BEHAVIOUR OF WINDMILL STRUCTURE UNDER WIND LOADING WITH CONSIDERATION OF SOIL-STRUCTURE INTERACTION

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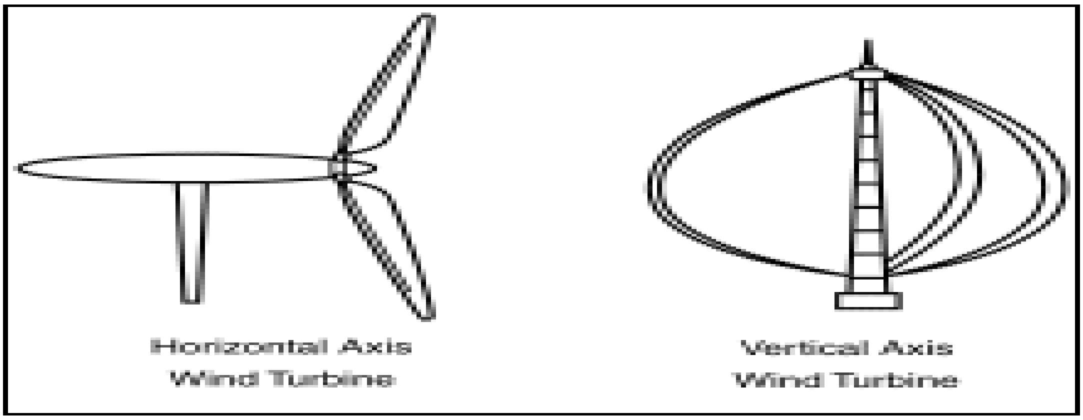
***Abstract* - Up until recently, people still only had visual impressions of what a windmill is, often associating it with the past and particularly before the industrial revolution. Today, things have come full circle, if you will and there is now a growing demand for large, technologically advanced windmills across the world. The term wind energy or wind power describe the process through which wind turbine convert the kinetic energy in the wind into electrical energy by the use of generator. All Engineered construction resting on the earth must be carried by a foundation. The foundation is the part of an engineered system which transmits to, and into, the underlying soil or rock the loads supported by the foundation and its self weight. Windmills although are structurally simple, their behaviour under the operating conditions is quit complex due to the static and dynamic effect of wind. Due to the operation of the mill during high wind makes the behaviour still more complex .This analysis includes comparative study of behaviour of windmill structure under wind loading,considering its effects on different types of soil strata and to find the suitable measures to be taken.**

***Keywords*- Wind analysis of windmill structure under dynamic loading, deflection, maximum bending and shear stress, actual settlement, maximum pressure on the soil.**

1. INTRODUCTION

1.1 Types of Windmill

Wind turbines can rotate about either a vertical or a horizontal axis, the latter being both older and most common type. Horizontal-axis wind turbines (HAWT) have the electrical generator & the main rotor shaft at the top of tower, and should be pointed into the wind. Vertical-axis wind turbines (VAWT) have the main rotor shaft arranged vertically. One of the major advantage of this kind of arrangement is that the turbine need not to be necessarily pointed into the wind in order to be effective, which is a plus point on a location where the wind direction is exceedingly variable.



1.2 Efficiency of Wind mill

Not all the energy of blowing wind can be harvested, since conservation of mass requires that as much mass of air exits the turbine as enters it. Betz's law gives the maximal achievable extraction of wind power by a wind turbine as 59% of the total kinetic energy of the air flowing through the turbine. Further inefficiencies, such as rotor blade friction and drag, gearbox losses, generator and converter losses, reduce the power delivered by a wind turbine. Commercial utility-connected turbines deliver 75% to 80% of the Betz limit of power extractable from the wind, at rated operating speed. Efficiency can decrease slightly over time due to wear.

2. SOIL-STRUCTURE INTERACTION

Soil-structure interaction plays an important role in the behaviour of foundations. For structures like beams, piles, mat foundations and box cells it is very essential to consider the deformational characteristics of soil and flexural properties of foundations. It can be seen that when interaction is taken into account, the true design values arrived at may be quite different from those worked out without considering interaction. In general in most of the cases interaction causes reduction in critical design values of the shear and moments etc. However, there may be quite a few locations where the values show an increase. Because of these possibilities they have their own roles to play in economy and safety of structure

Soil Properties used for Analysis

(As Per Joseph E. Bowles foundation engineering reference)

Soil Type	Modulus of Subgrade KN/m^3	Poisson Ratio	Modulus of Elasticity(N/mm^2)
Hard soil strata	96000	0.4	96
Medium soil strata	45000	0.4	45
Soft soil strata	10500	0.4	10.5

3. MODELLING AND ANALYSIS

Tower of the wind mill is modelled with 4-noded tetrahedral elements in STAAD. All elements are connected to each other with proper boundary condition. Details of the finite element model of tower are as below:-

No. of joints = 2916, No. of plates = 2880

No. of supports = 36, Degree of freedom = 17388

Final band width = 2913, Size of stiffness matrix =

4. WIND LOAD CALCULATION

Windmills are cylindrical and high rise structures, so the normal method of load calculation cannot be used, so the load is calculated by IS-4998 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.

4.1 Calculation of Design wind pressure

Basic parameters required for the calculation of the wind pressure are :

- **Basic wind speed** - Basic wind speed is based on peak gust velocity averaged over a short time interval of about 3 seconds and corresponds to mean heights above ground level in an open terrain. It is worked out for 50 year return period. And it is for height up to 10m.
- **Design wind speed** - The basic wind speed shall be modified to include the following effects to get design wind velocity at any height for the chosen structure.
- **Risk coefficient** k_1 **-** Buildings and structures presenting a low degree of hazard to life and property in the event of failure, such as isolated towers in wooded areas, farm buildings other than residential buildings and for different wind effects k_1 factor is as given in Table 4.1.

Table 4.1 Risk *coefficient* (k_1)

Wind (m/see)	33	39	44	47	50	55
k_1 factor	0.94	0.92	0.91	0.90	0.90	0.89

- **Terrain, Height and structure** size **Factor** k_2 *-Thc* terrain category used in the design of a structure may vary depending on the direction of wind under consideration. For the analysis of windmill let's consider the category 2 structure, which is open terrain with well scattered obstructions having height generally between 1.5 to 10 m.

Table 4.2 Terrain, Height and structure size Factor k₂

Height (M)	10	20	30	40	50	60	70	84
fe_2 Factor	0.93	1.000	1.04	1.08	1.101	1.109	1.128	1.147

Topography factor k_3

The topography factor is given by the following equation

$$k_3 - 1 + c.s \qquad [4.1]$$

Where, c has the following values:

Slope (θ)	
$3° < \theta \leq 170$	1.2
>170	0.36

For windmill tower c = 1.2 and S = 0.2

$$\therefore k_3 = 1 + 1.2 \text{ x } 0.2$$

$$= 1.24$$

Design wind pressure is given by the Eq. No 4.1

$$P_z = 0.6\, V_z^2 \qquad [4.2]$$

And,

$$V_z = k_1 k_2 k_3 V_d \qquad [4.3]$$

Where,

P_z- Design wind pressure, V_z= Design wind speed

k_1 = Risk coefficient ,k_2 = Terrain, Height and structure size Factor

k_3 = Topography factor , V_d = Design wind speed

Design wind speed and design wind pressure calculated as per Eq. no. 4.2 and Eq. no.4.3 are tabulated in Table No.4.3 and Table No.4.4. As wind speed changes according to height, Windmill tower is divided in eight parts each of 10 m height, hence wind pressure is calculated per 10 meter height. Change in wind pressure according to height is shown in Fig No.4.1.

Table 4.3 Design wind speed (IS -875 Part 3)

Height (m)	Design wind speed Vz (m/s)					
	33	39	44	47	50	55
10	767.792923	1027.225	1279.23	1427.714	1615.792	1911.903
20	887.724503	1187.68	1479.05	1650.727	1868.184	2210.548
30	960.162823	1284.595	1599.74	1785.427	2020.628	2390.929
40	1035.44186	1385.31	1725.164	1925.408	2179.05	2578.384
50	1076.10053	1439.707	1792.905	2001.013	2264.615	2679.629
60	1091.7955	1460.705	1819.055	2030.198	2297.644	2718.711
70	1129.52645	1511.185	1881.919	2100.359	2377.047	2812.666
80	1155.79926	1545.947	1925.534	2149.214	2432.321	2878.169

Table 4.4 Design wind pressure (IS 875- Part 3)

Height (m)	Design wind pressure Pz=0.6*Vz*Vz					
	33	39	44	47	50	55
10	767.792923	1027.225	1279.23	1427.714	1615.792	1911.903
20	887.724503	1187.68	1479.05	1650.727	1868.184	2210.548
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60	1091.7955	1460.705	1819.055	2030.198	2297.644	2718.711
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80	1155.79926	1545.947	1925.534	2149.214	2432.321	2878.169

Wind Load by Simplified Method

The along wind-load or drag force per unit height of the windmill at any level shall be calculated from the Eq.No.4.4.

$$F_z = p_z C_D d_z \qquad [4.4]$$

p_z = design wind pressure in N/mm^2 at height z, and, z = Height of any section of the windmill in m measured from top of foundation.

C_D=drag coefficient of the windmill to be taken as 0.8 , d_z = Diameter of windmill at height z in m.

Wind load calculated by simplified method is listed in Table No. 4.5. It is observed that as wind speed increase there is increase in magnitude of wind force.

Wind load by simplified method (IS4998)

Height (m)	simplified method Fz=Pz*Cd*dz					
	33	39	44	47	50	55
10	39.925232	53.41568	66.51996	74.24113	84.0212	99.41897
20	42.6107762	57.00865	70.99438	79.23491	89.67283	106.1063
30	42.2471642	56.52217	70.38857	78.55878	88.90762	105.2009
40	41.4176744	55.4124	69.00654	77.01634	87.16199	103.1353
50	38.7396191	51.82945	64.5446	72.03648	81.52612	96.46664

60	34.937456	46.74257	58.20976	64.96634	73.52461	86.99876
70	31.6267407	42.31319	52.69374	58.81006	66.55733	78.75466
80	27.7391822	37.10272	46.2128	51.58112	58.37571	69.07605

Equivalent Static Load (Dynamic Analysis)

equivalent static load = $W = G \times C_f \times P_z \times A_{net}$						
Height	33 m/sec	39 m/sec	44 m/sec	47 m/sec	50 m/sec	55 m/sec
10	113.31	158.6165	204.6689	232.8523	268.5369	326.0485
20	75.4722067	105.4888	135.4573	155.1737	178.8435	214.6743
30	69.4289897	97.36509	125.4324	143.1027	164.8881	200.6602
40	62.6235237	87.77325	113.4468	129.3874	149.047	181.9307
50	53.1352616	74.72771	96.54581	109.6972	126.7894	154.609
60	42.7634461	60.12964	77.67511	88.56212	99.16999	124.6101
70	34.1379039	47.80544	61.74652	70.39564	81.34637	98.9001
80	13.4231234	18.85885	24.35616	27.66923	31.97093	38.99727

5. APPLICATION OF WIND LOAD

Dynamic wind loads are applied at different levels of windmill tower as joint load along positive X- direction for the analysis of windmills for the wind load in STAAD Pro 2006.Application of loads at different joints is shown in the Fig No4.3 and Fig No 4.4.

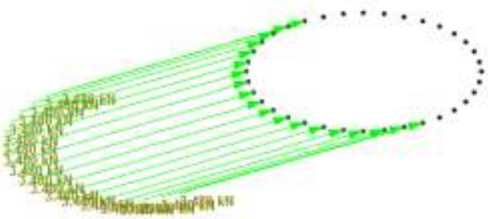


Fig.1.wind load per node in STAAD pro-2006

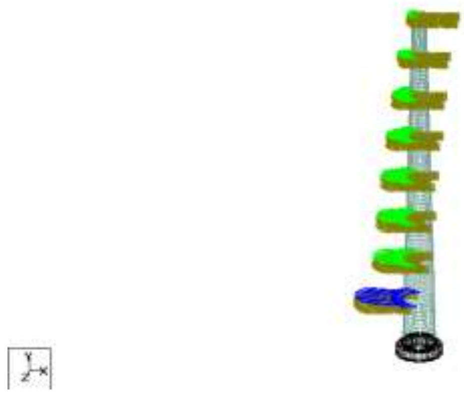


Fig. 2 Application of wind loads at various level on wind mill

6. RESULTS:

Table 6.1 Deflection varying with wind speed

wind speed (m/sec)	Deflection (mm)		
	soft soil	medium soil	Hard soil
33	107.278	106.285	106.125
39	150.429	149.038	148.814
44	194.079	192.28	191.996
47	221.16	219.114	218.784
50	253.758	251.504	251.026
55	310.865	307.998	307.537

Table 6.2 Maximum bending stresses in windmill tower due to wind analysis

wind speed ((m/sec)	maximum bending stresses (N/mm2)		
	soft soil	medium soil	hard soil
33	5.06	5.01	4.99
39	6.5	6.45	6.43
44	7.95	7.91	7.89
47	8.86	8.82	8.8
50	9.95	9.91	9.89
55	11.8	11.8	11.8

Table 6.3 Maximum shear stresses in windmill tower due to wind analysis

wind speed (m/sec)	maximum shear stresses (N/mm2)		
	soft soil	medium soil	hard soil
33	0.349	0.349	0.349
39	0.488	0.488	0.488
44	0.629	0.629	0.629
47	0.717	0.717	0.717
50	0.825	0.825	0.825
55	1	1	1

Table 6.4 Maximum vertical reactions transferred to the foundation due to wind loads

wind speed (m/sec)	soft soil	medium soil	hard soil
33	340.71	341.85	343.05
39	439.78	440.62	442.301
44	539.948	540.501	542.643
47	602.243	602.952	605.247
50	677.543	678.485	680.462
55	807.52	808.781	810.706

7. Stability of foundation

Table 7.1 Actual settlement of the foundation due to wind load analysis

wind speed (m/sec)	Actual settlement (mm)		
	soft soil	medium soil	hard soil
33	4.34	4.32	0.63
39	4.48	1.2	0.63
44	1.2	1.2	1.2
47	4.48	1.2	1.2
50	4.48	1.2	0.63
55	0.59	1.2	0.63

Table 7.2 Maximum pressure on the soil due to wind load analysis

wind speed (m/sec)	maximum pressure (KN/m2)		
	soft soil	medium soil	hard soil
33	47.05	46.94	60.73
39	46.991	53.917	60.734
44	54.127	53.917	53.917
47	46.991	53.917	53.813
50	46.991	53.917	60.734
55	62.02	53.917	60.734

Fig.(A) Bending stresses at 33m/sec in soft soil

Fig. (B)Bending stresses at 39m/sec in soft soil

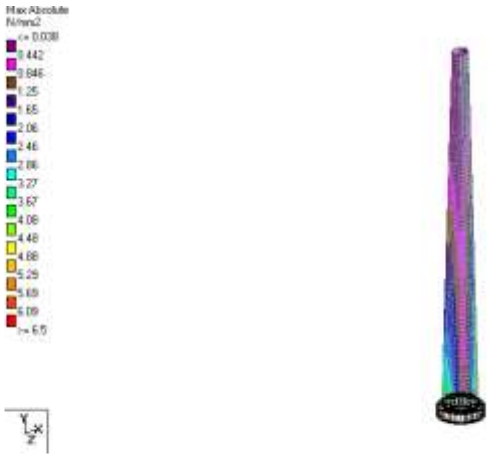
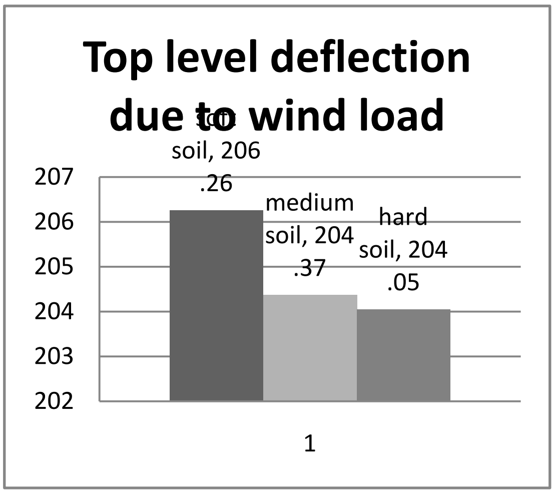


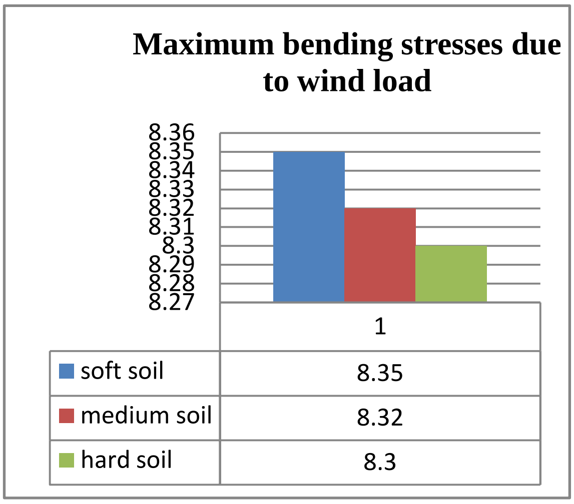
Fig. (c)Bending stresses at 44m/sec in soft soil

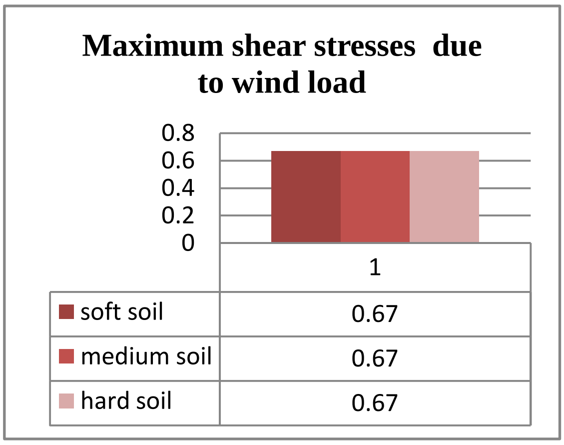
Fig. (d)Bending stresses at 50m/sec in soft soil

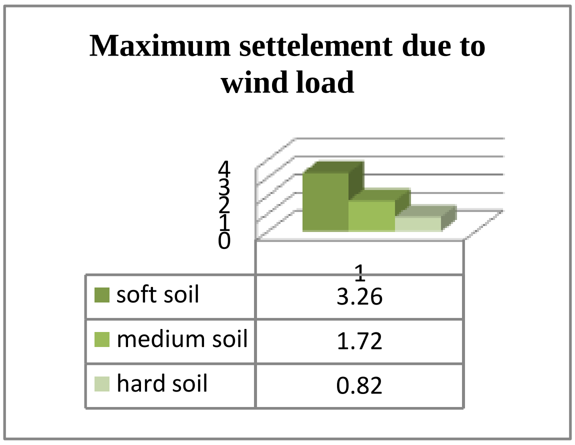
Fig. (e)Bending stresses at 55m/sec in soft soil

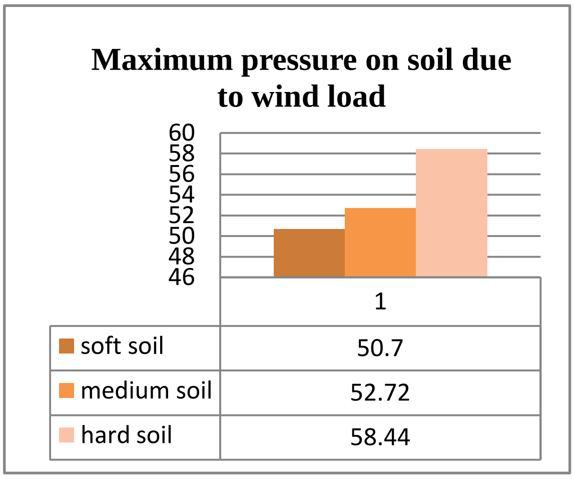
Following are the graphs based on calculation











7. CONCLUSION

- The dynamic effect of wind is significant and has to be considered in the analysis of windmills.
- When dynamic effects of wind are considered the stability of windmill has to be thoroughly checked.
- Soil-structure interaction plays an important role when windmill is founded on soft soil.

7.1 Discussion of Results

Wind analysis has been carried out for the considered windmill considering the dynamic effects. It is a general practice of design to consider only the static effect. But from the analysis it has been observed that the loads due to dynamic effects are to the extent of four times that considering only static effects. When dynamic effects are considered the permissible stresses are likely to remain within the limits, but it might create stability problems for the windmills. The foundations have to be carefully proportioned so as to avoid such failures

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