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Analysis of Self-Supported Steel Chimney with the Effects of Geometrical Parameters

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ABSTRACT

Steel stacks are smoke releasing slender and tall structures constructed for various power plant or oil and gas industries. Steel chimney are subjected to static and dynamic loadings. Static analysis is carried out by static wind loading and dynamic analysis is carried out by considering both seismic loading as well as dynamic wind loadings. Geometry of a steel chimney plays an important role in behavior of structure under lateral loading. This is because geometry is the important for the stiffness parameters of the chimney. However, the basic geometrical parameters of the steel chimney (e.g, height of chimney, diameter at top, etc.) are associated with the corresponding site conditions.

Present study deals with investigate the effect of height to base diameter ratio and top to base diameter ratio on behavior of self-supported steel chimney. A total of 49 number of steel chimney configured with seven different heights and top diameter of chimney are selected and analyzed for wind loadings and seismic loadings as per Indian standards (IS: 6533 part2) and IS 1893(part 4). The effect of geometric parameters on self-supported steel chimney is found out using STAAD Pro Vi8 and MS-Excel.

Keywords - Dynamic Wind, Geometrical Parameter, Static Wind, Steel Stack, STAAD PRO

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I. INTRODUCTION

Chimneys are very important industrial structures for discharged waste harmful gases at higher elevation in atmosphere. These structures are tall, slender and tapering with circular cross-sections. For construction different materials are used such as concrete, steel or masonry. Steel chimneys are ideally suited for process work where a low thermal capacity required and short heat-up period. Also, steel stacks are economical up to 45m height. Fig-1 shows a cantilever steel chimneys located in a power plant.

Geometry of a steel stacks plays an important role in behaviour of structure under lateral loading. This is because geometry is primarily responsible for the stiffness parameters of the chimney. However, the basic geometrical parameters of the steel chimney (e.g, height of chimney, diameter at bottom, etc.) are associated with the corresponding actual site conditions.

Fig – 1 Cantilever steel chimney

1.1. Proposed Work

This work is focused on effects of Flue duct opening and Geometrical Parameter like height to base diameter, top to base diameter ratio. For various number of steel chimney configurations with different heights of chimney are selected and analysed for wind loadings and seismic loadings as per Indian standards (IS: 6533 part2) and IS 1893(part 4).

- Chimneys are considered to be fixed at their support. Soil flexibility is not considered in the present study

- All chimneys considered here are of single-flue type
- Uniform thickness is considered over the full height of the chimney.
- Diameter of flared base of the chimney were kept constant for all the cases
- Only wind load and seismic load are taken into consideration for analysis

II. ANALYSIS OF STEEL CHIMNEY

Analysed self-supported steel chimney as per Indian Standard IS 6533 (Part 1 & 2):1989 through an example calculation. A typical chimney to be located at Mumbai is taken for the example. The chimney is first analysed for static wind load, seismic loading, and Dynamic wind load for mode (1, 2, and 3), Design lateral wind, and check for possible resonance

2.1. Assumptions

1. The wind pressure varies with the height. It is zero at the ground and increase as the height increases. For the purpose of design it is assumed the wind pressure is uniform throughout the height of the structure.
2. The calculation purpose of static wind. It is assumed that the load (projected area multiplied by the wind pressure) is acting at the centre of pressure.
3. The base of the stack is perfectly rigid and the effect of the gussets and stool plate on the deflection and the stresses in the stack is not considered. This is applicable only for manual calculations.
4. There are no additional lateral movements from the duct transferred to the stack and suitable arrangement has to be provided to absorb this movement from the duct.
5. Earthquake causes impulsive ground motions, which are complex and irregular in character, changing in period and amplitude each lasting for a small duration. Therefore resonance of the type as visualized under steady-state sinusoidal excitations will not occur, as it would need time to build up such amplitudes.
6. Earthquake is not likely to occur simultaneously with maximum wind or maximum flood or maximum sea waves

2.2. Description of selected steel stacks/chimneys

1. Type of stack = circular self-supporting industrial steel stacks
2. Heights of stacks: 30 m ,35m,40m,45m ,50m ,55m,60 m (short stacks)
3. Variation in top diameter for each stack for fixed value of base diameter will be in the following ratios (ratio Db/Dt): 0.45, 0.48, 0.5, 0.53, 0.56, 0.59 and 0.63
4. Height to base diameter ratios (h/Db): 6, 7, 8, 9, 10, 11, 12
5. Number of chimneys: 49
6. Type: unlined single flume.
7. Flare height: one third of total height.
8. Thickness of chimney shell = 16mm (constant for all stacks)
9. Base: Medium
10. Location: Mumbai
11. Wind speed: 44 m/s
12. Material: Mild steel

2.3. Permissible stress

The material of construction of chimney should conform to IS 2062:2006
Yield stress of the steel: F_y = 250MPa
The minimum permissible stress in compression due to above load combinations for circular chimney with construction material mentioned above is given in table-3, IS 6553(part2): 1989 as a function of:
h_{level}= Effective height for consideration of buckling
D= mean diameter of the chimney at the level considered
T=thickness at the level considered
Maximum permissible stress in tension:
Permissible stress in tension: fallow tension = 0.6fy =150 MPa (Ref: IS-800: 1984; Clause: 4.11)
Maximum permissible stress in shear: $f_{allowsh} = 0.4 f_y$ =100 MPa
(For un-stiffen web as per Ref:-IS-800:1984; Clause: 6.4.2)

2.4. Loading

Static and Dynamic wind response includes dynamic force, dynamic moment and corresponding deflections Calculations are done by using excel sheets. Sample calculation results for chimney are shown below.

- **Self-weight of chimney**

Let level h be the distance from the top of chimney to the level considered
G_i =weight of the part of the chimney above the level considered

A_i = area of the steel section at the level considered.
Mass density of the material used for chimney =78.5 kN/m^3
Weight of the (platform+ access ladder+ helical strake+ rain cap + etc) is assumed to be 20% of the self-weight of chimney shell

- **Static Wind Load Calculation**

A static force called as drag force, obstructs an air stream on a bluff body like chimney. The distribution of wind pressure depends upon the shape and direction of wind incidence. Due to this a circumferential bending occurs and it is more significant for larger diameter chimney. Also drag force creates along-wind shear forces and bending moments.

According to IS: 875(Part 3)-2015-Code of Practice for Wind Loads
Design wind speed (Vz) = Vb x k1 x k2 x k3 x k4
Basic wind speed (Vb)
Probability factor (k1)
Terrain Roughness and height factor (k2)
Topography factor (k3)
Importance factor for the cyclonic region (k4)
Design wind pressure (Pz) =0.6 x Vz
Shape factor for steel (C) =0.7
Static force = C x Pz x area of segment

- **Seismic Effect**

For seismic analysis, chimney is behaved like a cantilever beam with flexural deformations. Analysis is carried out by following one of the methods according to the IS code provision,
1. Response-spectrum method (first mode)
2. Time-history response analysis.
3. Modal-analysis technique (using response spectrum)

For chimneys which are less than 90m high called as short chimney, response spectrum method is used.

- **Response-spectrum method**

This method consists of three steps such as,
I. Fundamental period
II. Horizontal seismic force
III. Determine design shears and moments
The fundamental period of the free vibration is calculated as,

$$T = C_T \sqrt{\frac{W_T h}{E_S Ag}}$$

Where,
CT = coefficient depending on slenderness ratio of the structure
WT = total weight of the structure including weight of lining and contents above the base,
A = area of cross-section at the base of the structural shell
H = height of the structure above the base
Es = modulus of elasticity of material of the structural shell
g = acceleration due to gravity

SHEAR AND MOMENT

According to IS: 1893 (Part 4)-2005 Code of Practice for Earthquake Resistant Design of Structures
Design static seismic base shear (V) = C_v A_h W D_V
Where,
C_v= Coefficient of shear force depending on slenderness ratio
Ah = Design horizontal acceleration spectrum value
W= Total weight of structure
D_v= Distribution factors for shear
Design static bending moment (M) = Ah W h DM

Where DM= Distribution factors for shear

h = height of Centre of gravity of structure above base

- **Dynamic Wind Load Calculation**

Design wind load should take into consideration the dynamic effect due to pulsation of thrust caused by the wind velocity in addition to the static wind load. Wind load is a combination of steady and a fluctuating component. Due to turbulence effect the Wind load varies in its magnitude.

Dynamic coefficient for the **1st mode**: $\xi_i = \frac{T_i V_b}{1200}$

Coefficient of dynamic influence corresponding to the above value of dynamic coefficient for unlined chimney
Coefficient of dynamic influence corresponding to the above value of dynamic coefficient for unlined chimney: 1.617 (ref. table-5, IS-6533 Part-2:1989)
Coefficient which takes care of the space correlation of wind pulsation speed according to height and vicinity of building structures: [2]
ν_1= 0.7 (ref. table-7, IS-6533 Part-2:1989 for 30m height and ξ =0.0066)
The fundamental mode shape ordinate of the chimney at height from ground is taken from (STAAD PRO) software for respective mode
Calculation of deduced acceleration:

$$\eta = \frac{Y_{ij} \sum_{k=1}^{r} Y_{ik}\ Pstatic\ m_k}{\sum_{k=1}^{r} Y_{ik}^2\ M_k}$$

Where
Y_{ij} and Y_{ik} = relative ordinates of mode shape corresponding to the centres of j_{th} and k_{th} zones in the ith mode of oscillation
r = nos. of zone into which the chimney mk= coefficient of pulsation of speed thrust for the centre of the k^{th} zone

- **Total design lateral force**

Total design lateral force (P_k), bending moment (M_k) and deflection (k) due to wind load should be calculated from static and dynamic calculations corresponding to the i^{th} mode of natural oscillation and summed up according to the following formulae: [2]

$$P_k = P_{st\,k} + \sqrt{\sum_{i=1}^{s} \left(P_{dyn\,k}\right)^2}$$

$$M_k = M_{st\,k} + \sqrt{\sum_{i=1}^{s} \left(M_{dyn\,k}\right)^2}$$

$$\gamma_k = \gamma_{st\,k} + \sqrt{\sum_{i=1}^{s} \left(\gamma_{dyn\,k}\right)^2}$$

Where: $P_{st,k}$ and $P_{dyn,k}$ = The static and dynamic wind load acting at mid-point of k^{th} zone, respectively
$M_{st,k}$ and $M_{dyn,k}$ = Bending moment due to static and dynamic wind pressure acting at k^{th} zone, respectively

γ_{stk} and $\gamma_{dyn,k}$ = deflections due to static and dynamic wind pressure respectively at the k^{th} zone i^{th} respect to the original position
s = number of modes of oscillation.

- **Check for Resonance**

Fundamental period of vibration for this chimney: T
Fundamental frequency of the vibration: f = 1/T
Stroughal critical velocity: v_{cr} =86.50 m/s (ref. clause A-3, IS-6533 Part- 2:1989)
Basic wind velocity: V_b =44 m/s
V_d = 49.28 m/s (at 30m)
Velocity (stroughal critical velocity) range for resonance:
$V_{resonce}$ UL = 0.8 V_d = 39.42 m/s
$V_{resonce}$ LL = 0.33 V_d = 16.26 m/s
Self-supporting chimney, checking for resonance shall be carried out if the critical velocity V_{cr} as determined is within the range $V_{resonce}$ LL to $V_{resonce}$ LL

2.5. Result and Discussion

49 selected chimneys with different dimensions as explained in the previous section were analysed for dynamic wind load as per IS 6533 (Part-2): 1989 using MS- EXCEL to calculate base shear, base moment and deflection at top for each chimney as follows

Table -1: Base moment (kNm) of the chimney for different top-to-base diameter ratio and height to base diameter ratio

		Dt/Db						
		0.63	0.59	0.56	0.53	0.50	0.48	0.45
h/Db	6	2310.20	2166.74	2040.46	1928.16	1826.79	1736.11	1654.25
	7	3380.25	3176.89	2996.75	2835.60	2690.56	2559.48	2440.58
	8	4818.24	4553.99	4319.43	4108.17	3915.61	3741.29	3583.56
	9	6673.19	6320.64	5988.40	5699.30	5462.57	5239.67	5037.04
	10	8434.99	7967.09	7605.92	7265.11	6957.14	6682.79	6432.37
	11	10448.91	9928.07	9466.70	9046.21	8640.25	8276.58	7946.24
	12	12741.13	12070.45	11474.31	10943.01	10462.30	10032.36	9643.84

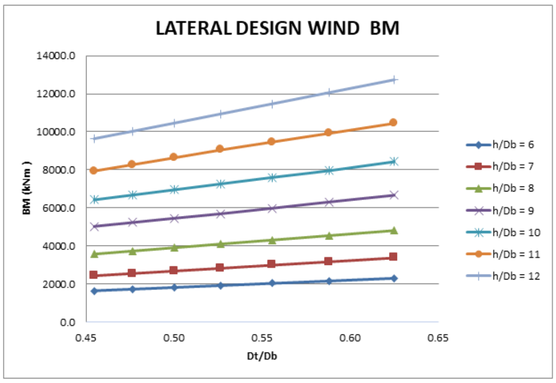

Chart -1: Base moment of the chimney as a function of top-to-base diameter ratio

Table -2: Base Bending stress (MPa) of the chimney for different top-to-base diameter ratio and height to base diameter ratio

		Dt/Db						
		0.63	0.59	0.56	0.53	0.50	0.48	0.45
h/Db	6	7.42	6.96	6.56	6.20	5.87	5.58	5.32
	7	10.86	10.21	9.63	9.11	8.65	8.23	7.84
	8	15.48	14.64	13.88	13.20	12.58	12.02	11.52
	9	21.45	20.31	19.25	18.32	17.56	16.84	16.19
	10	27.11	25.60	24.44	23.35	22.36	21.48	20.67
	11	33.58	31.91	30.42	29.07	27.77	26.60	25.54
	12	40.95	38.79	36.88	35.17	33.62	32.24	30.99

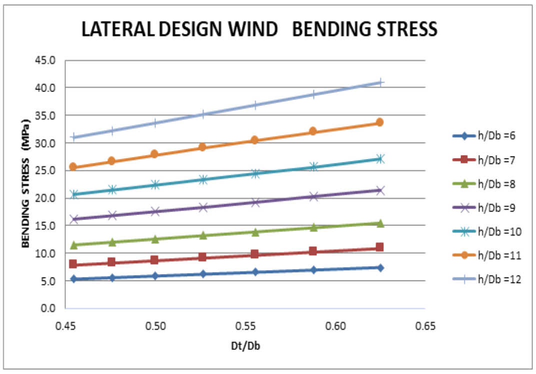

Chart -2: Base bending stress of the chimney as a function of top-to-base diameter ratio

Table -3: Shear force (kN) of the chimney for different top-to-base diameter ratio and height to base diameter ratio

		Dt/Db						
		0.63	0.59	0.56	0.53	0.50	0.48	0.45
h/Db	6	147.28	139.66	132.95	126.94	121.51	116.63	112.20
	7	180.64	171.40	163.19	155.82	149.21	143.19	137.73
	8	219.48	208.83	199.34	190.88	183.04	175.99	169.60
	9	263.58	250.97	239.27	228.99	220.34	212.26	204.92
	10	298.49	283.65	271.76	260.70	250.65	241.66	233.51
	11	334.58	319.19	305.54	293.11	281.33	270.71	261.08
	12	372.13	354.15	338.39	324.18	311.34	299.81	289.33

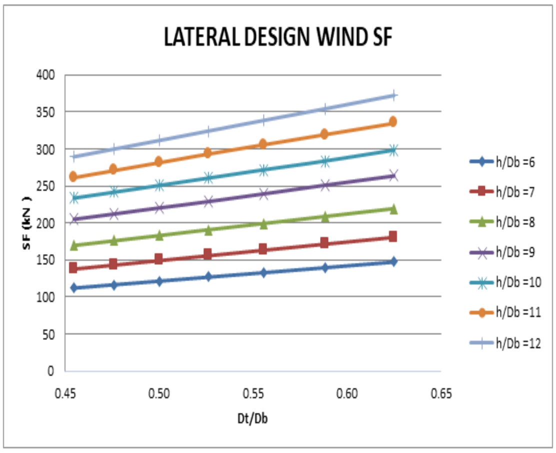

Chart -3: Shear force of the chimney as a function of top-to-base diameter ratio

Table -4: Deflection at top (mm) of the chimney for different top-to-base diameter ratio and height to base diameter ratio

		Dt/Db						
		0.63	0.59	0.56	0.53	0.50	0.48	0.45
$\frac{h}{D_h}$	6	8.37	8.87	9.38	9.93	10.50	11.09	11.71
	7	15.67	16.75	17.86	19.02	20.23	21.49	22.78
	8	28.02	30.22	32.52	34.94	37.47	40.10	42.85
	9	47.84	51.72	55.59	59.78	64.59	69.49	74.64
	10	72.24	77.68	84.18	90.81	97.87	105.36	113.22
	11	106.27	115.04	124.35	134.12	143.93	154.28	165.14
	12	152.69	164.55	177.05	190.35	204.47	219.39	235.15

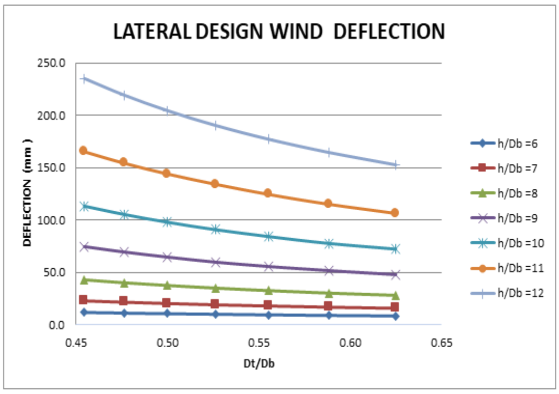

Chart -4: Deflection of the chimney as a function of top-to-base diameter ratio

III. CONCLUSIONS

From above analysis it is found that the base moment increases with the increase of top-to-base diameter ratio almost proportionally. The rate of increase in base moment is slightly less for lower value of height-to-base diameter ratio.

Maximum bending stresses and base shear in the chimney also calculated and presented in Chart- 2 and Chart-3 for different height-to-base diameter ratio and top-to-base diameter ratio. This chart also shows similar results, i.e., that base stress and base shear increases with the increase of top-to-base diameter ratio

Maximum deflection in the chimney also calculated and presented in Chart- 4 for different height-to-base diameter ratio and top-to-base diameter ratio. This chart shows that deflection decrease with the increase of top-to-base diameter ratio

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