

EFFECT OF SOIL - STRUCTURE INTERACTION ON SEISMIC RESPONSE OF TALL CHIMNEYS.

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ABSTRACT

The problem of soil structure interaction in seismic analysis of massive structure has received due attention since the last two decades as it may be inevitable to build large structures at locations with less favorable geotechnical consideration in seismically active regions. Uncertainty about soil stiffness might cause considerable uncertainty about frequency content of structural response and may sometimes modify expected value of frequency content. Hence it is important to account for soil structure interaction in modeling of structure. In the present study a chimney 215m high is studied for its earthquake response for two cases 1) considering rigid base without soil effect 2) considering the effect of subsoil in foundation, using Time History analysis considering two major Indian Earthquakes. The chimney and soil below is modeled in SAP which uses Finite element formulation considering 5054 elements. The results for response, at different levels in chimney are plotted for both types of earthquakes under the influence of both above mentioned cases. It is seen that the soil structure interaction effect significantly modifies the earthquake behavior of chimneys. The study is therefore of great importance.

Keywords: Finite Element formulation, Chimney, Soil Structure Interaction, Earthquake Duration

INTRODUCTION

The study of effects of soil structure interaction on the seismic response of tall chimneys and other slender structures has received some attention in last twenty years. The analysis of superstructure without modeling the foundation and conversely analyzing foundation without considering rigidity of structure may both result in misleading estimate of responses. It is therefore necessary to carry out analysis by considering soil, foundation and structure which all parts of single compatible unit [23]. The type of soil supporting foundation and nature of seismic excitation modifies the seismic behaviour of chimney. The chimney would behave in different manner when they are subjected to different earthquakes excitations and different soil conditions. Hence it is important to account for soil structure interaction in modeling of a structure.

ANALYSIS OF SOIL STRUCTURE INTERACTION

Mathematical Formulation

The most common SSI approach used for the 3-D soil structure systems is based on “added motion” formulation [29]. The method requires for field motions at the base of structure be calculated for SSI analysis. To develop the fundamental of SSI dynamic equilibrium equations, consider a 3-D soil structure system shown in Fig 1

Consider the case where the SSI model is divided into three sets of node points. The common nodes at the interface of the structure of foundation are identified with “c”; and other nodes within the structure are “s” nodes and those within the foundation are “f” modes. From the stiffness approach in structural analysis, the dynamic force equilibrium of the system in terms of absolute displacement, V, by the following sub – matrix equation:

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$$\begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} U_s \\ U_c \\ U_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \dots (1)$$

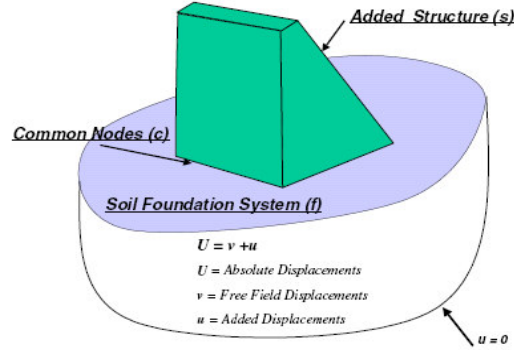


Figure 1 .Soil Structure interaction model

Where the mass and the stiffness at the contact nodes are the sum of the contributions from the structures (s) and foundation (f), are given by:

$$M_{cc} = M_{cc}^{(s)} + M_{cc}^{(f)} \text{ and } K_{cc} = K_{cc}^{(s)} + K_{cc}^{(f)} \quad \dots (2)$$

In terms of absolute motion, there are no external forces acting on the system. However, the displacements at the boundary of the foundation must be known. To avoid solving this problem directly, the dynamic response of foundation without structure is calculated. In many cases, these free field solution can be obtained from a simple one dimensional site model. The 3-D free field solution is designated by absolute displacements U and absolute accelerations \ddot{U} . By a simple change of variables, it is now possible to express the absolute displacements U and accelerations \ddot{U} in terms of displacements u relative to the free – field displacements v . Thus,

$$\begin{bmatrix} U_s \\ U_c \\ U_f \end{bmatrix} = \begin{bmatrix} u_s \\ u_c \\ u_f \end{bmatrix} + \begin{bmatrix} v_s \\ v_c \\ v_f \end{bmatrix} \text{ and } \begin{bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{bmatrix} = \begin{bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{bmatrix} + \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} \quad \dots (3)$$

thus equation (1) becomes

$$\begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} u_s \\ u_c \\ u_f \end{bmatrix} = - \begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} - \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} v_s \\ v_c \\ v_f \end{bmatrix} = R \quad \dots (4)$$

If the free field displacement v_c is constant over the base of the structure, the term v_s is the rigid body motion of the structure. Therefore, equation (4) can be further simplified by the fact that the static rigid body motion of the structure is:

$$\begin{bmatrix} K_{ss} & K_{sc} \\ K_{cs} & K_{cc} \end{bmatrix} \begin{bmatrix} v_s \\ v_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \dots (5)$$

Also, the dynamic free – field motion of the foundation requires that:

$$\begin{bmatrix} M_{cc}^{(f)} & 0 \\ 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} + \begin{bmatrix} K_{cc}^{(f)} & K_{cf} \\ K_{cf} & K_{ff} \end{bmatrix} \begin{bmatrix} v_c \\ v_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \dots (6)$$

Thus right hand side of equation (4) becomes

$$R = \begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc}^s & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ 0 \end{bmatrix} \quad \dots \quad (7)$$

Hence, the right – hand side of the equation (7) does not contain the mass of the foundation. Therefore, 3 – D dynamic equilibrium equations for complete soil structure interaction system with damping added are of the following form for a lumped mass system:

$$M\ddot{u} + C\dot{u} + Ku = -m_x\ddot{v}_x(t) - m_y\ddot{v}_y(t) - m_z\ddot{v}_z(t) \quad \dots \quad (8)$$

where M, C, K are the mass, damping and stiffness matrices respectively of soil structure model. The added relative displacements, u exists for the soil structure system and must be set to zero at the sides and bottom

of the foundation. The terms $\ddot{v}_x(t), \ddot{v}_y(t), \ddot{v}_z(t)$ are the free field components of acceleration if the structure is not present. The column matrices, mi are directional masses for the added structure.

Problem statement

For analysis a chimney 215m high with outer diameter of 9.6m at top, bottom diameter 18.21m and shell thickness 0.25m at top and 0.6m at bottom was considered. It is important to note that when we consider soil structure interaction the non – linearity is because of soil and not the structure. This is because when large massive structures are located on relatively softer soils, bounded region of soil adjacent to the structure behaves in a non-linear fashion and affects the response of structure due to dynamic loading [24]. The soil is idealized in single strata beneath the foundation, which consist of annular raft foundation having the internal and external diameter 12.8 m and 30.8m respectively and having height of 2.5m. The raft and the soil surrounding it is modeled considering solid elements. The properties of different types of soils that were used in study are tabulated below.

Table 1 Properties of different type of soils

Velocity of Shear waves m/s	Velocity of primary waves m/s	Soil Type	Density KN/m3	Poisson's ratio γ	Shear modulus G (KN/m2)	Elastic Modulus KN/m2
150	400	Soft Soil	16	0.49	36700	14.95 x 104
300	700	Stiff Soil	20	0.45	183500	25.836 x 105
600	1900	Dense Soil	22.4	0.35	322000	50.53 x 107
1200	4000	Rock	25.6	0.3	3758900	30.42 x 107

$$E_s = \left[\frac{V_p^2}{(1-\gamma)} \rho(1-2\gamma)(1+\gamma) \right] \times 0.15$$

The value of E was calculated using where, V_p is velocity of primary wave. Based on this analysis it is found that soil non-linearity can increase or decrease the response of structure based on type of soil that is soft or hard, on seismic excitation and type of structure [16].

Understanding the importance of effect of soil structure interaction on the seismic response of tall slender structures, in this study attention is focused on evaluating the seismic response of tall chimney considering the effect of soils with different shear velocity ranging from 150 m/s to 1200 m/s (soft soil to hard strata respectively) and comparing the results obtained with those from fixed base assumption. The emphasis is mainly laid in comparison of acceleration profile and displacement since these are more directly related to forces on the structure. These responses were found by doing seismic analysis considering the Time History Analysis using a long duration (Bhuj Earthquake) and a short duration earthquake (Koyna earthquake).

The details regarding PGA, total duration of quake, Peak acceleration are shown in the table below.

Table 2 Properties of different type of soils

Earthquake excitation	Peak acceleration m/s^2	PGA g	Total duration (sec)
Bhuj	1.04 @ 46.005	0.106	132.515
Koyna	0.65 @ 2.664	0.066	7.02

DISCUSSION OF RESULTS

Acceleration Profile

It can be seen from the figure 2, that maximum acceleration response for soils having shear velocity less than 600m/s is a smooth line however the nature changes for soil having shear velocity greater than 600m/s. The curve for such soils is highly undulated.

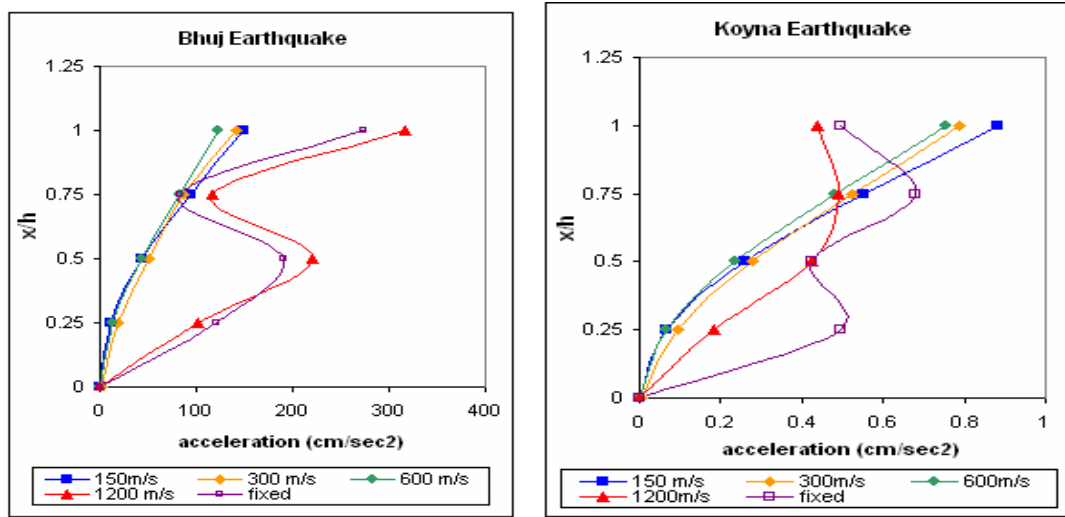
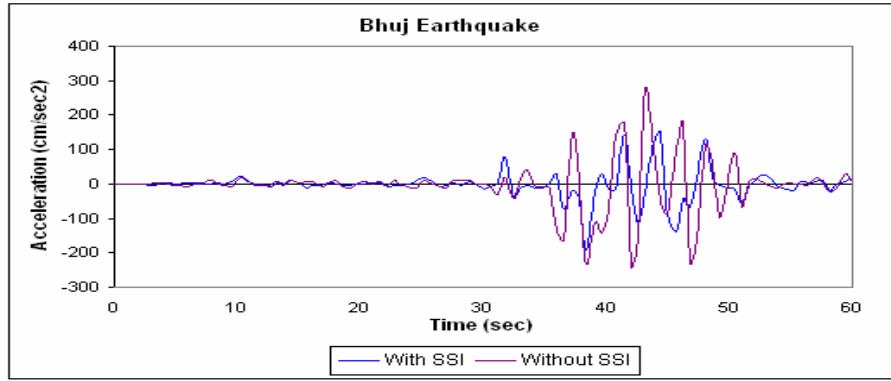


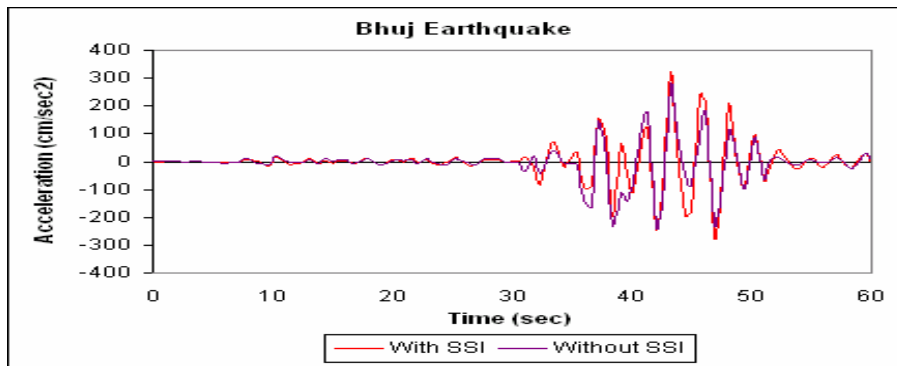
Figure.2 Maximum Acceleration response over chimney height

This is because of the fact that for soil having low shear wave velocity has high amount of damping which reduces the peak accelerations on the chimney. However soils having $V_s > 600 \text{m/s}$ have low damping value and the response obtained for them is same as that obtained under fixed base assumption. This is true for long and short duration earthquakes. However the value of peak acceleration may change in each earthquake.

For long duration earthquake maximum peak response is at top and 0.5h height from base of the chimney for stiff soils and fixed base condition but for a short duration earthquake the peak response occurs at 0.75h and 0.25h from the base. The reason for this to happen is that long duration earthquake with high PGA have more energy flux and it takes large time (delay response) for the structure to dissipate energy. The energy gets dissipated after the getting transferred up to full length of chimney hence the top portion has maximum acceleration. However for a short duration earthquake the energy associated with earthquake waves is comparatively less. By the time energy is dissipated only few meters of chimney is subjected to high energy of earthquake waves. It is necessary to know the acceleration plot of a Time history along with the acceleration plot resulting from it at different points in the structure. This is important because the acceleration records of a particular earthquake may give its behavior at that particular site however the behavior of structure under the influence of such an earthquake is a localized phenomenon and is different for different points in the structure.



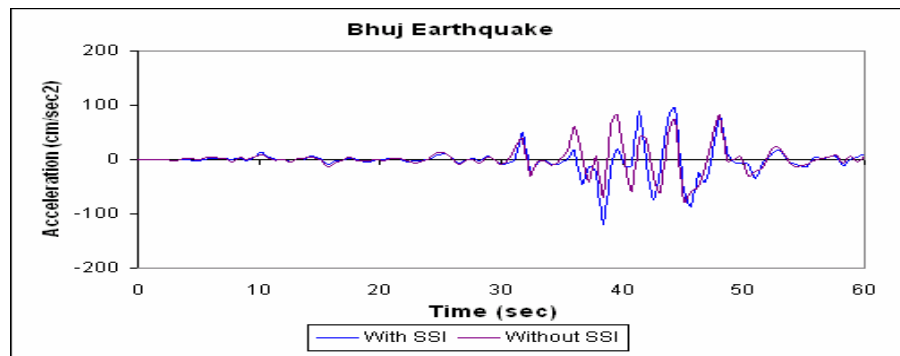
(a) For soils having shear velocity < 600m/s



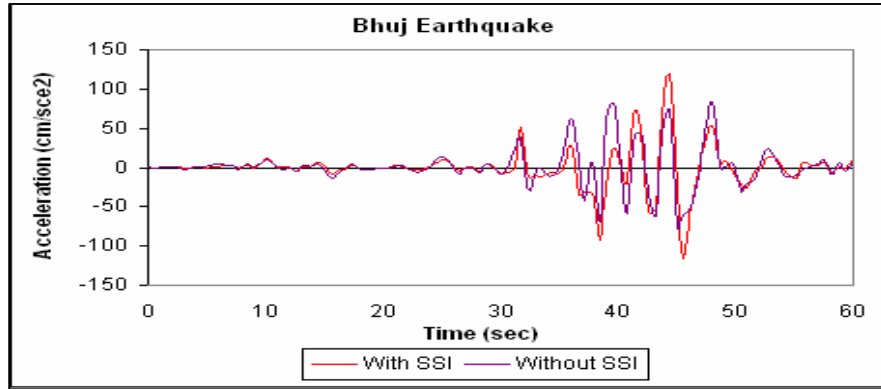
(b) For soils having shear velocity > 600m/s

Figure 2. Acceleration response at the top of chimney for , Bhuj Earthquake.

It is seen from the above graph that the values obtained by assuming fixed base without SSI is more than that obtained by assuming flexible base with SSI effect. Thus the consideration of SSI effect reduces the peak acceleration at the top of chimney. Also the time for peak acceleration response may vary for fixed base assumption as compared to flexible base by few seconds. The difference of response in both the cases is also noteworthy. It is seen that the responses for 0.75h height from base becomes almost 55% less the value obtained at top for fixed condition for long duration earthquake. However the values of response does not change for SSI condition for the same earthquake As a result the values obtained considering SSI effect is more than that assuming fixed base condition.



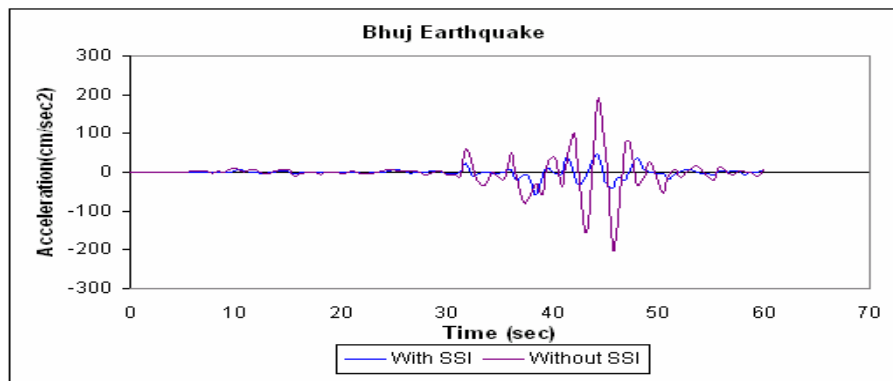
(a) For soils having shear velocity < 600m/s



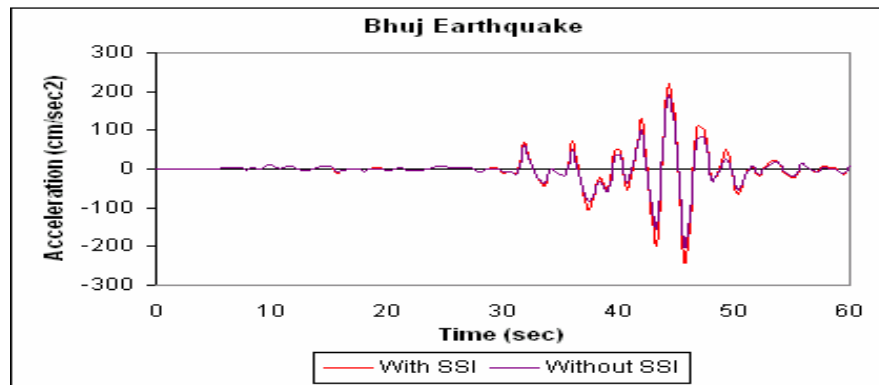
(b) For soils having shear velocity $> 600\text{m/s}$

Figure 4. Acceleration response at 0.75h height of chimney, for Bhuj Earthquake.

It can be observed that as we go towards base the acceleration response due to SSI effect decreases tremendously. The fixed base response increases upto 50% at 0.5h height of the chimney, while that due to flexible base it decreases by 25% as compared to upper section for long duration earthquake (Figure 5). As seen from the Figure 6, at 0.25h height, the fixed base assumption gives somewhat higher value however in actual case the acceleration is very less. This is because the soil will dampen the acceleration response.

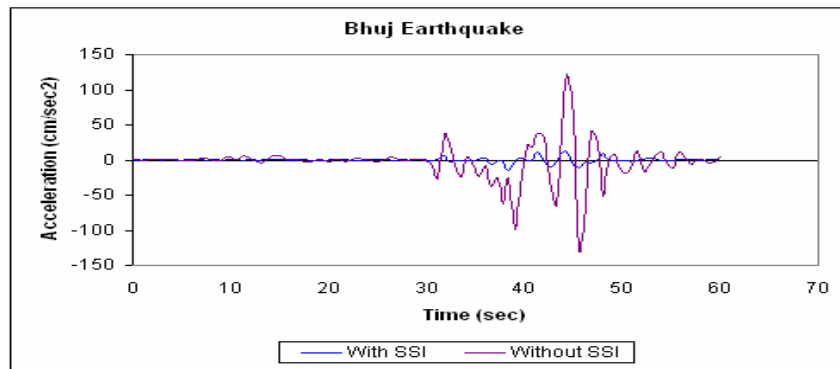


(a) For soils having shear velocity $< 600\text{m/s}$



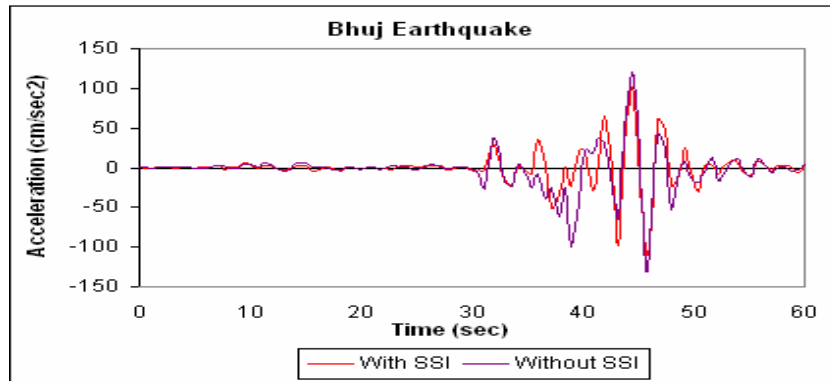
(b) For soils having shear velocity $> 600\text{m/s}$

Figure 5 . Acceleration response at 0.5h height of chimney for, Bhuj Earthquake.



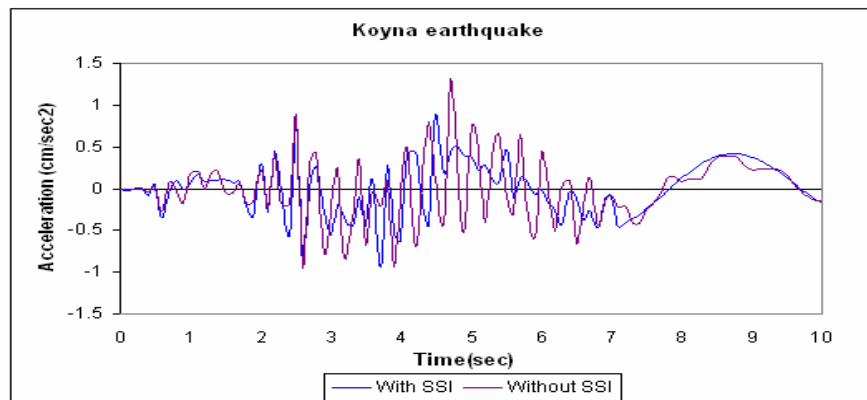
(a) For soils having shear velocity < 600m/s

The acceleration response of a chimney, assuming fixed base are more than the actual acceleration values. Thus assuming fixed base for soils having shear velocity less than 600m/s will overestimate forces in the lower portion of chimney leading to higher cross section at base and thus attracting more inertia forces and hence base shear.

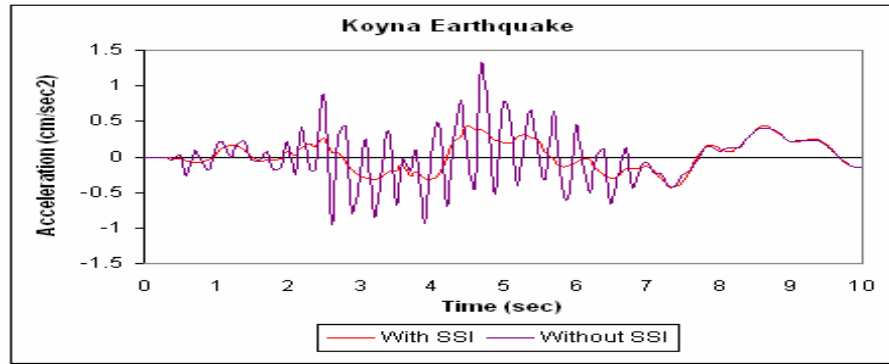


(b) For soils having shear velocity > 600m/s

Figure 6. Acceleration response at 0. 25h height of chimney for, Bhuj Earthquake.



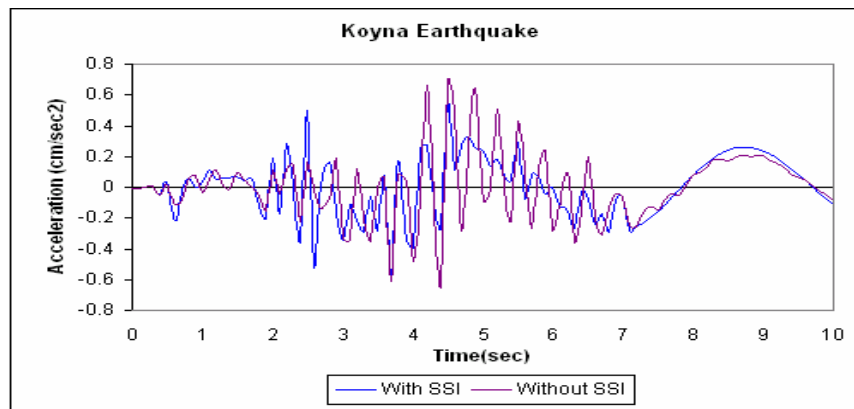
(a)For soils having shear velocity < 600m/s



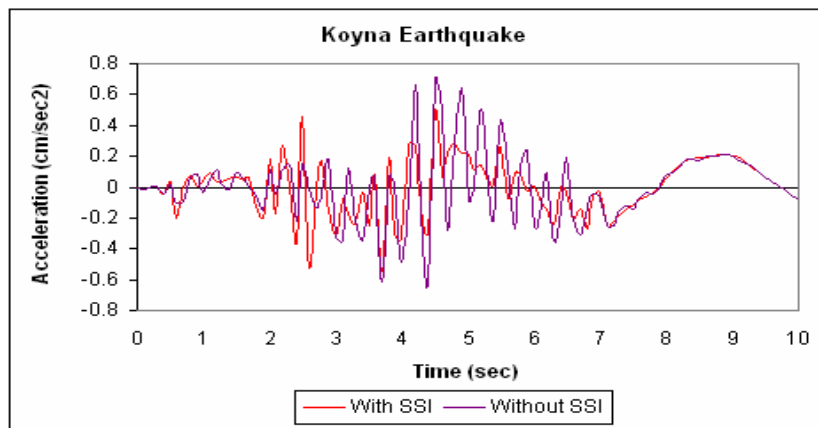
(b) For soils having shear velocity > 600m/s

Figure7. Acceleration response at the top of chimney, for Koyna Earthquake.

For very stiff soils like those having shear velocity $V_s = 1200\text{m/s}$ the response at top assuming fixed base is same as that obtained by assuming it to be flexible taking SSI effect in account for long duration earthquake. However the short duration earthquake does not show such a response. Infact for such an earthquake, the response due to SSI effects are less than that obtained without SSI effect accept for the last few seconds.



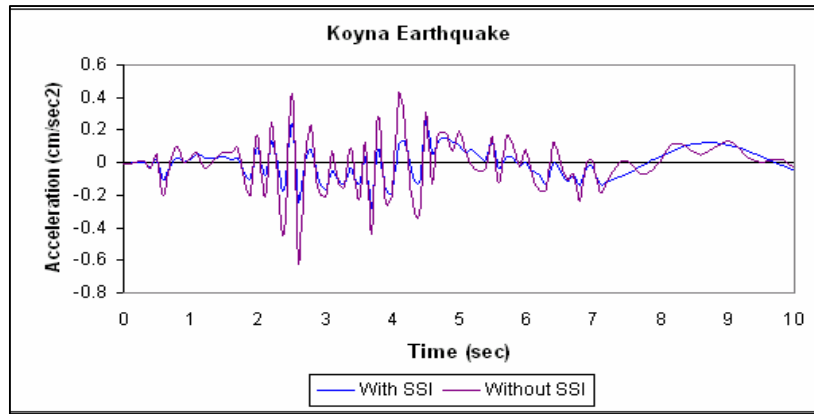
(a) For soils having shear velocity < 600m/s



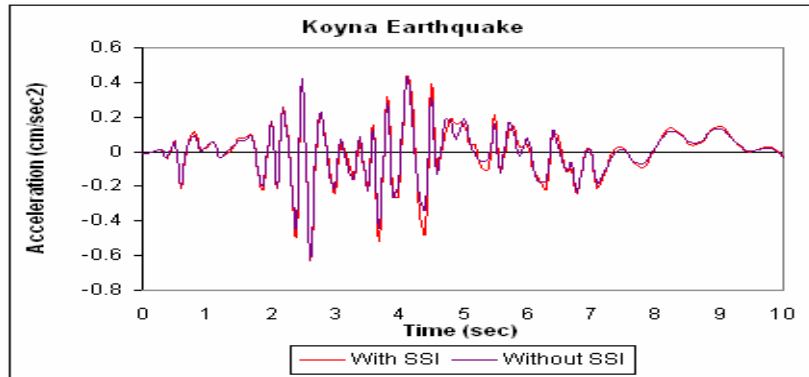
(b) For soils having shear velocity > 600m/s

Figure 8. Acceleration response at the 0.75h of chimney, for Koyna Earthquake.

For short duration earthquake at 0.75h height from the top, the response due to SSI though less than that by fixed base, increases compared to that obtained for top height. Also, the earthquake response due to SSI though less than that by fixed base, increases compared to that obtained for top height.



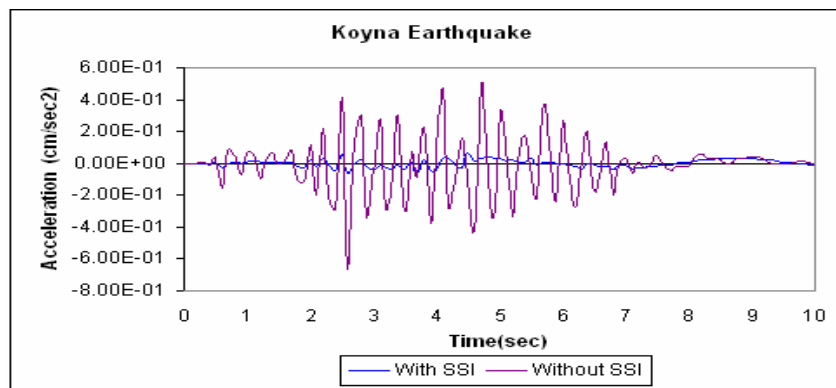
(a) For soils having shear velocity < 600m/s



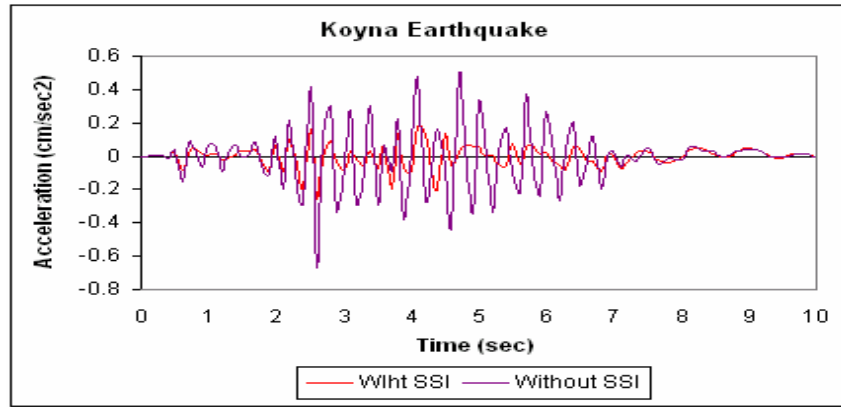
(b) For soils having shear velocity > 600m/s

Figure 9. Acceleration response at the 0.5h of chimney, for Koyna Earthquake.

At this height, 0.5h from the top the acceleration in presence of SSI reduces upto 60% as compared to that at 0.75h for long duration earthquake and up to 40% for short duration earthquake.



(a) For soils having shear velocity < 600m/s



(b) For soils having shear velocity > 600m/s

Figure 10. Acceleration response at the 0.25h of chimney, for Koyna Earthquake.

At this height the value of response for SSI decreases as compared to fixed base without SSI effect. This difference is more for short duration earthquake and less for long duration earthquake. But since the peak response value is very small for short duration earthquake the effect of SSI can be neglected for such an earthquake particularly when chimney is laid on stiff soils.

The nonlinearity in soil mass can result in increase or decrease in the displacement response depending on characteristic of ground motion and structure. This effect of soil on the displacement is more pronounced for softer soils. The displacement of the chimney increases as the height progresses and is maximum at the top. The chimney has a taper section having more stiffness at base as compared to the higher heights. This result in less displacement at base compared to the elevated sections. This fact holds true for all earthquake excitations. When the maximum displacement response is plotted for high earthquake excitations such as that of Bhuj Earthquake for fixed and flexible base, for different types of soils; it is seen that the displacement is maximum for all the points along the height of chimney, for soft soils characterized by shear velocity 150m/s. This displacement goes on reducing, as the soil gets stiffer.

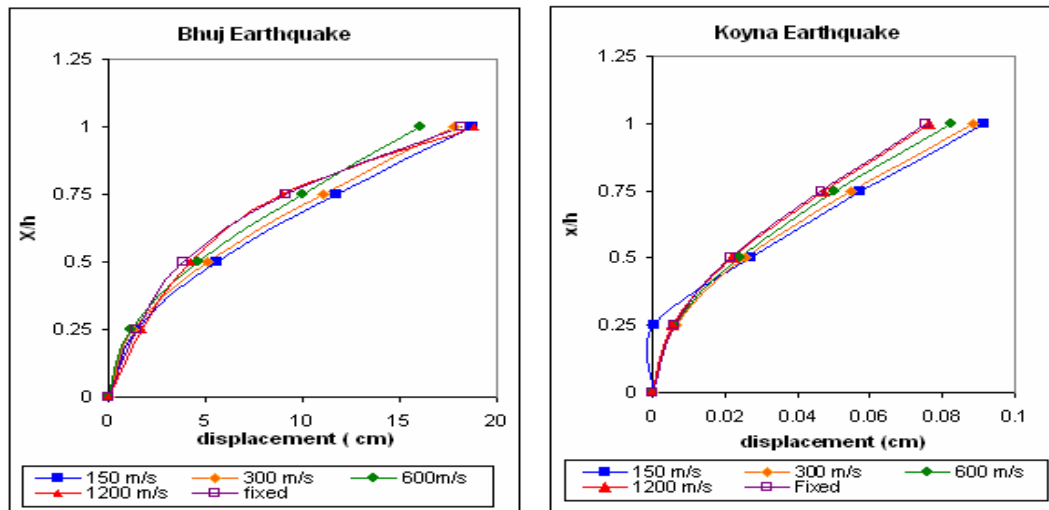


Figure 11 . Maximum Displacement response over chimney height

The displacement response for stiff soils like those having shear velocity 1200m/s is same as that obtained by considering fixed base thus ignoring SSI effects. Similar results are obtained for low earthquake excitations characterized by those like Koyna earthquake.

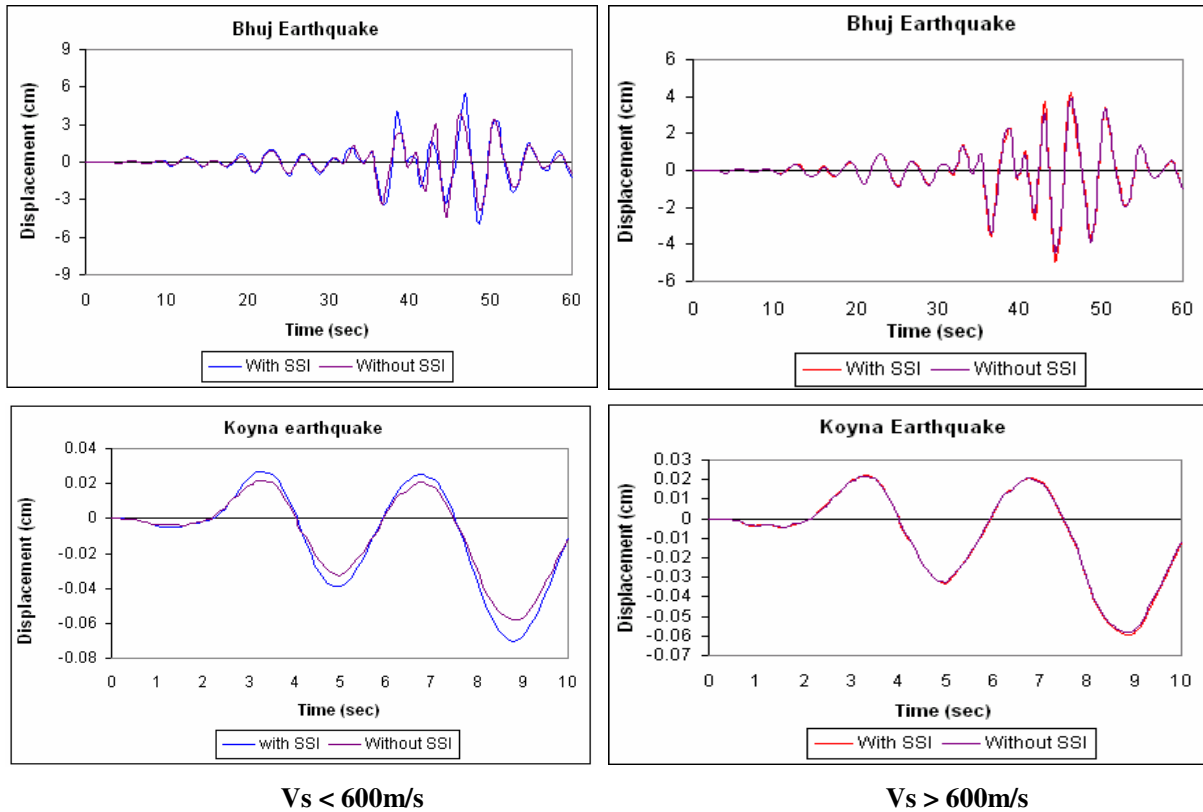


Figure 12. Displacement response at top of chimney for Bhuj and Koyna earthquake

The displacement response is more considering SSI effect than that without its consideration at all sections along the chimney height both for long and short duration earthquakes.

CONCLUSION

When a chimney was analysed using Time History analysis for different types of soils considering flexible base and fixed base, the obtained results showed the importance of soil structure interaction effects. Following conclusions can be made in this respect.

- The effect of SSI is prominent for soils having shear velocity less than 600 m/s as these could tend to increase or decrease the response as compared to the fixed base. For soils having shear velocity higher than this the response is similar to that obtained from fixed base condition. This showed that for stiffer soils having shear velocity larger than 600 m/s, soil structure interaction can be ignored and foundation can be assumed as fixed for long and short duration earthquakes.
- The response of chimney is maximum at sections 0.5h and h along the height of chimney for long duration earthquake. For short duration earthquake 0.75h and 0.25h respond maximum when fixed base is assumed.
- The effect SSI effect on the displacement is more pronounced for softer soils. For long duration earthquake the amplification in displacement response for soft soils as compared to fixed base at h, 0.75h, 0.5h and 0.25h are 3.08%, 28.41%, 42.51% and -3.89% respectively. For short duration Earthquake these values become 20.9%, 22.98%, 24.74% and -88.14% respectively.

It is thus concluded that seismic response of tall chimneys is influenced greatly by soil supporting its base and nature of earthquake excitations striking the base. Ignoring any one of them can significantly affect the performance of chimney during earthquake and lead to devastating effects.

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