Analysis of Foundation of Tall RC Chimney with 3D Finite Element Method

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ABSTRACT

3D finite element (FE) analyses were carried out for 100m and 400m high RC chimneys having piled annular raft and annular raft foundations considering the flexibility of soil subjected to across-wind load. Stiffness of supporting soil and foundation were varied to evaluate the significance of SSI. The integrated chimney-foundation-soil system was analysed by finite element software ANSYS based on direct method of SSI assuming linear elastic material behaviour. FE analyses were carried out for two cases of SSI namely (I) chimney with annular raft foundation and (II) chimney with piled annular raft foundation. The responses in raft such as bending moments and settlements were evaluated for both the cases and compared to those obtained from the conventional method of analysis of annular raft foundation. It is found that the responses in raft depend on the stiffness of the underlying soil and the stiffness of foundation.

INTRODUCTION

There is a high demand for increasing heights of chimneys as they are directly related to social and economic aspects of the country. Heights of industrial chimneys range from a few meters to more than 400m. Chimneys should be analysed differently from other forms of tower structures because of their special geometric features. Wind loads are the predominant forces for tall chimneys. Along wind loads and across loads are the two components of wind loads.

The simplified form of transient wind load is available in most of the design wind codes for chimneys such as IS:4998 (Part 1)-1992, CICIND (2005), ACI 307-2008 etc. The effect of underlying soil flexibility is not considered in the above studies. In reality, chimney and foundation are resting on soil, which may not be rigid. The responses in the chimney and foundation depend on response of the soil and vice versa.

The present study is focused on the three dimensional (3D) SSI analyses of chimney with foundation under across wind load using finite element method.

PROBLEM DEFINITION

Few studies were observed in the area of wind responses on raft considering the three dimensional geometry of superstructure and the soil flexibility. Across wind load analysis was carried for chimneys with annular raft foundation and that with piled raft foundation resting on different types of soil. The integrated chimney-foundation-soil is analysed based on direct method of SSI assuming the linear elastic material behaviour.

Structural and geotechnical characteristics. 100m and 400m tall RC chimneys were selected for the study. The ratio of height (H) to base diameter (D_b), top diameter (D_t) to base diameter and base diameter to thickness at bottom (T_b) were taken as 7, 0.6 and 35 respectively for the chimney structure based on the study conducted by Menon and Rao (1997). The thickness at top of chimney (T_t) was taken as 0.4 times the thickness at bottom but the minimum thickness at top was kept as 0.2m. Two different foundations for chimney were taken and they are annular raft and piled annular raft, having uniform thickness for the raft. The ratio of outer diameter (Do) to thickness (t) of raft was taken as 12.5, 17.5 and 22.5 based on the study conducted Jayalekshmi *et al.* (2011). RC friction piles of 20m length (l) were assumed. For friction piles, the optimum spacing recommended is 3d where d is the diameter of the pile. Spacing of 3d ensures that interference of stress zones of adjacent friction piles is minimum and results in a high group efficiency. The diameter of the pile in the present study was assumed as 1m. Therefore s/d of 3 was selected for the present study. M30 grade concrete and Fe 415 grade steel were selected as the materials for chimney and foundation. The geometric parameters of chimney and foundation are given in Table 1.

Table 1. Geometric parameters of chimney, raft and foundation.

Chimney					Annular raft					No of piles
Height H (m)	Diameter		Thickness		Diameter		Thickness t (m)			
	at base D_b (m)	at top D_t (m)	at base T_b (m)	at top T_t (m)	External Do (m)	Internal Di (m)	Do/t= 12.5	Do/t= 17.5	Do/t= 22.5	
100	14.5	8.7	0.5	0.2	30	9	2.4	1.71	1.33	79
400	57.5	34.5	1.7	0.7	140	20	11.2	8	6.3	1697

Four types of dry cohesionless soil were considered in the analyses and they are S1, S2, S3 and S4 which represents loose sand, medium sand, dense sand and rock respectively. The properties of the soil stratum were defined by its mass density, elastic modulus and poisson's ratio as per Bowles (1997). Angle of friction corresponding to soil type and standard penetration number are given by Meyerhof (Fang, H.Y. ed. 1991). The lateral boundaries of soil were taken as four times the diameter of raft. Bedrock was assumed at a depth of 30m of the soil stratum [Tabatabaiefar and Massumi (2010)]. The properties of the soil stratum are given in Table 2.

Table 2. Properties of the soil types.

Soil types	Poisson's ratio, υ	Density, γ (kN/m³)	Elastic modulus, E (kN/m²)	Angle of friction (°)
S1	0.4	16	102,752	30
S2	0.35	18	445,872	35
S3	0.3	20	1908,257	40
S4	0.3	20	7633,028	45

Across wind load. The chimneys are classified as class *C* structures and assumed to be 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 as per IS:875 (Part 3)-1987. Across wind loads for chimneys were estimated based on Indian standard code, IS:4998 (Part 1)-1992. Two methods are described in this code to estimate the across wind load and they are (i) simplified method and (ii) random response method.

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

$$F_{zoi} = 4\pi^2 f_i^2 \eta_{oi} \int_{zo}^{H} m_z \phi_{zi} dz \quad (1)$$

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

where

f_i = natural frequency of chimney in the i^{th} mode of vibration in Hz
m_z = Mass per unit length of the chimney at section *z* in kg/m
ϕ_{zi} = mode shape function normalized with respect to the dynamic amplitude at top of the chimney in the i^{th} mode of vibration
η_{oi} = peak tip deflection due to vortex shedding in the i^{th} mode of vibration in m

Conventional analysis of annular raft foundation. The basic assumptions of conventional analysis of annular raft foundation given in IS:11089-1984 are i) The foundation is rigid relative to the supporting soil and the compressible soil layer is relatively shallow; and ii) The contact pressure distribution is assumed to vary linearly throughout the foundation. As per IS:11089-1984, the non-uniform pressure distribution under raft is modified to uniform pressure distribution *p*, and is given by $p_1+0.5\ p_2$, where p_1 is uniform pressure due to dead loads (V) and p_2 is pressure due to bending effects (M).

Finite element modeling. In this study, the finite element modeling and analysis was carried out by using the finite element software, ANSYS. In the finite element modeling, the chimney and raft were modeled with SHELL63 elements defined by four nodes having six degrees of freedom in each node. The three dimensional soil stratum and the pile were modeled with SOILD45 elements with eight nodes having three translational degrees of freedom at each node. Elastic continuum approach was adopted for modeling the soil. The surface-surface contact elements were used to evaluate the interaction between pile and soil. The pile surface was established as "target" surface (TARGE170), and the soil surface contacting the pile as "contact" surface (CONTAC174), these two surfaces constitute the contact pair. The coefficient of friction was defined between contact and target surfaces and is shown in Table 2.

The chimney shell was discretised with elements of 2m size along height and with divisions of 7.5^{o} in the circumferential direction. The height and diameter of chimney were varied linearly along the height. Annular foundation was discretised into 7.5^{o} in the circumferential direction. The pile was discretised as 2m size along the length of pile.

The wind load was applied in the chimney as equivalent point loads at 10 m intervals along the height after suitably averaging the load above and below each section. The horizontal translations at the lateral soil boundaries and all the movements at bed rock level were restrained. The finite element analysis was carried out for two cases of SSI; (I) chimney with annular raft and (II) chimney with piled annular raft. Three dimensional finite element model of the whole chimney-foundation-soil system was generated using the ANSYS software and is shown in Figure 1.

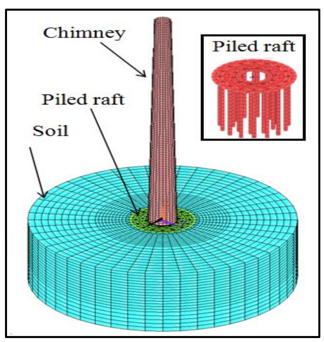

Figure 1. Finite element model of chimney-piled raft-soil system.

The responses in annular raft for the above two cases obtained from finite element method were compared with that from the conventional method. The variation of response in raft due to SSI from conventional method was evaluated.

RESULT AND DISCUSSIONS

The results are presented in terms of tangential and radial bending moments in raft and settlement of raft. The results obtained for first and second cases corresponding to raft and piled raft foundation are designated as *R* and *PR* respectively in graphs and tables. The bending moments evaluated from conventional method is designated as *IS11089* in graphs and tables. Effect of stiffness of soil and effect of stiffness of raft in modifying the response were evaluated.

Effect of stiffness of soil. Four types of soils were considered namely S1, S2, S3 and S4 which represent loose sand, medium sand, dense sand and rock respectively. The responses are maximum at the leeward side of SSI system. The representative graphs for different responses at various radial locations in the leeward side, from inner to outer edge of the raft are shown in Figure 2. The variation of maximum responses of the raft for the two cases of SSI is obtained from conventional analysis and is shown in Table 3.

Variation in tangential moment in raft. The tangential moment in raft obtained from the SSI analysis is compared with that obtained from the conventional analysis and is shown in Figure 2. From the SSI analysis of two cases, it is seen that the tangential bending moment in the raft increases with decrease in stiffness of soil. In conventional analysis, the maximum tangential moment in raft is obtained at inner edge of the raft and it decreases drastically towards the outer edge of the raft. The same pattern is seen for case I resting on soil type S1 and S2. The SSI analysis of case II shows that the maximum tangential moment in raft is obtained at chimney wind shield shell location (r/a=0.48 for 100m chimney and r/a=0.41 for 400m chimney). The same pattern of moment is observed in the raft for case I resting on soil types S3 and S4. This means that the location of maximum tangential moment is shifted from inner to chimney shell location when the stiffness of the supporting soil and stiffness of the foundation increases. The variation of maximum tangential moment in raft is tabulated in Table 3. It is seen that the tangential moment obtained from SSI analysis is less than that obtained from conventional analysis. The reduction of variation in tangential moment from case 1 to case II is 31% for the raft of Do/t=12.5 of 100m chimney resting on loose sand and this is found the maximum reduction due to the addition of piles.

Variation in radial moment in raft. From Figure 2, it is seen that the peak radial moment in raft is located at chimney wind shield location in raft from SSI as well as conventional analysis. The radial moment in raft decreases with increase in the stiffness of the soil. From Table 3, it is noted that the radial moment in raft of case I resting on loose sand and medium sand is more than that obtained from conventional analysis especially for the raft of larger thickness. The variations in moment for case I (Do/t=12.5) of 100m chimney are 95% and 55% for loose sand and medium sand respectively whereas that of 400m chimney are 77% and 37% for loose sand and medium sand respectively. The moment is reduced about 33-43% due to the addition of piles in annular raft resting on loose sand. For the medium sand, the above said reduction is 18-34%.

Variation in settlement of raft. It is observed from Figure 2, that as the soil type varies from loose sand to rock, the settlement of the raft decreases. The settlement pattern shows that the raft settles non-uniformly and maximum settlement is found from inner edge to chimney wind shield location in the leeward side of raft. It is seen that, the soil deformation is negligible for soil type S4 as the raft behave as rigid when interacting with S4. As per IS:1904-1978, the maximum permissible settlement for raft foundation on sand is 0.075m. The maximum settlement of raft for both the cases is tabulated in Table 3. It is noted that the settlement of raft of 400m chimney under case I founded on loose sand is more than the permissible limit. From case I to case II, the reduction in settlement of raft of 400m chimney is 53-62%.

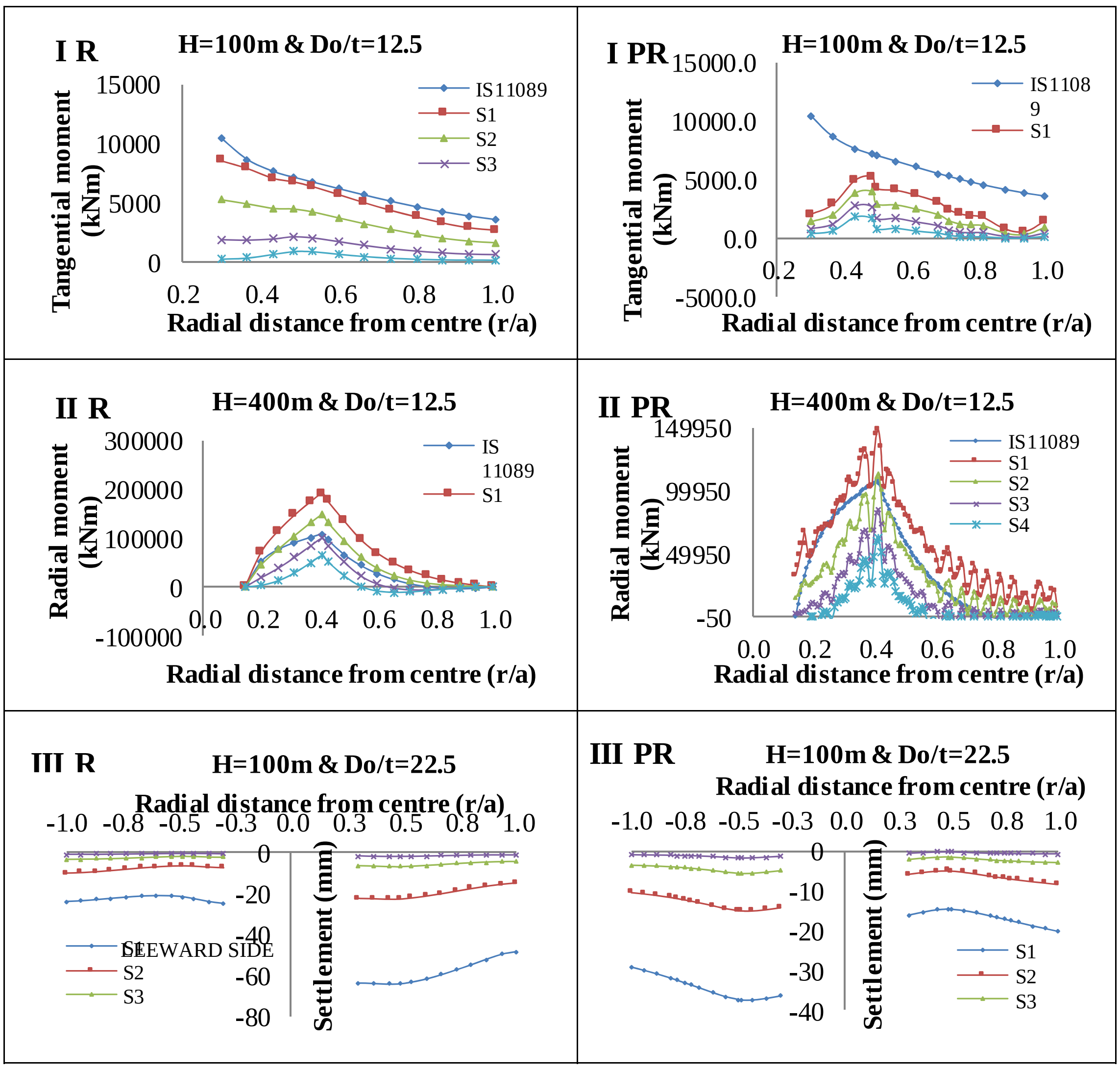

Figure 2. (I) Tangential moment (II) Radial moment and (III) settlement of raft of chimney with raft and pile raft foundations.

Table 3. Maximum response in raft.

Height of chimney (m)	Conventional method (IS11089)	Soil Type	Do/t =12.5		Do/t =17.5		Do/t =22.5	
			R	PR	R	PR	R	PR
Percentage variation of tangential moment (%)								
100	10456.96 kNm	S1	-18.4	-49.8	-44.4	-63.4	-64.4	-73.1
		S2	-49.8	-62.1	-74.8	-74.4	-84.3	-81.2
		S3	-79.7	-74.0	-89.6	-82.4	-93.6	-87.3
		S4	-91.6	-82.9	-95.6	-89.3	-97.3	-93.1
400	210338.65 kNm	S1	-35.3	-36.8	-59.3	-53.6	-70.7	-63.7
		S2	-62.5	-52.9	-77.5	-66.6	-84.5	-74.0
		S3	-81.3	-66.1	-89.1	-76.2	-92.5	-81.7
		S4	-91.1	-76.7	-94.8	-84.2	-96.4	-88.4
Percentage variation of radial moment (%)								
100	3920.78 kNm	S1	95.1	57.8	66.3	23.7	39.4	-2.1
		S2	55.0	21.4	16.9	-12.9	-8.0	-32.5
		S3	2.7	-13.8	-26.1	-39.8	-42.7	-54.4
		S4	-34.1	-42.0	-54.7	-61.3	-67.6	-72.4
400	108264.38 kNm	S1	76.7	36.5	42.9	4.9	19.1	-14.1
		S2	36.2	5.0	1.9	-21.7	-17.9	-35.8
		S3	-8.2	-21.3	-33.2	-41.3	-47.0	-52.3
		S4	-40.4	-42.8	-57.9	-58.0	-67.9	-66.7
Maximum settlement (mm)								
100	As per IS:1904-1986, permissible settlement is 75mm	S1	55.6	33.6	59.5	35.7	64.6	37.5
		S2	19.9	13.7	21.7	14.6	22.9	15.1
		S3	6.3	5.3	6.7	5.5	6.9	5.7
		S4	1.7	1.7	1.8	1.8	1.9	1.9
400		S1	113.9	61.1	121.5	65.0	130.8	69.1
		S2	42.7	26.2	45.6	27.8	48.8	29.4
		S3	14.0	10.8	14.8	11.5	15.7	12.2
		S4	4.1	3.9	4.4	4.2	4.6	4.4

Effect of stiffness of 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 ratios are 12.5, 17.5 and 22.5. The tangential and radial moment in raft increases with decrease in Do/t ratio while the settlement in raft increases with increase in Do/t ratio. The variations of radial moment in raft of case I resting on loose sand from that obtained from conventional analysis are increased by 95%, 66% and 39% for Do/t ratios of 12.5, 17.5 and 22.5 respectively for 100m chimney. It is seen that the settlement of raft from case I to case II is more for raft of Do/t=22.5 compared to raft of Do/t=12.5. For the 400m chimney resting on loose sand, a reduction of 62% of settlement is observed for raft of Do/t=22.5 from case I to case II whereas that of Do/t=12.5, is the reduction 53%.

CONCLUSIONS

The following conclusions are drawn from the present study. (i) Considerable increase in the radial moment in raft due to interaction with loose sand and medium sand as compared to the conventional method. (ii) The location of maximum tangential moment in raft shifted from inner edge to chimney wind shield due to increase in stiffness of foundation and supporting soil. (iii) The settlement of raft is reduced by 62% due to the addition of piles in the annular raft foundation of higher elevation chimney resting on loose sand. (iv) Piles are very effective in reducing the responses in the raft when the chimney founded on loose sand and medium sand. (v) The moment in raft increases with increase in thickness of raft.

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