Earthquakes and Structures, *Vol. 7, No. 2 (2014) 233-250*
DOI: http://dx.doi.org/10.12989/eas.2014.7.2.233

Dynamic soil-structure interaction studies on 275m tall industrial chimney with openings

B.R. Jayalekshmi[1], Ansu Thomas[*2] and R. Shivashankar[1]

[1]*Department of Civil Engineering, National Institute of Technology Karnataka.*
[2]*Department of Civil Engineering, National Institute of Technology Raipur*

(Received May 21, 2013, Revised March 8, 2014, Accepted March 20, 2014)

Abstract. In this paper, a three dimensional soil-structure interaction (SSI) is numerically simulated using finite element method in order to analyse the foundation moments in annular raft of tall slender chimney structures incorporating the effect of openings in the structure and the effect of soil flexibility, when the structure-soil system is subjected to El Centro (1940) ground motion in time domain. The transient dynamic analysis is carried out using LS-DYNA software. The linear ground response analysis program ProShake has been adopted for obtaining the ground level excitation for different soil conditions, given the rock level excitation. The radial and tangential bending moments of annular raft foundation obtained from this SSI analysis have been compared with those obtained from conventional method according to the Indian standard code of practice, IS 11089:1984. It is observed that tangential and radial moments increase with the increase in flexibility of soil. The analysis results show that the natural frequency of chimney decreases with increase in supporting soil flexibility. Structural responses increase when the openings in the structure are also considered. The purpose of this paper is to propose the need for an accurate evaluation of the soil-structure interaction forces which govern the structural response.

Keywords: dynamic soil-structure interaction; seismic response; LS-DYNA; industrial chimney; natural frequency; non-reflecting boundary; soil flexibility

1. Introduction

Analysis of tall reinforced concrete (RC) chimney and its foundation is conventionally carried out by considering fixity at base. But soil flexibility is recognized to have a significant effect on the dynamic behaviour of the structures. 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. Two important characteristics that distinguish the dynamic SSI system from other general dynamic structural systems are the unbounded nature and the nonlinearity of the soil medium.

The strength of the chimney may be weakened through the introduction of openings. Openings

*Corresponding author, Assistant Professor, E-mail: ansuthomasmace@gmail.com
[a]Associate Professor
[b]Professor

http://www.techno-press.org/?journal=eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

have to be strengthened to prevent local reduction of strength, fatigue resistance, instability and reduction or increase of the resonance frequency. An important improvement can be obtained by reinforcing each side of openings with vertical bars so that the moment of inertia over the opening is equal to the inertia of the full cross section. The shell in the vicinity of the openings should be designed for over strength in both flexure and shear (CICIND 2005).

A 3-D dynamic high-rise structure-foundation-soil interaction model based on substructure method, and a compiled computer program, was established by Shiming and Gang (1998). According to Wilson (2003), tall reinforced concrete chimneys respond in a complex manner under earthquake excitation. Pallare's *et al*. (2006) studied the seismic behaviour of industrial masonry chimneys. The dynamic response of an infinitely long strip foundation resting on an elastic and inelastic half-space was investigated by Zhang and Tang (2007). The numerical analysis results presented reveal that dynamic responses of shallow foundations strongly depend on amplitude and frequency of the input motion. The effect of SSI becomes prominent for heavy structures resting on relatively soft soils, for example nuclear power plants, high rise buildings and elevated highways on soft soil (Kramer 2004; Gharad and Sonparote 2010). Fatahi *et al*. (2014) concluded that the conventional inelastic design procedure by only including the local site effect excluding SSI cannot adequately guarantee the structural safety for mid-rise moment resisting buildings higher than 5 storeys resting on soft soil deposits. Kharade *et al*. (2013) analysed the 235m tall sky-pod structure using pseudo static and time history analysis considering flexible base as well as fixed base, the obtained results showed the importance of soil-structure interaction effects. Due to consideration of SSI, time period extends about 35% compared to non SSI. RezaTabatabaiefar *et al*. (2013) concluded that the dynamic soil-structure interaction plays a considerable role in seismic behaviour of mid-rise building frames including substantial increase in the lateral deflections and inter-storey drifts and changing the performance level of the structures from life safe to near collapse or total collapse. When soil is subjected to dynamic loading as in a strong motion earthquake, large strains are induced (Sathish Kumar 2012).

Winkler model is the oldest and simplest method to model the subgrade which consists of infinite number of springs on a rigid base. Elastic continuum model is a conceptual approach of physical representation of the infinite soil media. For engineering purposes the time variation of ground acceleration is the most useful way of defining the shaking of ground during earthquake. This ground acceleration is discretised by numerical values at discrete time intervals. Integration of this time acceleration history gives velocity history, integration of which in turn gives displacement history (Mehta and Gandhi 2008). Rajasankar *et al*. (2007) presented a brief theoretical background on modelling a problem that involves dynamic SSI effects and subsequent issues to be addressed in the analysis. Linear transient dynamic analysis was carried out using finite element method and imposing transmitting boundary conditions at far field of layered elastic half-space. Wilson (2010) studied the performance of tall reinforced concrete chimney structures consisting of moderately ductile reinforced concrete and windshield lined with the Penn guardblock lining system, under the 2010 Chilean earthquake.

It is noticed that only a few research has been carried out to realise the effect of soil flexibility and effect of openings in large stack like structures. In the present study, an attempt has been made to evaluate the effect of soil-structure interaction in a real tall chimney considering the openings. For this, the geometric and material details of a 275 m tall real chimney are considered and time-history analysis is carried out using LS-DYNA software for various types of supporting soil. The response of chimney-raft system subjected to an actual ground motion as excitation supported on flexible soil are calculated and compared with conventional methods.

2. Modelling

2.1 Properties of chimney-raft-soil system

A 275m tall industrial chimney with annular raft foundation was idealized by finite elements and subjected to El Centro earthquake motion to study the effect of openings in the structure and the soil flexibility. Soils having different shear wave velocities were taken, i.e., 100m/s, 300m/s, 600m/s and 1500m/s. The free field motions in above soils for the El Centro bedrock motion was generated using ProShake software and was used for the SSI analysis. The mass density and poisson's ratio of reinforced concrete was taken as 25 kN/m^3 and 0.2 respectively. Table 1 gives the geometric and material properties of the chimney. The modulus of elasticity of concrete for

Table 1 Geometric and material properties of chimney

Elevation in chimney (m)	Mean diameter (m)	Thickness (m)	Grade of concrete
275	18.40	0.400	M30
155	18.40	0.400	M30
145	18.70	0.420	M35
135	19.20	0.460	M35
125	19.50	0.500	M35
115	20.00	0.550	M35
105	20.35	0.600	M35
95	20.80	0.650	M35
85	21.20	0.700	M35
75	21.60	0.750	M35
65	22.00	0.800	M35
55	22.45	0.854	M35
45	22.90	0.865	M35
35	23.35	0.900	M40
2	25.10	0.900	M40
0	25.10	0.900	M40
-2.8	25.10	0.900	M40

Table 2 Properties of the soil types

Designation	Soil types	Velocity of shear waves, Vs (m/sec)	Poisson's ratio, μ	Unit weight, γ (kN/m^3)	Elastic modulus, E (kN/m^2)
S1	Loose sand	150	0.4	16	102,750
S2	Medium sand	300	0.35	18	421,100
S3	Dense sand	600	0.35	20	1981,600
S4	Rock	1500	0.3	20	11910,000

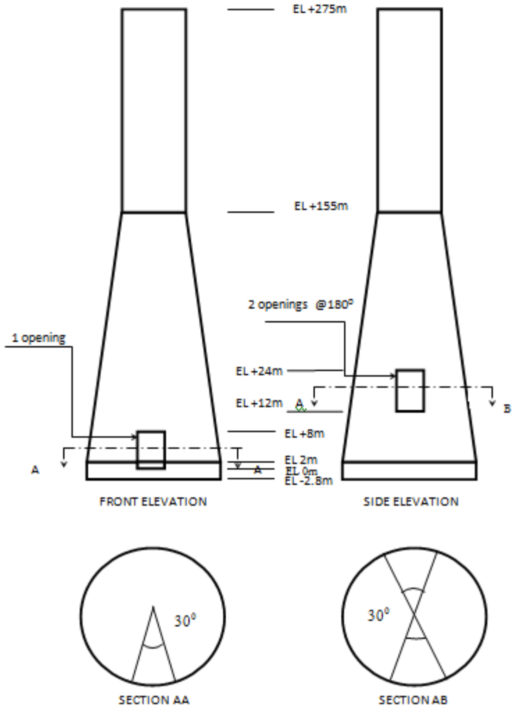


Fig. 1 Details of openings in the chimney

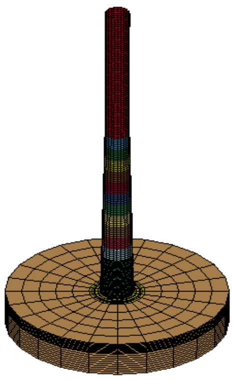


Fig. 2 3D Chimney-raft elastic soil continuum Model

chimney was calculated based on IS: 4998, 1992. Three major openings in chimney were considered in the study as shown in Fig. 1. i.e., one major construction opening and two flue openings. The construction opening of 8m height was provided at ground level (elevation = 0 m). The two diametrically opposite flue openings of 12m height were located at 12 m level. Annular raft foundation with uniform thickness of 4m having an external diameter of 42 m and internal diameter of 8.2 m was considered. Four types of soil with different flexibilities as mentioned before were used in this analysis. The soil properties are given in Table 2. The additional reinforcements provided in the vicinity of the structural openings were not considered.

2.2 Finite element modelling of chimney-raft-soil system

The chimney and the annular raft foundation were modelled using four node Belytschko-Lin-Tsay shell elements. The chimney structure and annular raft foundation were discretised into divisions of 15° in the circumferential direction. In order to create a finer mesh near the base of chimney with openings, the chimney shell was discretised with element of 1m length up to 35 m height from base and element of 2 m length from 35 m till top of chimney. The raft was discretised radially with elements having width equal to one tenth of the outer radius of raft.

The soil was modelled as a homogeneous elastic material by using constant stress solid element having 6 degrees of freedom. The boundless nature of the soil was modelled by lateral non-reflecting boundary in order to avoid the wave reflection problems. The bedrock is assumed to be at a depth of 30 m. Vertically, the soil block was discretised with 1m size solid element in top 10m depth near the foundation and 2 m size element in the bottom layer of 20 m till bedrock.

The material damping ratio for chimney and annular raft foundation was assumed as 5%. The G/G_{max} modulus reduction curve and the equivalent damping ratio versus shear strain relationship for sand given by Seed and Idriss (1970) were assigned to the soil deposit. The damping ratio was taken as 10% for soil.

3. Seismic action

The time history analysis of the model was carried out with ground motion corresponding to the longitudinal component of Imperial Valley earthquake at El Centro with a magnitude of 7.0 and peak ground acceleration of 0.343g. The total duration of the ground motion is 60sec. Ground response analysis was carried out for S1, S2, S3 and S4 soil considering the El Centro ground motion occurring on bedrock which is at 30m below the soil surface using ProShake software. The free field motions thus obtained for different soil conditions were then used for the seismic soil-structure interaction analysis. The horizontal loading due to wind and other causes were not considered. The stresses due to gravity loading were initiated in the structure-soil system. The effects due to vertical component of earthquakes are generally small and can be ignored (Reddy *et al*, 2011).

The time history of acceleration of free field ground motion obtained for different soils was applied at the soil-structure interface defined for the corresponding soil. Acceleration time history and associated Fourier spectrum of the El Centro bedrock motion are shown in Fig. 3 and Fig. 8 respectively. The acceleration time history and the Fourier spectrum curves for the El Centro ground motion at free field for S1, S2, S3 and S4 soil are shown from Figs. 4 to 7 and Fig. 9.

The ratios of peak acceleration of free field motion in different soil types to the PGA of bedrock motion are shown in Table 3. From the Figs. 3 to 7 and Table 3, it can be inferred that the acceleration time history vary quite significantly for the four different types of soils under the same earthquake, and the loose sand amplifies the ground motion more.

Table 3 Average ratios of PGA of free field motion to the PGA of bedrock motion for the different soil types

Magnitude	Average PGA (g)					PGA amplification			
	Bedrock motion	Free field motions							
		S1	S2	S3	S4	S1	S2	S3	S4
7	0.343	0.6673	0.5645	0.4869	0.3983	1.94	1.64	1.41	1.15

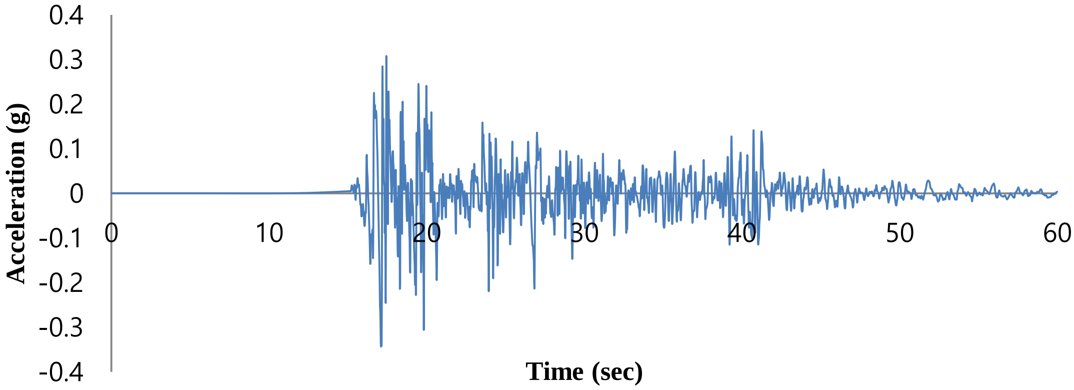


Fig. 3 Acceleration time history of the El Centro ground motion at bedrock (peak acceleration -0.343g)

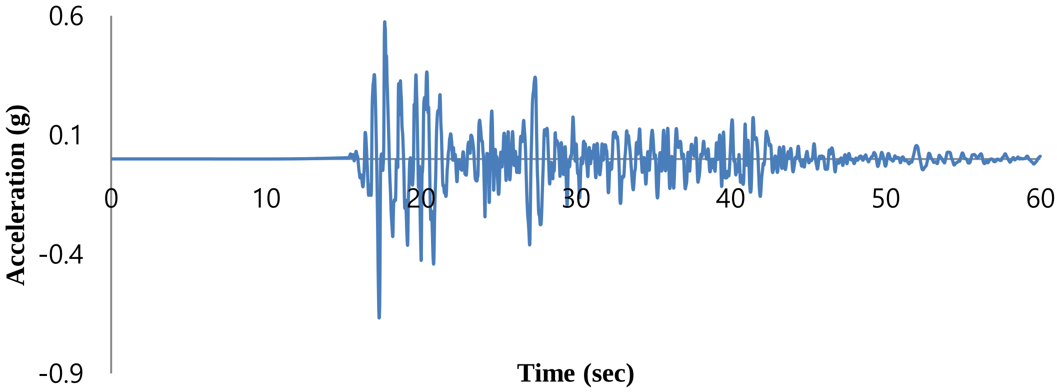


Fig. 4 Acceleration time history of the El Centro ground motion at free field for S1 soil type (peak acceleration -0.66g)

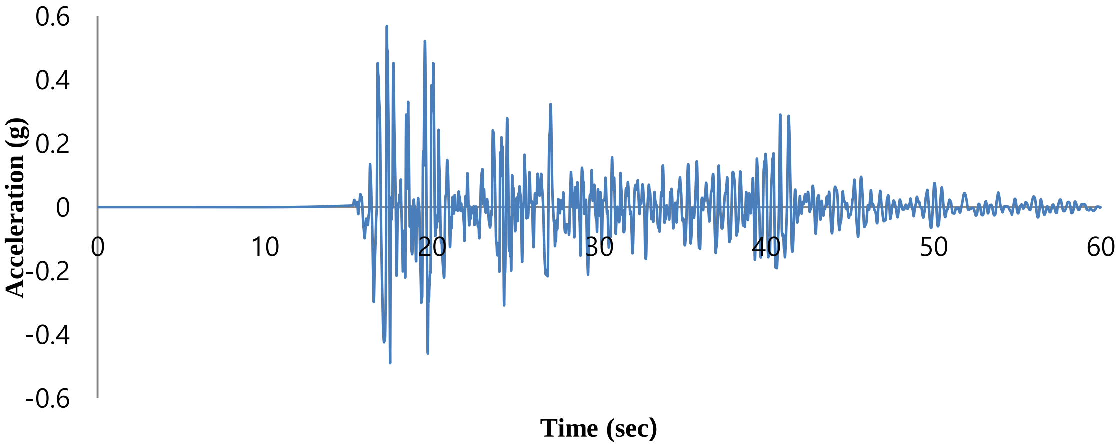


Fig. 5 Acceleration time history of the El Centro ground motion at free field for S2 soil type (peak acceleration -0.56g)

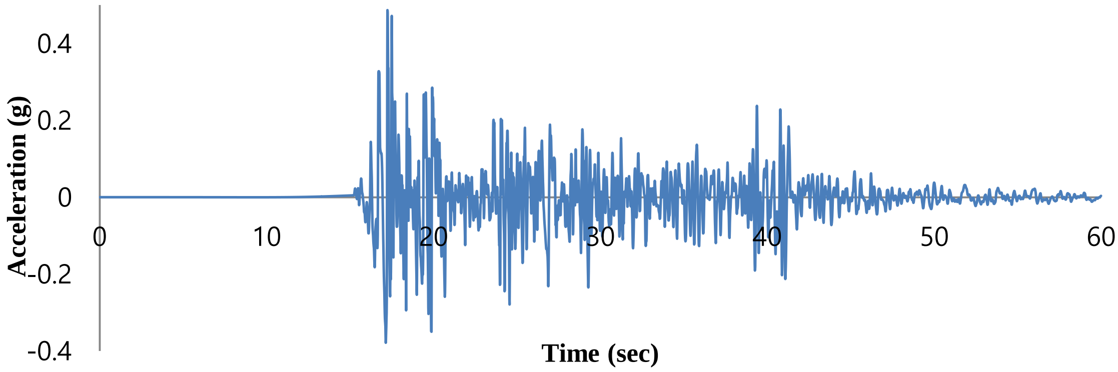


Fig. 6 Acceleration time history of the El Centro ground motion at free field for S3 soil type (peak acceleration-0.48g)

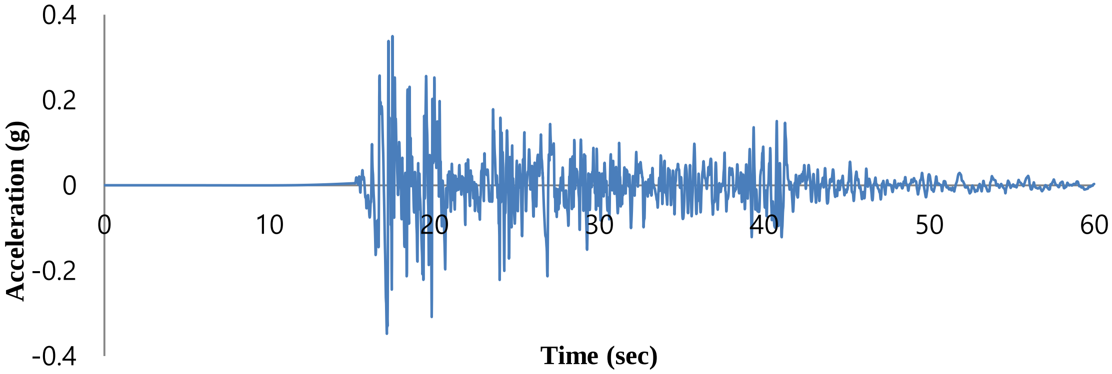


Fig. 7 Acceleration time history of the El Centro ground motion at free field for S4 soil type (peak acceleration- 0.398g)

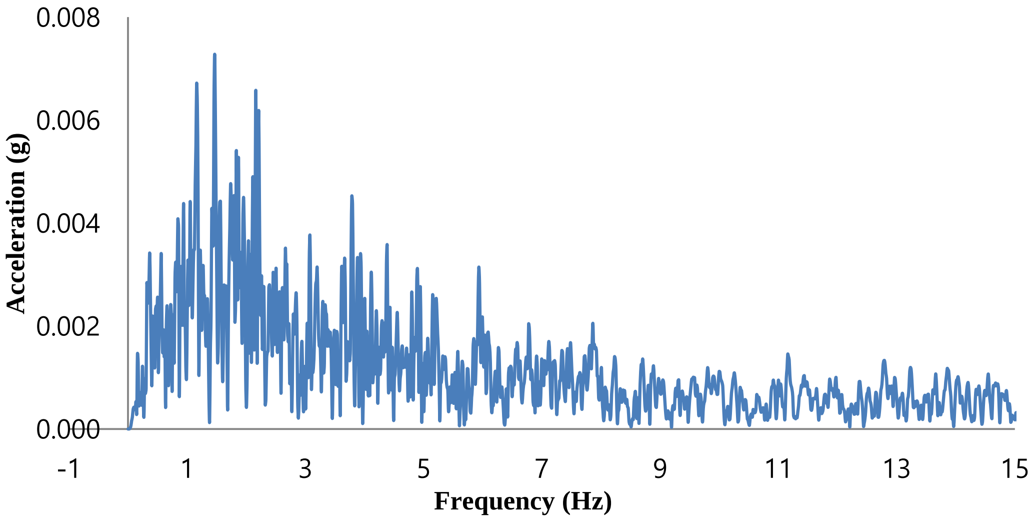


Fig. 8 Fourier spectrum curve for the El Centro ground motion at bedrock (0.343g)

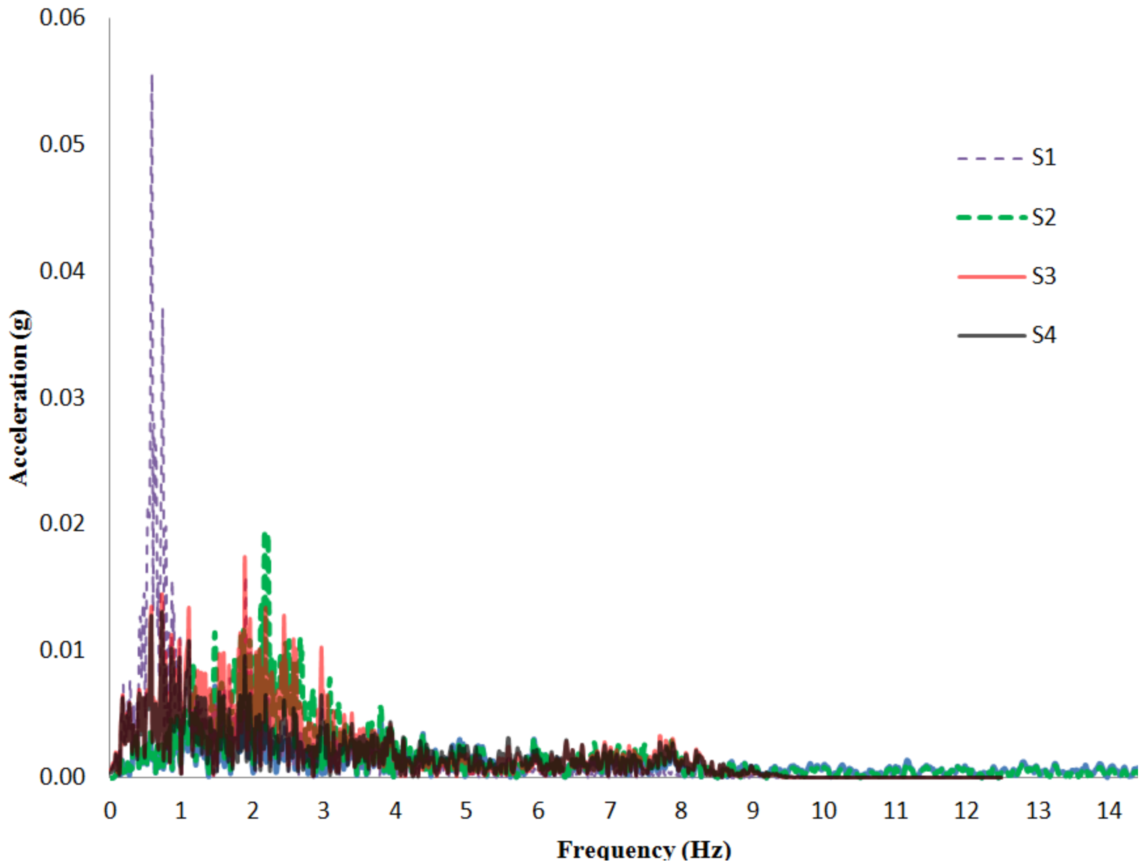


Fig. 9 Fourier spectrum curves for the El Centro ground motion at free field for S1, S2, S3 and S4 soils

4. Methodology

The seismic time history analysis of the soil-foundation-structure system was carried out with LS-DYNA, a finite element program for three dimensional nonlinear dynamic analyses of structures. Input motions were generated from ground response analysis using Proshake software.

4.1 Ground response analysis using Proshake

The process of obtaining the free field motion from bedrock motion is known as convolution. The influence of local site condition in modifying the nature of free field ground motion is studied by way of ground response analysis, which obtains the response at the free ground surface using wave propagation analysis with bedrock motion as input. According to the dimensionality of the problem, the ground response analysis could be three (3D), two (2D) or one dimensional (1D). Depending upon the site conditions and geometry, it may be decided whether 3D, 2D or 1D ground response analysis would be required. The one-dimensional ground response analysis provides a reasonably good estimate of the free field ground motion and is computationally simple. Because of these reasons, it is mostly used for ground response analysis. *(ProShake User's Manual, Version 1.1)*

4.2 Soil-structure interface

The soil is usually modelled with 8 node solid elements with 3 DOF at each node and raft foundation is modelled with the shell element having 6 DOF at each node. So at the interface between soil and raft a node compatibility problem would arise and there are chances of having a mesh mismatch. In order to take into account these problems of defining interface, LS-DYNA has a unique feature of defining a tied surface to surface contact between the soil surface and base of the structure. Interface can be defined in three dimensions by listing in arbitrary order, all triangular and quadrilateral segments that comprise each side of the interface. One surface of the interface is identified as a master surface and the other as a slave. (*LS-DYNA Keyword User's Manual, Version 971)*

During the static analysis phase of the model the interface was defined using the keyword *INTERFACE_SSI_STATIC_ID. A tied contact surface was created between the raft and soil using the specified segment sets, with the soil segment set as master segment set and the raft segment set as the slave. Naturally, the two segment sets should not have merged nodes and can be non-matching in general. However, the area covered by the two surfaces should match. This interface definition will record the static reactions at the base of the structure, which were to be used in a subsequent dynamic analysis of the soil-structure system subjected to earthquake excitation. During the transient analysis, the same interface was identified using the keyword *INTERFACE_SSI_ID. This card allows the analysis to start from static state of the structure.

4.3 Non-reflecting boundaries

Nonreflecting boundaries were defined in the software using a keyword *BOUNDARY_NON_REFLECTING as a collection of segments, and segments were equivalent element faces on the boundary. These types of boundaries were used to prevent artificial stress wave reflections generated at the model boundaries from re-entering the model and contaminating the results. Internally, LS-DYNA computes an impedance matching function for all non-reflecting boundary segments based on an assumption of linear material behaviour. Thus the finite element mesh should be constructed so that all significant nonlinear behaviour is contained within the discrete analysis model.

4.4 Procedure of SSI in LS-DYNA

The Soil-Structure Interaction analysis under earthquake excitation may be carried out in LS-DYNA as follows:

(1) Geometrical modelling: The soil-structure model can be generated using LS-PrePost, a pre-processor for LS-DYNA software. The interface between soil and structure is defined by a tied surface to surface contact and an absorbing layer called Non-Reflecting boundary is defined around the truncated domain.

(2) Static analysis: Carry out a static analysis of the soil-structure system with the structure only subjected to gravity loading. The soil-structure interface is identified using *INTERFACE_SSI_STATIC_ID in order to record the static reactions at the base of the structure, which are to be used in subsequent dynamic analysis of the soil-structure system subjected to earthquake excitation.

(3) Transient analysis: Carry out the transient analysis as a full deck restart job, with only the structure initialized to its static stress state and the same soil-structure interface is identified using *INTERFACE_SSI_ID with the same ID as in the static analysis. The transient analysis is carried out using the input file as the new dynamic keyword file and restart file as the 'd3dump02' produced by the static analysis.

The following points are to be taken care while in the transient stage of analysis: The structure mesh must be identical to the one used for static analysis.

a. The soil mesh is expected to be different from the one used for static analysis, especially because non-reflecting boundary models may be used for transient analysis.

b. The meshes for the structure (raft) and the soil need not match at the interface.

c. Only the structure must be subjected to static loads, via *LOAD_BODY_PARTS

d. The earthquake ground motions are specified using the keyword *BOUNDARY_FREE_FIELD_GROUND_MOTION_NODE_ID. The free field earthquake ground motions can be specified at certain locations defined by either nodes or coordinates on a soil-structure interface. The specified motions are not imposed directly at the nodes, but are used to compute a set of effective forces in the soil elements adjacent to the soil-structure interface according to the effective seismic input-domain reduction method (*LS-DYNA Keyword User's Manual*, *Version 971*).

5. Discussion of results

5.1 Variation in natural frequency

It is seen that the natural frequency of the chimney structure with flexible-base condition is less as compared to the fixed-base system because the flexibility of soil medium below foundation decrease the overall stiffness. A reduction of 27-53% in natural frequency is observed for first five modes of the chimney resting on soft soil compared to fixed base (Table 4). A reduction of 2.5% is

Table 4 Natural Frequencies of 275 m chimney with opening

Mode		1	2	3	4	5
Natural frequency (cycles/sec)	Fixed	0.2953	0.3020	1.2202	1.2220	2.2150
	S1	0.2137	0.2160	0.9109	0.9178	1.0380
	S2	0.2604	0.2647	1.0493	1.0568	1.9868
	S3	0.2828	0.2884	1.1498	1.1536	2.2150
	S4	0.2921	0.2985	1.2019	1.2021	2.2150

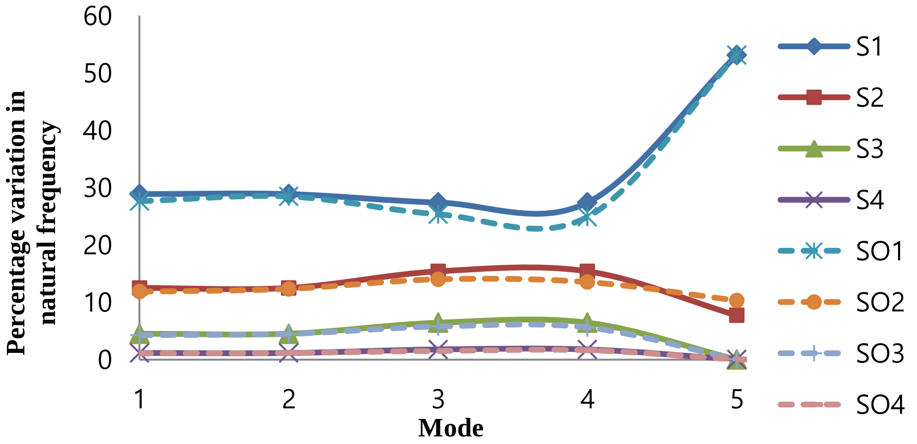


Fig. 10 Percentage variations in natural frequency

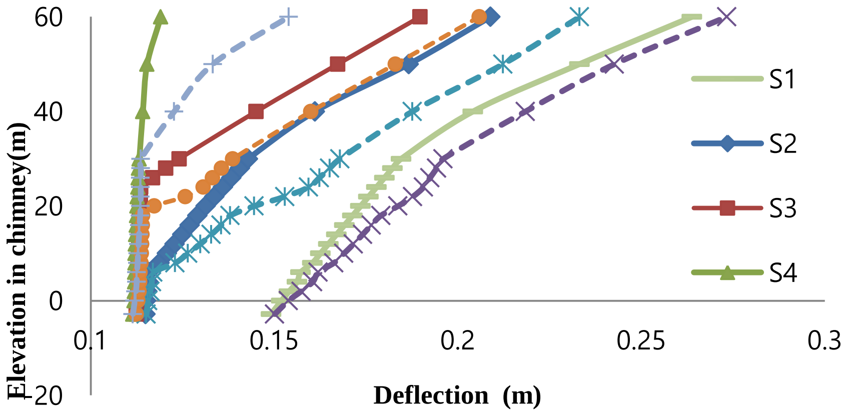


Fig. 11 Deflection of chimney

observed due to the effect of openings when the structure rests on soft soil (Fig. 10). SO1, SO2, SO3 and SO4 represent the response of chimney structure with openings, resting on soil types S1, S2, S3 and S4. Effect of flexibility of soil causes more variation in higher modes.

5.2 Variation in seismic response of chimney

5.2.1 Deflection of chimney shell

The lateral deflection of the chimney base for 60 m height at base is depicted in Fig. 11. It is seen that the maximum percentage variation of deflection of chimney with flexible base from that of fixed base is 108%, 77%, 56% and 17% for the soil types S1, S2, S3 and S4 respectively(Fig 11). Compared to the fixed base, the maximum percentage variation of deflection in chimney is found to be decreasing by 19%, 3%, and 7% for soil types S1, S2 and S3 due to openings in structure. The designations FO and F are used to represent fixed base chimney with and without openings. The chimney on soil type S1 deforms more due to the flexibility of supporting soil.

5.2.2 Tip deflection of chimney

The tip deflection of chimney with fixed base is 0.62m and the tip deflection of chimney with openings with fixed base is 0.66 m.

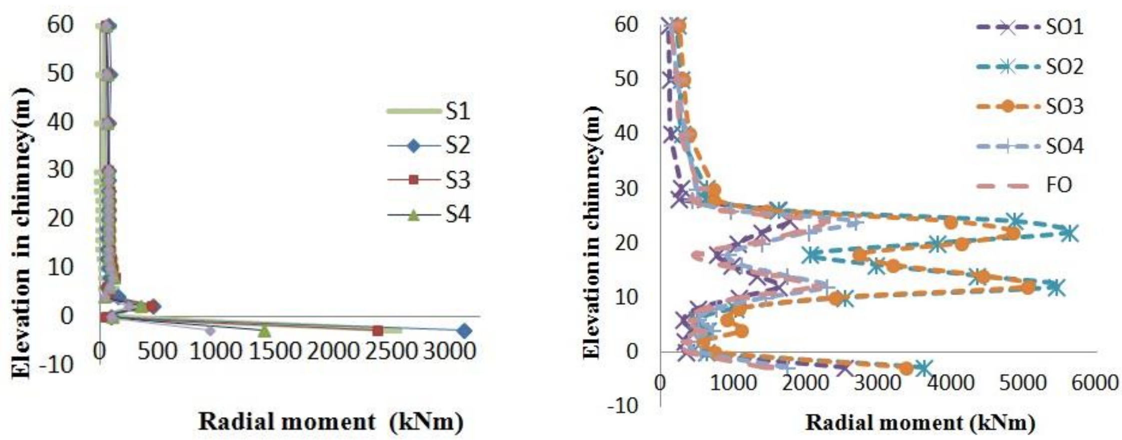
Except the structures resting on medium soil S2, the tip deflection of chimney increases as the soil flexibility increases as seen from Table 5. Due to the effect of openings in structure, the tip deflection is increased by 1.4%, 7%, 11% and 10% for structures resting on soil S1, S2, S3 and S4 respectively.

5.2.3 Radial moment in chimney shell

Radial moment is seen to be more for structures resting on the medium (S2) soil (Fig. 12). The maximum percentage variation of radial moment of chimney with flexible base from that of fixed base is 98%, 101%, 81.57% and 19.62% for the soil types S1, S2, S3 and S4 respectively. The values of radial moment at the base are abruptly changing due to the stiffness variation resulted from a change in geometry i.e., cylindrical geometry to a tapered section at an elevation of 2m.An increase of 310% in variation of radial moment is observed when openings are also considered in structure resting on medium soil. This may be due to the fact that the input motion for medium soil has higher amplitude frequency contents in initial modes. The percentage variation of the moment increases drastically around the openings in the structure. Hence the openings should be stiffened around to take care of these additional stresses.

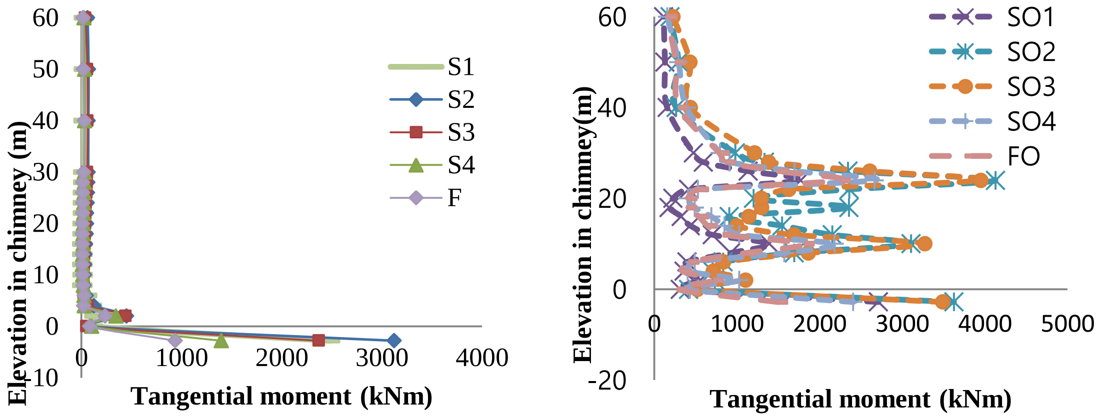
Table 5 Tip deflection of chimney

Base Condition		Tip deflection of chimney (m)	
		Chimney with opening	Chimney without opening
Soil	S1	0.81	0.822
	S2	0.649	0.69
	S3	0.76	0.724
	S4	0.7	0.69
Fixed		0.66	0.62



(a) Chimney without openings (b) Chimney with openings

Fig. 12 Radial moments in chimney



(a) Chimney without openings (b) Chimney with openings

Fig. 13 Tangential moments of chimney

5.2.4 Tangential moment in chimney shell

Fig. 13 gives the maximum percentage variation of tangential moment of chimney shell with flexible base from that of fixed base as 81%, 494%, 227% and 60% for the soil types S1, S2, S3 and S4 respectively. An increase of 82% in tangential moment is observed when openings are considered in structure resting on medium soil. The results show that the effect of soil-structure interaction is more near the base of the structure. In real practice sufficient stiffening should be provided around the structural openings to strengthen the edges for these additional moments.

5.3 Variation in seismic response of raft

5.3.1 Settlement of raft

A maximum variation of 4.7% is found at the outer portion of raft due to openings in structure when it rests on soft soil (Fig. 14). As per IS 1904:1986, the maximum permissible settlement for raft foundation on sand is 0.075m. From the study it is seen that the chimney-raft system on loose sand exceeds the permissible settlement, hence it is required to compact the soil to nearly hard soil.

5.3.2 Differential settlement of raft

As shown in Fig. 15 the raft settles differentially 0.111 m, 0.045 m, 0.014 m and 0.003 m when the structure is resting on S1, S2, S3 and S4 respectively. It becomes 0.105 m, 0.042 m, 0.015 m and 0.003 m when the openings in the structure are considered. As per IS 1904:1986, the maximum permissible differential settlement for raft foundation on sand is 0.05 m. It is not preferable to construct the chimney-raft system on loose sand since it exceeds permissible limit.

5.3.3 Contact pressure under raft

The soil-structure interaction (SSI) affects the distribution of pressure between the foundation and the soil. The foundation is assumed to be rigid usually, which is stiff enough to distribute the load on it to the soil uniformly. But while considering soil-structure interaction the contact pressure follows a non-uniform pattern.

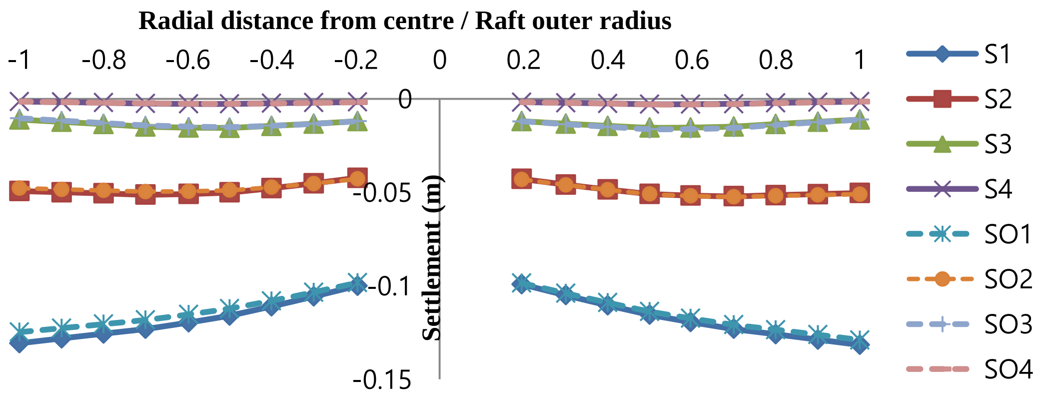


Fig. 14 Raft Settlement

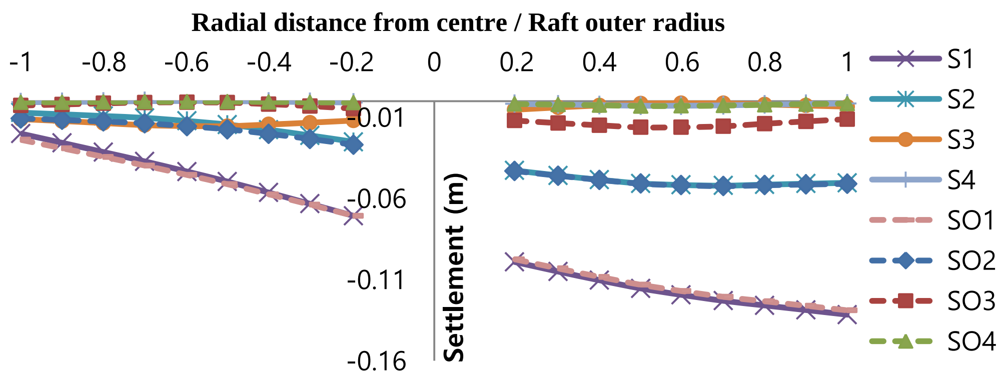


Fig. 15 Differential Settlement of Raft

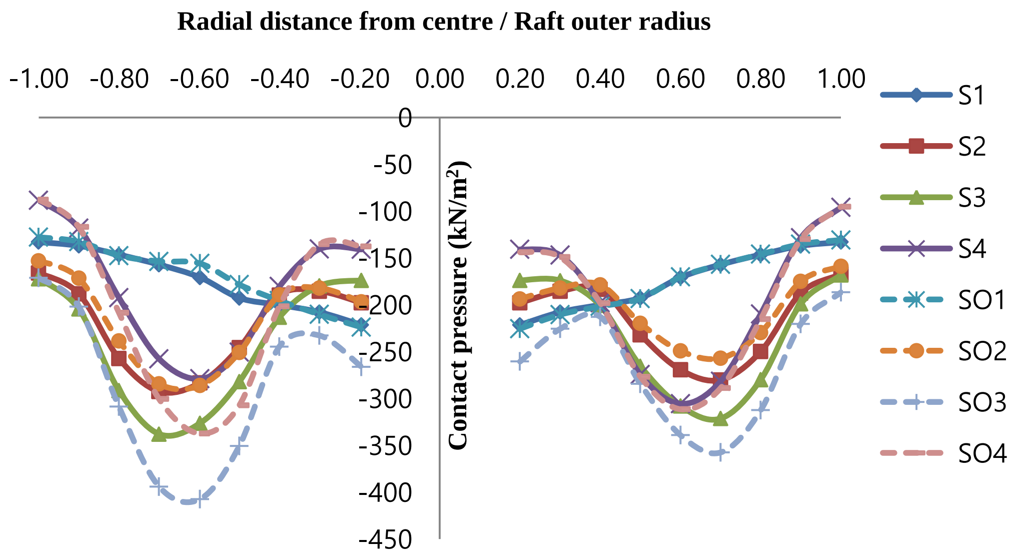


Fig. 16 Contact pressure under raft

The pressure distribution in Fig. 16 is seen to be an inverted bell shaped for S2, S3 and S4, having maximum pressure at chimney shell location for S4. Due to the effect of opening in structure, the pressure distribution is seen to be increased by 11% at the chimney shell location for dense soil. As per National Building Code of India 1983, the safe bearing capacity is 100kN/m^2 for S1, 245kN/m^2 for S2. It is 440kN/m^2 for S3 and S4. The analyses results show that the raft foundation is under safe pressure distribution when it rests on S3 and S4 soil types.

5.3.4 Radial moment in raft

The annular raft of chimney is analysed by conventional method also according to Indian standard code of practice, IS 11089: 1984 without considering the flexibility of soil. It is observed that the radial moment increases due to soil flexibility and it is seen to be maximum for the raft foundation resting on medium soil. From the Fig. 17, it is clearly understood that the radial moment in the raft is maximum at the chimney shell location. The percentage variations of the moments from conventional method (IS 11089) are 219%, 302%, 272% and 18% for S1, S2, S3 and S4 respectively.

5.3.5 Tangential moment

The tangential moment is seen to be more for raft foundation resting on medium soil (Fig.17). The percentage variations of the moments from conventional method (IS 11089) are 332%, 392%, 260% and 11% for S1, S2, S3 and S4 respectively. The conventional analysis of the structure according to Indian standard code of practice, IS 11089: 1984 was carried out without considering the flexibility of soil.

The frequency content of the El Centro ground motion at free field for medium sand is such that the maximum values of acceleration spectra are around 1.8 to 2.4 Hz. Since the natural frequency of chimney resting on medium sand at higher modes are near to these frequency values the dynamic responses are severely affected by the ground motion with which its dynamic moment responses are much higher than the response of other chimneys especially which are supported on loose sand. Possible resonance effect due to the frequency content of the ground motion matching that of medium soil plays an important role in increasing the structural response.

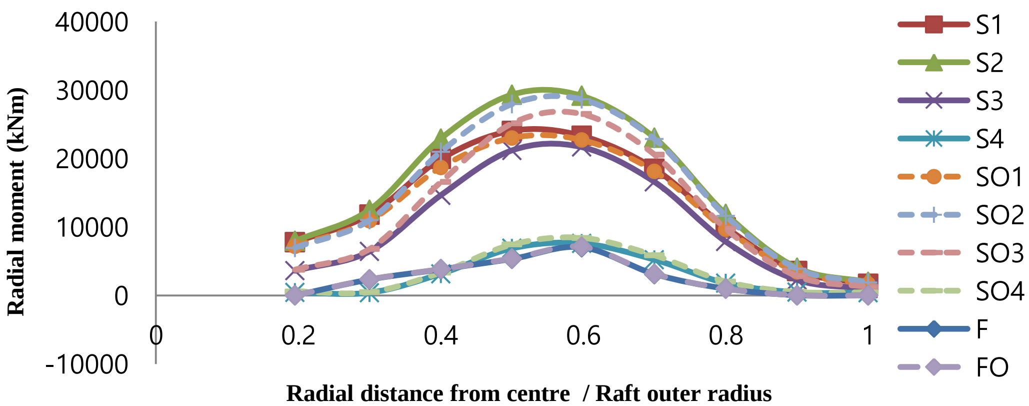


Fig. 17 Radial moment in raft

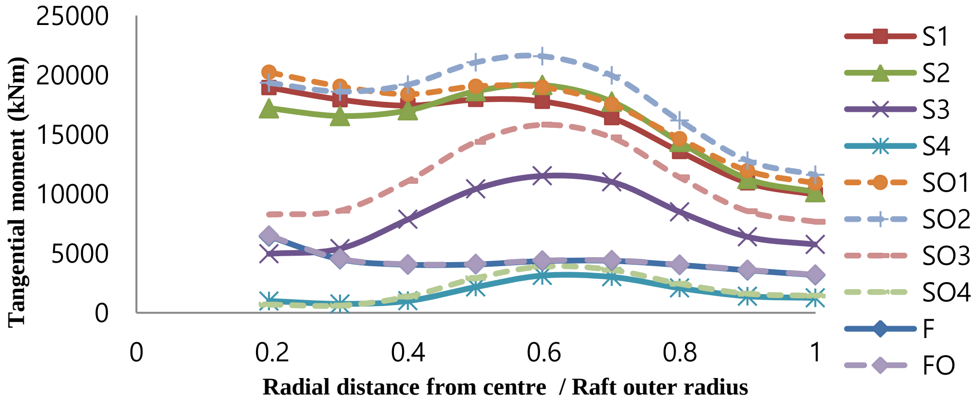
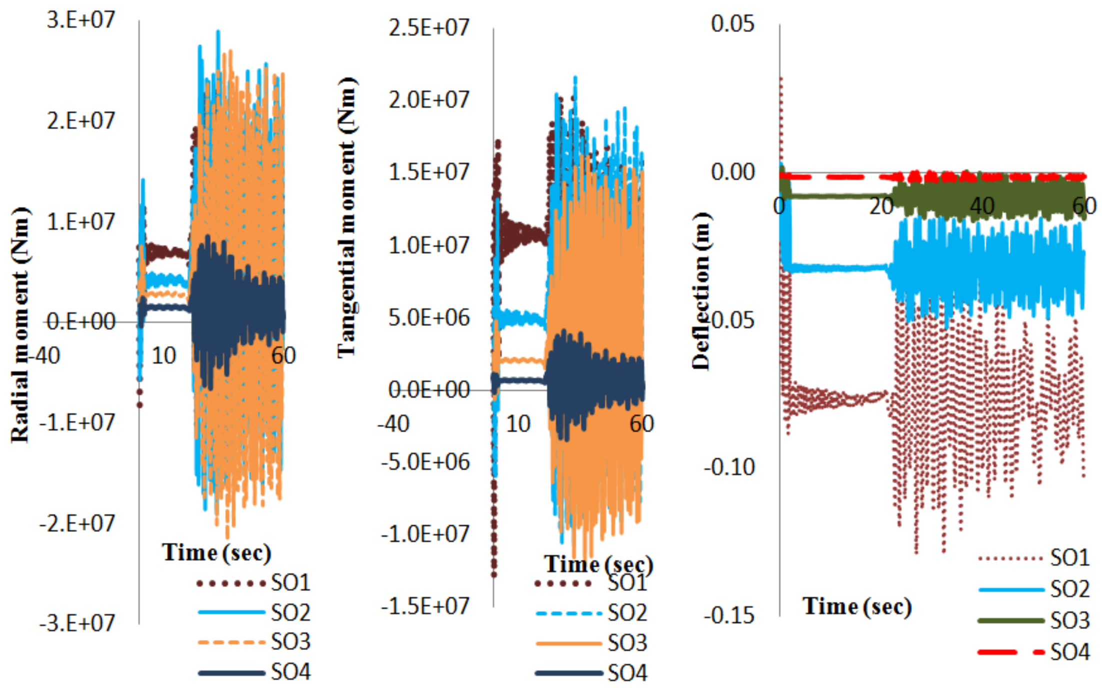


Fig. 18 Tangential moment in raft



(a) Radial moments in raft (b) Tangential moments in raft (c) Deflection in raft

Fig. 19 Time history of response in raft foundation of chimney with openings

Table 6 Displacement of base of chimney shaft

Soil base	Chimney with opening (m)	Chimney without opening (m)
loose	0.14968	0.14869
medium	0.11512	0.11497
dense	0.11243	0.11238
rock	0.11148	0.11148

5.4 Displacement of base of chimney shaft

From Table 6 and Fig 11 it is clearly seen that the displacement of the chimney base reduce as the soil stiffness increases for structures with and without opening. Due to the effect of openings in the structure, the displacement of base at the chimney shell location on raft founded in soft soil is increased by 0.6%.

5.5 Time history plots

Fig. 19 shows the time history response of maximum moments and deflection in raft for structure with opening resting on S1, S2, S3 and S4 soil types. The moment responses in raft are the maximum when the structure is resting on S2 soil type. The response of the overall structure is affected by the modification in natural frequency due to flexibility of soil. The raft settles more when it is founded on soil S1 and the settlement is less for support on S4.

5. Conclusions

A tall RC chimney supported by raft foundation resting on different soils has been idealized by finite elements and analysed for the El Centro earthquake data. The transient analysis was carried out using LS-DYNA software and the response was analysed.

From the analysis it is summarised as: There is considerable variation in the stress resultants in chimney and raft due to the effect of soil flexibility. Percentage variation in tangential moments of chimney is more compared to that in radial moments. It is not desirable to construct the chimney on loose sand since the differential settlement of raft foundation exceeds the permissible value as per IS 1904:1986.The edges of the flue openings should be provided with extra stiffened members to withstand the additional stresses due to soil flexibility. The effect of soil-structure interaction has more influence near the base of the structure. The effect of flue opening is to increase the radial and tangential moment in chimney and raft when the chimney is founded on flexible soils. The dynamic response of chimney and raft is affected mainly due to modification of dynamic characteristics and frequency content of input motion considering the flexibility of base.

References

Fatahi, B., Tabatabaiefar, S.H.R. and Samali, B. (2014), “Soil-structure interaction vs Site effect for seismic design of tall buildings on soft soil”, *Geomech. Eng.*, **6**(3), 293-320.

Gharad, A.M. and Sonparote, R.S. (2010), “Soil structure interaction of chimney”, *Int. J.Civil and Struct. Eng.*, **1**(3), 404-413..

IS: 1904 (1986), “Design and construction of foundations in soils, General Requirements”, *Bureau of Indian standards*, New Delhi.

IS: 11089 (1984), “Code of practice for design and construction of ring foundation”, *Bureau of Indian standards*, New Delhi.

IS: 4998 (1992), “Indian standard criteria for design of reinforced concrete chimneys”, *Bureau of Indian standards*, New Delhi.

Kramer, S.L. (2004), *Geotechnical Earthquake Engineering*, Pearson education, Singapore.

Kharade, A.S., Kapadiya, S.V. and Belgaonkar, S.L. (2013), "Earthquake analysis of tall sky-pod structures by considering the soil structure interaction effect", *Int. J. Emer. Tech. Adv. Eng.*, **3**(1), 447- 454.

LS-DYNA Ver971 (2009), "LS-DYNA Theory Manual", Livermore Software Technology Corporation, California, USA.

LS-DYNA Ver 971 (2009), "LS-DYNA Keyword user's Manual", Livermore Software Technology Corporation, California, USA.

Mehta, D. and Gandhi, N.J. (2008), "Time response study of tall chimney under the effect of soil structure and long period earthquake impulse" *Proceeding of the 14th World Conference on Earthquake Engineering*, Beijing, China, October.

National Building Code of India (1983), Group 1, *Bureau of Indian standards*, New Delhi.

Pallare, F.J., Aguero, A. and Martın, M. (2006), "Seismic behaviour of industrial masonry chimneys", *Int. J. Solids Struct.*, **43**, 2076-2090.

Pro Shake version 1.1 User's Manual, EduPro Civil Systems, Inc. Redmond, Washington.

Rajasankar, J., Nagesh, R. Iyer, B. Yerraya Swamy, Gopalakrishnan, N. and Chellapandi, P. (2007), "SSI analysis of a massive concrete structure based on a novel convolution/deconvolution technique." *Sadhana*, **32**(3), 215-234.

Reddy, K.R.C., Jaiswal, O.R. and Godbole, P.N. (2011), "Wind and earthquake analysis of tall RC chimneys", *Int. J. Earthq. Sci. Eng.*, **04**(06), 508-511.

Reza Tabatabaiefar, S.H., Fatahi, B. and Samali, B. (2013), "Lateral seismic response of building frames considering dynamic soil-structure interaction effects", *Struct. Eng. Mech.*, **45**(3), 311-321.

Sathish Kumar, K. (2012), "Characterization of dynamic soil properties", *Advanced Course on Geotechnical Earthquake Engineering, CSIR-SERC*, Chennai, India.

Seed, H.B. and Idriss, I.M. (1970), "Soil moduli and damping factors for dynamic response analysis, *Report no. UCB/EERC 70-10*, University of California, Berkely.

Shiming, W. and Gang, G. (1998), "Dynamic soil-structure interaction for high-rise buildings", *Dynamic Soil-Structure Interaction Current Research in China and Switzerland*, *Developments in Geotechnical Engineering*, Tsinghua University, Beijing, China.

The CICIND chimney book (2005), *Industrial Chimneys*, International Committee on Industrial Chimneys, Switzerland.

Wilson, J.L. (2003), "Earthquake response of tall reinforced concrete chimneys", *Eng. Struct.*, **25,** 11-24.

Wilson, J.L.(2010), "Performance of tall reinforced concrete chimney structures in the 2010 chilean earthquake", *Australian Earthquake Engineering Society Conference*, Perth, Western Australia.

Xu, C. and Spyrakos, C.C. (1996), "Seismic analysis of towers including foundation uplift", *Eng. Struct.*, **18**(4), 271-278.

Zhang, J. and Tang, Y. (2007), "Radiation damping of shallow foundations on nonlinear soil medium", *4th International Conference on Earthquake Geotechnical Engineering*, UC Los Angeles, Earthquake Engineering, UCLA Civil and Environmental Engineering, June.

CC