

Seismic Soil-Structure Interaction Studies on Tall Chimneys

Ansu Thomas, B. R. Jayalekshmi, R. Shivashankar

Abstract—A detailed estimation of seismic soil-structure interaction (SSI) effect on tall reinforced concrete chimneys resting on raft foundation is presented in this paper. The transient analysis of chimney-raft-soil system is carried out using LS-DYNA software. Bhuj (2001) earthquake motion in time domain is used to excite the finite element model of soil-structure system. For incorporating the significance of soil-structure interaction (SSI), four types of soils are used based on shear wave velocity. Responses in terms of radial and tangential moments of raft foundation that are obtained from the analysis of the model are compared with that obtained from conventional method according to the Indian standard code of practice, IS 11089:1984. The results show that the seismic SSI effects are significant in the variation of natural frequency and radial and tangential moment especially if the structure is founded on very soft soil. The analysis results show that the natural frequency decreases and tangential and radial moment increases with increase in soil flexibility. There is a considerable decrease in the variation of both moments with increase in the ratios of outer diameter to thickness of raft.

Index Terms— dynamic soil-structure interaction, industrial chimney, LS-DYNA, natural frequency, non-reflecting boundary, seismic response, soil flexibility.

1 INTRODUCTION

SOIL-structure interaction represents the difference in structural response obtained by assuming the motion at the foundation to be the same as the free-field ground motion and by considering the modified or actual motion of the foundation. Neglecting soil stiffness might cause considerable underestimation of design forces. Hence it is important to account for soil-structure interaction in modelling of structure. The potential beneficial effect of SSI was apparently first noted by Housner who considered the rocking motion of the structure on the soil [3]. The importance of SSI effects on the seismic behaviour of tall chimneys is also noted by Navarro [2].

Modelling soil-structure interaction in dynamic analysis falls into two main categories namely, multistep methods (substructure approach) and direct methods depending on the modelling strategy adopted for the soil adjacent to the structure. The structure and soil are treated as a whole system in direct method. The region of the soil adjacent to the structure-soil interface is also explicitly modelled. Artificial boundary must be introduced so as to cover the unbounded soil domain.

In substructure method, the structure and the soil are treated as two different substructures. Each substructure can be analysed using a best-suited computational technique. This is done by combining the force-displacement relationship of the soil with the discretized motion equation of the structure which results in the final system of equation of the total dynamic system.

The methods of modelling the soil may be divided into five categories of varying complexity [8]:

- i. Equivalent static springs and viscous damping located at the base of the structure only
- ii. Shear beam analogy using continua or lumped masses and springs distributed vertically through the soil profile

- iii. Elastic or viscoelastic half-space
- iv. Finite elements
- v. Hybrid model finite elements and half-space properties

Generally the dynamic behaviour of chimneys is analysed by using a lumped model approximation where the lumped masses are assumed to be connected to one another through elastic massless elements and usually the structure is assumed to be fixed at the base without considering any interaction between the soil and the structure. Rajasankar et al. [7] presented a brief theoretical background on modelling a problem that involves dynamic SSI effects and subsequent issues to be addressed in the analysis. A parametric study on the seismic structural response of 100 to 400m high chimneys has been carried out for estimating the effect of flexibility of soil and thickness of foundation.

2 PARAMETRIC STUDIES ON THE SEISMIC RESPONSE OF TALL CHIMNEYS

2.1 Properties of chimney-raft-soil system

The seismic analyses of 100m to 400m high reinforced concrete chimneys with annular raft foundation founded in different types of soils were carried out. The ratio of height to mean base diameter of 12 and ratio of top diameter to base diameter of 0.6 were taken for modelling the chimney. The base of the chimney is supported by rigid annular raft foundation with uniform thickness. The overall diameter of a foundation for a concrete chimney is typically 50% greater than the diameter of the chimney shaft at ground level [1]. To study the effect of thickness of raft foundation in chimneys, three different outer raft diameter to raft thickness ratios (D_o/t) were considered. Details of different geometric parameters of chimney and annular raft foundation are given in Table 1. M30 grade concrete and Fe 415 grade steel were selected as the materials for both chimney and raft [6]. The mass density and poisson's ratio of reinforced concrete was taken as 25.5kN/m^3 and 0.15 respectively.

Four types of soil were used in this study. The soil properties are given in Table 2. Soil medium is infinite. In this analysis, a finite element model of an elastic continuum was used to represent the soil.

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Therefore it was required to keep the soil boundary away at sufficient finite distance so that the waves propagated from the soil were not reflected back. The soil taken for modelling was four times the breadth of foundation for sideways with non-reflecting boundaries and bedrock was assumed to be at a depth of 30m for all chimneys.

Table.1. Geometric parameters of chimney and raft

Chimney	Height (m)	100	200	400	
	Diameter at base D_b (m)	8.5	17	33.5	
	Diameter at top $D_t=0.6D_b$ (m)	5.1	10.2	20.1	
	Thickness at base $T_b=D_b/35$ (m)	0.3	0.5	1	
	Thickness at top $T_t=0.4T_b$ (m)	0.2	0.2	0.4	
Annular Raft	External diameter D_o (m)	20	35	86	
	Internal diameter D_i (m)	6	10	16	
	Thickness t (m)	$D_o/t = 12.5$	1.6	2.8	6.88
		$D_o/t = 17.5$	1.2	2	5
$D_o/t = 22.5$		0.9	1.6	3.9	

Table.2. Properties of soil

Designation	Soil types	Shear wave velocity, V_s (m/sec)	Poisson's ratio, ν	Density, γ (kN/m^3)	Elastic modulus, E (kN/m^2)
S1	Loose sand	100	0.4	16	45,668
S2	Medium sand	300	0.35	18	445,872
S3	Dense sand	600	0.3	20	1908,257
S4	Rock	1200	0.3	20	7633,028

2.2 Finite element modelling of chimney-raft-soil system

The chimney-raft-soil system was analysed by finite element software LS-DYNA assuming its linear elastic behaviour. The chimney and the annular raft foundation were modelled using four noded Belytschko-Lin-Tsay shell elements, which has both bending and membrane capabilities. The element has six degrees of freedom at each node. The chimney shell was discretised with element of 2m size along height and with divisions of 7.5° in the circumferential direction. Annular foundation was discretised into 1m, 2m and 4m in the radial direction for 100m, 200m and 400m chimneys respectively and 7.5° in the circumferential direction.

Finite element model of an elastic continuum was adopted for modelling of soil. Eight noded fully integrated solid hexahedron elements with three translational degrees of freedom at each node were used for the 3-D modelling of soil. Non-reflecting boundaries in the lateral boundaries in LS-DYNA were used to simulate the effect of infinite soil medium. The nodes at the interface of bottom of foundation and the soil were completely coupled and the chimney-raft-soil system was analysed using direct approach by considering the linear elastic behaviour of whole system. The modelling of the chimney-raft-soil system was generated using the ANSYS software

and is shown in Fig.1. The dynamic analysis was carried out using LS-DYNA software.

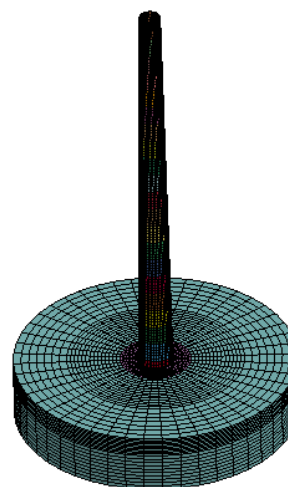


Fig.1. Chimney-raft-soil model

2.3 Seismic Analysis

The time history analysis of the chimney-raft-soil system was carried out with ground motion corresponding to the Kutch earthquake at Bhuj with a magnitude of 7.0 and peak ground acceleration 0.105g. The duration of the earthquake is 133 seconds. But for the analysis, the loaded earthquake data was limited to 30 seconds without losing the peak ground acceleration and it was scaled up to 0.3g. Using the *BOUNDARY_PRESCRIBED_MOTION SET in LS-DYNA, the time history of acceleration was applied in the global X direction of the entire soil-structure model. Acceleration time history and associated Fourier spectrum of this ground motion are shown in Figs. 2 & 3 respectively.

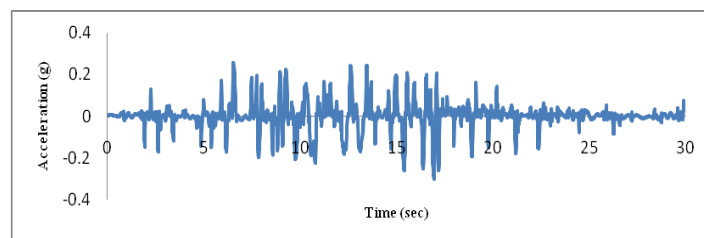


Fig.2. Acceleration time history of Bhuj ground motion

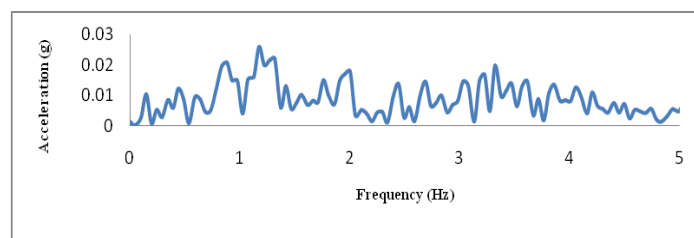


Fig.3. Fourier spectrum curve of Bhuj ground motion

The material damping ratio was assumed as 5% for chimney and

annular raft foundations. In this study equivalent-linear properties were used to take into account non-linearity of soil. The G/G_{max} modulus reduction curve and the equivalent damping ratio versus shear strain relationship for sand given by Seed and Idriss were assigned to the soil deposit [4]. The horizontal loading due to wind and other causes were neglected. The stresses due to gravity loading were initiated in the integrated structure-soil system.

The peak structural response in terms of radial and tangential bending moments of annular raft were noted down for different types of soil for different height of chimney models with different raft thickness ratios. Structural response variation due to the effect of flexibility of soil and thickness of raft has been studied. The bending moments obtained from soil-structure interaction analysis were compared with that obtained from conventional method according to the Indian standard code of practice [5].

3 DISCUSSION OF RESULTS

3.1 Variation in natural frequency

Modal analyses of all the chimney models were carried out for fixed-base and flexible-base conditions. It is seen that the natural frequency of the chimney structure with flexible-base condition decreases compared to the fixed-base system because of the flexibility of soil medium below foundation. Table 3 shows first five natural frequencies of 400 m high chimney with raft thickness ratio of $D_o/t=17.5$.

Table.3. Natural Frequencies of 400m chimney with $D_o/t=17.5$

Mode No.	Fixed-Base	Soil-Base			
		S1	S2	S3	S4
1	0.2007	0.1498	0.1789	0.1910	0.1968
2	0.2007	0.1501	0.1791	0.1913	0.1971
3	0.8315	0.3849	0.7528	0.7956	0.8189
4	0.8315	0.4232	0.7529	0.7956	0.8190
5	1.7914	0.4477	1.1234	1.7771	1.7789

It is observed that the natural frequency decreases with increasing flexibility of soil and with decreasing raft thickness. A reduction of 20%, 25% and 31% is noticed for raft thickness ratio of $D_o/t=12.5$, $D_o/t=17.5$ and $D_o/t=22.5$ for 400m chimney resting on S1 as compared with fixed base conditions; slight variation in the symmetric mode frequencies are observed due to soil flexibility.

3.2 Variation in tangential and radial moments of raft

3.2.1 Effect of flexibility of soil

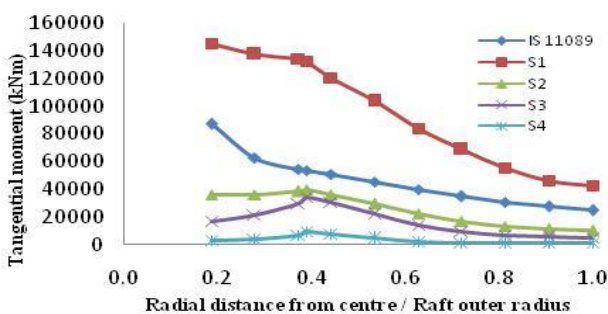


Fig.4. Variation of tangential moment in 400m chimney of $D_o/t=17.5$

Representative variation in tangential moments in raft foundation from conventional method [5] as well as SSI analysis for 400m chimney with $D_o/t=17.5$ founded on different types of soil is shown in Fig.4. It is observed that in most of the cases, the maximum tangential moment is obtained at interior of raft and it decreases towards the exterior parts in both methods.

The tangential moments obtained from the SSI analysis of tall chimney founded on type of soil S2, S3 and S4 ($V_s > 300m/s$) is lower than that predicted by the conventional method. The seismic analysis of chimney considering rigidity at base overestimates the moments of foundation. The maximum percentage variations of tangential moments are 47%, 157% and 170% for 100m, 200m and 400m high chimneys founded on loose sand respectively. Therefore SSI should be considered in the seismic analysis if the structure is constructed on loose sand. From the parametric study it is seen that, tangential moments decreases with decrease in flexibility of soil.

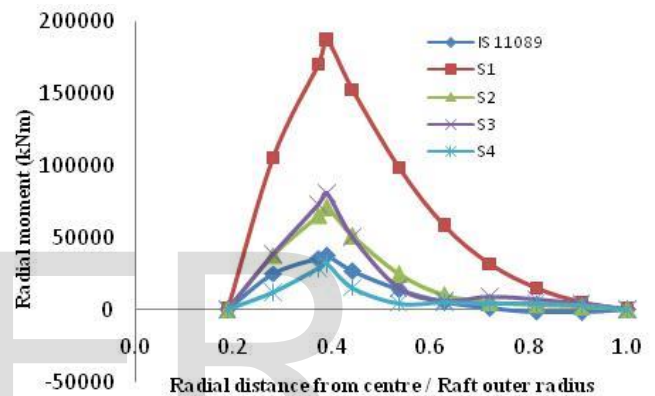


Fig.5. Variation of radial moment in 400m chimney of $D_o/t=17.5$

Representative variation in radial moments in raft from conventional method as well as SSI analysis for 400m chimney with $D_o/t=17.5$ founded on different types of soil is shown in Fig.5. It is observed that for SSI and conventional method, the maximum radial moment values are seen at chimney shell location. For all the models the radial moment calculated by conventional method is less compared with that of SSI method.

The radial moments obtained from the SSI analysis of tall chimney founded on loose sand and medium sand ($V_s < 300m/s$) shows higher percentage variation when compared to fixed base condition. The maximum percentage variations of radial moments are 160%, 368% and 397% for the 100m, 200m and 400m high chimneys respectively. In all cases the radial moments decreases with decrease in flexibility of soil.

3.2.2 Effect of thickness of raft

The effect of thickness of raft is investigated by considering D_o/t ratios of 12.5, 17.5 and 22.5. Representative figures of tangential and radial moment in raft for the 100m tall chimneys resting on loose sand S1 are shown in Figs. 6 and 7. It is seen that as the thickness is reduced, the moments are also reduced due to the flexible behaviour of raft.

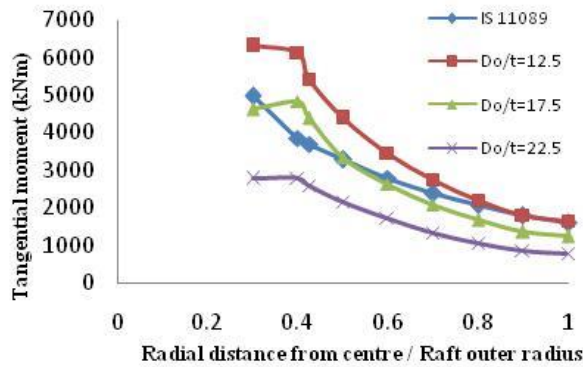


Fig.6. Variation of tangential moment in 100m chimney on S1

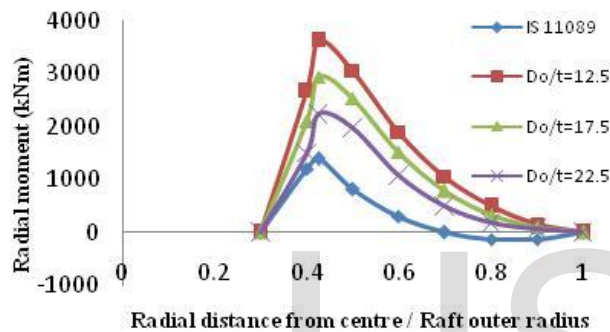


Fig.7. Variation of radial moment in 100m chimney on S1

3.2.3 Time history plots

The time history response of tangential and radial moments in raft for 400m high chimney with D_o/t ratio 17.5 resting on S1, S2, S3 and S4 are shown in Figs. 8 and 9. The dynamic moment response in raft foundation of chimney resting on loose sand is severely affected. The change in natural frequency affects the response of the overall structure.

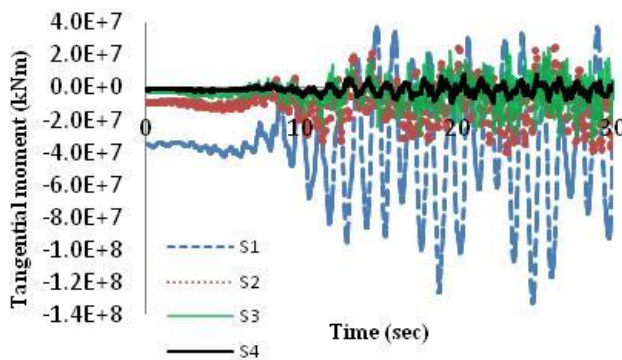


Fig.8. Time history of tangential moment response of 400 m chimney with $D_o/t=17.5$

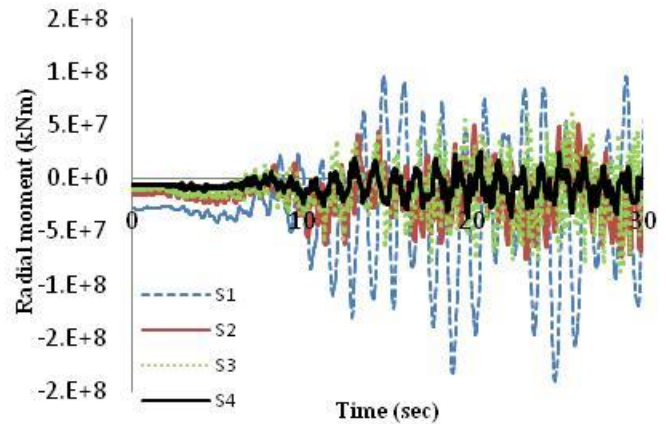


Fig.9. Time history of radial moment response of 400 m chimney with $D_o/t=17.5$

4 CONCLUSION

Finite element seismic analyses of the chimney-raft-soil system were carried out with four types of soils with different shear wave velocities and the results are compared with those obtained through IS codal provisions. Based on the parametric study on the seismic response analysis of chimneys, the following conclusions are drawn.

- (i) The natural frequency of the structure decreases with increase in soil flexibility and by the decrease in raft thickness.
- (ii) Tangential and radial moments of annular raft of chimney increase with increase in flexibility of soil.
- (iii) Tangential and radial moments of annular raft of chimney decrease as the thickness of raft is reduced.
- (iv) The radial moments in raft varies more compared to tangential moments due the effect of seismic soil-structure-interaction.

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