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SEISMIC PERFORMANCE ANALYSIS OF WIND TURBINE STRUCTURES UNDER DIFFERENT GROUND-SHAKING CONDITIONS

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ABSTRACT
With the rising demand for sustainable energy, there has been a rise in the deployment of large-scale wind turbines in areas of different seismic hazards. This study explores the seismic response of a 2MW wind turbine under various ground shaking conditions under the influence of soil–structure interaction effects, dynamic wind loading and different soil strata. A detailed finite element model of a 106 m tall wind turbine was created using the quadrilateral element in the tower and the foundation system. The SSI's were incorporated using equivalent spring constants for the interaction between the foundation and underlying soils. Three real site soil investigation reports were used to assess the structural response of the wind turbine for various seismic conditions and soil properties. The variation of the foundation deflection, dynamic response and the dominant frequency in different seismic intensity zones were evaluated in the analysis. The results show that wind turbine systems built on competent soils and in low seismic zones demonstrate better seismic performance. Under seismic loading, soft soil conditions, in contrast, markedly raise the vulnerability of the structures. The results suggest that SSI and site-specific soil conditions should be taken into account for seismic design of wind energy infrastructure.

KEYWORDS: Wind turbine; Seismic response; Soil–structure interaction; Response spectrum analysis; Foundation settlement; Wind loading.

1. INTRODUCTION

As the world's little supply of fossil fuels has effectively ceased production and consumption, the necessity for alternative energy sources is growing. Wind power has the most promise for meeting demand because it is both affordable and environmentally friendly, outperforming other renewable energy sources like solar, tidal, and geothermal power. [1] According to the annual wind report produced by the Global Wind Energy Council (GWEC) in 2021, the worldwide wind sector had its best year ever in 2020, with a growth rate of 53% from the previous year. The wind industry has proven to be remarkably resilient, installing over 93 GW of wind power in spite of a difficult year marked by disruptions to the global supply chain and project development. [2]

More and better wind mill technology is available, and wind energy is already one of the options for producing power. Wind turbines have been steadily getting taller in recent years in an effort to harness more energy from greater altitudes [4, 5]. Wind mill supports towers often take the form of either monopoles or lattice towers. The benefits and drawbacks of each tower style are different. Increasing the wind mill's height causes the monopole towers' wall thickness to grow, which in turn causes the cost to rise and certain parts to become uneconomical. Lattice towers are constructed at the construction site of wind turbines by riveting together different angle or box pieces. Tower members are only ever subjected to axial forces in lattice towers because the loads are resisted by the truss action of the members [6, 7]. Wind is able to travel through the open lattice members of the towers, reducing the wind loads on the structure. Increasingly wind resource data has been collected to confirm the possibility of intensified energy production as the concept of taller towers has grown increasingly popular. Raising the turbine's height makes it a dynamically sensitive, single-degree-of-freedom system. As a result, the study takes soil effects into account when analyzing the towers' dynamics [8].

The location, size, type, and height of a wind turbine are the primary factors that determine the quantity of wind energy that may be generated. Powering a few light bulbs is possible with some tiny turbines, such the ones mounted on sailboats, which can produce as low as a few hundred watts. The Vestas V90, a 3 MW utility-scale turbine, is at the opposite end of the range [8]. An engineered system's foundation is responsible for transferring the loads it supports, as well as its own weight, to the soil or rock beneath. In addition to the strains already existent in the Earth's bulk due to material self-weight and geological history, the tensions that result in soil aside from those at the surface are considerable.

A windmill's base can be square, rectangular, or otherwise configured similarly. When it comes to strength and longevity, windmill foundations are subject to extremely rigorous Seismic response standards. The strength of the concrete's reinforcing structure is also affected by this unequal loading. Reinforcing bars or steel mesh are the typical components of windmill foundation reinforcement structures.

2. SOIL-STRUCTURE INTERACTION

It is two-way interaction between a structure and foundation built upon it. When a structure's loads and movements impact the soil around it, and the soil reacts by impacting the structure, this phenomenon is called soil-structure interaction. The foundation's behavior is significantly influenced by the soil-structure interaction. The factors to be considered for analyzing the windmill with SSI effect is soil category, size of footing, elastic spring constants, Modulus of sub-grade reaction. The circular raft type foundation is considered for windmill analysis of different soil strata. The diameter of raft provided for High-Strength soil profile, semi-competent soil layer & weak soil strata is 8 m, 10m & 12m respectively with raft thickness 1m.

2.1 Coefficient of Sub-grade reaction

One common tool for structural study of foundation members is the modulus of subgrade reaction, which is a link between soil pressure and deflection. It has a wide range of applications, including continuous footings, mats, and pilings. Equation 1 of the seismic response gives the modulus of the sub-grade reaction.

$$K_S = \frac{q}{\delta} \qquad [1]$$

Where, q - Soil pressure, K_s - coefficient of sub-grade reaction, and δ - Deflection. The soil profile characteristics that are used for the analysis are given below in the table 1 which is taken from 3 different ground analysis reports of In-situ soil samples.

Table 1 Soil profile characteristics

Soil Category	Unit Weight of Soil (KN/m2)	Integrity Factor	Allowable Bearing Pressure (KN/m2)	Poisson Ratio (μ)	Coefficient of Sub-grade (KN/m^3)	Coefficient of Elasticity (KN/m^3)
competent soil layer	19	3	580	0.3	102353	43200
Semi-competent soil layer	18	3	436	0.3	68842	12500
weak soil layer	15	3	190	0.3	25909	4200

3. STRUCTURAL SYSTEM DEVELOPMENT

Data collected of in-situ 2 MW windmills steel tubular structure with cylindrical form, having a diameter (D) of 4.3 m and high (L) of 106 m, are designed. The thickness of steel tower is 16 mm. the steel type is mild steel is used. Each element of windmill system foundation & windmill tower is modeled using finite element technique as a Quadrilateral Meshing in STAAD Pro V8i 2024 software. Proper boundary conditions connect all elements to each other. With 8319 joints, 2880 plates, 36 supports, and 49680 degrees of freedom, the tower's finite element model is detailed as follows.

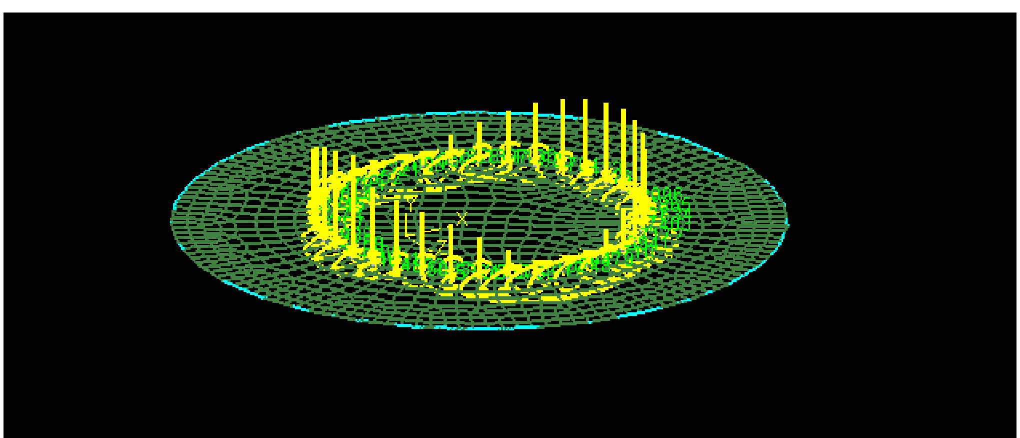

Fig. 1 Software Modeling of windmill Foundation by Software

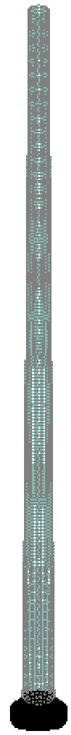

Fig. 2 Software Modeling of windmill Tower by software

4. WINDMILL TOWER SHY OF WIND LOAD

Atmospheric pressure and temperature gradients work together to generate wind. Nevertheless, wind speeds at any altitude are never static, and it is more practical to divide their instantaneous magnitude into a mean value and a fluctuating component around this mean time. The averaging time used to analyze the weather data determines the average value, which might range from a few seconds to a few minutes.

Taking dynamic response into account, this study analyses wind turbines for wind load at 33 m/sec, 39 m/sec, 44 m/sec, 47 m/sec, 50 m/sec, and 55 m/sec. There are three different kinds of support conditions that are analyzed: fixed-based, semi-fixed-based, and flexible-based. In this chapter, we also compare the findings of the analyses about the significant response quantities. We use the IS-875 (Part-3):2015 approach to calculate the fundamental wind pressure and wind load.

Equation (2) of the seismic response provides the peak along the wind base bending moment for the design.

$$F_z = C_{f,z} * A_z * \bar{p}_d * G \qquad [2]$$

Where,

A_z = effective frontal area of the structure at any height z, (m^2)

F_z = design peak along wind load on the structure at any height z

G = Gust Factor

$C_{f,z}$ = the drag coefficient of the structure corresponding to the area A_z

$\bar{p}_d$ = design hourly mean wind pressure corresponding to $\bar{V}_{z,d}$ & obtained as 0.6 $\bar{V}^2_{z,d}$

$\bar{V}_{z,d}$ = Design hourly mean wind speed at height z, in m/s

From above design peak along wind load on each element structure (Nodal load) is obtained and tabulated in table 2

Table 2 Design peak along wind load on each element the structure (Nodal load)

Height (m)	$F_z = C_{f,z} * A_z * \bar{p}_d * G$					
	33	39	44	47	50	55
10	0.62	0.82	1.12	1.38	1.76	2.36
20	1.09	0.58	0.64	0.76	0.85	1.09
30	1.25	1.74	1.84	1.43	1.32	1.04
40	0.48	0.75	0.97	1.10	1.21	1.21
50	0.48	0.75	0.97	1.11	1.26	1.48

60	0.19	0.28	0.36	0.41	0.48	0.58
70	0.19	0.27	0.36	0.41	0.47	0.58
80	0.19	0.27	0.35	0.40	0.46	0.56
90	0.19	0.27	0.35	0.40	0.46	0.56
100	0.15	0.21	0.27	0.31	0.36	0.44
106	0	0	0	0	0	0

5. WINDMILL STRUCTURE SHY OF SEISMIC LOAD

Predicting seismic excitation is a challenging task. Proper design and construction are thus the sole means of protecting structures in Seismic excitation areas from seismic loads. To achieve this goal, one must have a thorough comprehension of seismic activity, its dynamic effects, and the response of associated structures. The level of danger is directly impacted by the structural resistance, seismic response, and the dynamic reaction of a structure to seismic excitation vibration. It is important to learn about structural features and seismic excitation in order to conduct an analysis for seismic excitation loads. Response spectrum approach is used for the dynamic examination of structures.

5.1 Response Spectrum Methodology

An example of this approach would be to apply a succession of SDOF systems to a particular ground motion and then graphically display the peak response, which could be displacement, velocity, or acceleration. Using the structure's inherent frequency and seismic response frequencies, this methodology reveals the structure's response to seismic excitation.

5.1.1 Lumped Mass

It is the portion of the structure's weight that is considered to be effective in generating seismic forces during Seismic excitation. It is a full dead load plus weight of rotor plus weight of Nacelle plus Weight of blades. W = Dead Load + Weight of rotor + Weight of Nacelle + Weight of Blades = 4282.7 KN

5.1.2 Equivalent lateral force at base (V_B)

The entire horizontal force acting on a structure's base during seismic excitation is known as the design equivalent lateral force at base, and it happens as a result of the seismic load delivered to the structure. The foundation of a building can resist and endure the maximum lateral force that can be anticipated as a result of seismic ground motion. Seismic response equation no. 3 is to be used to determine the equivalent lateral force at the base of the structure in any of its primary directions.

$$VB = Ah * W \quad [3]$$

Where, A_h - Design Horizontal Seismic coefficient, W - Lumped mass.

5.1.3 Principal vibration Period (T_a)

The Principal vibration period of windmill structure is calculated by following Seismic response Eqn. No.4

$$T_a = \frac{0.09h}{\sqrt{d}} \quad [4]$$

While h is the structure's height from the foundation in meters, which is 108.5, and d is the building's base dimension at plinth level along the seismic response direction, which is 4.3. The basic translational natural period of oscillations, expressed mathematically, is around 4.71 seconds in seconds.

5.1.4 Design Horizontal Seismic coefficient (A_h)

The design horizontal seismic coefficient of windmill structure is evaluated from following Seismic response Eqn. No.5

$$A_h = \frac{\left(\frac{Z}{2}\right)\left(\frac{Sa}{g}\right)}{\left(\frac{R}{I}\right)} \quad [5]$$

Where, Z is the Seismic Provinces Factor (As per IS 1893 (part 1):2016), I is the Importance Factor for critical and lifeline structure (1.5), R is the Response Reduction Factor (Steel Building with SMRF = 5), $\frac{Sa}{g}$ is the Design Acceleration Coefficient for different soil categories. The values of all terminologies are taken from IS 1893 (part 1):2016.

5.1.5 Ground Shaking Conditions

The Ground Shaking Conditions describe how the ground behaves and forces acts during Seismic excitation. The different seismic condition refers to the varying level of seismic Provinces, types of seismic waves, ground motion conditions, soil and site conditions. The research work is done only on two seismic conditions. Firstly, seismic Provinces (II-low intensity zone, III-Moderate intensity Zone, III-Severe intensity zone, IV-Very severe intensity zone) and secondly with different soil strata (Soft, Medium and Hard) are considered for analysis. The different seismic Provinces are considered as per IS 1893 (part 1):2016 and soil strata is taken from actual site soil testing report and the soil profile characteristics are given in table 1.

5.1.6 Loading Conditions

The windmill is generally put through to seismic weight and foundation load. In that the seismic weight is the most considering factor for transform behavior of windmill structure. The loads applied to the windmill structure are estimated according to the methodology of IS 1893 (part 1):2016 and IS 456:2000.

5.1.7 Load Combinations

- Service Load Combinations

1.0 x DL
0.9 x DL ± 1.5 x ELX
1.0 x DL + 1.0 x WLX/ELX
1.0 x DL ± 1.0 x WLX/ELX
1.0 x DL + 0.8 x WLX/ELX
1.0 x DL ± 0.8 x WLX/ELX
0.9 x DL + 1.0 x WLX/ELX
0.9 x DL ± 1.0 x WLX/ELX

- Ultimate Load Combinations

1.5 x DL
1.5 x DL + 1.5 x WLX/ELX
1.5 x DL ± 1.5 x WLX/ELX
1.2 x DL + 1.2 x WLX/ELX
1.2 x DL ± 1.2 x WLX/ELX
1.2 x DL ± 1.2 x WLX/ELX
1.2 x DL + 1.2 x WLX/ELX
1.5 x DL ± 1.5 x WLX/ELX
1.2 x DL + 1.2 x WLX/ELX
1.5 x DL ± 1.5 x WLX/ELX
1.5 x DL + 1.5 x WLX/ELX

6. RESULTS AND DISSCUSSION

- **Maximum Response Amplitude**

The response of the windmill changes according to the height from ground level. From response amplitude of all the Seismic excitations it is concluded that as intensity of Seismic excitation intensifies, deflection response of the windmill also intensifies and it is maximal at the top level in each case. The strongest reaction is seen when the soil basis is weak. The maximum reaction amplitude occurs naturally when soil softens because the earth's rigidity gradually decreases.

Table 3 Maximum Response Amplitude in windmill Tower due to Seismic Response Load

Seismic Provinces	**Response Amplitude (mm)**		
	Weak soil	**Semi-competent soil**	**Competent soil**
zone II (0.10)	95.851	89.406	79.665
zone III (0.16)	152.930	135.642	125.187
zone IV (0.24)	229.395	204.356	182.087
zone V (0.36)	344.093	306.534	273.131

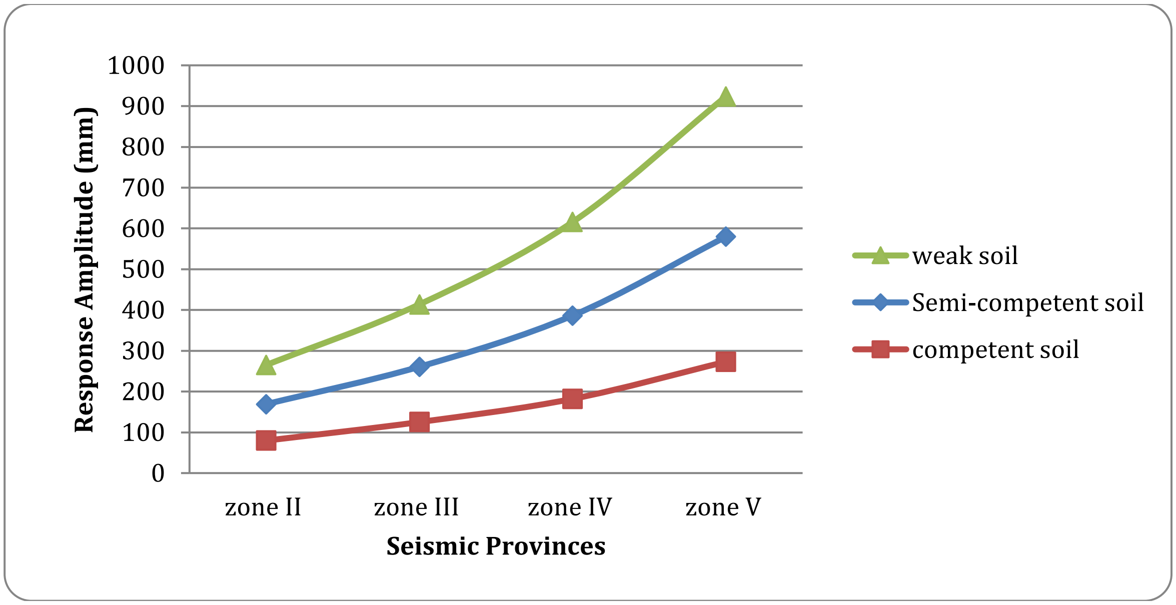

Fig. 3 Maximum Response Amplitude in windmill Tower due to Seismic Response Load

- **Stability of the Foundation**

Soil stability is essential for foundation stability because it determines whether or not an engineered structure can be built on top of the soil without experiencing shear and with settlements that are acceptable for that building. Building frames are susceptible to structural deterioration and excessive wear and settlements when they settle too much. Equivalent lateral force at base resistance and settlements must be investigated for every building. For comparison purposes ratio of equivalent lateral force at base of the model with respect to that of fixed based model is termed as normalized equivalent lateral force at base. It simply represents the amplification of equivalent lateral force at base due to change in support conditions. The Table 3 represents equivalent lateral force at base values for all four base condition & four Seismic excitation zones.

Table 4 Maximum Equivalent lateral force at base of windmill Tower due to Seismic Response Load

Seismic Provinces	Weak soil	Semi-competent soil	Competent soil
zone II (0.10)	22.91	22.14	20.7
zone III (0.16)	36.66	32.41	32.53
zone IV (0.24)	54.99	50.60	47.32
zone V (0.36)	82.49	75.89	70.98

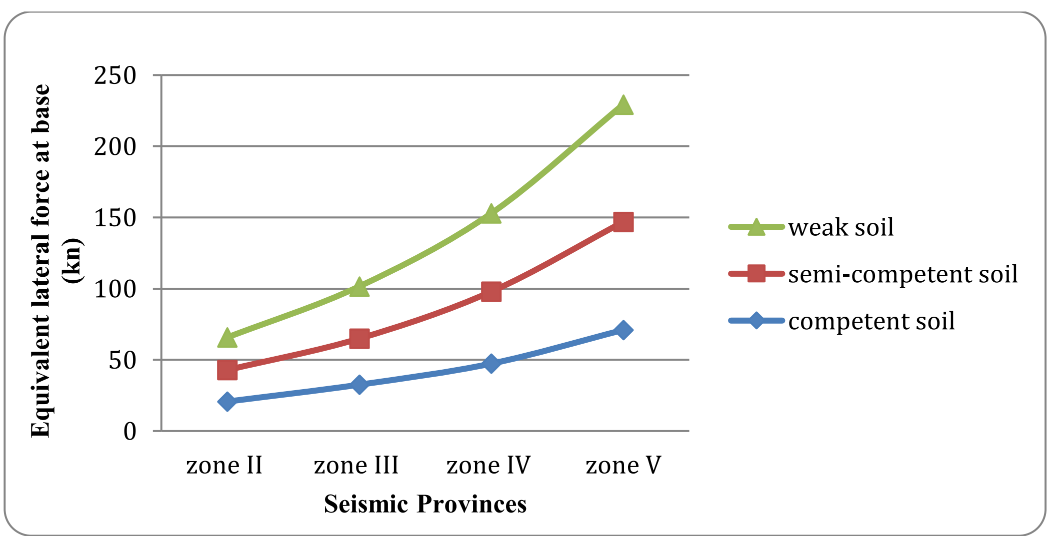

Fig. 4 Equivalent lateral force at base of windmill Tower due to Seismic Response Load

- **Integrity of Windmill Tower**

For the Integrity of tower, bending and Peak shearing stresses by the analysis should not exceed the permissible values. It is observed from the analysis that bending stresses are highest at the bottom level plates of the tower. The permissible bending stress in tension and compression=σ_{bt} = σ_{bc} = 0.66f_y, where f_y is the yield stress of steel. For steel of yield strength 250 N/mm^2, σ_{bt} = 0.66 x 250 = 165 N/mm^2. Also the permissible Peak shearing stress in steel member is 0.40 f_y =σ_s = 0.4 x 250 = *100* N/mm^2. From Table 4 & Table 5 it is observed that no bending and Peak shearing stress is exceeding the permissible stress hence windmill tower is safe in bending and shear.

Table 5 Greatest Flexural stresses in windmill tower due to Seismic Response Load

Seismic Provinces	Weak soil	Semi-competent soil	Competent soil
zone II (0.1)	7.86	7.45	6.71
zone III (0.16)	12.6	6.05	10.5
zone IV (0.24)	18.9	17	15.3
zone V (0.36)	28.3	25.5	23

Table 6 Peak Shearing stresses in windmill tower due to Seismic Response Load

Seismic Provinces	Weak soil	Semi-competent soil	Competent soil
zone II (0.1)	3.89	3.69	3.32
zone III (0.16)	6.24	2.98	5.22
zone IV (0.24)	9.35	8.44	7.6
zone V (0.36)	14	12.7	11.4

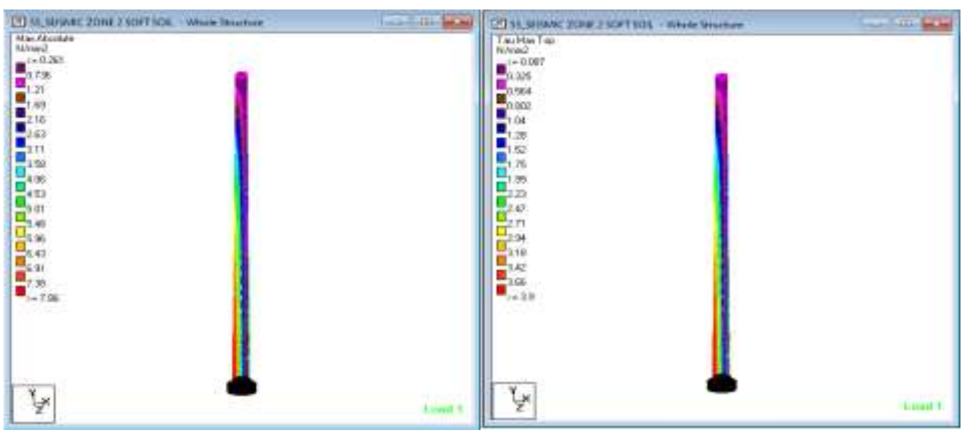

Fig. 5 Greatest Flexural stress & Peak shearing stress in windmill tower for zone II (0.1) in Soft soil

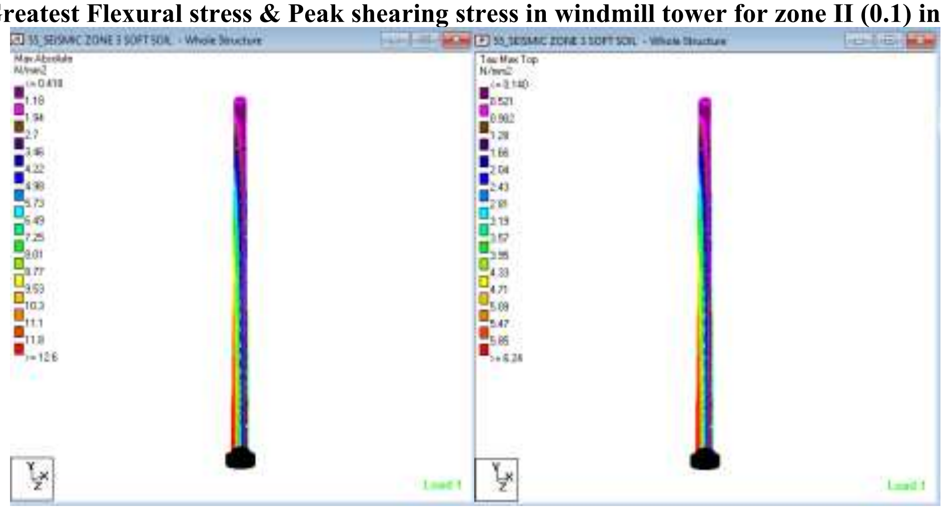

Fig. 6 Greatest Flexural stress & Peak shearing stress in windmill tower for zone III (0.16) in Soft soil

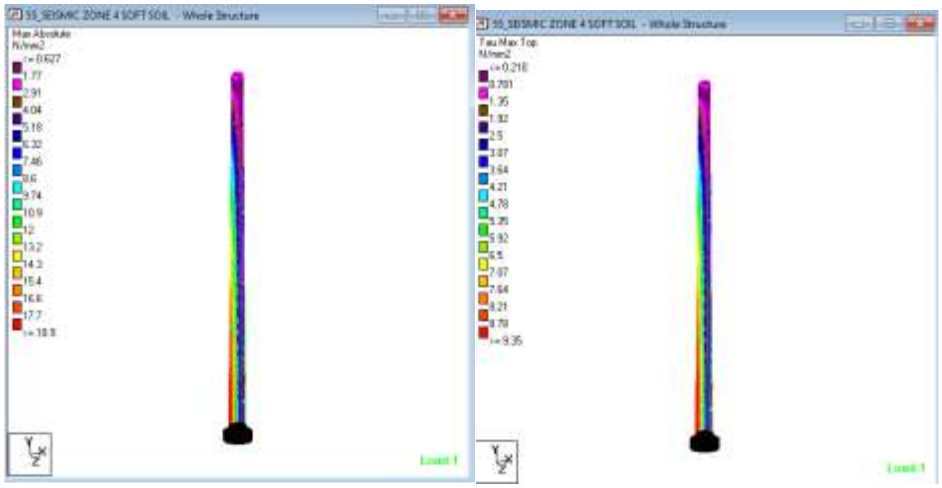

Fig. 7 Greatest Flexural stress & Peak shearing stress in windmill tower for zone IV (0.24) in Soft soil

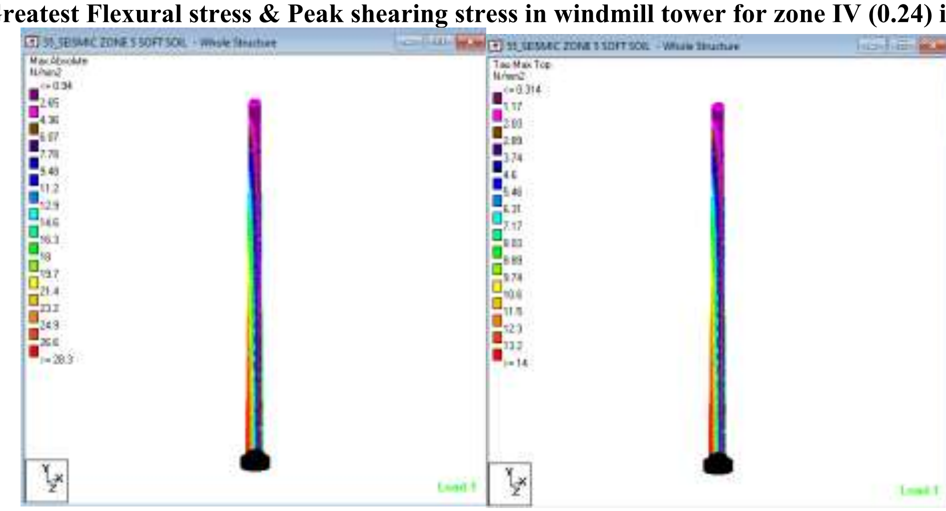

Fig. 8 Greatest Flexural stress & Peak shearing stress in windmill tower for zone V (0.36) in Soft soil

- **Settlements in the foundation**

Actual settlements for different type of support condition and for selected Seismic excitations are listed in Table No 6. The IS-1904 gives the tolerable settlement 75 mm for sand and hard clay strata, 100 mm for plastic clay strata having raft foundation. From Table results it is observed that no settlement values in any case exceeds the Permissible settlement hence this system of windmill tower and foundation is safe in settlement criteria. It is also observe that settlement of the windmill system intensifies as soil becomes softer. And for high intensity Seismic excitations settlement of the windmill system is high in magnitude.

Table 7 Actual settlement of the foundation due to Seismic excitation load

Seismic Provinces	**Actual settlement (mm)**		
	Weak soil	**Semi-competent soil**	**Competent soil**
zone II (0.10)	1.80	0.68	0.45
zone III(0.16)	2.33	0.62	0.57
zone IV (0.24)	3.03	1.11	0.72
zone V(0.36)	4.08	1.49	0.96

- **Bearing strength of foundation**

Foundation must be designed for pressure intensity much smaller than the ultimate bearing capacity to provide a suitable factor of Integrity (F_s). Let us assume safe bearing capacity, factor of Integrity & soil profile characteristics for different soil strata given in table 1. Maximum pressure on the soil from foundation is listed in table 7.

Table 8 Maximum pressure on the soil due to Seismic excitation load

Seismic Provinces	Maximum pressure (KN/m2)		
	Weak soil	Semi-competent soil	Competent soil
zone II (0.1)	49.823	50.087	48.718
zone III (0.16)	64.369	45.739	62.031
zone IV (0.24)	83.733	81.816	78.671
zone V (0.36)	112.780	110.013	105.295

From Table 7 it is observed that actual pressure on the soil is less than the safe bearing capacity of the soil, or foundation on hard, medium and weak soil strata. Hence this system of windmill tower and foundation is safe in bearing strength of foundation for all four seismic conditions.

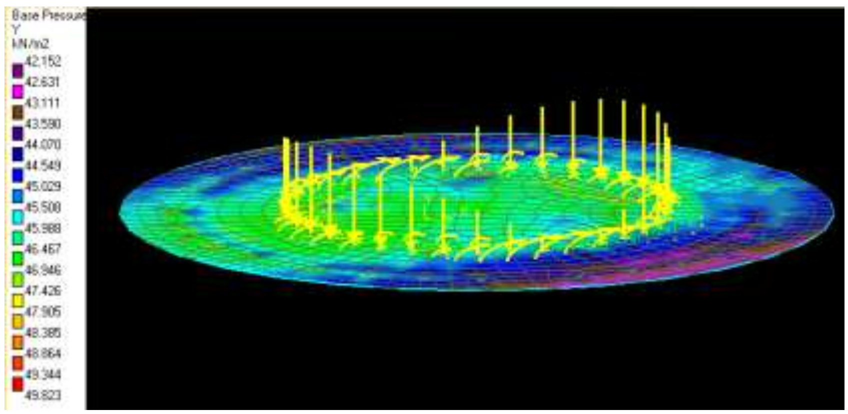

Fig. 9 Maximum pressure at zone II in soft soil

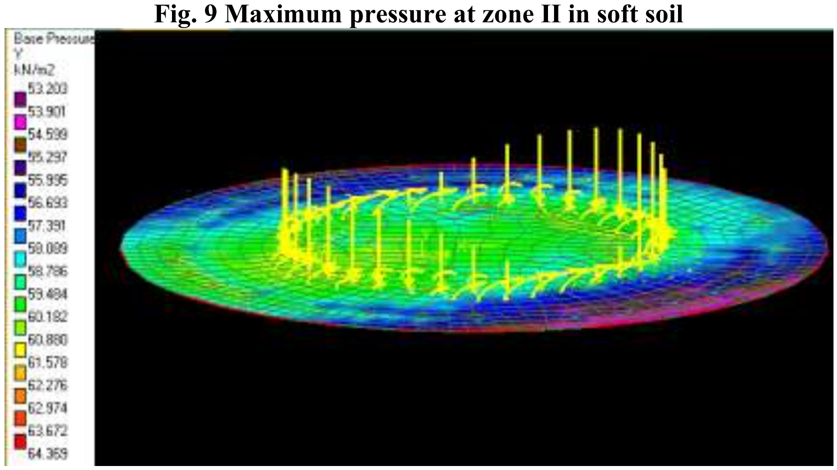

Fig. 10 Maximum pressure at zone III in soft soil

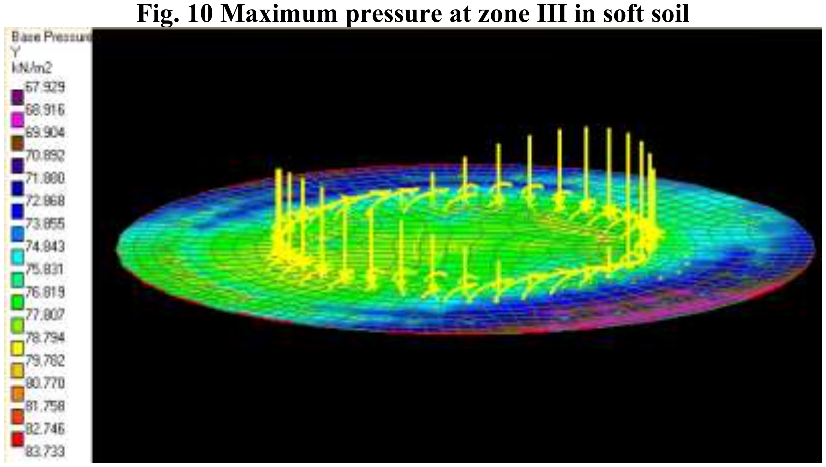

Fig. 11 Maximum pressure at zone IV in soft soil

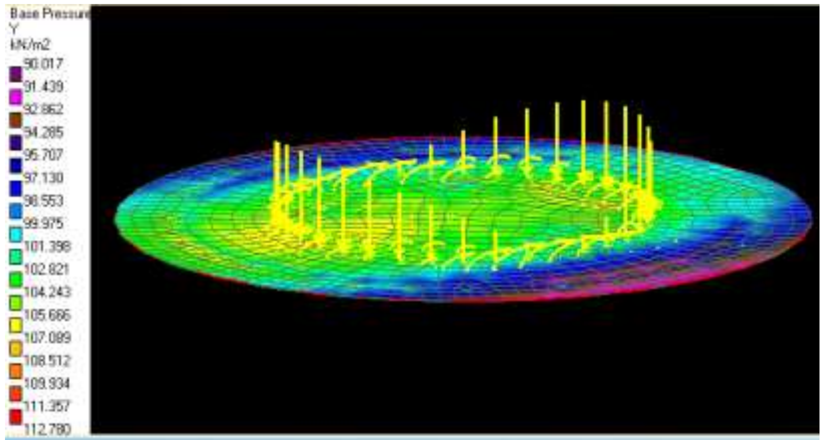

Fig. 12 Maximum pressure at zone V in soft soil

CONCLUSION

The analysis of windmill structure under four considered Seismic excitations, response of the windmills for different Seismic excitations are different and are particular about the selected Seismic excitations hence cannot generalize for all ground conditions. Geotechnical aspects of the ground are one more matter of concern. As soil particles are not same at all the heights but it is considered same for the analysis and there are lots of variation in soils but in this paper only three types of soils are considered for the analysis. Hence we cannot generalize the analysis results to all type of soils and all type of Seismic conditions. The analysis of structure for two different Ground Shaking Conditions is safe under all criteria given by IS code provision for dynamic Seismic excitation loading. But if the Seismic excitations are occurring in the areas of higher seismic intensity have low dominant frequencies Seismic response frequencies and higher deflection they are likely to cause substantial damage to the windmill on soft soils systems. Therefore the structure also has to be investigated for all other Ground Shaking Conditions like faulting, seismic waves and ground motions. Further from analysis results it has been observed that foundation system is likely to have stability problems during Seismic excitations, since the bearing capacity of soil is exceeded in the case of very severe intensity zone on weak soil strata. Soil-structure interaction plays an important role when windmill is founded on soft soil. From seismic analysis result it can be concluded that the most suitable windmill structures are those who is with low seismic intensity & lesser deflection of foundation other than soft soils.

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