3414.21
	2.73	2.73	5.01
	SAFE	SAFE	SAFE

4.3 Design of Foundation

Based on the STADD.foundation software the following circular raft foundation had been designed and results are summarised in Table 12. The critical design results are furnished in Table 13.

Table12 Raft foundation design details

S. No	Item	Seismic load in hard strata	Seismic load in medium strata	Seismic load in soft strata	Wind load in any strata
1.	Footing Diameter (mm)	18000	20000	22000	24000
2.	Footing Thickness (mm)	1000	1000	1000	1000
3.	Reinforcement at bottom face of the footing	16mm ∅ at 130 mm C/C	20mm ∅ at 190 mm C/C	25 mm∅ at 290mm C/C	25mm ∅ at 150mm C/C
4.	Reinforcement at top face of the footing	16mm ∅ at 160 mm C/C	16mm ∅ at 160 mm C/C	16mm∅ at 160mm C/C	20mm ∅ at 250mm C/C
5.	Lateral ties	12mm ∅ at 250 mm C/C	12mm ∅ at 250 mm C/C	12mm∅ at 250mm C/C	12mm ∅ at 250mm C/C

Table13 Critical Raft foundation design details

S. No.	Item	Critical design results
1.	Footing Diameter (mm)	24000
2.	Footing Thickness (mm)	1000
3.	Reinforcement at bottom face of the footing	25mm∅ at 150mm C/C
4.	Reinforcement at top face of the footing	20mm∅ at 150mm C/C
5.	Lateral ties	12mm∅ at 250mm C/C

5. CONCLUSIONS

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

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