

## Research Article

# Soil-Structure Interaction Analysis of 300 m Tall Reinforced Concrete Chimney with Piled Raft and Annular Raft under Along-Wind Load

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A three-dimensional (3D) soil-structure interaction (SSI) analysis of 300 m high reinforced concrete chimneys having piled annular raft and annular raft foundations subjected to along-wind load is carried out in the present study. To understand the significance of SSI, four types of soils were considered based on their flexibility. The effect of stiffness of the raft was evaluated using three different ratios of external diameter to thickness of the annular raft. The along-wind load was computed according to IS:4998 (Part 1)-1992. The integrated chimney-foundation-soil system was analysed by commercial finite element (FE) software ANSYS, based on direct method of SSI assuming linear elastic behaviour. FE analyses were carried out for two cases of SSI (I) chimney with annular raft foundation and (II) chimney with piled raft foundation. The responses in chimney such as tip deflection, bending moments, and base moment and responses in raft such as bending moments and settlements were evaluated for both cases and compared to that obtained from the conventional method of analysis. It is found that the responses in chimney and raft depend on the flexibility of the underlying soil and thickness of the raft.

## 1. Introduction

The height of many industrial chimneys in India is more than 200 m. The tallest chimney in India is Dahanu Thermal Power Station's Chimney (1995) at Mumbai with a height of 275.3 m, and chimney of GRES-2 Power Station (1987) at Kazakhstan is the tallest chimney in the world with a height of 419.7 m. The need of increasing the height of chimney is very essential as it is directly related to social and economic aspects of any country. Due to the unique geometrical features like tall, slender, and tapering geometry, the analysis of chimney should be considered separately from other forms of tower structure.

The wind loads are more predominant forces than the seismic loads for very tall chimney. It is very difficult to analyse the chimneys with transient wind loads precisely by available analytical procedures because of uncertain variability of wind, and therefore a designer is forced to use approximate design techniques, Manohar [1]. Most of

the design wind codes for chimney, IS:4998 (Part 1)-1992 [2], CICIND [3], ACI 307-2008 [4], and so forth, simplified the dynamic wind loads by considering two components, namely, a steady wind load component and a fluctuating component. This method is known as gust factor method, which is derived by Davenport [5] and modified by researchers Simiu [6] and Solari [7], and it is mainly used to compute the wind loads in the along-wind direction.

In addition to the along-wind load, chimneys are subjected to loading in the direction transverse to the along-wind. This is called across-wind load, and it is associated with the phenomenon of vortex shedding which causes transverse aerodynamic loads and consequent transverse oscillations. Many studies have been conducted and different expressions were formulated by several researchers like Vickery and Clark [8], Kwok and Melbourne [9], Davenport [10], Melbourne [11], and so forth to evaluate the response of structures due to across-wind. Wind response of chimney was studied by

John et al. [12], Kawecki and Zurański [13], Harte and van Zijl [14], and Arunachalam et al. [15].

The effect of foundation and underlying soil flexibility is not considered in the above studies of wind load analysis of structure. Annular raft foundations are more reasonable and economical than the full circular raft for chimney. If the ground conditions are not suitable for raft foundations, piled foundations can also be used. Skin friction piles are more suitable to chimney foundations than end bearing piles, since greater uplift capacity is generally available (CICIND [16]). SSI effect on raft foundation was studied by Melerski [17] and Brown [18]. Many researches (Nguyen et al. [19], Huang et al. [20], Lee et al. [21], Chaudhary [22], and Mendonça and de Paiva [23]) have been conducted to study the interactions between the components of a piled raft foundation such as the piles, raft, and soil. The effectiveness of raft foundation and the contribution of raft on piled raft were studied by Leonga and Huat [24]. The effect of stiffness of superstructure is not considered in these studies.

In reality, chimney and foundation rest on soil, which may not be rigid. The response of the chimney and foundation depends on response of the soil and vice versa. This related behaviour between the soil and the structure is known as soil-structure interaction (SSI). Winkler spring model (Jayalekshmi et al. [25], Bowles [26], and Chowdhury and Dasgupta [27]) and finite element models of an elastic continuum (Rajasankar et al. [28] and Tabatabaiefar and Massumi [29]) are the two generally used soil models for SSI. Studies by Pour and Chowdhury [30] and Jayalekshmi et al. [25] have proved that due to the flexibility of underlying soil, the structural response may increase or decrease when compared to conventional method of analysis in which the base of the structure is rigid, and hence such massive structures need to be analysed by incorporating the effects of SSI.

The limited studies in the area of 3D SSI analysis of chimney with foundation under along-wind load focus the scope of this paper. In the present study, three-dimensional finite element analyses were carried out for a 300 m high chimney with annular raft and piled annular raft foundations considering the flexibility of soil under along-wind load. Along-wind load caused maximum base moment in chimney, and hence the structural response was studied for this wind load.

## 2. Problem Definition

The problem under investigation consisted of industrial RC chimneys with annular raft or piled raft foundation resting on different types of soil subjected to along-wind load. The integrated chimney-foundation-soil is analysed based on direct method of SSI in which analysis of structure and soil is carried out in single step.

*2.1. Structural Characteristics.* A 300 m high chimney was selected for the study. The ratio of height to base diameter, top diameter to base diameter, and base diameter to thickness at bottom were taken as 12, 0.6, and 35, respectively, for the chimney structure based on the study conducted by

Menon and Rao [31] and Jayalekshmi et al. [25]. The thickness at top of chimney was taken as 0.4 times the thickness at bottom. According to these ratios, the base diameter and the top diameter of chimney were selected as 25 m and 15 m respectively. The thickness of chimney at base and top were taken as 0.7 m and 0.3 m, respectively.

Two different foundations were taken for the present study, and they are annular raft, and piled annular raft, respectively. The raft part of both foundations was of uniform thickness. The overall diameter of a raft for a concrete chimney is typically 50% greater than the diameter of the chimney windshield at ground level (CICIND [16]). Therefore, the outer diameter and the inner diameter of the raft were selected as 60 m and 12 m, respectively. To study the effect of foundation flexibility, the thickness of raft was varied as 4.8 m, 3.4 m, and 2.7 m, respectively, corresponding to outer diameter to thickness ratios ( $D_o/t$ , raft-thickness ratio) of 12.5, 17.5, and 22.5 (Jayalekshmi et al. [25]). RC friction piles of 1 m diameter ( $d$ ) and 20 m length ( $l$ ) such that  $l/d = 20$ , and provided at spacing ( $s$ ) of 3 m ( $s/d = 3$ ), were considered for the study based on general design. Piled raft foundation consisted of 306 such piles. M30 grade concrete and Fe 415 grade steel were selected as the materials for chimney and foundation.

*2.2. Geotechnical Characteristics.* Four types of dry cohesionless soil were considered in the analyses, and they are S1, S2, S3, and S4 which represent dry loose sand, dry medium sand, dry dense sand, and rock, respectively. The properties of the soil stratum were defined by its mass density, shear modulus of elasticity, and Poisson's ratio as per Bowles [26], and it is given in Table 1. Bedrock was assumed at a depth of 30 m of the soil stratum (Tabatabaiefar and Massumi [29]). The lateral boundaries of soil were taken as four times the diameter of raft for which the response due to static load is expected to die out (Wolf [32]).

## 3. Estimation of Along-Wind Load as per IS:4998 (Part 1)-1992

There are two methods for estimating along-wind load for chimneys as per IS:4998 (Part 1)-1992 [2]. 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. According to IS:875 (part 3)-1987 [33], terrain category 2 is an open terrain with well-scattered obstructions having heights generally between 1.5 m and 10 m.

*3.1. Simplified Method.* The along-wind load or drag force per unit height (N/m) of the chimney at any level is calculated from

$$F_z = p_z \cdot C_D \cdot d_z, \quad (1)$$

where  $p_z$  = design wind pressure in  $\text{N/m}^2$  at height  $z$ ,  $z$  = height of any section of chimney from top of foundation in m,  $C_D$  = 0.8 drag coefficient of chimney, and  $d_z$  = diameter of chimney at height  $z$  in m.

TABLE 1: Properties of the soil types.

Soil types	Elastic modulus, $E$ (kN/m <sup>2</sup> )	Poisson's ratio, $\nu$	Density, $\gamma$ (kN/m <sup>3</sup> )	Shear modulus, $G$ (kN/m <sup>2</sup> )	Angle of friction (°)
S1	102,752	0.4	16	36,697	30
S2	445,872	0.35	18	165,138	35
S3	1908,257	0.3	20	733,945	40
S4	7633,028	0.3	20	2935,780	45

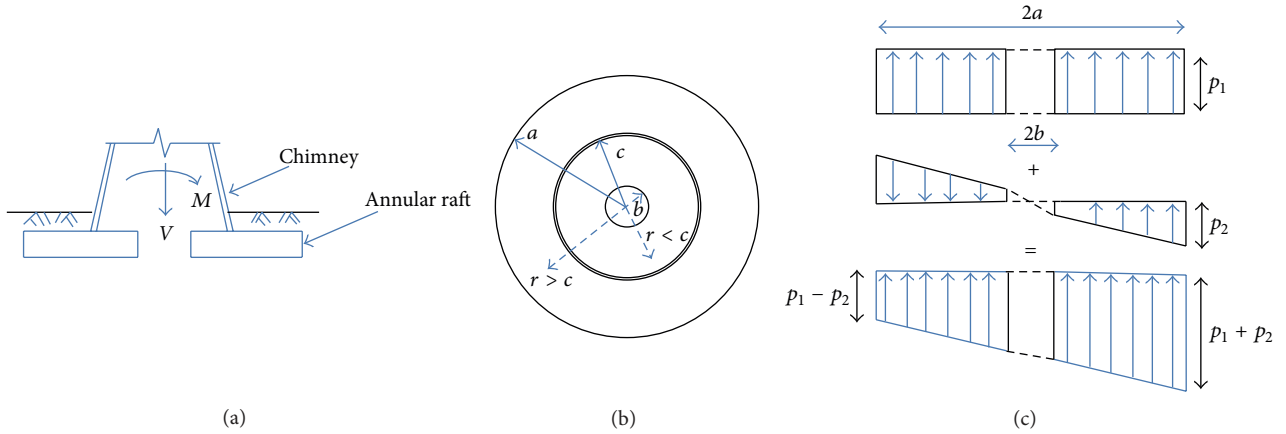


FIGURE 1: (a) Cross-sectional elevation of chimney and annular raft foundation. (b) Plan view of chimney and annular raft foundation. (c) Pressure distribution under the annular raft due to dead weight and bending moment.

3.2. *Random Response Method.* The along-wind load per unit height at any height  $z$  on a chimney is calculated from

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

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

$$F_{zm} = \bar{p}_z \cdot C_D \cdot d_z, \quad (3)$$

where  $\bar{p}_z$  is the design pressure at height  $z$ , due to HMW in N/m<sup>2</sup>,  $\bar{p}_z = 0.6 \bar{V}_z^2$ , where  $\bar{V}_z =$  HMW speed in N/m<sup>2</sup>, and  $F_{zi}$  is the wind load in N/m height due to the fluctuating component of wind at height  $z$ :

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

where  $G$  is the gust factor which is calculated from

$$G = 1 + g_f \cdot r \cdot \sqrt{B + \frac{SE}{\beta}}, \quad (5)$$

where  $g_f$  = peak factor defined as the ratio of the expected peak value to RMS value of the fluctuating 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,  $\beta$  = coefficient of damping of the structure, and  $H$  = total height of the chimney in m.

#### 4. Analysis of Annular Raft Foundation as per IS:11089-1984

The basic assumptions of conventional method of analysis of annular raft foundation given in IS:11089-1984 [34] are (i) the foundation which 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. The cross-sectional elevation and plan of chimney with annular raft foundation and the pressure distribution under annular raft are given in Figure 1. As per IS:11089-1984 [34], the nonuniform pressure distribution under annular raft is modified to uniform pressure distribution  $p$  and is given by  $p_1 + 0.5p_2$ , where  $p_1$  is uniform pressure due to dead loads ( $V$ ), and  $p_2$  is pressure due to bending effects ( $M$ ) as shown in Figure 1. The formulae for circumferential and radial moments  $M_t$  and  $M_r$ , respectively, are given below.

For  $r < c$

$$M_t = \frac{pa^2}{16} \left[ \left\{ 4 \left( 1 + \frac{b^2}{r^2} \right) \left( \log_e \frac{a}{c} + \frac{1}{2} - \frac{c^2}{2a^2} \right) \right\} + \frac{r^2}{a^2} - \frac{4b^2}{a^2} \left\{ \log_e \frac{r}{a} + \frac{3}{4} \left( \frac{1}{3} + \frac{a^2}{b^2} + \frac{a^2}{r^2} \right) - \frac{a^2 + r^2}{a^2 - b^2} \cdot \frac{b^2}{r^2} \log_e \frac{a}{b} \right\} \right],$$

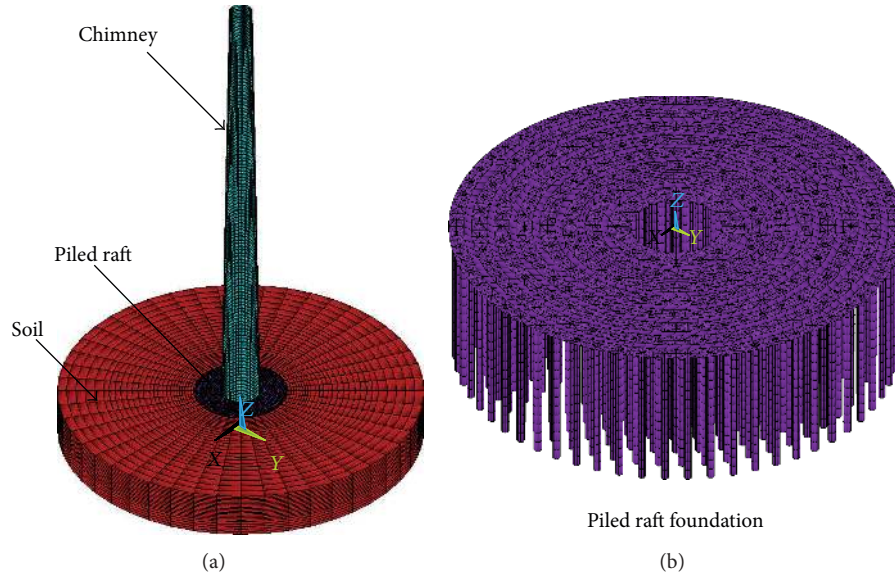


FIGURE 2: Finite element model of (a) integrated chimney-piled raft-soil system (b) piled raft foundation.

$$M_r = \frac{pa^2}{16} \left[ \left\{ 4 \left( 1 - \frac{b^2}{r^2} \right) \left( \log_e \frac{a}{c} + \frac{1}{2} - \frac{c^2}{2a^2} \right) \right\} + \frac{3r^2}{a^2} - \frac{4b^2}{a^2} \left\{ \log_e \frac{r}{a} + \frac{3}{4} \left( 1 + \frac{a^2}{b^2} - \frac{a^2}{r^2} \right) + \frac{a^2 - r^2}{a^2 - b^2} \cdot \frac{b^2}{r^2} \log_e \frac{a}{b} \right\} \right]. \quad (6)$$

For  $r > c$

$$M_t = (M_t)_{r < c} + \frac{pa^2}{16} \left[ 4 \left( 1 - \frac{b^2}{a^2} \right) \left( \log_e \frac{c}{r} + \frac{1}{2} - \frac{c^2}{2r^2} \right) \right],$$

$$M_r = (M_r)_{r < c} + \frac{pa^2}{16} \left[ 4 \left( 1 - \frac{b^2}{a^2} \right) \left( \log_e \frac{c}{r} - \frac{1}{2} + \frac{c^2}{2r^2} \right) \right], \quad (7)$$

where  $a$  and  $b$  are the outer and inner radius of annular raft, respectively,  $r$  is the radial distance, and  $c$  is the radius of chimney windshield at base.

## 5. Finite Element Modeling

In this study, the finite element modeling and analyses were carried out by using the commercial finite element software. 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 is modeled with SOILD45 elements with eight nodes having three translational degrees of freedom at each node. The pile is also modeled using SOILD45 elements. 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 to comprise the contact pair. The coefficient of friction was defined between contact and target surfaces and is shown in Table 1.

The chimney shell was discretised with element of 2 m size along height and with divisions of 7.5° in the circumferential direction. Chimney properties were varied linearly along the height. Annular foundation was discretised into 7.5° in the circumferential direction.

The materials for chimney and foundation were selected as M30 grade concrete and Fe 415 grade steel. The modulus of elasticity for chimney was taken as 33.5 Gpa as per IS:4998 (Part 1)-1992 [2] and that for foundation was taken as 27.39 Gpa. The Poisson's ratio and density of concrete were taken as 0.15 and 25 kN/m<sup>3</sup>, respectively, for both chimney and foundation.

Elastic continuum approach was adopted for modeling the soil. The material properties such as elastic modulus, Poisson's ratio, and density for the three-dimensional soil stratum were taken from Table 1. 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 raft and top of soil were completely coupled. Three-dimensional finite element model of the whole chimney-piled raft-soil system was generated using the commercial finite element software and is shown in Figure 2.

The wind load computed as per IS:4998 (Part 1)-1992 [2] was applied in the chimney as point loads at 10 m intervals along its height after suitably averaging the load above and below each section. The integrated chimney-foundation-soil system was analysed based on direct method of SSI by assuming the linear elastic behaviour of the whole system. For along-wind, the loads were applied in the horizontal Y



direction of chimney. The gravity load was also applied to the SSI model.

The effect of soil-structure interaction was studied for a 300 m high industrial RC chimney with annular raft and piled raft under along-wind load. FE analyses were carried out for two cases of soil-structure interaction (I) chimney with annular raft (II) chimney with piled raft. The results obtained for chimney from both cases of FE analysis were compared with that obtained from the analysis of chimney with rigid base. The results obtained for raft from both cases of FE analysis were compared with that obtained from conventional method (IS:11089-1984 [34]) of analysis of annular raft foundations. The results evaluated for chimney are presented in terms of lateral tip deflection, tangential and radial bending moments, and base moments. The responses obtained for raft are presented in terms of tangential and radial bending moments and settlements. The effect of soil-structure interaction on the above response was studied based on four different types of soil, according to their flexibility and three different ratios of outer diameter to thickness of raft. The results obtained for chimneys with raft foundation and piled raft foundation are designated as R and PR, respectively, in graphs and tables. The bending moments of the raft evaluated from conventional method is designated as *IS11089* in graphs. The results obtained from the FE analysis of chimney with rigid base is represented as *Fixed* in graphs.

### 6. Result and Discussions

SSI studies were conducted for chimney with annular raft and piled raft foundations under along-wind loads. The responses in chimney such as tip deflection, bending moments, and base moments and responses in raft such as bending moments and settlement were investigated.

**6.1. Effect of Flexibility of Soil.** Four types of soils were selected, namely, S1, S2, S3, and S4 which represent loose dry sand, medium dry sand, dense dry sand, and rock, respectively, in order to study the effect of soil-structure interaction. The responses in chimney and raft were investigated considering rigid and flexible base of chimney-raft system.

**6.1.1. Lateral Tip Deflection of Chimney.** The lateral tip deflection of chimney is obtained from the analysis of chimney with flexible base and rigid base. The lateral deflection at various elevations of the chimney with annular raft foundation resting on four types of soil and that of chimney with rigid base is shown in Figure 3. It is found that the deflection of chimney increases with increase in flexibility of soil. The contour of lateral displacement of 300 m chimney with flexible base and rigid base are shown in Figure 4. The tip deflection is tabulated in Table 2. It is seen that the tip deflection of chimney obtained from the analysis of chimney with rigid base is lower than that from the SSI analysis. Maximum increase in tip deflection of 63.97% is found for chimney with annular raft ( $D_o/t = 22.5$ ) under flexible soil type S1 from

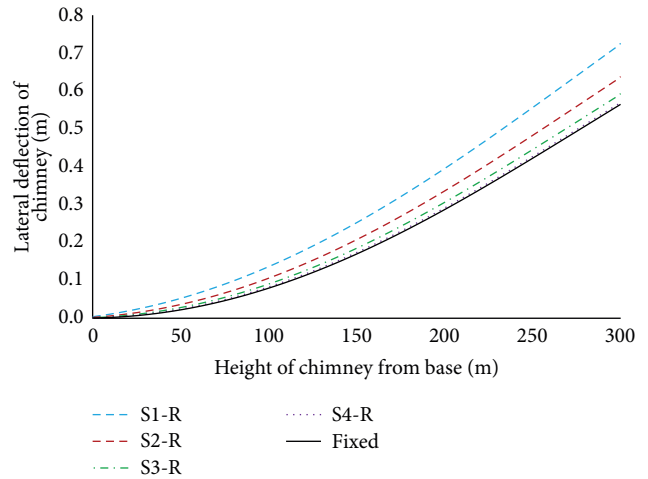


FIGURE 3: Lateral deflection of chimney for case I ( $D_o/t = 12.5$ ).

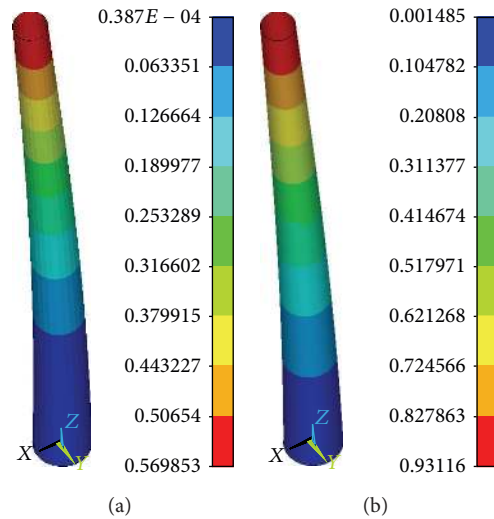
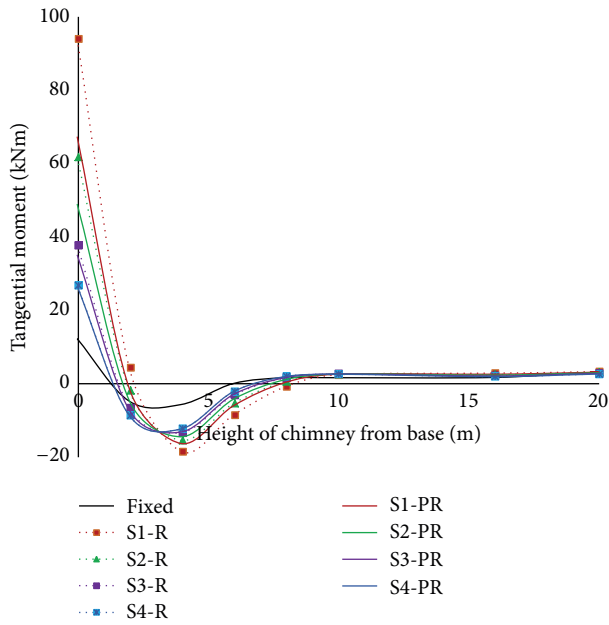


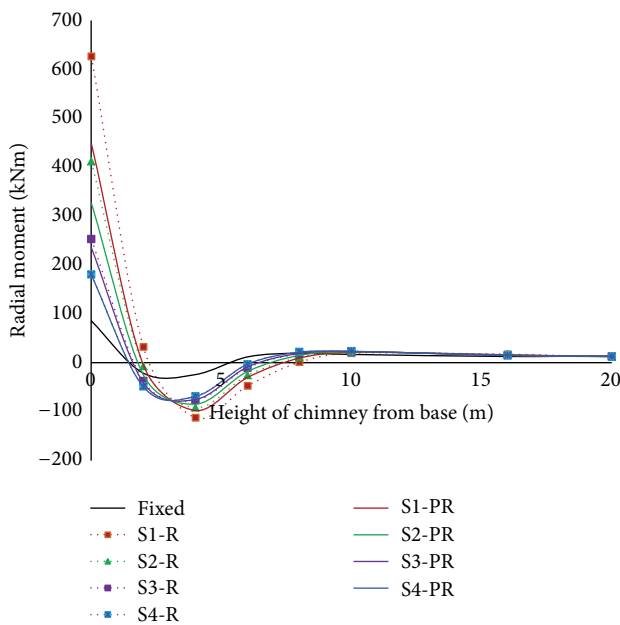
FIGURE 4: Contour of lateral deflection of chimney with (a) rigid base (b) flexible base (case I,  $D_o/t = 22.5$ , soil type S1).

the chimney with rigid base. Due to the addition of piles, the deflection of chimney is reduced considerably, and the above said maximum variation is reduced to 36.41% from the rigid-base analysis of chimney. Similarly, the increase in tip deflection due to SSI effect in case I and case II founded on soil type S2 is 27.07% and 16.45%, respectively. These variations are 8.45% and 6.39%, respectively, for soil type S3 and 1.95% and 1.79%, respectively, for soil type S4. It is clear that the soil-structure interaction studies are relevant for chimney resting on soil types S1 and S2 as the variation of tip deflection from rigid base analysis is considerable.

**6.1.2. Tangential and Radial Bending Moments of Chimney.** The tangential and radial bending moments of chimney are evaluated from the SSI analysis for two cases and for chimney with rigid base and shown in Figure 5. The maximum



(a)



(b)

FIGURE 5: (a) Tangential moment. (b) Radial moment in chimney ( $D_o/t = 12.5$ ).

tangential and radial moments are obtained at the base of the chimney for all the cases considered. It is also observed that the effect of soil flexibility on tangential and radial moments response is negligible beyond 10 m height from the base of chimney. The bending moment response increases with increase in flexibility of soil. The tangential and radial bending moments are tabulated for the two cases of SSI analysis of chimney and chimney with rigid base and are shown in Table 2. It is found that the maximum tangential

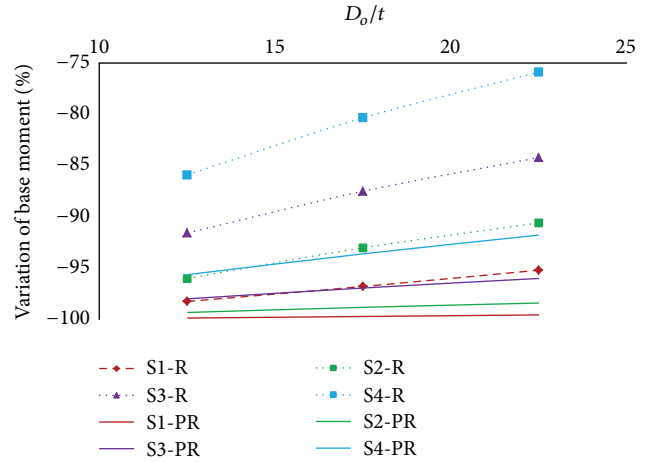


FIGURE 6: Variation of base moment of chimney.

moment of chimney with annular raft of large thickness resting on soil type S1 is increased by 7.63 times of that of the chimney with rigid base. For piled raft of chimney with large thickness, the moment is less when compared to that of case I. The maximum moment in chimney with piled raft of  $D_o/t = 22.5$  resting on the soil type S1 is increased by 5.47 times of that of the chimney with rigid base.

**6.1.3. Base Moment of Chimney.** The base moment of chimney was computed according to IS:4998 (Part 1)-1992 [2] based on two methods. The base moment of the chimney estimated from simplified method and random response method are 1138288 kNm and 2124915 kNm, respectively. The flexibility of soil is not considered in these IS code methods. The base moment was evaluated from FE analysis for two cases of chimney resting on the soil types S1, S2, S3, and S4. The percentage variations of base moment of chimneys considering SSI from those estimated by random response method are shown in Figure 6. The base moment of chimney decreases with increase in flexibility of the soil. The base moment of chimney obtained from the finite element analysis of two cases resting on all types of soils (S1, S2, S3, and S4) is less than that obtained from IS:4998 (Part 1)-1992 [2]. The base moment of chimney for case II is lower than that of case I.

**6.1.4. Tangential and Radial Bending Moments in Raft.** The chimney wind shield is located in the raft at  $r/a = 0.42$ , where  $r$  is the radial distance and  $a$  is the outer radius of annular raft. The representative graphs for tangential and radial moments at various radial locations in the leeward side, from inner to outer edge of the raft of chimneys, are shown in Figure 7. From the SSI analysis of two cases, it is seen that the bending moment in the raft decreases with decrease in flexibility of soil. In conventional method, the maximum tangential moment in raft is obtained at inner edge, and maximum radial moment in raft is obtained at chimney wind shield location.

The contour of the tangential moment in the raft from two cases of SSI analysis is shown in Figures 8 and 9. The response

TABLE 2: Maximum values of tip deflection, tangential, and radial moments in chimney.

Rigid base analysis	Soil type	Soil-structure interaction analysis					
		$D_o/t = 12.5$		$D_o/t = 17.5$		$D_o/t = 22.5$	
		R	PR	R	PR	R	PR
Tip deflection of chimney (m)							
0.573	S1	0.726	0.660	0.823	0.720	0.935	0.770
	S2	0.638	0.614	0.684	0.640	0.717	0.657
	S3	0.593	0.586	0.605	0.595	0.612	0.601
	S4	0.571	0.570	0.574	0.573	0.576	0.575
Tangential bending moment (kNm)							
12.31	S1	94.04	67.33	148.99	96.69	190.62	118.73
	S2	61.74	48.98	79.47	61.08	91.47	68.80
	S3	37.73	35.15	42.44	39.00	45.55	41.24
	S4	26.79	26.61	28.14	27.76	29.03	28.51
Radial bending moment (kNm)							
85.71	S1	626.18	448.50	987.56	640.54	1260.00	784.22
	S2	411.48	326.86	526.83	405.52	604.69	455.57
	S3	252.43	235.47	282.65	260.20	302.65	274.50
	S4	180.50	179.37	189.06	186.68	194.67	191.48

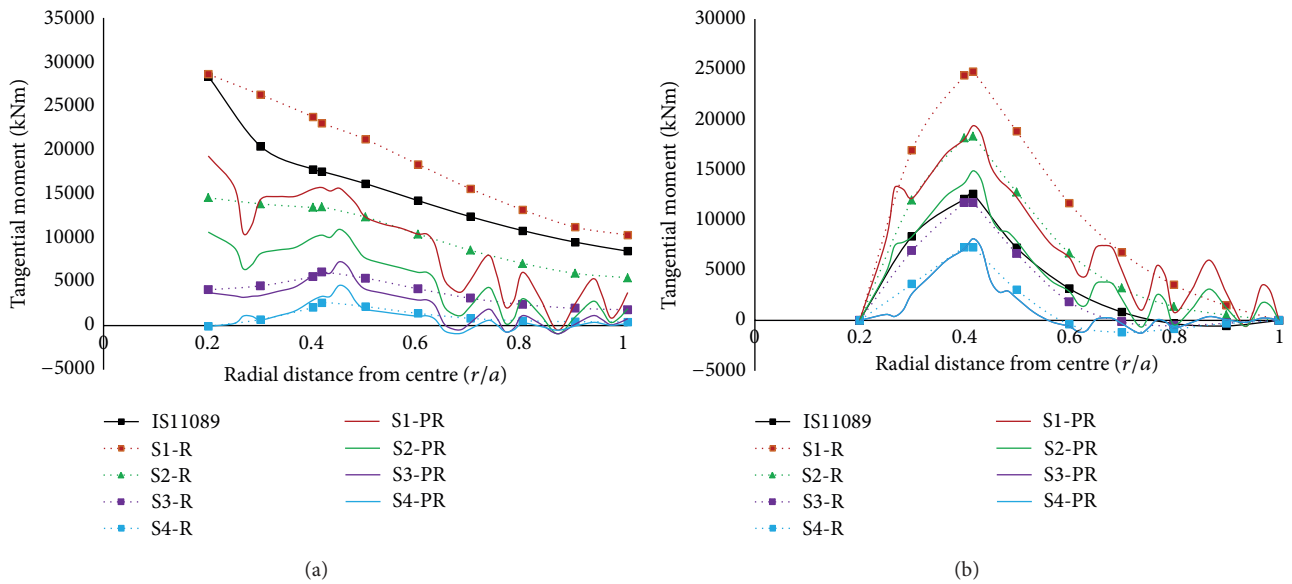


FIGURE 7: (a) Tangential moment. (b) Radial moment in raft ( $D_o/t = 12.5$ ).

of chimney and raft is more in the leeward direction of wind force on the chimney-raft system. The absolute maximum value of tangential moments is seen at the inner edge of the raft for case I resting on soil type S1, and for all other soil types, the absolute maximum values are found at chimney wind shield location in raft. In the case of chimney with piled raft, the absolute maximum tangential moment in raft is seen at chimney wind shield location. For both the cases, it is observed that the higher tangential moments in raft ranges from inner edge of the raft to chimney wind shield location. The contour of the radial moment in the raft from two cases

of SSI analysis is shown in Figures 10 and 11. For both the cases the absolute maximum radial moments in raft is found at chimney wind shield location. The maximum moment response is obtained at the leeward direction of wind force on the chimney raft system.

The absolute maximum tangential and radial moments in raft obtained from SSI analysis and conventional method under along-wind loads are shown in Table 3. It is found that the tangential moment in raft of  $D_o/t = 12.5$ , from SSI analysis of case I resting on soil type S1, is higher than that from conventional method. All other analysis result of

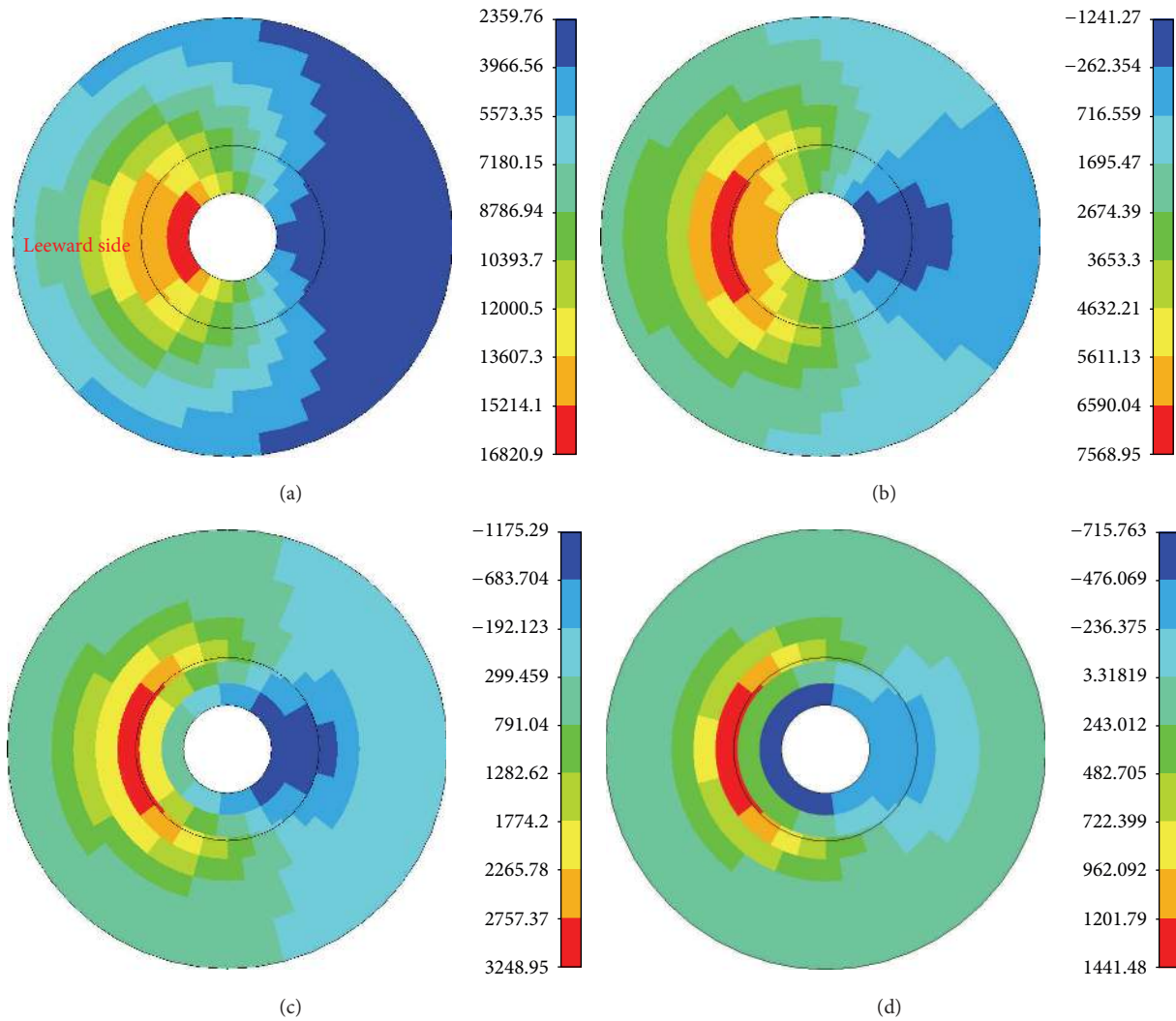


FIGURE 8: Contour of tangential moment in raft ( $D_o/t = 17.5$ ) for case I resting on soil types (a) S1, (b) S2, (c) S3 and (d) S4.

case I shows that the tangential moment in raft evaluated from the conventional method is higher than that of SSI method. The tangential moment in raft is reduced in case II, when compared to that in case I, and it is lower than that obtained from the conventional method. For all  $D_o/t$  ratios, the absolute maximum radial moment in raft is high for case I under soil types S1 when compared to that in conventional method. Due to addition of piles, the moment gets reduced, but the radial bending moment in raft ( $D_o/t = 12.5$  and  $D_o/t = 17.5$ ) of chimney with piled raft resting on soil type S1 is still higher than that from conventional method. It is observed that the radial moments are reduced due to the inclusion of the effect of flexibility of the underlying soil, especially in the case of S3 and S4 soil types.

The increased tangential and radial moments variations of 0.9% and 96.78%, respectively, are observed for case I ( $D_o/t = 12.5$ ) founded on soil type S1 from conventional method. For the same soil-structure system of case II, the variation of tangential moment is decreased by 31.95%, and radial moment is increased by 54.23% from conventional

method. This increase in moments as compared to the conventional method reveals the necessity of considering the flexibility of supporting soil in the analysis of chimney and foundations.

**6.1.5. Settlement in Raft.** Figure 12 presents the representative diagrams of the settlement of raft ( $D_o/t = 12.5$ ) for both the cases at various radial locations from windward side to the leeward side along the centre of the raft. It is observed that as the flexibility of soil decreases, the settlement of the raft decreases. The contour of the settlement of the raft of both cases ( $D_o/t = 17.5$ ) from SSI analysis due to along-wind load is shown in Figures 13 and 14. The settlement pattern shows that the raft settles nonuniformly with maximum displacement ranges from inner edge to chimney wind shield location in the leeward side of the raft resting on soil types S1 and S2. For the stiffer soil type S4, the maximum settlement of raft is at the chimney shell location only. It is seen that the soil deformation is negligible for soil type S4 as the raft behave as rigid when interacting with S4. Table 3 shows the maximum



TABLE 3: Absolute maximum tangential and radial moments and settlement of the raft.

Conventional method	Soil type	Soil-structure interaction analysis					
		$D_o/t = 12.5$		$D_o/t = 17.5$		$D_o/t = 22.5$	
		R	PR	R	PR	R	PR
Tangential bending moment (kNm)							
28361.6	S1	28607.0	19299.0	16821.0	10914.0	10474.0	8291.1
	S2	14554.0	10952.5	7476.7	7090.3	4917.3	5280.2
	S3	6079.8	7248.7	3204.8	4584.4	2103.6	3319.0
	S4	2625.3	4565.5	1400.7	2716.6	914.8	1812.0
Radial bending moment (kNm)							
12572.1	S1	24740.0	19390.5	19510.5	14806.0	16038.5	12126.0
	S2	18315.5	14897.5	13135.0	10971.5	10379.7	9013.2
	S3	11714.3	11154.5	8120.8	8217.9	6300.8	6689.3
	S4	7286.7	8133.0	4801.8	5797.8	3515.1	4534.6
Settlement (mm)							
As per IS: 1904–1986 [35], permissible settlement is 0.075 m	S1	72.52	40.52	78.15	42.58	82.60	44.29
	S2	26.18	16.67	27.48	17.34	28.40	17.87
	S3	8.08	6.46	8.36	6.66	8.64	6.84
	S4	2.26	2.15	2.35	2.22	2.42	2.30

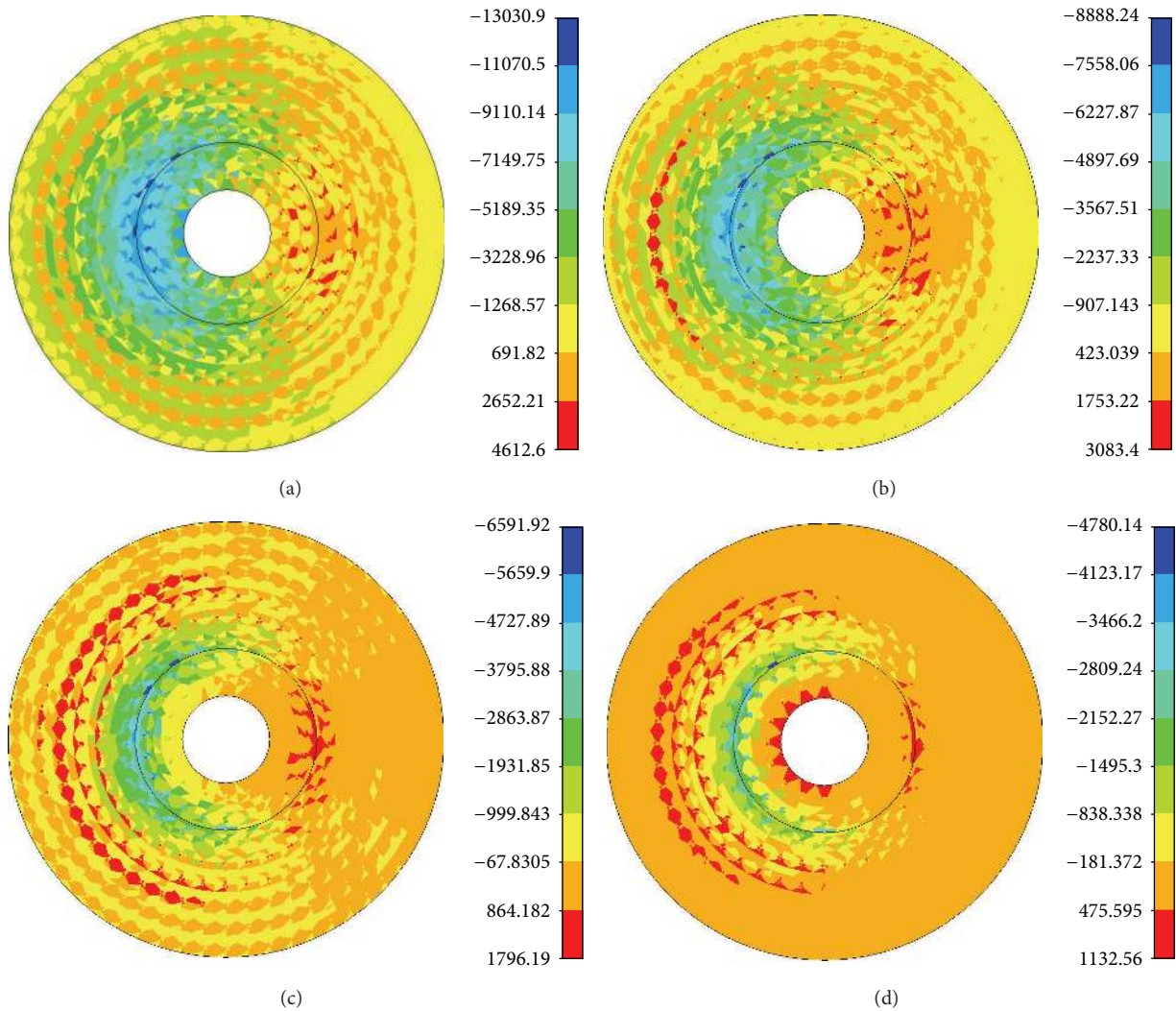


FIGURE 9: Contour of tangential moment in raft ( $D_o/t = 17.5$ ) for case II resting on soil types (a) S1, (b) S2, (c) S3, and (d) S4.

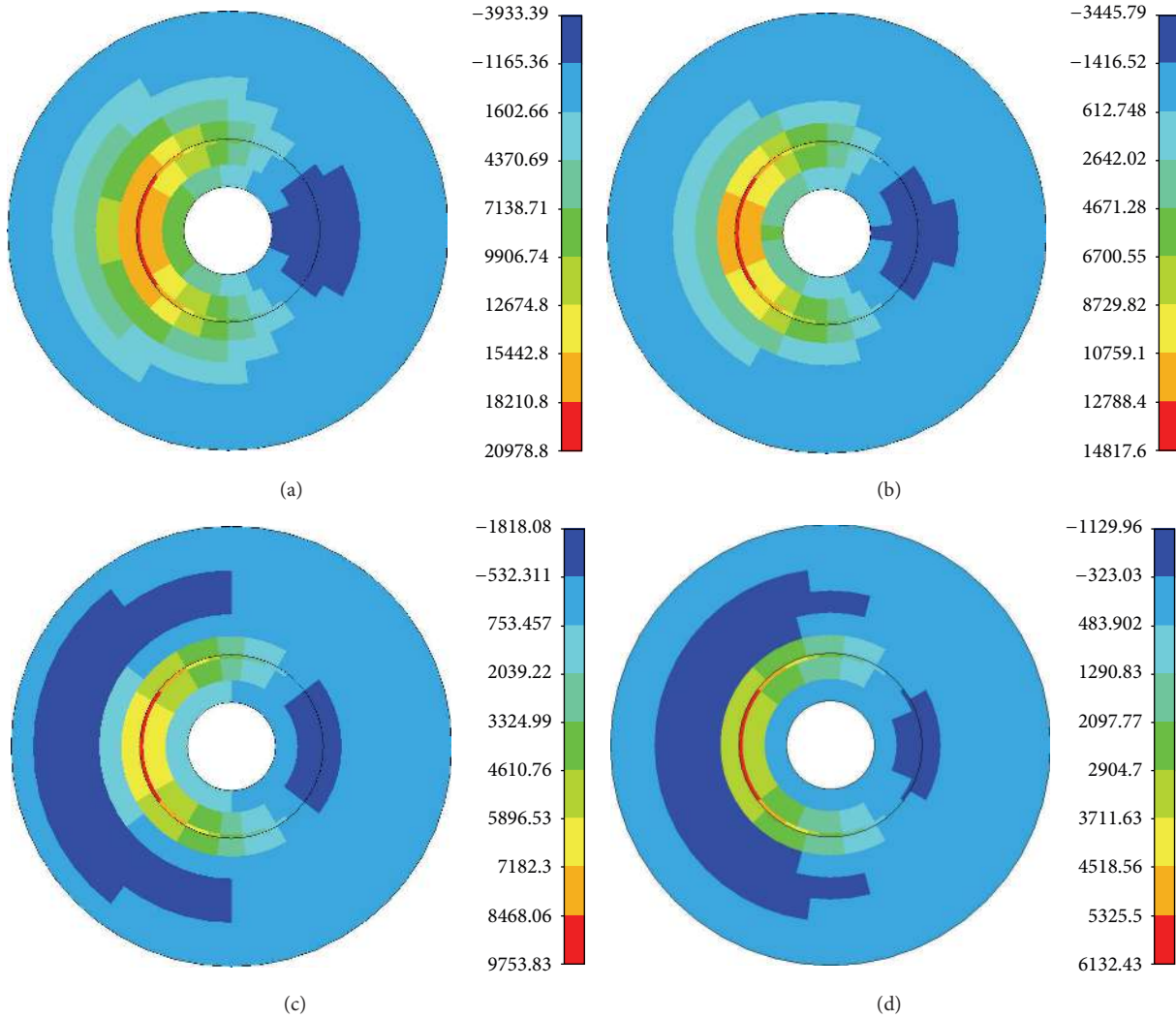


FIGURE 10: Contour of radial moment in raft ( $D_o/t = 17.5$ ) for case I resting on soil types (a) S1, (b) S2, (c) S3, and (d) S4.

settlement of raft from SSI analysis of both cases. As per IS 1904–1978 [35], the maximum permissible settlement for raft foundation on sand is 75 mm. Maximum settlements of raft of  $D_o/t = 17.5$  and  $D_o/t = 22.5$  obtained for case I resting on soil type S1 are 78.15 mm and 82.60 mm, respectively, which exceed the permissible settlement. The settlement of raft is reduced considerably in case II. The maximum settlement of raft evaluated from the SSI analysis of case II is 44.29 mm for the above soil-structure system. From the SSI analysis of both cases, it is found that the maximum reduction in variation of settlement of raft ( $D_o/t = 22.5$ ) resting on soil type S1 of case II from case I is 46.38%. The reductions in variation of settlement of raft for soil types S2, S3, and S4 of case II from case I are 37.1%, 20.83%, and 5.16%, respectively. This shows that the piled raft foundations are more effective for chimney resting on loose dry sand.

**6.2. Effect of Thickness of Raft.** The effect of thickness of the raft was investigated by considering three different ratios of diameter to thickness ( $D_o/t$ ) of the raft, and the values

are 12.5, 17.5, and 22.5. It is found that the responses in chimney like tip deflection, tangential and radial moment, and base moment of chimney increases with increase in raft-thickness ratio. As the raft thickness increases, that is, from  $D_o/t = 17.5$  to  $D_o/t = 12.5$  in case I, an increase of 50% is seen in both bending moments of chimney. This is due to the interaction among rigid foundation and the chimney. Therefore, the foundation stiffness also should be considered in the analysis of chimney. The tangential and radial moment in raft increases with decrease in  $D_o/t$  ratio, while the settlement in raft increases with increase in  $D_o/t$  ratio. This is due to the rigid behavior of the raft for lower values of raft thickness ratio. It shows that the thickness of raft affect the response of the chimney and raft.

**6.3. Conclusions.** Soil-structure interaction analysis of 300 m tall reinforced concrete chimney with piled raft and annular raft under along-wind load has been carried out in the present study. For this, four types of dry cohesionless soils such as loose sand, medium sand, dense sand, and rock were

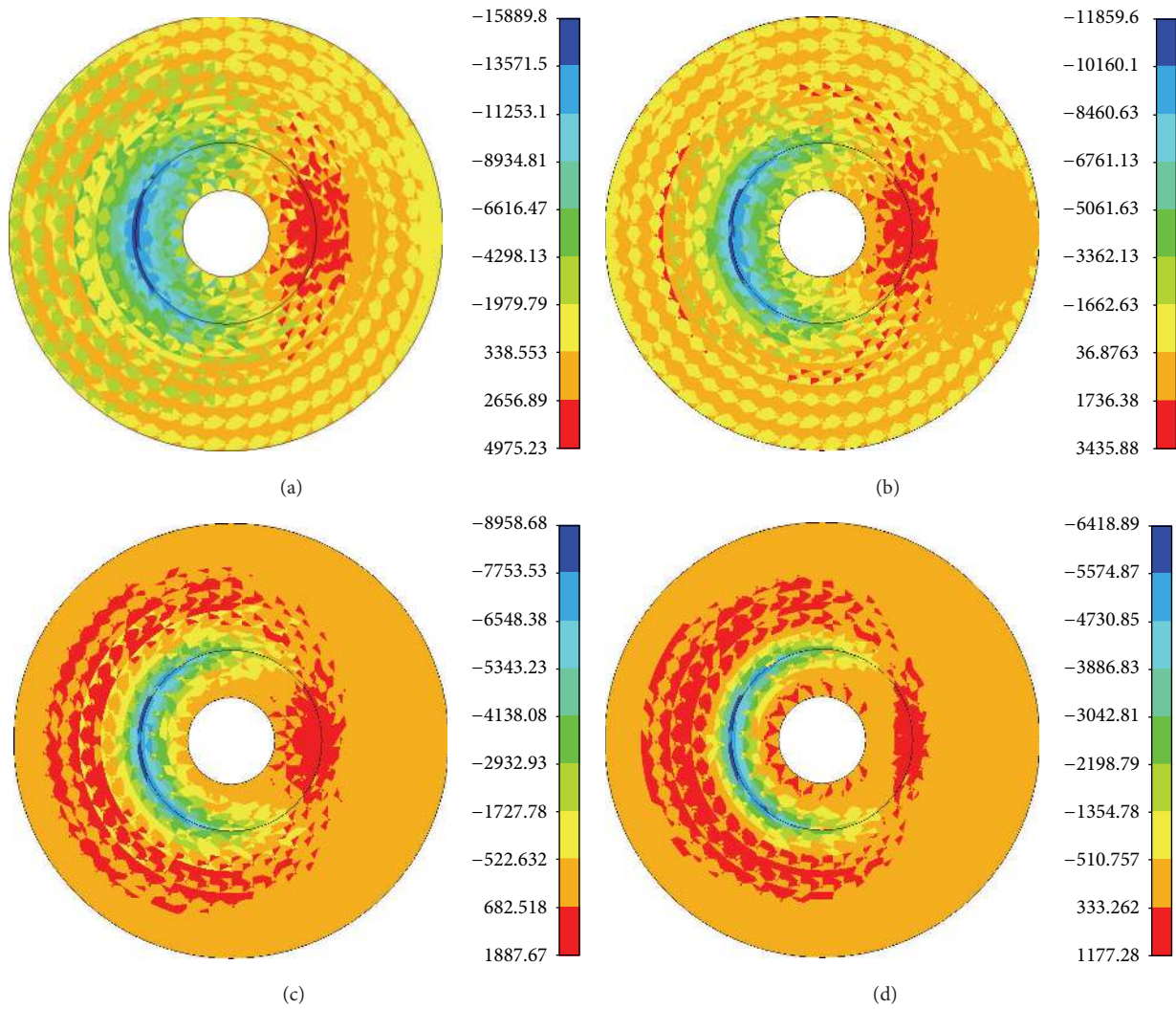


FIGURE 11: Contour of radial moment in raft ( $D_o/t = 17.5$ ) for case II resting on soil types (a) S1, (b) S2, (c) S3, and (d) S4.

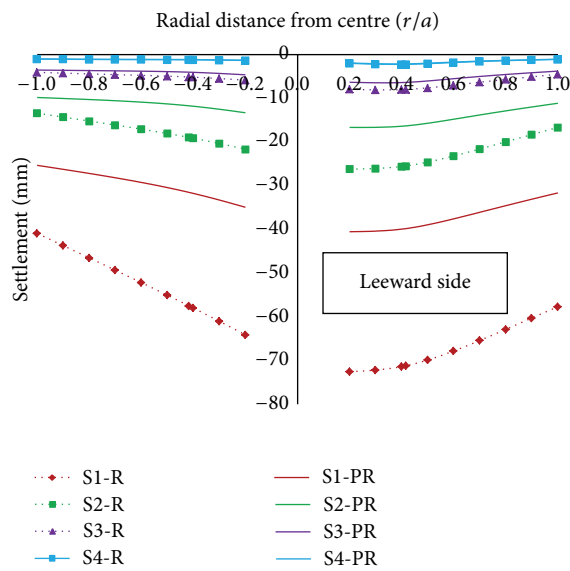


FIGURE 12: Settlement of raft ( $D_o/t = 12.5$ ).



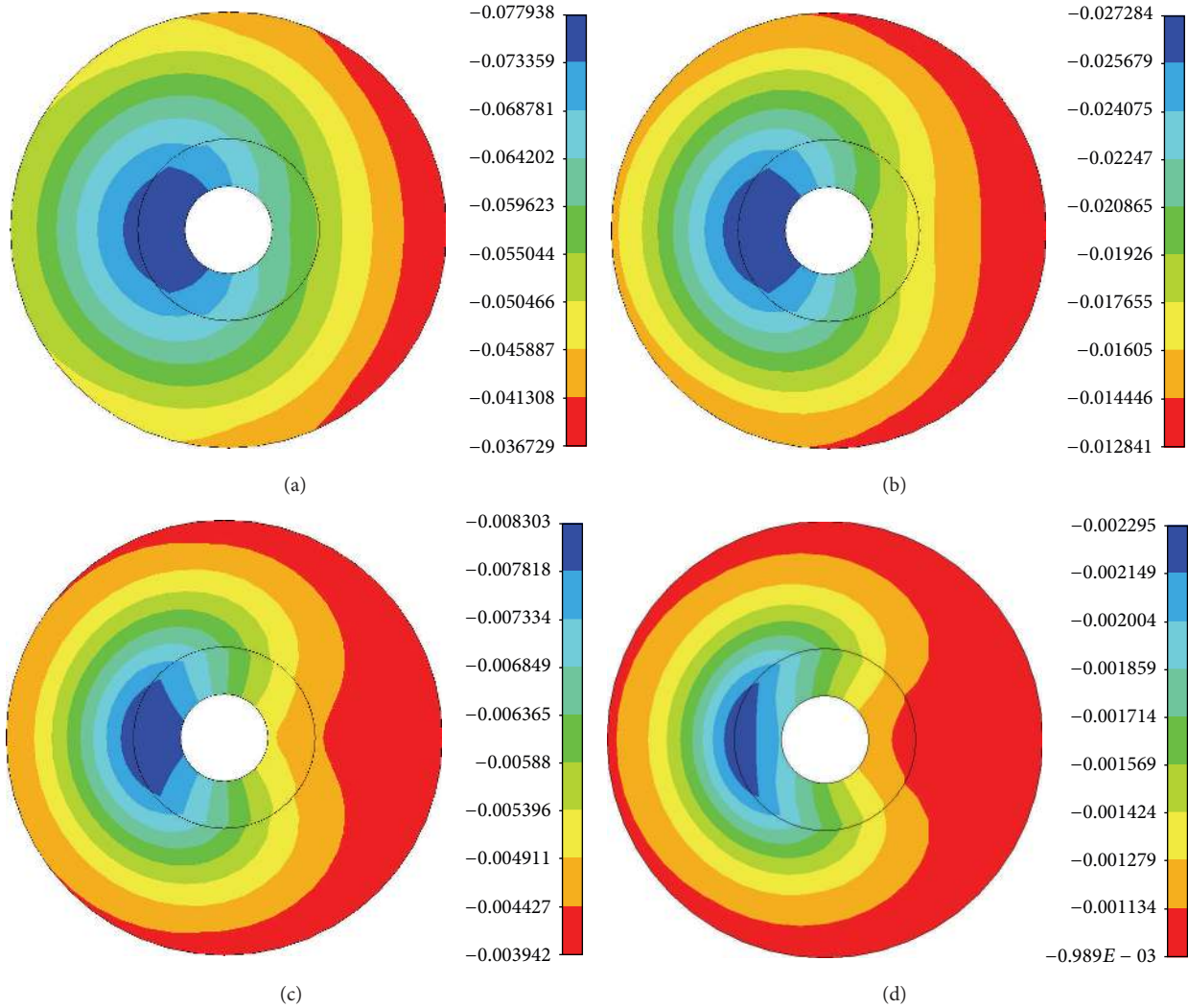


FIGURE 13: Contour of settlement of raft ( $D_o/t = 17.5$ ) for case I resting on soil types (a) S1, (b) S2, (c) S3, and (d) S4.

considered based on their flexibility. The effect of stiffness of the raft was evaluated using three different ratios of external diameter to thickness of the annular raft. The modification in structural response in chimney such as tip deflection, tangential and radial moment, and base moment and the responses in raft such as tangential and radial moment and settlement were evaluated. The following conclusions are drawn from this study.

- (i) The tangential and radial moment in chimney from the SSI analysis is considerably more than that obtained from the analysis of chimney with rigid base, and hence it is necessary to consider the effect of underlying soil in the analysis of chimneys.
- (ii) The tip deflection and tangential and radial moment of chimney and the responses in raft such as tangential and radial moment and settlement increase with increase in flexibility of soil.
- (iii) The base moment of the chimney increases with decrease in flexibility of the soil. The base moment of chimney resting on rock is lower than that obtained from rigid base analysis.
- (iv) The radial moment in raft obtained from the conventional analysis is lower than that evaluated from the analysis of chimney founded on loose sand and medium sand.
- (v) The response of chimney and raft of chimneys with piled raft foundation is significantly less than that of chimneys with annular raft foundation founded on loose sand and medium sand.
- (vi) The structural response of chimney and settlement of raft increases, whereas the tangential and radial moments in raft decrease with reduction in the thickness of raft slab due to the increased flexibility of the foundation.



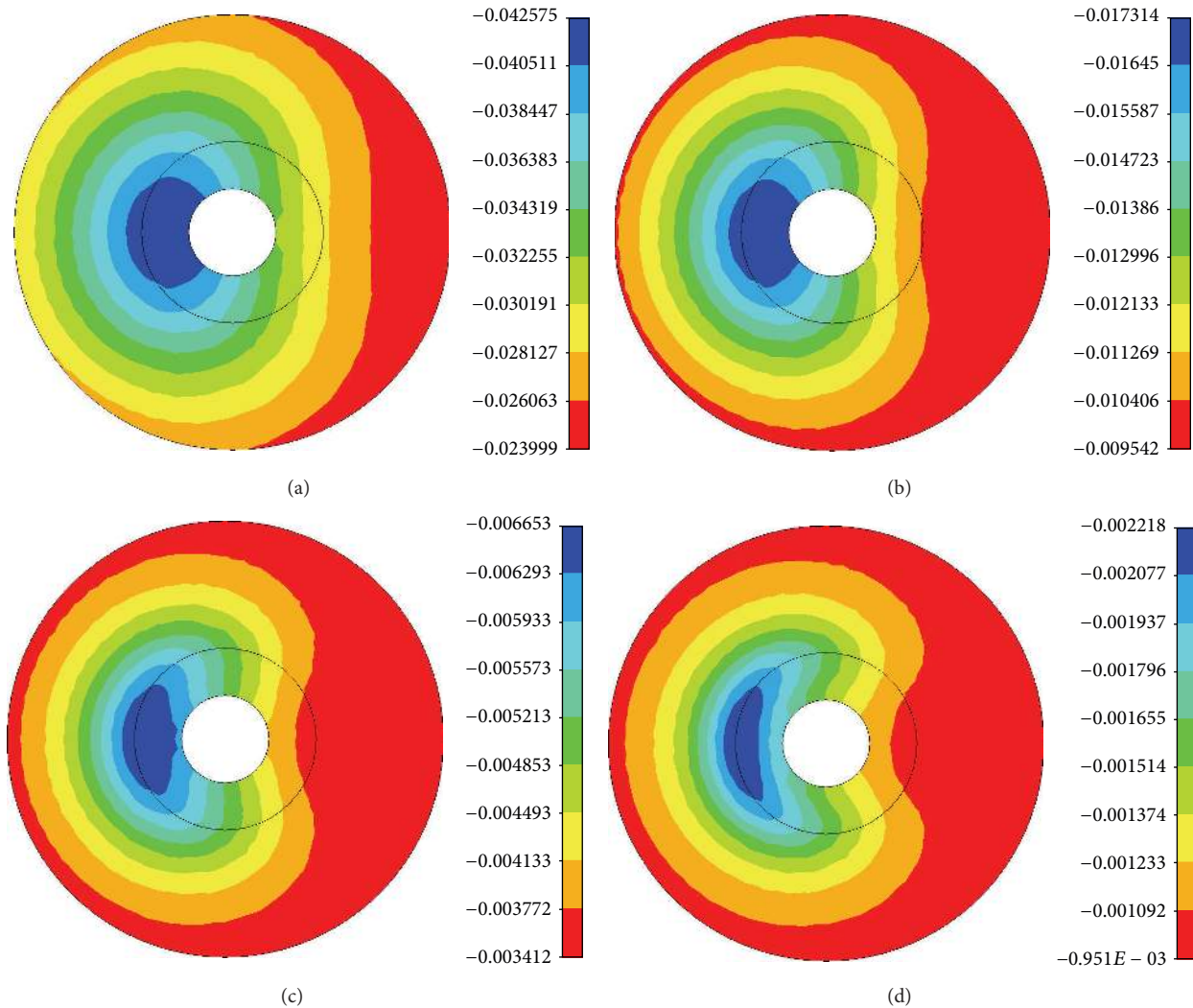


FIGURE 14: Contour of settlement of raft ( $D_o/t = 17.5$ ) for case II resting on soil types (a) S1, (b) S2, (c) S3, and (d) S4.

## Disclosure

All of the authors are researchers/academicians and none of the authors have any direct/indirect financial relation or benefit with the commercial identity (software ANSYS) mentioned in the paper.

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