International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

Across Wind Response of Tall Reinforced Concrete Chimneys Considering the Flexibility of Soil

Jisha S. V.
Ph.D Scholar,
Dept. of Civil Engg.,
National Institute of Technology
Karnataka, India

Dr. B. R. Jayalekshmi
Associate Professor,
Dept. of Civil Engg.,
National Institute of Technology
Karnataka, India

Dr. R. Shivashankar
Professor,
Dept. of Civil Engg.,
National Institute of Technology
Karnataka, India

Abstract

A three dimensional soil-structure interaction (SSI) analysis of tall slender reinforced concrete chimneys with annular raft foundation subjected to across wind load is carried out in the present study. Different ratios of external diameter to thickness of the annular raft and different ranges of height of the chimneys were selected for the parametric study. To understand the significance of SSI, four types of soils were considered based on their flexibility. The chimneys were assumed to be located in terrain Category 2 and subjected to a maximum wind speed of 50m/s as per IS:875 (Part 3):2003. The across wind load was computed according to IS:4998 (Part 1):1992. The integrated chimney-foundation-soil system was analysed by finite element software ANSYS based on direct method of SSI assuming linear elastic behaviour. Structural response in terms of deflection of chimney and base moments of chimney were evaluated from the SSI analysis and the results were compared with that obtained from chimney model with rigid base.

1. Introduction

The tall chimney structures are used to discharge the pollutants to atmosphere at higher elevations. Chimneys are being constructed with slender dimensions and tapering geometry. The analysis of chimney under wind and seismic load should be treated separately from that of other forms of tower structure because of their unique geometry.

The SSI problem has become an important feature of structural and geotechnical engineering, particularly for the massive constructions on soft soils such as nuclear power plants, bridges, chimneys etc. Analysis of chimney is generally carried out assuming fixed base ignoring their foundation and flexibility of underlying soil. Many recent researches showed that the flexibility of soil affects the dynamic response of the chimneys especially under earthquake force. There are a few studies available for the across and along-wind response of the tall chimney with their foundations considering the flexibility of soil.

2. Literature Review

The effect of wind on tall structures has two components, namely along wind and across wind. Along-wind loads are accompanied by 'gust buffeting' causing a dynamic response in the direction of the mean flow due to the drag component of the wind force on the chimney. The across-wind loads are associated with the phenomenon of 'vortex shedding' which causes the chimney to oscillate in a direction perpendicular to the direction of wind flow due to lift component of the wind force. The concept of wind force calculation is given in most design codes for chimneys [1-3]. Davenport [4] devised the gust factor method and this method has been widely used for along wind calculation during the past three decades. Following Davenport's formulation, several researchers [5-6] suggested various modifications to the gust factor method. Menon and Rao [7-8] reviewed the prevailing international codal recommendations to determine the design along-wind and across wind moments in reinforced concrete chimneys. Different expressions for the across wind response were formulated in refs [9-12].

Pour and Chowdhury [13] proposed a semi analytic mathematical model of SSI of tall chimneys based on both seismic and aerodynamic response. It is found that while interacting with soft soils and when compared to analysis of chimney with fixed base, the base moment of the tall chimney may increase up to 10% due to longitudinal wind load and decrease up to 50% due to across wind load. This variation of base moment may affect the design forces of chimney. The effect of soil-structure interaction of tall reinforced concrete industrial chimneys with annular raft foundation due to along wind load was studied in ref [14] and found that due to the effect of flexibility of supporting soil there is a considerable reduction in the bending moments in the annular raft foundation

3. Direct Method of SSI

There are two major methods for analysing the SSI problems: the direct method and substructure method. In direct method, the entire soil-foundation-structure system is modelled and analysed in a single step. In this method, the structure and a finite bounded soil zone adjacent to the structure (near field) are modeled by the standard finite-element method and the effect of the surrounding unbounded soil (far field) is analyzed approximately by imposing transmitting boundaries along the near-field/far-field interface. Computational effort is more in direct method. In substructure method the interaction region can be chosen to coincide with the interface of bounded and unbounded domain. There are so many numerical methods available to solve the soil-structure interaction problem namely the finite element method [14], boundary element method, hybrid (FE-BE) method [15], finite–infinite element method [16].

From an extensive literature review, the superiority of the finite element method in modeling of complete structure-foundation-soil system under direct method of SSI is noticed. In the present study, three dimensional finite element analysis was carried out for a chimney structure with annular raft foundations considering the flexibility of soil under across wind load based on direct method of SSI.

4. Structural Characteristics of the Model

For the present study, chimneys with height ranges from 100m to 400m were selected. The ratio of height to base diameter (slenderness ratio), the ratio of top diameter to base diameter (taper ratio), the ratio of base diameter to thickness at bottom were taken as 12, 0.6 and 35 respectively for the chimney structure. The thickness at top of chimney was taken as 0.4 times the thickness at bottom but the minimum thickness at top was kept as 0.2m. The base of the chimney was supported on rigid annular raft foundation with uniform thickness. The outer diameter of raft was taken as nearly the twice of base diameter of chimney [2]. Chimneys with various thickness of raft foundation corresponding to outer diameter to thickness ratios (raft-thickness ratio, Do/t) of 12.5, 17.5 and 22.5 were considered to study the effect of thickness of foundation. Details of different geometric parameters of chimney and annular raft foundation are given in Table 1 and Table 2 respectively. M30 grade concrete and Fe 415 grade steel were selected as the materials for both chimney and raft.

5. Geotechnical Characteristics of the Model

An elastic continuum soil model was used in the study. The soil is a semi-infinite medium, an unbounded domain. For static loading, a fictitious boundary at a sufficient distance from the structure, where the response is expected to have died out from a practical point of view, can be introduced [17]. This leads to a finite domain for the soil which can be modeled similar to the structure. The total discretized system, consisting of the structure and the soil can then be analysed as per the direct method of SSI.

To study the effect of SSI, four types of soil were considered based on the shear wave velocity of soil. S1, S2, S3 and S4 are the soil types which represent loose sand, medium sand, dense sand and rock respectively. The soil properties are given in Table 3. The lateral boundaries of soil were taken as four times the breadth of foundation. The bedrock was assumed at a depth of 30m.

Table 1. Geometric parameters of chimney

Height of Chimney H (m)	Diameter at base Db (m)	Diameter at top Dt=0.6Db (m)	Thickness at base Tb=Db/35 (m)	Thickness at top Tt (m)
100	8.5	5.1	0.3	0.2
200	17	10.2	0.5	0.2
400	33.5	20.1	1	0.4

Table 2. Geometric parameters of annular raft

Height of Chimney H (m)	Annular Raft				
	External diameter Do (m)	Internal diameter Di (m)	Thickness, t (m)		
			Do/t =12.5	Do/t =17.5	Do/t =22.5
100	20	6	1.6	1.2	0.9
200	35	10	2.8	2	1.6
400	86	16	6.88	5	3.9

Table 3. Properties of the soil types

Soil types	Shear wave velocity , Vs (m/sec)	Poisson's ratio, υ	Density , γ (kN/m^3)	Elastic modulus , E (kN/m^2)
S1	150	0.4	16	102752
S2	300	0.35	18	445872
S3	600	0.3	20	1908257
S4	1200	0.3	20	7633028

6. Estimation of Across Wind Load as per IS:4998 (Part 1) 1992

There are two methods for estimating wind loads for chimneys as per IS: 4998 (Part 1):1992. They are simplified method and random response method. These chimneys are classified as Class C structures located in terrain Category 2 and subjected to a maximum wind speed of 50 m/s. Terrain Category 2 is an open terrain with well scattered obstructions having heights generally between 1.5m and 10m, IS:875 (Part 3):2003 [18].

6.1. Simplified Method

The amplitude of vortex excited oscillation perpendicular to direction of wind for any mode of oscillation shall be calculated by the formula

$$\eta_{oi} = \frac{\int_0^H d_z \phi_{zi} d_z}{\int_0^H \phi_{zi}^2 d_z} \times \frac{C_L}{4\pi S_n^2 K_{si}} \qquad (1)$$

where

η_{oi} = peak tip deflection due to vortex shedding in the i^{th} mode of vibration (m)

C_L = peak oscillatory lift coefficient, 0.16

H = height of chimney (m)

K_{si} = mass damping parameter for the i^{th} mode of vibration

S_n= Strouhal number, 0.2

ϕ_{zi} = mode shape function normalized with respect to the dynamic amplitude at top of the chimney in the i^{th} mode of vibration

Periodic response of the chimney in the i^{th} mode of vibration is very strongly dependent on a dimensionless mass damping parameter K_{si} calculated by the formula

$$K_{si} = \frac{2m_{ei}\delta_s}{\sigma d^2} \quad (2)$$

where

m_{ei} = equivalent mass per unit length (kg/m) in the i^{th} mode of vibration

$$m_{ei} = \frac{\int_0^H m_z \phi_{zi}^2 d_z}{\int_0^H \phi_{zi}^2 d_z} \quad (3)$$

δ_S = logarithmic decrement of structural damping

σ = mass density of air = 1.2 kg/m^3

d = effective diameter taken as average diameter over the top 1/3 height of the chimney (m)

The sectional shear force (F_{zoi}) and bending moment (M_{zoi}) at any height zo, for the i^{th} mode of vibration, shall be calculated from the following equation

$$F_{zoi} = 4\pi^2 f_i^2 \eta_{oi} \int_{zo}^{H} m_z \phi_{zi} dz \quad (4)$$

$$M_{zoi} = 4\pi^2 f_i^2 \eta_{oi} \int_{zo}^{H} m_z \phi_{zi} (z - zo) dz \quad (5)$$

where

f_i = Natural frequency of chimney (Hz) in the i^{th} mode of vibration

m_z = Mass per unit length of the chimney at section z (kg/m)

6.2. Random Response Method

Calculation of across-wind load is made by first calculating the peak response amplitude at the specified mode of vibration (usually the first or second). The taper of all chimneys under consideration was less than 1in 50. The relevant expressions for chimneys with taper less than or equal to 1 in 50 is given below. Taper is defined as {2 (d_{av}-d_{top})/H} where d_{av} is the average outer diameter over the top half of chimney and d_{top} is the outer diameter at top of chimney.

For chimney with little or no taper (average taper over the top one-third height is less than or equal to 1 in 50) -the modal response, at a critical wind speed is calculated by the formula

$$\eta_{oi} = \frac{\dfrac{1.25\overline{C}_L d\phi H_i}{\pi^2 S_n^2} \times \dfrac{\sigma d^2 \sqrt{\dfrac{\sqrt{\pi}L}{2(\cap+2)}}}{m_{ei}}}{\left(\dfrac{1}{H}\displaystyle\int_0^H \phi_{zi}^2 dz\right)^{\frac{1}{2}} \left(\beta - \left(\dfrac{k_a \sigma d^2}{m_{ei}}\right)\right)^{\frac{1}{2}}} \quad (6)$$

where

$\cap$ =Equivalent aspect ratio=H/d

$\overline{C_L}$ =RMS lift coefficient, 0.12

L= Correlation length in diameters, 1

k_a=Aerodynamic damping co-efficient, 0.5

7. Finite Element Modeling

The integrated chimney-raft-soil system was analysed by finite element method using ANSYS software. The chimney and annular raft foundation were modeled using four node elastic SHELL63 element. The element has six degrees of freedom at each node. SOILD45 elements were used for the 3-D modeling of soil. It is defined by eight nodes having three translation degrees of freedom at each node. The chimney shell was discretised with element of 2m size along height and with divisions of 7.5^0 in the circumferential direction. Chimney properties were varied linearly along the entire height. Annular foundation was discretised into 7.5^0 in the circumferential direction and 1m, 2m, 3m and 4m in the radial direction for 100m, 200m, 300m and 400m chimneys respectively. The wind load was applied in the chimney as equivalent point loads at 10 m intervals along their height after suitably averaging the load above and below each section. The lateral movements at the soil boundaries were restrained. All the movements were restrained at bed rock level. The nodes at the interface of bottom of foundation and top of soil were completely coupled and the integrated chimney-raft-soil system was analysed using direct method of SSI. The analysis was carried out assuming the linear elastic behaviour of the integrated chimney-raft-soil system. Three dimensional finite element model of the whole chimney-raft-soil system was generated using the ANSYS software and is shown in Fig. 1.

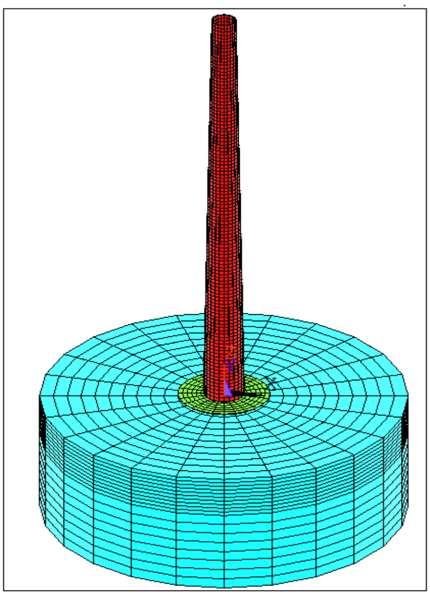


Figure 1. Finite element model of chimney-raft-soil system

The maximum deflection and base moment of chimney structure were evaluated from the SSI analysis of chimney-raft model and the results were compared with that obtained from chimney model with rigid base. The response of the chimney due to the effect of flexibility of soil, thickness of the raft and height of chimney was studied.

8. Results and Discussions

The effect of soil-structure interaction was studied for chimney with raft foundations due to across wind load. The tip deflection and base moment of chimney were investigated.

8.1. Effect of flexibility of soil

To study the effect of SSI, four types of soils were selected namely S1, S2, S3 and S4 representing loose sand, medium sand, dense sand and rock respectively. The deflection and base moment of chimney were investigated considering rigid base and flexible base for the chimney-raft structure.

8.1.1. Deflection of chimney. The deflection at various elevations of the chimney with fixed base and resting on four types of soil are shown in Fig. 2.

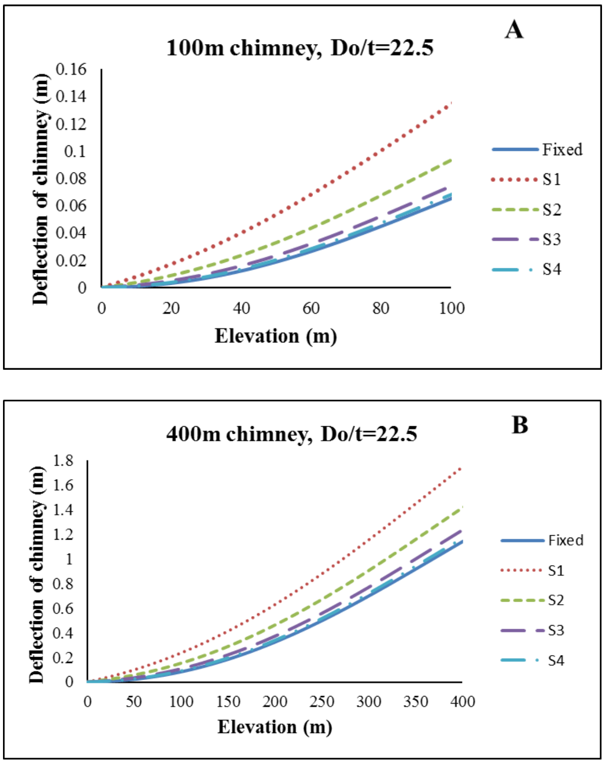
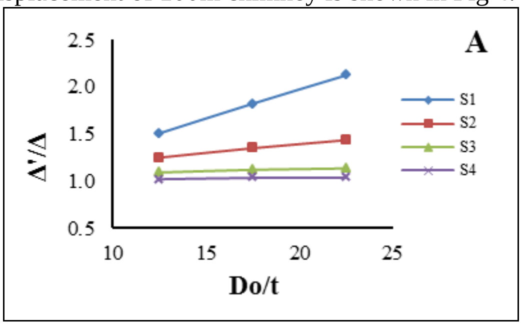


Figure 2. Deflection of chimney (A) 100m (B) 400m

The deflection of chimney increases with increase in flexibility of soil. The normalised values of tip deflection of chimney (Δ'/Δ, ratio of maximum value of tip deflection of chimney with flexible-base to that of fixed-base) were obtained and are shown in Fig. 3. It is seen that the normalised tip deflection of chimney increases with increase in the flexibility of soils for all chimneys under consideration. The soil-structure interaction studies are significant for chimney-raft system founded on soil types S1 and S2 since the normalised value of tip deflection value is more than one. But the chimneys founded on soil type S3 and S4 does not differ much from that of structures modeled as fixed base as the normalised value of tip deflection is nearer to one. The contour of lateral displacement of 100m chimney is shown in Fig 4.



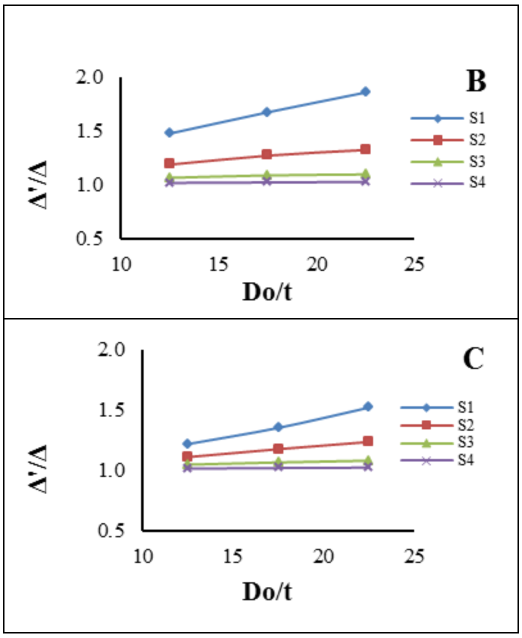


Figure 3. Normalized tip deflection of chimney (A) 100m (B) 200m (C) 400m

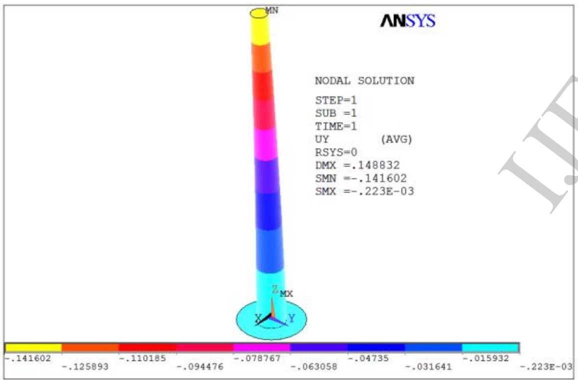


Figure 4. Contour of lateral displacement of 100m chimney

8.1.2. Base moment of chimney. The base moment of chimney was computed according to IS:4998 (Part 1) 1992 considering rigidity at base of the structure and is shown in Table 4.

Table 4. Base moment of chimney with fixed base as per IS:4998 (Part 1) 1992

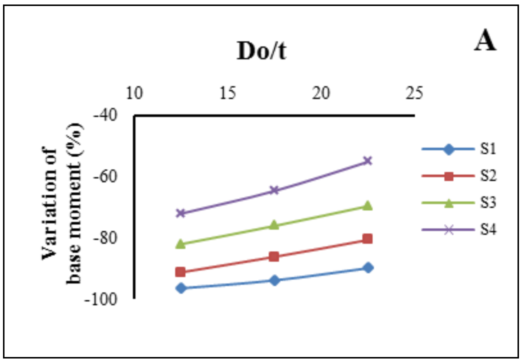
Height of Chimney (m)	100	200	400
Base Moment (kNm) (i) Simplified method	38787	393407	7841886
(ii) Random Response method	20556	259215	5082837

The base moment of the chimney estimated from simplified method is higher than that of the random response method in the across wind analysis of tall chimney as per IS: 4998 (Part 1) 1992. The base moment was evaluated for a chimney-raft structure resting on the soil which has an infinite value of shear wave velocity corresponding to an elastic modulus (E) of 1e15, representing very hard rock.

Table 5. Base moment of chimney from SSI analysis (Do/t=12.5)

Height of Chimney (m)	100	200	400
Base Moment (kNm) S1	1385	7309	95107
S2	3416	15464	213182
S3	6976	30254	455926
S4	10842	48841	786363
Hard Rock	38793	393489	7841890

Table 5 shows the values of base moment of the chimney from the analysis of chimney-raft structure resting on soil with shear wave velocity of 150m/s, 300m/s, 600m/s, 1200m/s and ∞. It is seen that the base moment computed from simplified method of IS: 4998 (Part 1) 1992 is matching with that obtained from the across wind analysis of chimney-raft structure resting on soil with Vs=∞. The base moment of chimney increases with increase in stiffness of the soil. The base moment of chimney obtained from the finite element analysis of chimney-raft structure resting on all types of soils (S1, S2, S3 and S4) is less than that obtained from IS: 4998 (Part1)1992. The percentage variations of base moment of chimneys considering SSI from the simplified method were obtained and are shown in Fig.5.



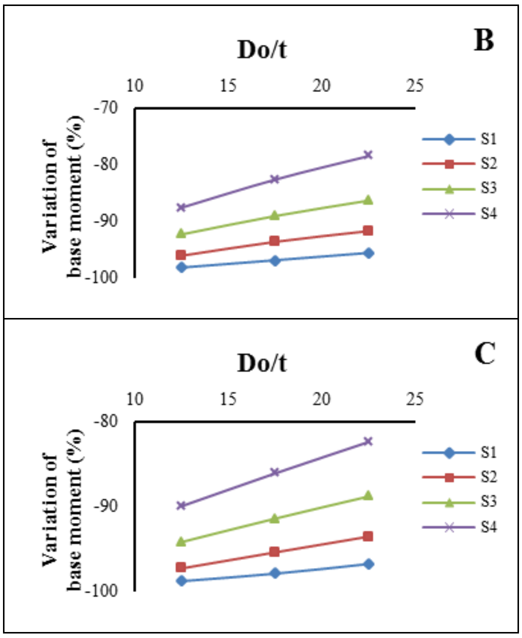


Figure 5. Variation of base moment of chimney (A) 100m (B) 200m (C) 400m

8.2. Effect of thickness of the raft

The effect of thickness of the raft was investigated by considering three different ratios of diameter to thickness (Do/t) of the raft and the values are 12.5, 17.5 and 22.5.

It is found that the normalized tip deflection and base moment of chimney increases with increase in raft-thickness ratio. The 100m chimney with raft resting on soil type S1 shows a decrease in variation of moment of 96% and 89% with increase in the raft-thickness ratio of Do/t=12.5 and Do/t=22.5 respectively. It shows that the stiffness of foundation affect the response of the structure. Therefore analysis of chimney without considering their foundation may mislead the results.

8.3. Effect of height of chimney

The chimneys of height 100m, 200m and 400m were considered to investigate the effect of height of chimney due to the SSI analysis. It is seen that the magnitude of maximum tip deflection of chimney increases with their height but the normalised tip deflections of chimney decreases with the height. There is a little variation of percentage variation of base moment of chimneys with height of 100m and 400m with raft resting on soil type S1. The variations of base moment of chimney for a chimney-raft resting on soil type S3 are 69% for 100m chimney and 88% for 400m chimney. The variations of base moment of chimney increase with height while interacting with stiffer soils.

9. Conclusions

The following conclusions are drawn from the present study.

1. It is necessary to consider the effect of soil-structure interaction for chimneys resting on loose and medium sand because for those SSI models, the normalised value of tip deflection of chimney is more than one.
2. The maximum deflection in chimney increases with increase in raft-thickness ratio.
3. The normalised tip deflection of chimney decrease with increase in height of chimney
4. The base moment of chimney decreases due to the effect of soil-structure interaction
5. The maximum decrease in variation of base moment of chimney can be seen for chimney-raft structure founded on loose soil.
6. The base moment of chimney increases with increase in raft-thickness ratio.

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