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Earthquake and Wind Analysis of a 100m Industrial RCC Chimney

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ABSTRACT: Chimneys are usually designed for loads produced by seismic effect and wind. So, it is inevitable to analyse the dynamic response of chimney due to effect of earthquake and wind loads. On account of changes in geometry of the chimney, structural analysis such as response to earthquake and wind oscillations becomes more critical. The prime focus of this paper is to compare the wind analysis results with seismic analysis results of a 100m reinforced concrete chimney. Earthquake analysis is carried out as per IS 1893(part 4): 2005 and wind load analysis is carried out as per draft copy CED38(7892):2013 (third revision of IS 4998(part 1):1992). Finally, the maximum values acquired in wind analysis and seismic analysis are compared for deciding the design values.

KEYWORDS: Rcc chimneys, wind loads, earthquake loads, combined design loads, wind analysis, seismic analysis.

I. INTRODUCTION

Chimneys, as we know them today, are tall slender structures which fulfil an important function. They had a humble origination as household outlets and over the years, as outlets grew larger and taller, they came to be known as chimneys. A cluster of them is a stack. Chimneys or stacks are very vital industrial structures for emission of environmental unfriendly gases at a higher elevation level such that the gases do not contaminate surrounding atmosphere. These structures are generally larger, taller, and slender and are with circular cross-sections.
Nowadays due to rapid industrialization, a huge demand for tall chimney structures came into existence. The main objective of chimney is to safeguard the environment from poisonous gases released by industries, by releasing them into atmosphere at such heights and velocities, such that the concentration of pollutants is kept within acceptable limits at ground level. Due to increasing in demand for control of air pollution, the need of tall chimney structures is at an increasing rate since the last few decades, and this trend in the direction of construction of taller chimneys will continue further. Tall reinforced concrete (RC) chimneys form a key constituent of major industries. The major forces that contribute to damage of a tall chimney structure in industries are earthquake forces and wind loads. However, if chimney is located in higher wind speed zone and lower seismic zone, then, wind loads become comparable, if not more, than may earthquake forces. Chimney is designed by considering the combined effect of along wind and across wind loads. In this paper the combined design loads are evaluated as perm the design given by draft copy CED 38(7892):2013.
The main objective of this paper is to analyse the 100m RCC chimney for design wind loads and earthquake loads and compare them to decide the most critical loads for the design of chimney shell.

Details of the chimney are as follows:

1. Height of the chimney	100m
2. Thickness of shell at bottom	0.8m
3. Thickness of shell at top	0.1m
4. Grade of concrete	M25
5. Ratio of height to base diameter	11
6. Ratio of top diameter to base diameter	0.6,0.8,1
7. Basic wind speed	50m/s
8. Foundation type	RCC circular mat

Description of loading:
Density of various materials considered for design,
Concrete – 25kN/m^3
Structural steel – 78.5kN/m^3
Insulation – 1kN/m^3
Live load – 5kN/m^3
Wind load:
The following wind parameters are followed in accessing the wind loads on the structure
Terrain category -2
Class of structure – c
Basic wind speed – 50m/s
Risk coefficient k_1 – 1.08
K_2 factor taken from IS 4998(part 1):1992
Topography factor k_3– 1
Earthquake force data:
Earthquake load for the chimney has been calculated as per IS 1893(par 4): 2005
Zone factor – 0.16,0.24,0.36
Seismic zone – III, IV, V
Importance factor (I) – 1.5
Reduction factor (R) – 3

II.WIND LOADS CALCULATION

Wind load analysis is carried out as per Draft copy CED 38(7892):2013 (third revision of IS 4998(part 1):1992):
In tall free-standing structures wind is the predominant force acting. The wind force acting on tall structures can be categorized into two components, they are

- Along wind force
- Across wind force

Along-wind loads are generated by the 'drag' constituent of the wind force on the chimney, whereas the Across-wind loads are generated by the corresponding 'lift' constituent.

This study involves the assessment of the along-wind and across-wind loads of chimney using

- IS 875 (Part 3) -1987: Code of Practice for design loads
- Draft copy CED 38(7892):2013 (third revision of IS 4998(part 1):1992).
- IS 4998 (Part 1)-1992: Criteria for design of RCC chimneys..

Design Wind Pressure:

Firstly, for calculation of moment due to along wind we first have to find the Design hourly wind speed V (z). The design wind speed, V (z) in m/s can be computed by multiplying V_b with modification factors, k_1, $k_2$and k_3, and is given by:

$$\overline{V}(z) = V_b k_1 \overline{k_2} k_3 \tag{1}$$

$$\text{Where } \overline{k_2} = 0.1423 \left[ln\left(\frac{z}{z_o}\right)\right](z_o)^{0.0706} \tag{2}$$

Zo is the aerodynamic roughness height which depends on terrain category. 0.002 m for terrain category 1, and 0.02 m for terrain category 2 and other terrain categories.
The design wind pressure due to hourly mean wind speed, P (z) in N/m2, corresponding to V (z) shall be evaluated as follows

$$\overline{p}(z) = \frac{1}{2}\rho_a\{\overline{V}(z)\}^2 \tag{3}$$

Where is the mass density of air, taken equal to 1.2 kg/m^3
Calculation of Along-wind loads:

The along-wind load, F(z) per unit height at any level, z on a chimney is equal to the sum of the mean along-wind load, F(z) and the fluctuating component of along-wind load, F'(z) and shall be calculated as given below:

$$F(z) = \overline{F}(z) + F'(z) \tag{4}$$

Here, the mean along-wind load $\overline{F}(z)$, shall be computed as:

$$\overline{F}(z) = \overline{C_D} d(z)\overline{p}(z) \tag{5}$$

Where Cd is the mean drag coefficient taken as 0.8 d (z) is the outer diameter of chimney at height z.

The fluctuating component of along-wind, F(z) in N/m, at height z shall be computed as

$$F'(z) = 3\frac{(G-1)}{H^2}\left(\frac{z}{H}\right)\int_0^H \overline{F}(z)\, z dz \tag{6}$$

The Gust response factor is computed as:

$$G = 1 + g_f r_t \sqrt{B + \left(\frac{SE}{\beta}\right)} \tag{7}$$

Where

g_f is the peak factor, defined as the ratio of expected peak value to root mean square value of the fluctuating load, given by:

$$g_f = \sqrt{2\ln(\nu T)} + \frac{0.577}{\sqrt{2\ln(\nu T)}} \tag{8}$$

$$\text{Where}\ \nu T = \frac{3600\ f_1}{\left(1+\frac{B\beta}{SE}\right)^{1/2}} \tag{9}$$

T is the sample period taken as 3600s

r_t is the twice the turbulence intensity at the top of the chimney, given by

$$r_t = 0.622 - 0.178 \log_{10} H \tag{10}$$

B is the background factor indicating the slowly varying component of wind load fluctuations, given by

$$B = \left\{1 + \left(\frac{H}{265}\right)^{0.63}\right\}^{-0.88} \tag{11}$$

E is a measure of available energy in the wind at the natural frequency, given by

$$E = \frac{\left\{123\left(\frac{f_1}{\overline{V}(10)}\right)H^{0.21}\right\}}{\left\{1+\left(330\frac{f_1}{\overline{V}(10)}\right)^2 H^{0.42}\right\}^{0.83}} \tag{12}$$

S is the size reduction factor, given by

$$S = \left\{1 + 5.78\left(\frac{f_1}{\overline{V}(10)}\right)^{1.14} H^{0.98}\right\}^{-0.88} \tag{13}$$

V(10) is the mean hourly wind speed above ground level at 10 m height in (m/s)

β is the structural damping as a fraction of critical damping to be taken as 0.016 for along-wind loads.

f_1 is the natural frequency of unlined chimney in the first mode of vibration in Hz.

B. Across wind loads:

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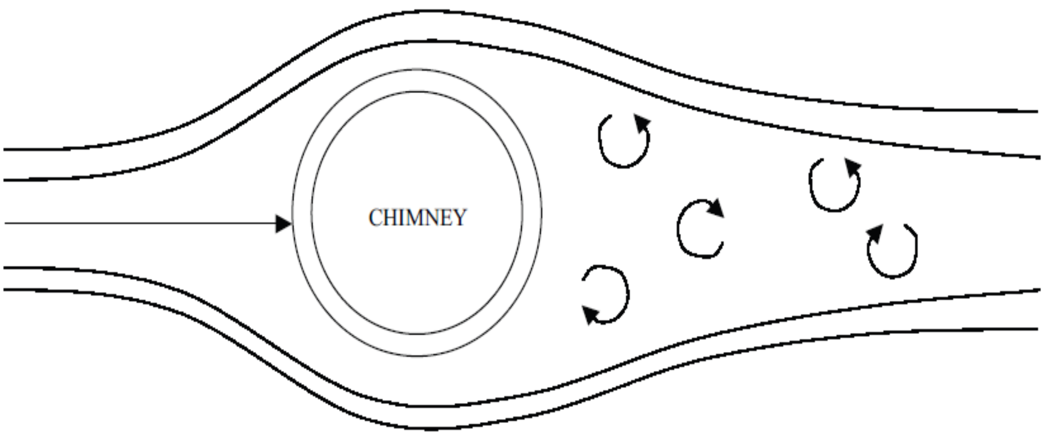

Fig 1. Across- Wind effect

These lift forces cause the chimney to oscillate in the perpendicular direction of the wind flow. Across-wind loads due to vortex shedding in the first and second modes shall be considered in the design of all chimney shells when the critical wind speed Vcris lies between 0.5 V(z_{ref}) and 1.3 V(z_{ref}). Across-wind loads are neglected outside this range. The peak moment at base, Mac of across-wind loads shall be calculated as given below, which defines

$$M_{ac} = \left[g_{ac} S_s C_L \frac{\rho_a V_{cr}^2}{2} dH^2\right] * \left[\frac{\pi}{4(\beta_s+\beta_a)}\right]^{0.5} * S_p * \left\{\frac{2L}{\left(\left(\frac{H}{d}\right)+C_E\right)}\right\}^{0.5} \tag{14}$$

The above equation defines the peak moment at base Mac for different values of V* and $\overline{V}_*$ is evaluated between 0.5V (z_{ref}) and 1.3V (z_{ref}). When $V_* \geq V(z_{ref})$, Mac shall be multiplied by

$$\left\{1.0 - 0.95\left[\frac{\overline{V}_* - \overline{V}(z_{ref})}{\overline{V}(z_{ref})}\right]\right\} \tag{15}$$

Where
S_s is the mode shape factor. 0.57 for the 1st mode and 0.18 for the 2nd mode
g_{ac} is the peak factor for across-wind load taken as 4.0
C_E is the end effect factor taken as 3
C_L is the RMS lift coefficient and is given by

$$C_L = C_{Lo} F_{1B} \tag{16}$$

Where
C_{Lo} is the RMS lift coefficient modified for local turbulence and is given by

$$C_{Lo} = -0.243 + 5.648\, I_{ref} - 18.182\left[I_{ref}\right]^2 \tag{17}$$

Where

$$I_{ref} = \frac{1.0}{\ln\left(\frac{z_{ref}}{z_o}\right)} \tag{18}$$

z_{ref} is the reference height given by $z_{ref} = (5/6)H$

$$F_{1B} = -0.089 + 0.337\, \ln\left(\frac{H}{d}\right) \tag{19}$$

F_{1B} shall be between 0.2 and 1.0

$$V_{cr} = \frac{f_1\, d}{S_t} \tag{20}$$

Where f_1 is the natural frequency of unlined chimney in the first modes of vibration in Hz.

$$S_t = 0.25 F_{1A} \tag{21}$$

Where

$$F_{1A} = 0.333 + 0.206\, \ln\left(\frac{H}{d}\right) \tag{22}$$

F_{1A} shall between 0.6 and 1.0

$$\beta_s = 0.01 + \frac{0.10\left[\bar{V}_* - \bar{V}(z_{ref})\right]}{\bar{V}(z_{ref})} \tag{23}$$

β_s shall be between 0.01 and 0.04

$$\beta_a = \frac{K_a \rho_a d^2}{m_{ave}} \tag{24}$$

Where
m_{ave} is the average mass in top one third of chimney per unit height (kg/m)

$$K_a = K_{ao}\, F_{1B} \tag{25}$$

$$K_{ao} = \frac{-1.0}{(1+5 I_{ref})\left[1 + \frac{|k-1|}{I_{ref}+0.10}\right]} \tag{26}$$

Where,

$$k = \frac{\bar{V}_*}{V_{cr}} \tag{27}$$

$$S_p = \frac{k^{1.5}}{\sqrt{B_w}\,(\pi^{0.25})}\, exp\left[-\frac{1}{2}\left(\frac{1-k^{-1}}{B_w}\right)^2\right] \tag{28}$$

Where
B_{ow} is the band width parameter, given by
$B_w = 0.10 + 2\, I_{ref}$
L is the correlation length coefficient taken as 1.2
Using M_{ac}, the across-wind load per unit height at any height, $F_{ac}(z)$ in N/m, shall be calculated based on the corresponding mode shape of the chimney as given below:

$$F_{ac}(z) = \frac{M_{ac}\, m(z)\varphi_i(z)}{\int_0^H m(z)\varphi_i(z) z\, dz} \tag{29}$$

Using Fac(z), the across-wind bending moments at any height, Mac(z), can be obtained.

Natural frequencies:

For preliminary design, the natural frequency of unlined chimney in the first mode of vibration, f_1 (in Hz) may be approximated using the following formula:

$$f_1 = 0.2\left(\frac{d_o}{H^2}\right)\sqrt{\frac{E_{ck}}{\rho_{ck}}}\left(\frac{t_o}{t_{zh}}\right)^{0.3} \tag{30}$$

III.EARTHQUAKE LOAD CALCULATION

Analysis procedure for earthquake load as per 1893(part 4): 2005.Seismic action on chimneys are an additional source of natural loads acting on the chimney. Seismic action or the earthquake is a short and strong disruptions of the ground. Following are the steps required for calculation of moment and shear force.

1.) Fundamental time period
2.) Horizontal seismic force
3.) Design shears and moments

1) The fundamental period of the free vibration is calculated as,

$$T = C_T \sqrt{\frac{W_t h}{E_s A g}} \tag{31}$$

2) The horizontal seismic coefficient A_h, shall be obtained by using the period T from the codes given in 1S 1893(-Part 1). The design horizontal seismic coefficient A_h, for Design Basis Earthquake (DBE) shall be resolved by the following expression taken from IS 1893 (Part 1):

$$A_h = \frac{Z}{2} * \frac{S_a}{g} * \frac{I}{R} \tag{32}$$

3) Shear force V, and moment for stack structures from top at a distance X, shall be calculated by the following expression:

a) $V = C_v A_h W_t D_v$ (33)

b) $M = A_h W_t \bar{h} D_m$ (34)

IV.STAAD Pro Model

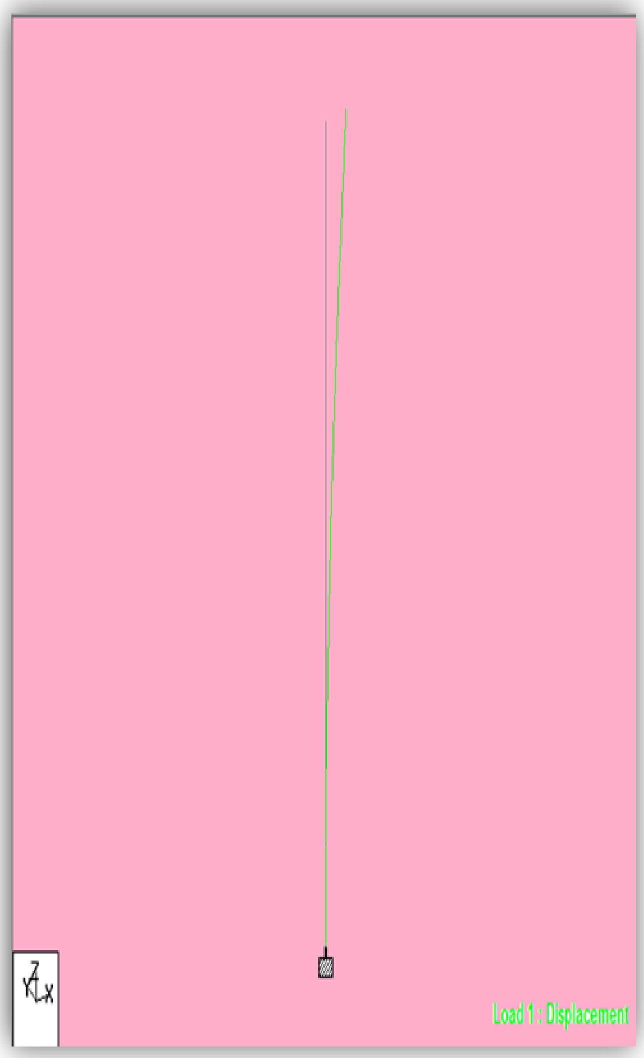

Fig 2. Staad model for chimney

V. Results

Free vibration characteristics of chimney:

Chimney Height (m)	Natural frequency(Hz)		Time period(sec)	
	1st mode	2nd mode	1st mode	2nd mode
100	1.972	9.361	0.5072	0.1068

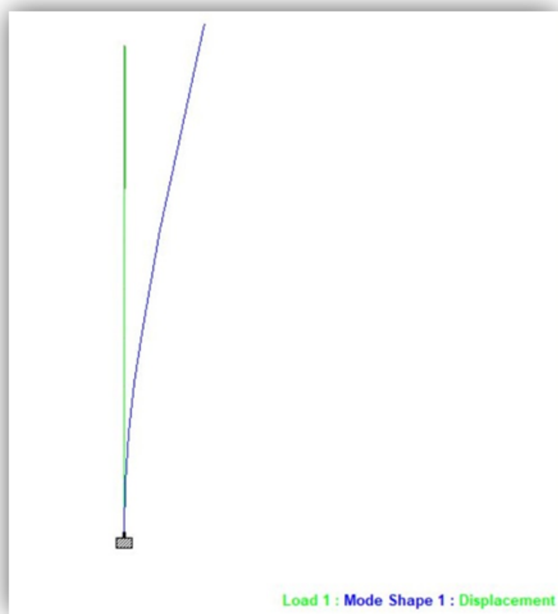

Figure 2: Mode Shape 1

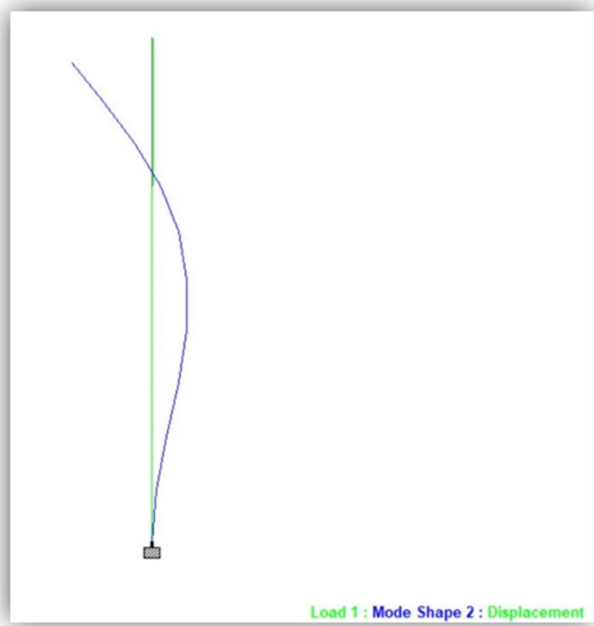

Figure 3: Mode Shape 2

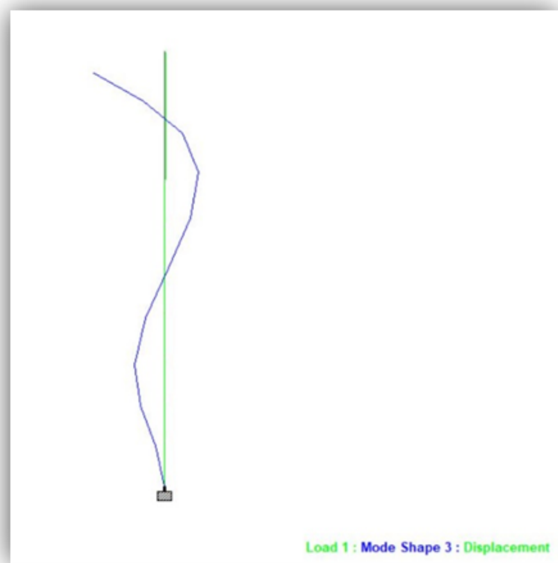

Figure 4: Mode Shape 3

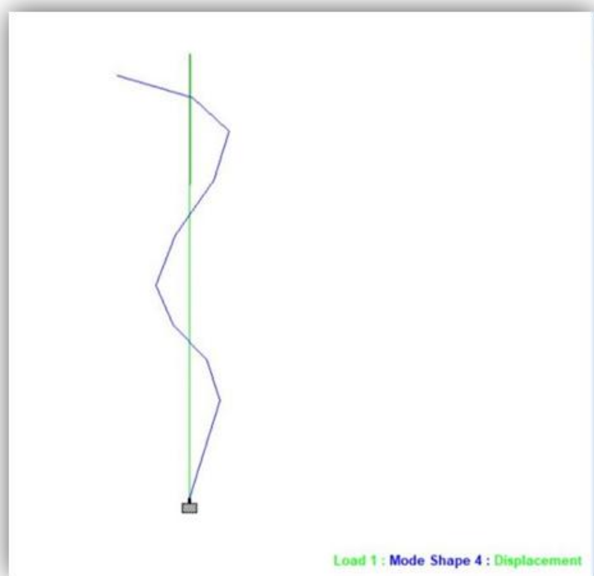

Figure 5: Mode Shape 4

Results of earthquake analysis:

S.no	Zone no.	Zone factor	Shear force(kN)			Bending moment(kNm)		
			Ratio of top diameter to base diameter			Ratio of Top diameter to base diameter		
			0.6	0.8	1	0.6	0.8	1
1	III	0.16	1274.4	1357.9	1436.6	42274.2	47321.4	51989.9
2	IV	0.24	1911.5	2036.9	2155	63411.3	70982.0	77984.8
3	V	0.36	2867.3	3055.3	3232.4	95117.0	106473.1	116977.2

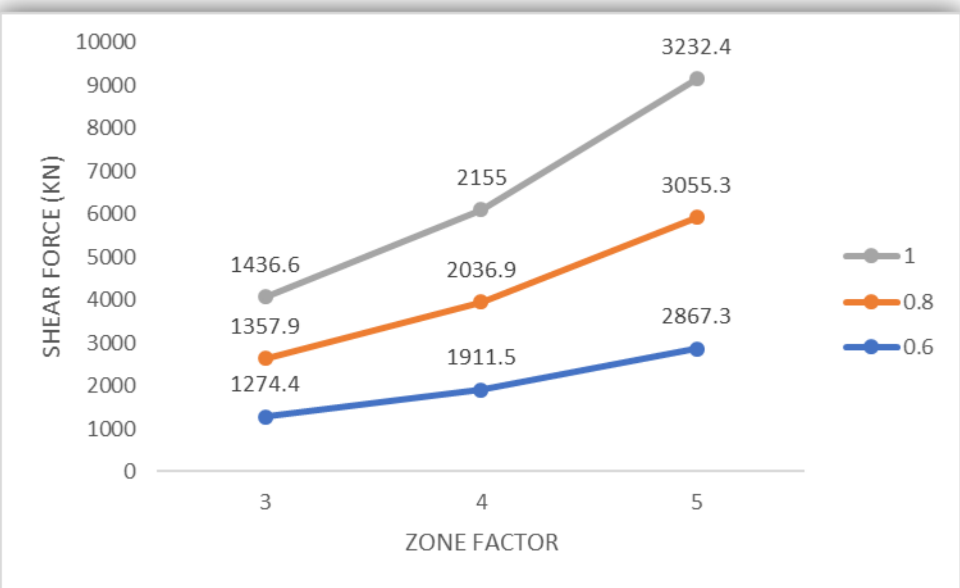

Figure 6: Variation of Shear Force for distinct Earthquake Zones

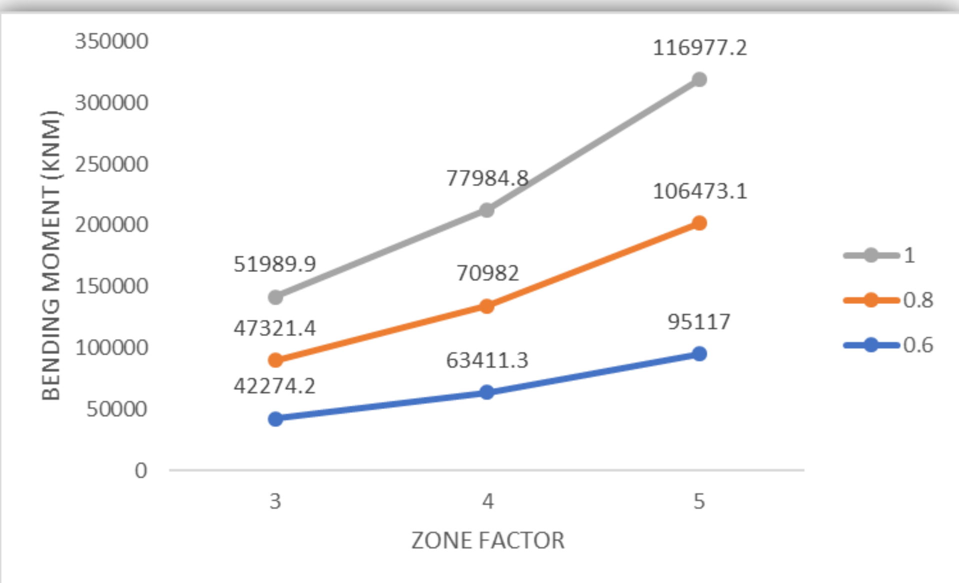

Figure 7: Variation of Bending Moment for distinct Earthquake Zones

Results of wind analysis:

Chimney height (m)	Base shear (kN)			Base moment (kNm)		
	Along wind	Across Wind	Combined wind	Along wind	Across wind	Combined wind
100	89.19	4080.87	4081.84	4890	294898.65	294939.16

VI.CONCLUSIONS

- From above table results, it is clear that shear force and bending moment increases with increase in zone factor values.
- The effect of wind force is quite significant as compared with the earth quake forces over 100m RCC Chimney.
- The geometry of chimney has to be chosen in order that the deflection produced at the top of chimney is well within the permissible limits.
- On comparison of loads acting on an industrial RCC chimney, the wind loads are the governing loads for design of chimney shell.

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