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SSI ANALYSIS OF TALL CHIMNEYS WITH ANNULAR RAFT CONSIDERING VARIABLE SOIL PROFILE

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ABSTRACT
SSI analysis of a 200m reinforced concrete chimney with annular raft foundation under along-wind load is carried out in the present study. To study the effect of geometrical properties of chimney, different ratios of height to base diameter(slenderness ratio) are selected. The ratio of outer diameter to thickness of raft were also varied. To understand the effect of flexibility of soil, variable soil profile is considered below the foundation. Three different soil layers were considered below the foundation.Along-wind loads are calculated as per IS:4998-1992. Three dimensional analysis of chimney was carried out using ANSYS software. Lateral tip deflection in chimney and the settlement in raft were obtained in the analysis. The results show that the responses in chimney are affected by the flexibility of soil, slenderness ratio of chimney and thickness of raft.

KEYWORDS: Chimney, along-wind, SSI

INTRODUCTION
Chimneys are tall and Chimneys are tall and slender structures used to discharge waste gases high into the atmosphere. Increase in number of power plants and other manufacturing industries gave rise to taller chimneys. Stricter control on air pollution also necessitates the use of taller chimneys. Dahanu Thermal Power Station possesses the tallest chimney in India, located in Mumbai with a height of 275.3 meters. Sagardighi Thermal Power Station chimney, Korba Power Plant chimney, Anpara B Power Plant chimney and Tata Power Corporation chimney are the other tall chimneys situated in India.

Chimneys are tall and slender structures with unique geometrical properties. They have tapering geometry. Hence the analysis of these structures are different from other structures. The major loads acting on chimneys are wind loads and seismic loads. There are two types of wind loads acting on chimneys. Along-wind loads and across wind loads. These wind loads can be calculated using standard codes. Since chimneys are slender structures, its foundation should be given importance. Raft foundations are normally preferred as chimney foundations. Annular rafts are chosen considering the economy.

In conventional analysis rigidity is assumned at the base of the chimney. But in reality, the soil below the foundation is compressible. To analyse the effect of flexibility of soil, a variable soil profile is chosen below the foundation. The results of SSI analysis of chimney is compared with that of fixed chimney. Chimneys with uniform soil profile is also considered and the results are compared with that of variable soil profile and fixed chimney.

METHODOLOGY
Properties of Chimney
A 200m reinforced concrete chimney was chosen for the analysis. Three ratios of height of chimney(H) to diameter at the base(D_b) (slenderness ratio) chosen are 7,12 and 17. Ratio of top diameter to base diameter is chosen as 0.6. Ratio of base diameter to thickness at the bottom of chimney was 35. The thickness at top of chimney was taken as 0.4 times the thickness at bottom. The minimum thickness at top was kept as 0.2 m. All the geometrical properties are given in Table 1. M30 concrete and Fe415 steel were selected for the chimney. Linear elastic material behavior was assumed for the chimney. Poisson's ratio of 0.5 and modulous of elasticity of 33.5GPa were considered for the analysis. Density of concrete was taken as 25kN/m^2.

Properties of raft

Annular rafts with uniform thickness are considered for the study. Outer diameter of chimney is taken as 50% more than the chimney shaft at the ground level. Three ratios of outer diameter (D_o) to thickness of raft were chosen. The values are 12.5, 17.5 and 22.5. All the details of the raft are given in table 1. Linear elastic material behavior was considered for the study. M30 concrete and Fe415 steel were chosen as the materials for the raft. Poisson's ratio of 0.5 and modulus of elasticity of 27.39GPa were chosen. Density of concrete was taken as 25kN/m^2.

Table 1. Properties of chimney and raft.

Chimney						Raft				
Height of chimney (m)	Slenderness ratio H/D_b	Diameter at base D_b (m)	Diameter at top D_t (m)	Thickness at bottom (m)	Thickness at top (m)	Outer diameter (m)	Inner diameter (m)	Thickness (m)		
								D_o/t =12.5	D_o/t =17.5	D_o/t =22.5
200	7	29	17.4	0.82	0.35	60	16	4.8	3.42	2.7
	12	17	10.2	0.5	0.2	35	10	2.8	2	1.6
	17	12	7.2	0.35	0.2	26	6	2.08	1.5	1.2

Properties of soil

Three different soils were selected for the analysis. S1,S2 and S3 represent loose sand, medium sand and dense sand. These soils were placed one below the other each with 10m depth. Hard rock was assumed at a depth of 30m. A soil stratum wiith a boundary of 3 times the width of foundation was chosen for the analysis. The soils were defined by their elastic modulus, mass density and angle of friction. Properties of these soils are given in Table 2.

Table 2. Properties of soil

Soil type	Elastic modulus E (kN/m^2)	Poisson's ratio, v	Unit weight, ϒ (kN/m^3)	Angle of friction (^{0})
S1	108000	0.4	16	30
S2	446000	0.35	18	35
S3	1,910,000	0.3	20	40

Calculation of along-wind load as per IS:4998 (part-1)-1992

There are two methods for estimating along-wind and across-wind loads for chimneys as per IS: 4998 (Part 1) - 1992. They are simplified method and random response method. The chimneys are classified as class C structures located in terrain category 2 and subjected to a basic wind speed of 50 m/s.

Simplified Method

The along-wind load or drag force per unit height (N/m) of the chimney at any level is calculated from the equation,

$$F_z=p_z C_D.d_z \qquad (1)$$

Where,

p_z= design wind pressure in N/m^2 at height z, obtained in accordance with IS 875 (Part 3):1987

z = height of any section of chimney in m measured from the top of the foundation

C_D = drag coefficient of the chimney to be taken as 0.8

d_z = diameter of chimney at height z in m

Random response method

The along wind load per unit height at any height z on a chimney is calculated from the equation

$$F_z=F_{zm}+F_{zi} \qquad (2)$$

Where F_{zm} is the wind load in N/m height due to hourly mean wind (HMW) at height z,

$$F_{zm} = \bar{p}_z.C_D.d_z \qquad (3)$$

Where $\bar{p}_z$ is the design pressure at height z due to HMW in N/m^2, $\bar{P}_z = 0.6\bar{V}_z^2$, where $\bar{V}_z^2$ =HMW is the speed in m/s.

F_{zi} is the wind load in N/m height due to the fluctuating component of wind at height z

$$F_{zi} = 3.\frac{(G-1)}{H^2}.\frac{z}{H}.\int_0^H F_{zm}.z.dz \qquad (4)$$

Where,

G is the gust factor which is calculated from the equation

$$G = 1 + g_f.R.\sqrt{B + \frac{SE}{\beta i}} \qquad (5)$$

Where,

g_f = peak factor defined as the ratio of the expected peak value to RMS value of the fluctuating wind load
R= twice the turbulence intensity
B= background factor indicating the slowly varying component of wind load fluctuation
E= a measure of the available energy in the wind at the natural frequency of chimney
S= size reduction factor
βi = coefficient of damping of the structure
H = total height of the chimney in m

Finite element modeling of chimney-raft-soil system

Finite element software ANSYS is used for the modeling and analysis of the chimney-raft-soil system. Chimney and raft were modeled using SHELL181 element. It has both bending and membrane properties. Thickness of chimney was varied throughout the height of the chimney. The chimney and raft were discretized with divisions of 2m in the radial direction and 7.5 degrees in the circumferential direction. SOLID185 was used to model the soil. Three layers of soil each with different properties were modeled. Soil was discretized with divisions of 2m in the radial direction and 7.5 degrees in the circumferential direction. CONTACT174 and TARGET170 was used to create the interaction between the raft and the soil. Bonded contact was selected. The top of the soil and the raft were completely coupled. All the movements were restrained at the bedrock level. All the movements except the movement in the vertical direction were restrained at the lateral boundaries of the soil. Wind loads calculated as per IS codes were applied at an an interval of 10m for the entire height of chimney. Gravity loads were also applied. The finite element model of the chimney-raft-soil system is shown in Fig.1.

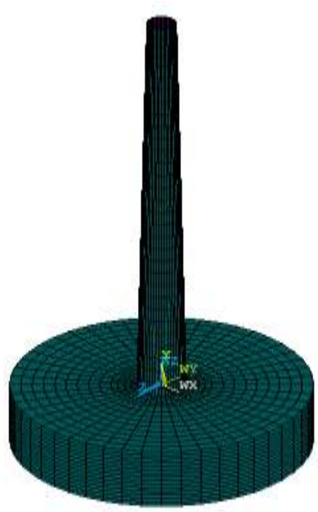

Fig.1 Finite element model of chimney-raft-soil system

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RESULTS AND DISCUSSION

Lateral Tip Deflection

Lateral tip deflection of chimney is obtained from the analysis of chimney with flexible base and fixed base. Lateral deflection of chimney (200m, H/Db=7,12,17) with fixed base, flexible base having single soil profile (S1-loose sand) and variable soil profile (S1,S2,S3) are depicted in graphical form and is shown in Fig.2. The maximum deflection is obtained at the tip of the chimney in all the cases.

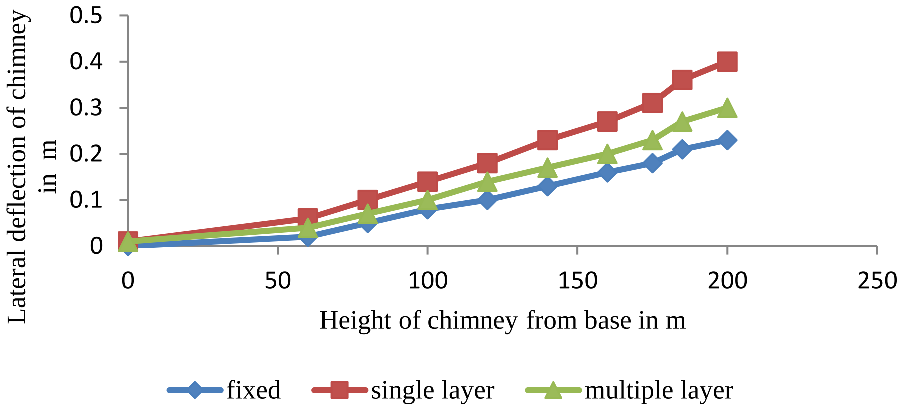

Fig.2 Lateral tip deflection of chimneys(H/D_b=12,D_o/t=22.5)

Contour of lateral deflection for H/D_b=7 and D_o/t=22.5 is shown in Fig.3. All the results are tabulated in Table 3. The lateral deflection of fixed chimney is less compared to chimney when SSI is considered in most of the cases. Chimney with variable soil profile have lesser deflection than that compared to uniform soil profile, the reason accounts to decreasing flexibility of soil. Maximum increase in tip deflection of 74% is found for H/D_b=7 and D_o/t=22.5 for uniform soil profile from fixed base chimney. When variable soil profiles are introduced there is a decrease in 50% from fixed base. It can also be seen that higher the slenderness ratio higher is the lateral tip deflection. It is valid in the entire cases i.e. fixed chimney, single layer of soil and multiple soil layers. Thickness of raft also affects the lateral deflection. Higher the thickness of raft, lesser is the tip deflection. There is a maximum increase in tip deflection of 88% from D_o/t=12.5 to D_o/t=22.5 for H/D_b=7.

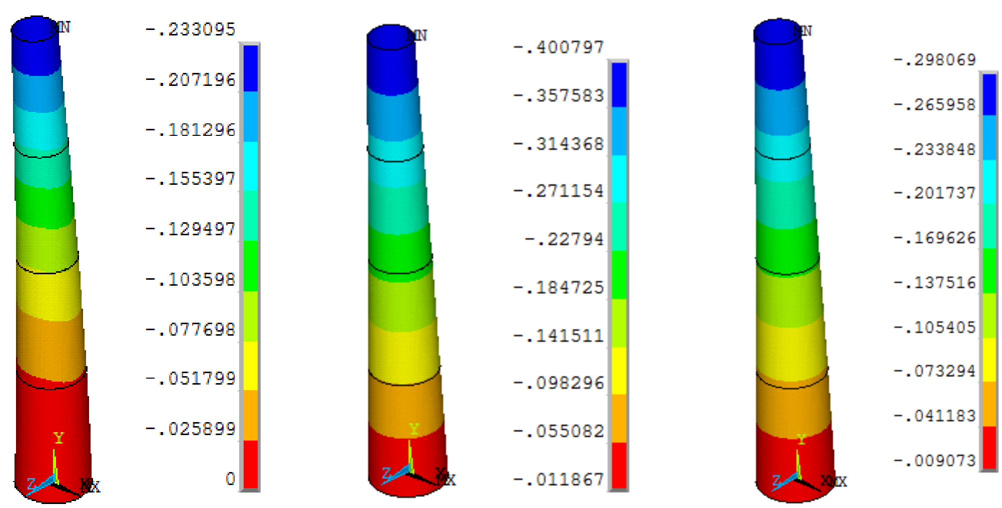

Fig.3 Contour lateral deflection for fixed chimney, uniform soil profile, variable soil profile (H/D_b=7, D_o/t=22.5)

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Table3. Maximum lateral tip deflection

Height of chimney (m)	Slenderness ratio (H/Db)	Lateral tip deflection in m						
		Fixed	Uniform soil profile			Variable soil profile		
			Do/t=12.5	Do/t=17.5	Do/t=22.5	Do/t=12.5	Do/t=17.5	Do/t=22.5
200	7	0.23	0.23	0.31	0.4	0.16	0.23	0.3
	12	0.59	0.48	0.65	0.81	0.38	0.53	0.68
	17	1.24	0.67	0.93	1.18	0.6	0.83	1.07

Settlement in Raft

The contour of settlement of the raft of chimney (H/D_b=7 and D/t=12.5) from SSI analysis due to along wind load is shown in Fig.4. The settlement pattern shows that the raft settles non-uniformly. It is seen that the maximum settlement of raft occurs at the leeward side of the raft and the maximum settlement values are concentrated at certain areas from inner edge to windshield location of chimney. It is also seen that in the leeward side of chimney, the settlement of the raft is almost same from inner edge to windshield location but it drastically decreases from the windshield location to the outer edge of the raft.

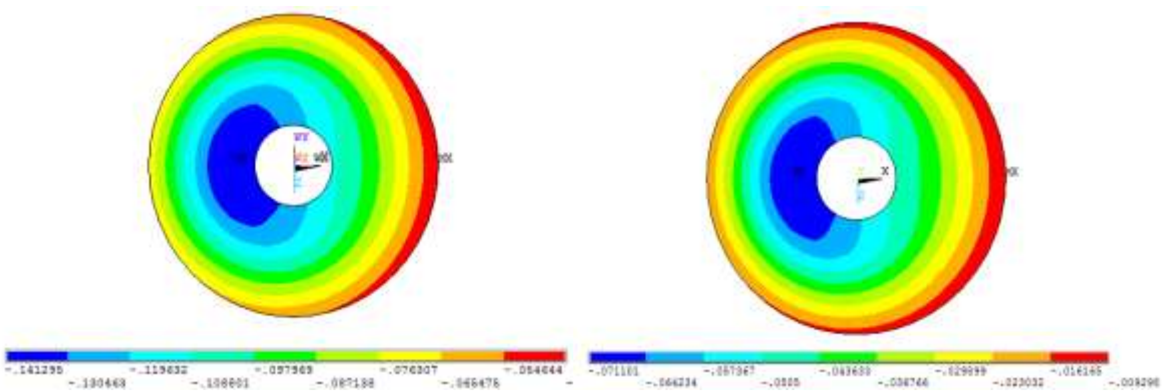

Fig.4 Settlements in raft with uniform soil profile, variable soil profile (H/Db=7, H/t=12.5)

The maximum settlements for the various cases are tabulated. (Table 4). It can be seen from the table that when variable soil profiles are introduced maximum settlement also decreases. There is a maximum of 50% decrease in settlement from uniform soil profile to variable soil profile for H/D_b=7. The elastic settlement at various radial locations of the raft of 200m chimney from SSI analysis due to along-wind load is shown in Fig.5.

Table 4. Maximum settlement in raft due to along-wind load

Height of chimney (m)	Slenderness ratio (H/Db)	Maximum settlement in m					
		Uniform soil profile			Variable soil profile		
		Do/t=12.5	Do/t=17.5	Do/t=22.5	Do/t=12.5	Do/t=17.5	Do/t=22.5
200	7	0.161	0.147	0.140	0.080	0.073	0.071
	12	0.134	0.124	0.121	0.070	0.067	0.067
	17	0.115	0.108	0.106	0.063	0.061	0.062

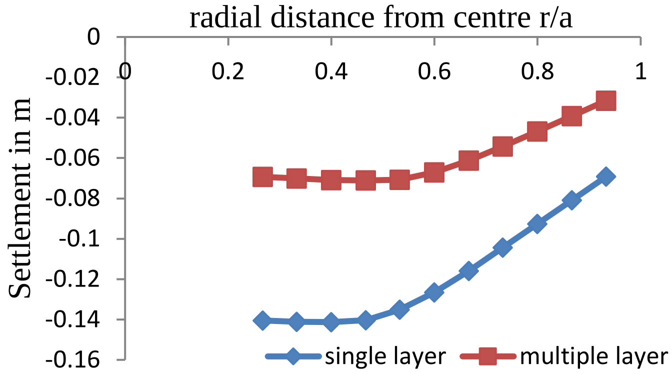

Fig.5 Settlement in raft of chimneys due to along wind load(H/Db=7, D/t=12.5)

To analyse the effect of raft thickness in the settlement behavior of raft, three different diameter to thickness (D_o/t) of raft are chosen, and the values are 12.5, 17.5 and 22.5. Settlement in raft increases with increase in D_o/t ratio. There is a maximum decrease of 13% from D_o/t=12.5 to D_o/t=22.5 for H/D_b=7. As the slenderness ratio increases settlement decreases. There is maximum decrease of 26% from H/D_b=7 to H/D_b=17 in case of single soil profile. For varying soil profile the maximum variation in decrease of settlement is 24% from H/D_b=7 to H/D_b=17.
The maximum permissible settlement as per IS:1904-1986 is 0.075m. In most of the cases, the value as per SSI analysis exceeds 0.075m in case of loose sand. Construction of chimneys on soil in which the settlement is more than 0.075m is not desirable from the geotechnical point of view as per Indian standards.

CONCLUSION

SSI analysis was carried out for tall reinforced concrete industrial chimneys with annular raft foundation on different soil layers with varying flexibility subjected to, along wind loads. Slenderness ratio of chimney and ratio of outer diameter to thickness of annular raft foundation were varied to study the effect of combined stiffness of structure-raft and soil system. Different soil layers are introduced beneath the annular raft foundation to study the effect of varying flexibility of soil.
The along wind loads were calculated as per IS: 4998(Part-1):1992 and applied on chimneys along their height. The lateral deflection of chimney and settlement in raft was obtained.
The following general observations are drawn from the interaction analysis of chimney-raft and soil system.

- The lateral deflection of the chimney is found to be the highest for fixed chimney. When SSI is considered, the deflection reduces.
- The maximum tip deflection is obtained at the top of the chimney in all the cases.
- As the slenderness ratio increases, the lateral deflection in chimney also tends to increase.
- Higher the thickness of raft, lesser is the tip deflection.
- Raft settles non-uniformly with maximum settlement near the inner edge of the chimney.
- Maximum settlement occurs at the leeward side of the chimney, with maximum settlement at the inner edge of the raft.
- When the stiffness of soil below the raft increases value of maximum settlement decreases.

As a whole it can be stated that the responses in chimneys are affected by

- Flexibility of soil below the raft.
- Slenderness ratio of chimney.
- Ratio of diameter to thickness of raft.

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