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Research paper

Effect of Cyclonic Load Factor on Monopole Towers

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Abstract

Considering the amount of tropical cyclonic related damages are disproportional to the return period in Indian coastal areas. For better safety of structures, the IS code875 (Part3)2015 presents the cyclonic importance factor (k_4 factor) according to the importance level of structure with a maximum value of 1.30 for post cyclonic importance structures category. This factor is recommended in static and dynamic analysis of wind load computations. This is the additional wind speed multiplication factor besides the offshore wind velocity multiplication factor of 1.15 that has been retained in the revised wind code 2015 version for coastal areas up to 200 Km. Monopole towers, which are vulnerable to cyclonic wind speeds, are ideal for use when zoning is difficult in urban areas. The towers with heights 30, 40 and 50m are modelled in STAAD.Pro (V8i) software to evaluate the k4 factor in static and dynamic analysis. The results suggested that when the design wind speed is increased by 30% (1.30) for k_4 factor in dynamic analysis contribute the more along wind internal stresses in comparison with static and offshore static analyses. The maximum internal stresses variations are observed in offshore dynamic conditions where k_4 factor of 1.30 in association with offshore wind velocity factor of 1.15 is considered. The effectiveness of these factors are reviewed with the cyclonic Gust factor values (Gc).

Keywords *IS 875 (Part-3): 2015, k_4 factor, Monopole tower, STAAD.Pro (V8i) software, Tropical cyclone.*

1. Introduction

The tropical cyclones are one of the dangerous natural disasters in India, with an uncertainty of high gale speeds and disproportional to the mean return period rendering huge property loss during the last decade. Many coastal cities along the east coastal regions are well experiencing high intensity cyclonic damages (Phailin, Hud, Wardh)[1,2,3]. Recognising these facts the IS code 875(part3) 2015 presents the cyclonic importance factor according to the importance of the structure [4].
During the last 10 years, we have seen an enormous expansion in the population of towers and masts due to the phenomenal growth in the television coverage and mobile phone networks [5] Telecommunication towers are broadly classified as free standing towers and guyed towers. The free standing /self-supporting towers are again classified as lattice towers and monopole towers. The monopole towers are ideal for use when zoning is difficult in the metropolitan city areas because these require lesser area when compared to lattice towers. In the history, the failure of towers and masts are high when compare to other structures of same economics social importance [5]
The hurricane investigations from the past history have repeatedly reported that wind and wind driven rain have been the cause of extensive damage to building components, their premises [6]. By observing the wind speed and the damage to buildings, the speed given in the basic wind speed map is often exceeded during the cyclones IS 875 (Part3): 2015[4]. To ensure better safety and performance of the structures in the cyclonic region, the IS 875 (Part3): 2015[4] introduced the k_4 factor (cyclonic Importance factor) for enhancing the design wind speed calculations for both static and dynamic wind load calculations. For Post cyclone importance structures the k_4 factor has a maximum value of 1.30. Besides the k_4 factor, the code has already recommended the offshore wind velocity factor of 1.15 as a wind speed multiplication factor for a distance of up to 200 km from the nearest coast.
In this paper, the impact of k_4 factor for post cyclonic importance structures category and offshore wind velocity factor on 30, 40 and 50m height monopole towers are analyzed in STAAD.pro (v8i) software [7] to find the variation of top displacements & tilt and internal forces such as shear forces & bending moments, for both static and dynamic analysis in accordance with IS 875 (Part3): 2015[4] code provisions. The results are tabulated in comparison with the IS 875-1987 version. The variation in the design wind pressure along with the height of the tower and Gust Factor variation are presented. The effectiveness of k_4 and offshore wind velocity factors in terms of Cyclonic Gust factors (G_C) are appraised.

2. Related Literatures

2.1 Cyclones on East Coast of India & Basic Wind Speed

Santhosh Kumar et al [6] reported that the extreme tropical cyclones were being dominated on the east coast and less frequent ones on the west coast of India. During the past couple of decades, there seems to have increased the incidence of cyclones. [1-3]
The design wind speeds for 70 meteorological centers of India for a return period of 50 years have been evaluated based on the Long-term data on hourly wind speed, it was concluded that for

the revision of the wind zone map is suggested except in coastal areas [8].

2.2 Cyclonic Importance Factor: Various Suggestions and Effects

Santhosh Kumar et al [6, 9] outlined the historical development of introduction to Cyclonic importance factors (k_4 factor) in India. The impact of a k_4 factor on A-type and Lean- to roof trusses for static analysis was examined. It was concluded that there was a substantial increase of internal forces when the k_4 factor was 1.30 only.

2.3. Towers

Pavan Kumar et.al [10] studied the structural behaviour of monopole and self-support telecommunication towers and concluded that preference of monopoles is suggested for a height of 40m.
Celio F. Carril Jr. et al [11] investigated on the wind incidence angle, the tower solidity, the shielding effect, and the influence of drag coefficient on the tower were analysed. Due to light weight of these structures, wind forces are the primary concern in the design. A lattice tower was designed based on existing towers with different bracing systems and was analysed with wind incidence angle of 0 degree, 45 degree and 90 degree. The obtained results showed that the interference factor does not depend much on the number of antennas, but for higher solidity, the designer should use the interference factor.
Balagopal et.al [12] The full scale experimental investigation is carried out to determine the deflection of different types of steel poles 8 &30 m height lighting masts and 132 and 400KV transmission poles and an analytical investigation has been carried out using FEM NE- Nastram software to find the natural frequency and deflection and concluded that the secondary effects are to be taken for steel transmission poles only

2.4. Dynamic Analysis (Gust Factor Method)

The wind force is essentially dynamic in nature, even though it is treated as a steady-state force for simplicity in the analysis and design of wind-sensitive structures such as free-standing lattice towers, tall buildings etc. The design forces obtained from the dynamic method analysis also represent the same trend as obtained from the Gust factor method (Richard Butt) [13]
The dynamic response becomes important when the natural frequency of towers in the first mode is below 1.00 Hz or the height of lateral dimension is more than 5.
For calculating the buffeting/ along wind load effect of the flexible/ tall structures, the design hourly wind velocity is multiplied by the Gust factor (G). This factor consists peak factor for upwind velocity fluctuation (background factor of approaching wind) (g_v) and peak factor for resonance (g_R) of the structure. These factors are introduced in IS 875 (Part3): 2015 only. But a single peak factor (g_f) provision was presented in IS 875 (Part-3): 1987[14].
Failure analysis of lattice towers for cyclonic wind speeds with gust loading factor method suggested that the conservation in design using G (Gust factor) may not be guaranteed in cyclonic region because of possible deviation in the parameters used in the design code IS 875 (Part-3): 1987, instead suggested the (Gc) cyclonic gust factor [15].
A conclusion made after the full-scale field experiment of lattice tower to study the wind, terrain and structural characteristics under normal and cyclone wind speed conditions suggested that these factors showed the significant variation during tropical cyclone wind periods [16].
Holmes [17-19] derived the different GRF (gust response factors) for top deflection, bending moment and shear forces by considering the corresponding influence coefficients in closed form solution.
Since wind and the structure interaction is complicated not only by the lack of the streamlined structural geometry and complex flow around them but by the complexity and uncertainty of the flow in the atmospheric boundary layer suggested the probabilistic point of view of the effect of the wind on structures [20]. The gust response factor computed by the standard codes of practice was found to be 25% higher than the values obtained by the spectral method [21]. All major international codes adopted the (GLF/GRF) gust loading factor/gust response factor approach for estimating the maximum wind load effects in the along wind direction for dynamic analysis of structures. However, each employs unique definitions of wind field characteristics, including the mean wind – velocity profile, turbulence intensity profile, and turbulence length scale and wind spectrum. These slight differences in the wind characteristics have resulted in discrepancies not only in GLF estimates but also in the mean wind load, which correspondingly lead to significant variation in the estimate of the wind-induced load effects [22].

2.5. Research Objectives

2.5.1. Static Analysis

Even so the revised IS 875 (Part3): 2015 [4] defined the same basic wind speed of IS 875 (Part-3): 1987 [14], for better safety of structures, the design wind speed in the cyclonic region is modified by the wind speed multiplication factor as a k_4 factor/cyclonic importance factor. For industrial structures, the k4 factor is 1.15 and for structures of post cyclonic importance category, the maximum value is 1.30.

2.5.2. Dynamic Analysis

In the dynamic analysis, despite IS 875 (Part3): 2015 [4] code specified the different gust factors for background and resonance conditions cannot guarantee the safety design of the towers in cyclonic prone areas. The code preferred the k_4 factor as an extra margin of safety against the unprecedented high cyclonic wind speeds. The code also specified the offshore wind velocity factor besides the k_4 factor to compute the wind speed calculation in the cyclone-prone region.
From the Tables 5 to 7 the fundamental frequencies of the towers are varying from 2.650 to 0.72 Hz, and even if some of the frequencies are more than 1Hz, the towers needed to be considered as dynamically sensitive in the code provisions IS 875(part3): 2015 [4]& IS 800: 2007 [23] since their aspect ratio is more than 5. Moreover, AS 3995-1994 [24] favored to adopt the static and dynamic methods for the towers whose first mode of natural frequency is more than 1 Hz Thus, this paper adopted both static and dynamic analysis of the tower.
From the above literature, it is found that, for static and dynamic analysis, the basic wind speed in the cyclonic prone region cannot exceed 50 m /s. However, there had been no studies found pertaining to the effect of incorporation of a k_4 factor and offshore wind velocity factor for the design of monopole tower structures in coastal areas. Hence, this paper examines the impact of the k_4 factor and offshore wind velocity factor for monopole towers of 30,40and 50 m heights in the cyclonic prone area.

3. Methods

3.1 Geometry of Monopole

At the first instance the slip joint tapered steel pipe is selected for designing the 30 height monopole telecommunication tower, the geometric properties are depicted in the fig 1 and table 1. Analyses have been carried out to compare the tubular sections and pipe sections for the 30 m height monopole, the steel tubular section rendered the better safety against the pipe sections, hence the tubular sections are considered for the 40and 50 m height towers. The sectional properties are shown in tables 2 to 4 and fig 2 to 4.The material properties are adopted from IS 800-2007[23] and IS 1161 -1998[24]. Tapered circular tubular sections of monopole tower models for three heights were modeled for STAAD Pro (V8I) software.

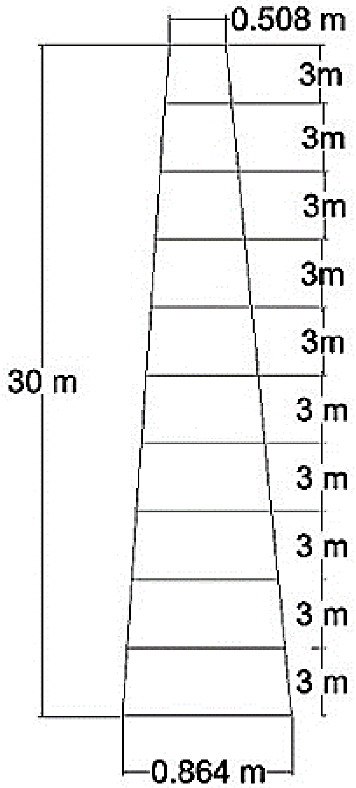

Fig. 1: 30m pipe monopole

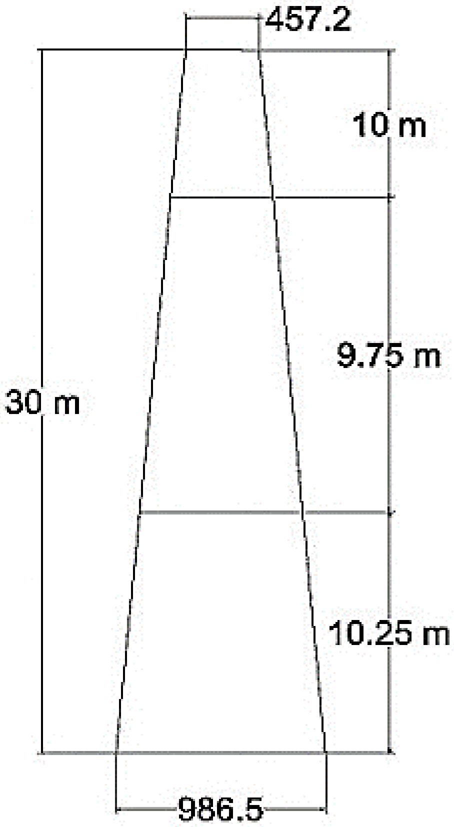

Fig. 2: 30m tube monopole

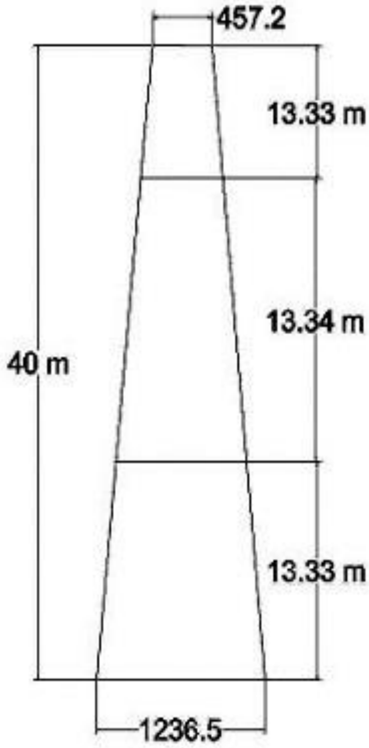

Fig. 3: 40m tube monopole with basic wind speed = 50m/sec.

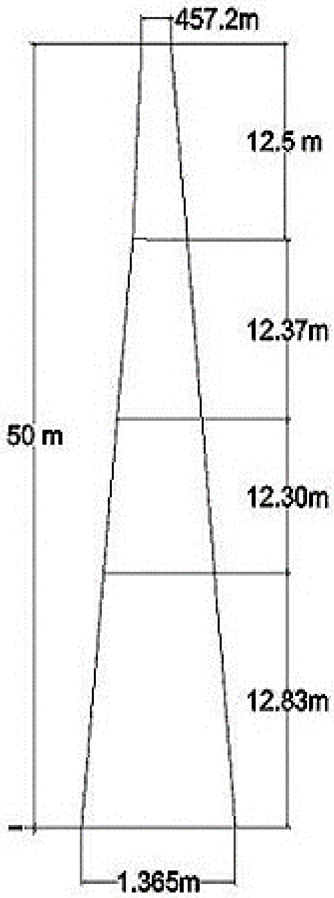

Fig. 4: 50m tube monopole

Table 1: Sectional properties of 30m height monopole

Number of panel	Panel height(m)	Elevation height(m)	Main leg (mm)	thickness(mm)
10	3	30	508	6
9	3	27	508	6
8	3	24	559	8
7	3	21	559	8
6	3	18	660	8
5	3	15	660	8
4	3	12	711	8
3	3	9	762	8
2	3	6	813	8
1	3	3	864	8

Table 2: Sectional properties of 30m height tube monopole

Elevation above base	Top dia(mm)	Bottom dia(mm)	Thickness (mm)
30	457.2	711.2	6
20	570.4	845.3	8.75
1.025	693.9	986.5	11.5

Table 3: Sectional properties of 40m height tube monopole

Elevation above base	Top dia(mm)	Bottom dia(mm)	Thickness (mm)
40	457.2	795.87	7
26.67	650.33	1018.93	9.75
13.33	859.34	1236.5	12.5

Table 4: Sectional properties of 50m height tube monopole

Elevation above base	Top dia(mm)	Bottom dia(mm)	Thickness (mm)
50	457.2	774.7	6
37.5	628.62	973.32	9.5
25.13	814.62	1165.13	12
12.83	993.81	1365.4	14.5

Table 5: Rayleigh frequencies for 30m tube monopole

Rayleigh frequency	IS 875:1987	IS 875:2015	IS 875:2015	IS 875:2015
		(K4=1)	(K4=1.15)	(K4=1.30)
static	1.6200	1.5500	1.3800	1.1400
off shore static	1.3600	1.3000	1.1600	1.0100
dynamic	1.2300	1.1500	1.0300	0.8300
offshore dynamic	1.0120	0.9700	0.8600	0.7200

Table 6: Rayleigh frequencies for 40m tube monopole

Rayleigh frequency	IS 875:1987	IS 875:2015	IS 875:2015	IS 875:2015
		(K4=1)	(K4=1.15)	(K4=1.30)
static	2.13	2.07	1.80	1.59
off shore static	1.85	1.80	1.56	1.38
dynamic	1.71	1.63	1.42	1.13
offshore dynamic	1.45	1.36	1.17	0.96

Table 7: Rayleigh frequencies for 50m tube monopole

Rayleigh frequency	IS 875:1987	IS 875:2015	IS 875:2015	IS 875:2015
		(K4=1)	(K4=1.15)	(K4=1.30)
static	2.6500	2.6000	2.2500	1.9900
off shore static	2.3000	2.2500	1.9600	1.7300
dynamic	2.2000	2.1100	1.8000	1.5600
offshore dynamic	1.9000	1.8100	1.5400	1.3400

3.2 Along Wind Force Calculation

3.2.1 Static Method

The IS 875(Part3):1987&2015 illustrated the total wind load "F_z" acting on monopole tower is computed from Eq (1 to 3). Where V_z = design wind speed at any height z in m/s; V_b is the basic wind speed for the zone reckoned for 3 Sec gust speed. K_1 = Probability factor/risk coefficient, K_2 = terrain roughness (category 2) and height factor varies according to the height of a structure, K_3 = topography factor and K_4 = importance factor for the cyclonic region (1, 1.15, and 1.30), Pz = wind pressure at height "z", in N/sqm, Ae = Effective Frontal area.

$$V_z = V_b * k_1 * k_2 * k_3 * k_4 \tag{1}$$

$$P_z = 0.6 * V_z^2 \tag{2}$$

$$F_z = C_f * A_e * P_z \tag{3}$$

3.2.1.2 Dynamic Method (Gust Factor Method)

The dynamic analysis of towers may be performed in the frequency domain based on the characteristic that depends upon the frequencies of both the approaching upwind action and the structural properties of the structure. This analysis focuses only on the wind action and does not consider any exposed areas related to non – structural elements such as ladders, feeders, platforms or antennas. It is a common approach to consider the wind forces on antennas and the effect on the computation of the wind forces but the IS 875 (Part3:1987 & 2015) Indian code does not cover the force coefficient for the Ancillaries such as Antennae.

Lattice Towers, which are wind sensitive structures, shall be designed for dynamic wind loads with hourly mean wind speed is a reference wind speed. For calculation of a long-wind loads and response (bending moments, shear forces or top deflections) in the dynamic analysis, the Gust Factor method is used (IS 875-2015). Along wind load on a structure at any height is computed by Equation (4)

$$F_z = C_{fz} * A_e * P_z * G \tag{4}$$

Where, Fz is the design peak along the wind load on the structure at any height z, $C_{f,z}$ is the force coefficient for the structure, A_z is the effective frontal area of the structure at height z, P_z is the design hourly mean wind pressure corresponding to $V_{z,d}$ as $0.6V_{z,d}^2$ (N/m^2), and G is the gust factor is calculated by the Equation (5).

$$G = 1 + \left(r * \sqrt{ g_v^r B_s * \left((1+\Phi)^2 \right) + \left(\frac{H_s g_R^2 SE}{\beta} \right) } \right) \tag{5}$$

Where B_s is the background factor, ϕ is the factor to account for the second-degree order turbulence factor, Hs is the height factor for resonance response, S is the size reduction factor, E is the spectrum of turbulence in the approaching wind stream, g_v and g_R are for background and resonant gust factors respectively and remaining factors are according to 2015 code provisions. In this analysis the P-Δ effect need not be considered pursuant to stipulation of ANSI/TIA -222-G [26] (self-supporting towers up to the height of 137 m.)

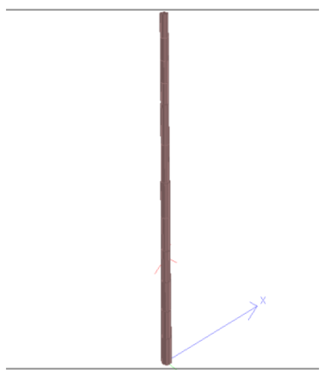

Fig. 5: 3D STAAD Model of monopole

4. Results and Discussion

The static and dynamic analyses have been performed for the K4 factor of 1.30 and offshore wind velocity factor of 1.15 for the 30, 40 and 50 m steel tapered circular tube monopole towers with the above equations 1 to 5. The Gust factor variations are depicted from fig 6 through 13. The STAAD model of tower is shown in fig 5. A comparison of lateral displacements, maximum bending moment, tilts and shear forces between IS 875 Part 3 (1987)and IS 875 Part3 (2015) for monopoles was performed and the results are discussed in the following paragraphs as mentioned below.

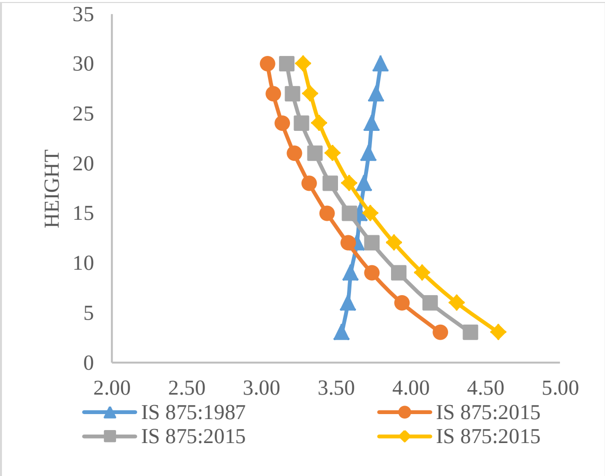

Fig. 6: Variation of gust for 30m monopole tower

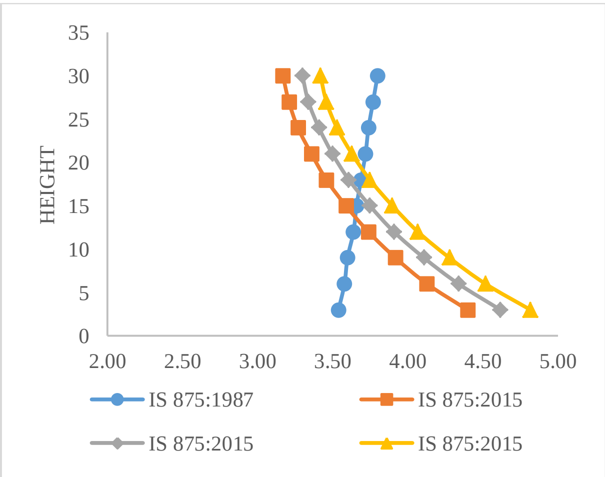

Fig. 7: Variation of gust with offshore for 30 m monopole tower

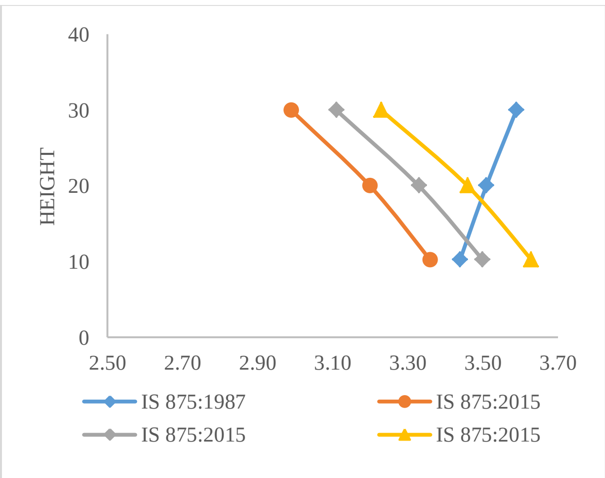

Fig. 8: Variation of gust for 30 m tube monopole tower

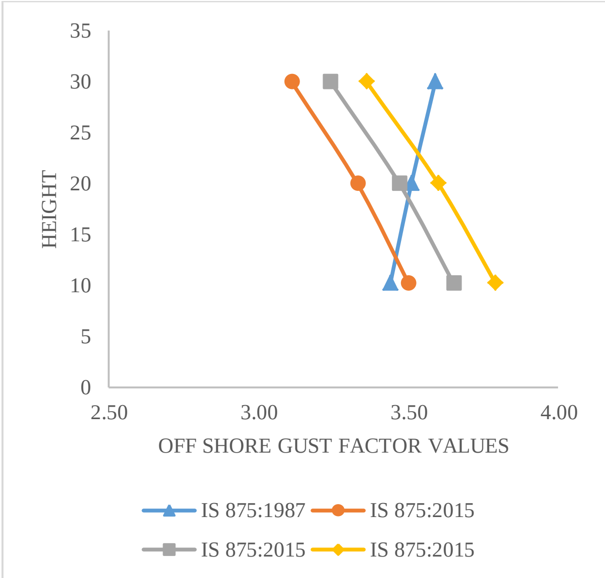

Fig. 9: Variation of gust with offshore for 30 m tube monopole tower

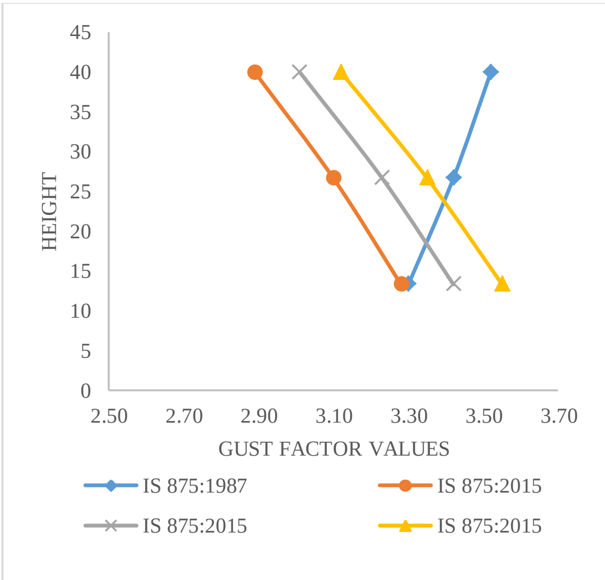

Fig. 10: Variation of gust for 40 m tube monopole tower

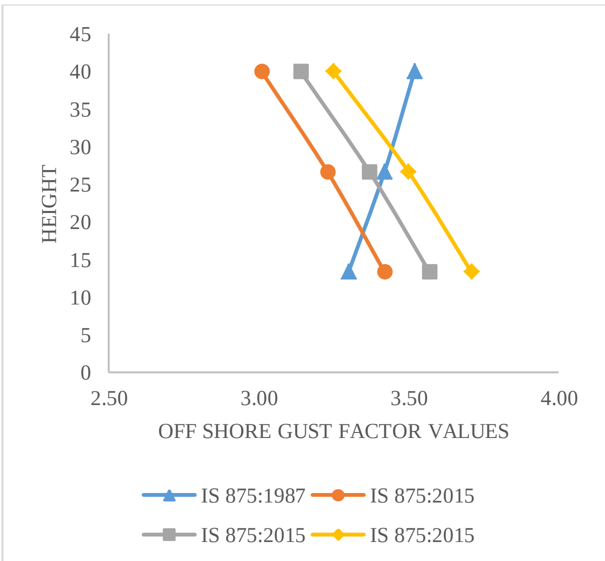

Fig. 11: Variation of gust with offshore for 40 m tube monopole

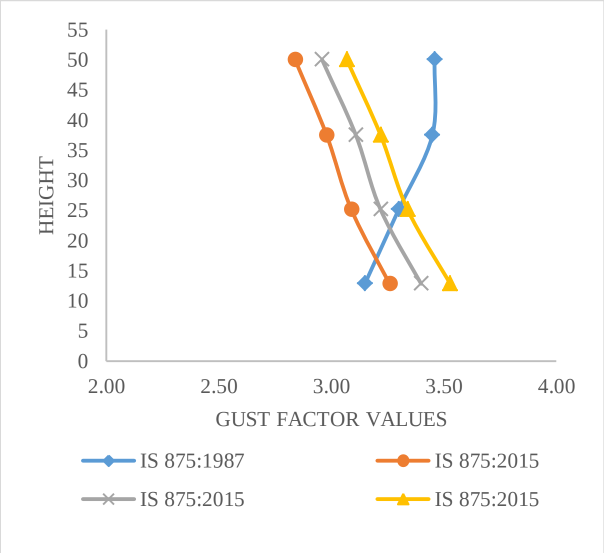

Fig. 12: Variation of gust for 50 m tube monopole

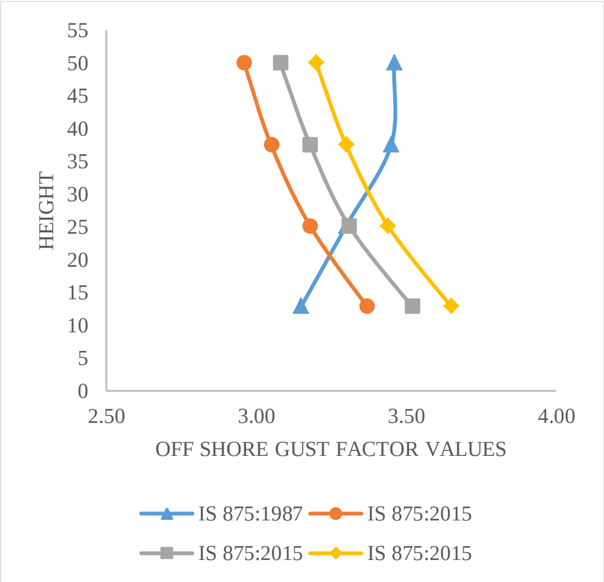

Fig. 13: Variation of gust with offshore for 50 m tube monopole

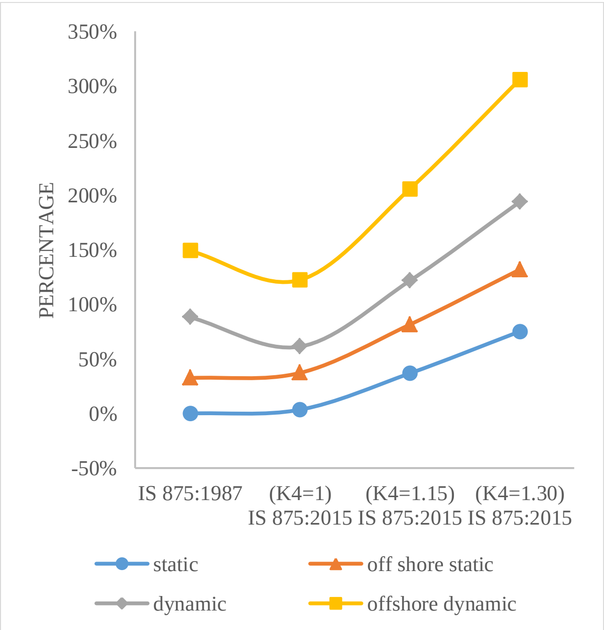

Fig. 14: Lateral displacement variation for 30m pipe monopole

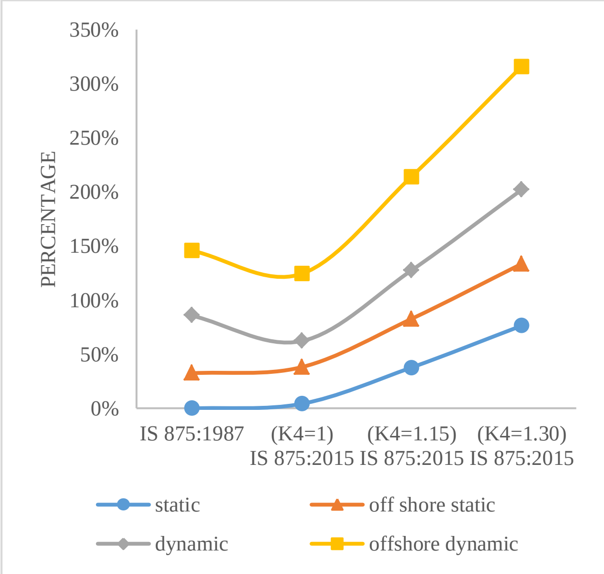

Fig. 15 Bending moment variation for 30m monopole

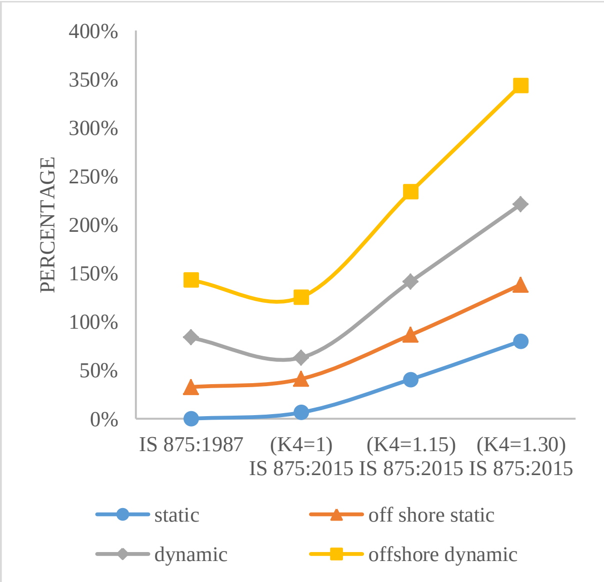

Fig. 16: Shear force variation for 30m pipe monopole

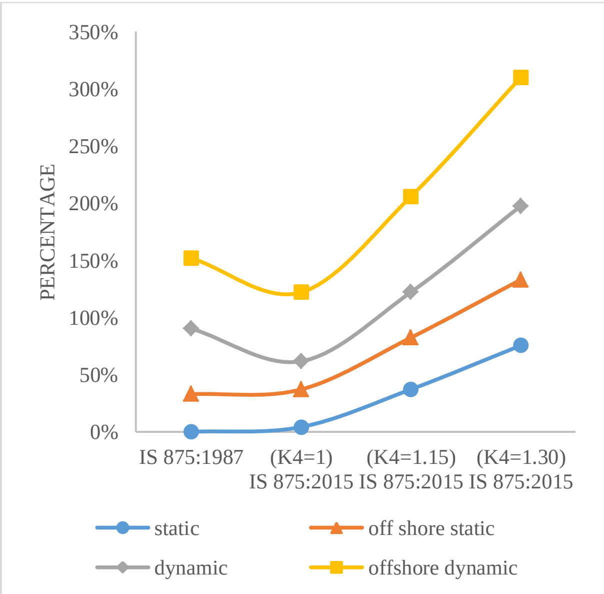

Fig 17: Tilt variation for 30m pipe monopole

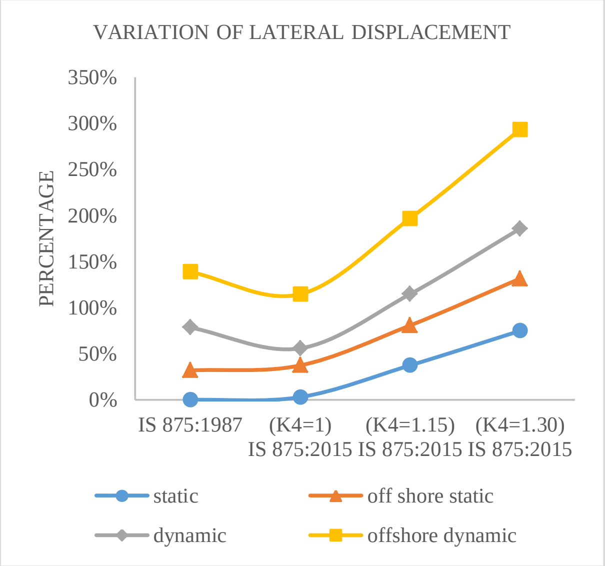

Fig. 18: Lateral displacement variation for 30m tube monopole

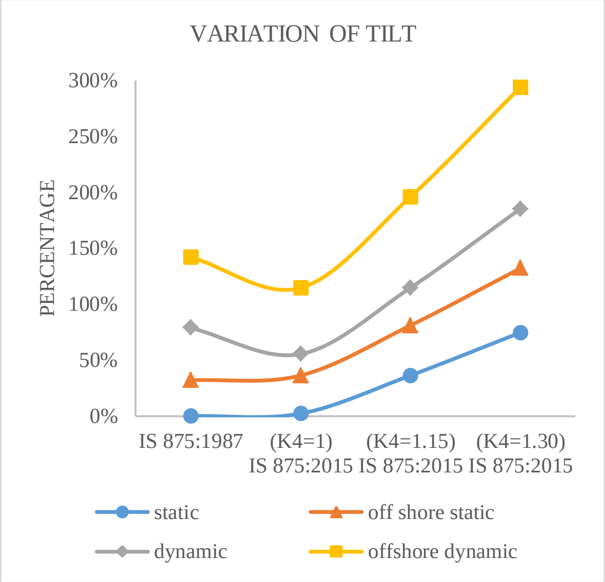

Fig. 21: Tilt variation for 30m tube monopole

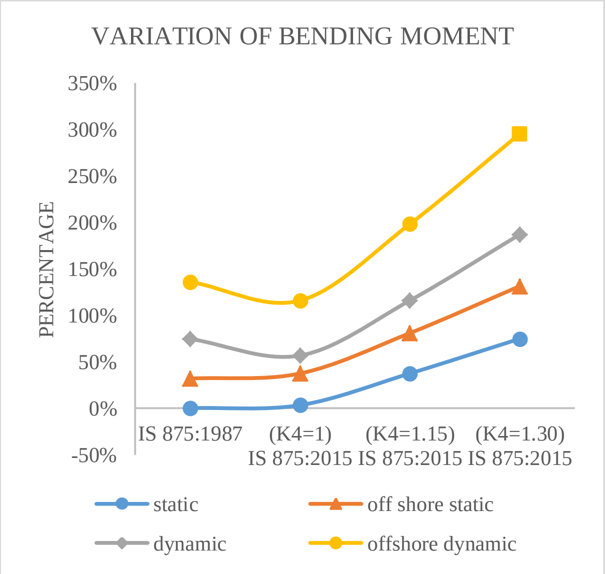

Fig. 19: Bending moment variation for 30m tube monopole

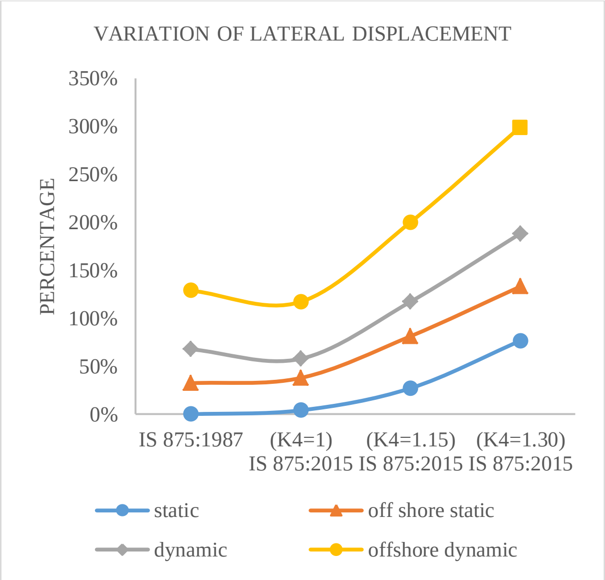

Fig. 22: Lateral displacement variation for 40m tube monopole

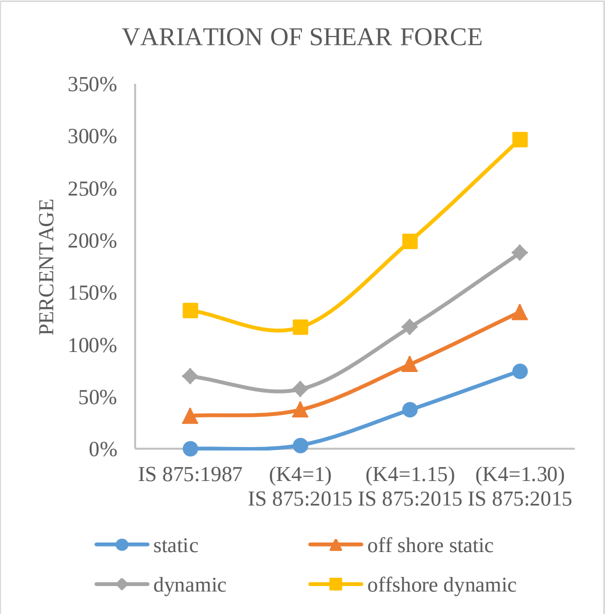

Fig. 20: Shear force variation for 30m tube monopole

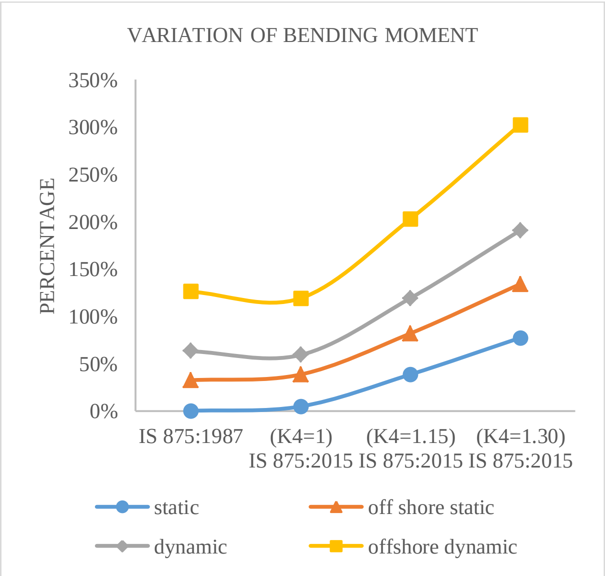

Fig. 33: Bending moment variation for 40m tube monopole

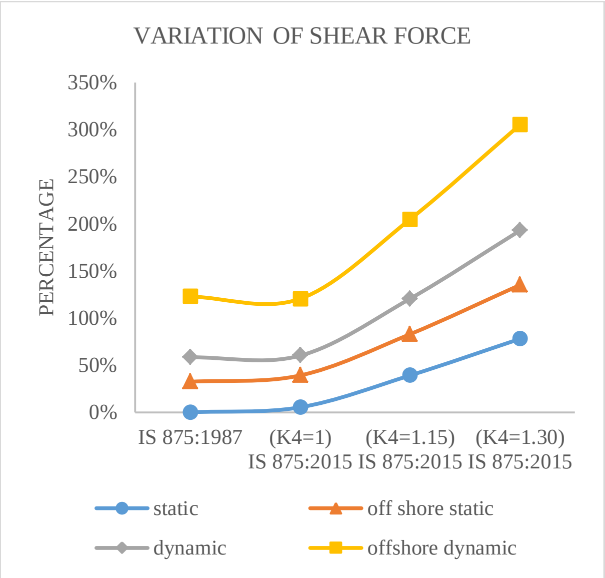

Fig. 24: Shear force variation for 40m tube monopole

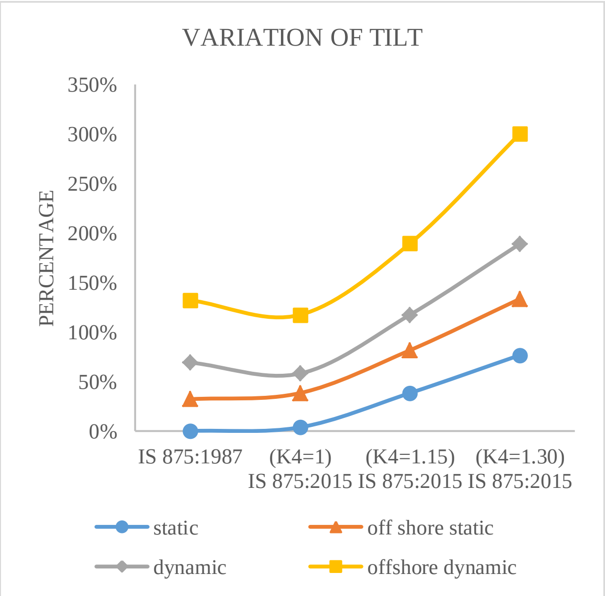

Fig. 25: Tilt variation for 40m tube monopole tower

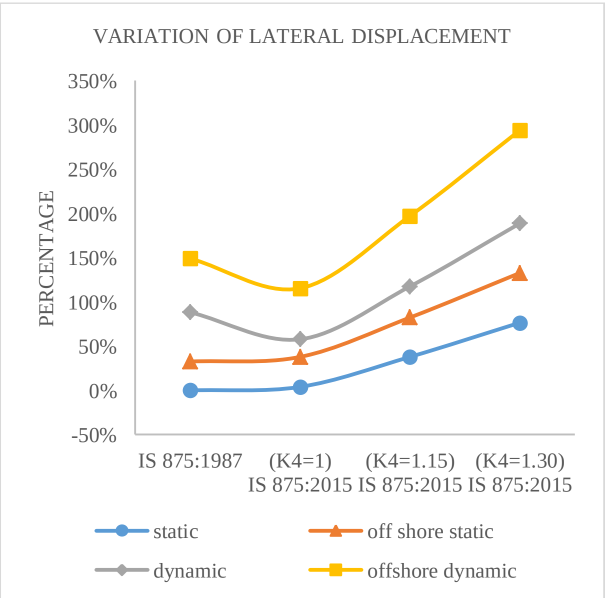

Fig. 26: Lateral displacement variation for 50m tube monopole

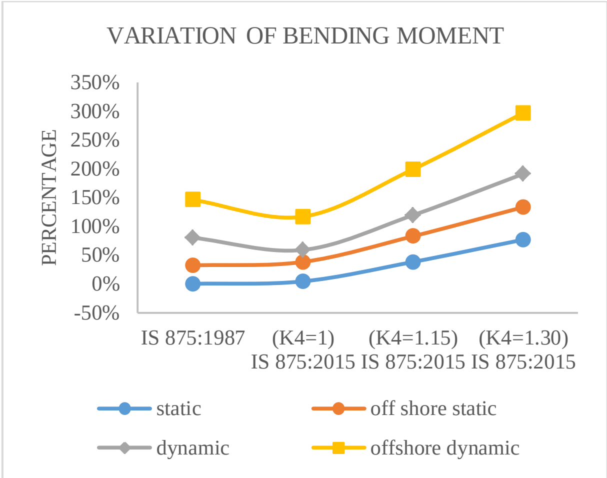

Fig. 27: Bending moment variation for 50m tube monopole

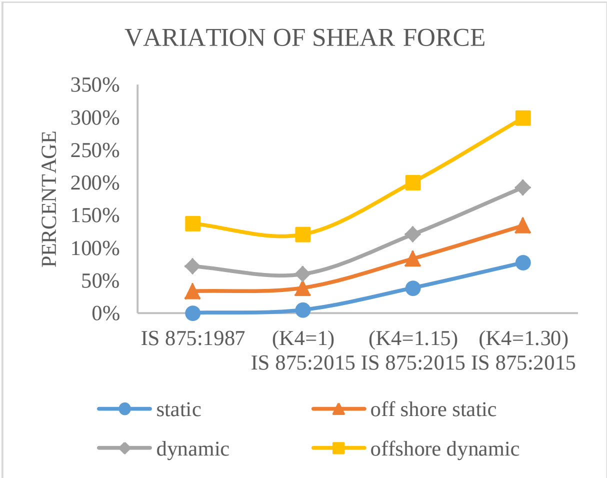

Fig. 28: Shear force variation for 50m tube monopole

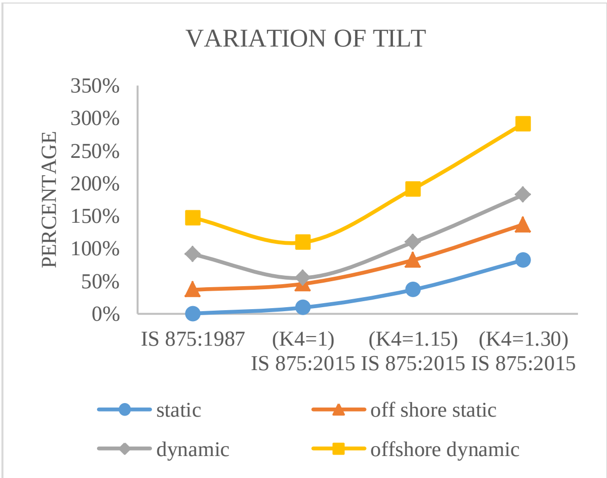

Fig. 29: Tilt variation for 50m tube monopole

5. Discussion

After stimulating the 1987 version wind forces and 2015 wind forces with k4 factor and in association of offshore wind speed factor, the following observations gave been drawn. The comparisons have been made with IS 875(Part) 3-1987 static wind loading provision.

1. From the figs 14 to 21,in comparison with 30m tube monopole tower, the 30m pipe section monopole tower has more lateral displacement, bending moment, shear forces and tilts,

hence the tube sections have been considered for the 30, 40 and 50m height monopole towers

2. With the figs 18 to 21 for 30m tube monopole tower in comparison with static load analysis when cyclonic factor 1.30 is taken in the static analysis and when offshore wind speed factor of 1.15 is multiplied in addition to the cyclonic factor of 1.30 maximum displacement varies 74.79%, 131.41%; maximum bending moment varies 74.60%, 131.18%; maximum shear force varies74.57%,131.07%; maximum tilt 74.46%,131.91%.and in dynamic analysis when cyclonic factor 1.30 in association with offshore wind speed factor of 1.15 maximum displacement varies 185.54% to 293.09% maximum bending moment varies186.80%, 302.42%; maximum shear force varies 187.57%, 296.61%; maximum tilt 185.10%, 293.61%.
3. With the figs 22 to 25 for 40m tube monopole tower in comparison with static load analysis when cyclonic factor 1.30 is taken in the static analysis and when offshore wind speed factor of 1.15 is multiplied in addition to the cyclonic factor of 1.30 maximum displacement varies (76.45%, 133%); maximum bending moment varies(77.11%, 133.91%); maximum shear force varies(77.84%,134.98%); maximum tilt (76.54%,133.33%). For dynamic analysis in comparison with static load analysis when cyclonic factor 1.30 is in association with offshore wind speed factor of 1.15 maximum displacement varies 188.17%, 299.23%; maximum bending moment varies190.58%, 302.42%; maximum shear force varies 192.71%, 304.95%; and maximum tilt varies 188.88% and 300%.
4. Among the figs 25 to 29, 50m tube monopole tower in comparison with static load analysis when cyclonic factor 1.30 is taken in the static analysis and when offshore wind speed factor of 1.15 is multiplied in addition to the cyclonic factor of 1.30 maximum displacement varies 76.38%, 132.55%; maximum bending moment varies 76.47%, 132.90%; maximum shear force varies 76.83%, 133.52%; maximum tilt varying 81.81%, 136.36%. In the dynamic analysis with k_4 factor in association with offshore wind speed factor of 1.15, maximum displacement varies 188.55%, 293.75%; maximum bending moment varies190.66%, 296.35%; maximum shear force varies 192.09%, 298.49%; maximum tilt 181.81%, 290.90% for dynamic and offshore dynamic considerations..

6. Conclusion

Analyses have been done for 30m pipe and 30m tube monopole, a 30m tube monopole tower shows greater strength when compared to 30m pipe monopole tower, hence the remaining 40m and 50m monopoles has been modelled with tube sections only.

After simulating the 30m monopole tower and tower heights of 30m, 40m, 50m tube monopole towers in STAAD. Pro software with provisions of IS 875 part 3 1987 code and provisions of 2015 code with k_4 factor and offshore wind velocity factor of 1.15 for both static and dynamic analysis and with thorough discussions above the following conclusions have been drawn

1. The maximum displacements, shear forces, bending moments, tilts, are observed in the offshore dynamic analysis where cyclonic importance factor 1.30 in association with offshore wind velocity factor1.15 are considered
2. The variation of displacements, shear forces, bending moments, tilts are more in the dynamic analysis with cyclonic factor 1.30 when compared to the static and offshore static analyses consideration.
3. The variation of along wind responses are increasing for 30m and 40 m and then slightly decreasing up to 50 m tower height because of variation of gust factor values.
4. The prenominal percentage variations are similar for deflection, bending moment a, tilt and shear force.
5. The gust factor is varying about 8% for k_4 factor and 12% in association of off shore wind velocity factors.

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