Time response study of tall chimneys, under the effect of soil structure Interaction and Long period earthquake Impulse.

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ABSTRACT :

Time period is an important means of evaluating the structural response of the structure subjected to large scale earthquake vibrations. It is necessary to study the response of tall structures like chimneys at various points rather than evaluation of the structural system on a whole. Seismic design of structures is generally carried out assuming fixed base ignoring the flexibility of soil. But, it has been observed that flexibility of soil medium below the foundation decreases the overall stiffness of the structure resulting in a subsequent increase in natural periods of the system. 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. The analysis is done using Time History analysis considering Bhuj Earthquake which is a long duration earthquake impulse. The main objective in using this earthquake was, to find out the effect on structure when hit by long duration and see how the response is modified, when soil effects are taken into the consideration. The analysis and results shows that the time period increases with increases with increase in soil flexibility. It remarkably increases up to 9% for soft soil in fundamental mode and up to 80-85% for higher modes.

KEYWORDS: Chimneys, Fundamental time period, soil structure interaction, time history analysis

1. INTRODUCTION

A rigid structure when subjected to ground motion moves back and forth with the ground in a rigid body motion. However, the motion of flexible structure due to ground motion is different. It is necessary to study the response of chimneys and other similar structures at various points rather than evaluation of the structural system on a whole. Time period is an important means of evaluating the structural response of the structure subjected to large scale earthquake vibrations. The lateral response of the system, may alter considerably due to change in natural periods. Seismic design of structures is generally carried out assuming fixed base ignoring the flexibility of soil. But, it has been observed that flexibility of soil medium below the foundation decreases the overall stiffness of the structure resulting in a subsequent increase in natural periods of the system. Thus the change in natural periods due to effect of soil structure interaction should be taken care of, as it is very important from analysis and design point of view.

1.1. Time History Analysis

Time-History analysis is not used frequently as compared to other conventional methods like response spectrum or modal analysis method because of lack of knowledge and availability of the actual ground motion data. However this is most accurate of all the methods. In this method structures response history is evaluated by subjecting it to a designed earthquake. The analysis is carried out for each incremental time interval and at each stage structural response is evaluated. The method consist of a step by step direct integration in which time domain is descritized into number of small increments δt and for each time interval the equations of motion are solved with the displacements and velocities of the previous step serving as initial functions.

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 descritized by numerical values at discrete time intervals.

Integration of this time acceleration history gives velocity history, integration of which in turn gives displacement history.

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1.2. Soil structure Interaction

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 problem of soil structure interaction in seismic analysis of massive structure has received due attention and has become increasingly important, as it may be inevitable to build large structures at locations with less favorable geotechnical consideration in seismically active regions. It was shown by Loren [17] that 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.

2. NUMERICAL METHODS FOR EVALUATION OF TIME HISTORY ANALYSIS AND SOIL STRUCTURE INETRACTION.

2.1. Procedure of time history analysis

In this method of dynamic analysis, instead of going through a process of determining response spectrum for a given ground motion and then applying the results to a given structure, it is possible by using computers to apply the earthquake motion directly to the base of a given structure. The procedure for time history analysis is as below:

1. The earthquake record is selected which represents the expected earthquake.
2. The record is digitized as a series of small time intervals of about 1/40 to 1/25 of seconds with given levels of acceleration occurring for each interval.
3. A mathematical model of the structure is set up. It usually consists of series of lumped masses linked by elastic links with damping factors. Each lumped mass represents one floor, and each link represents the elastic stiffness of framing members .The damping factors are introduced as expressions varying with the relative velocity of adjacent lumped masses.
4. The digitized record is applied to the model as accelerations at the base of the structure.
5. The computer integrates the motion equation of each mass as it is subjected to increments of elastic and damping forces through the connecting links and gives a complete record of the acceleration, velocity and displacement of each lumped mass.

2.2. Analysis of soil structure interaction

The most common SSI approach used for the 3-D soil structure systems is based on “added motion” formulation. This formulation is mathematically simple, theoretically correct, and easy to use. In addition, the formulation is valid for free field motion caused by earthquake waves generated from all sources. 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.

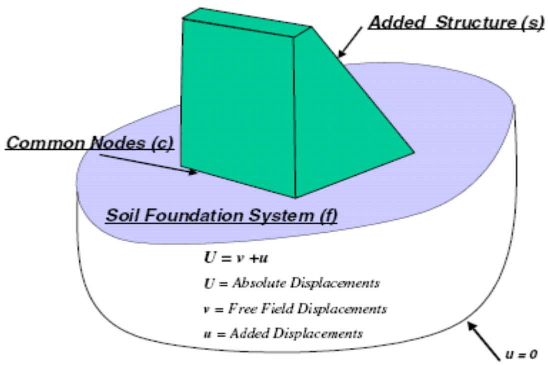

Figure 1 Soil Structure interaction model

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:

$$\begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} U_s \\ U_c \\ U_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \ldots (2.1)$$

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:

$$M_{cc} = M_{cc}^{(s)} + M_{cc}^{(f)} \quad \text{and} \quad K_{cc} = K_{cc}^{(s)} + K_{cc}^{(f)} \quad \ldots (2.2)$$

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,

$$\begin{bmatrix} U_s \\ U_c \\ U_f \end{bmatrix} = \begin{bmatrix} u_s \\ u_c \\ u_f \end{bmatrix} + \begin{bmatrix} v_s \\ v_c \\ v_f \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{bmatrix} = \begin{bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{bmatrix} + \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} \quad \ldots (2.3)$$

thus equation (2.3) becomes

$$\begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} u_s \\ u_c \\ u_f \end{bmatrix} = - \begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc} & 0 \\ 0 & 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} - \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{bmatrix} v_s \\ v_c \\ v_f \end{bmatrix} = R \quad \ldots (2.4)$$

If the free field displacement *vc* is constant over the base of the structure, the term *vs* is the rigid body motion of the structure. Therefore, equation (2.4) can be further simplified by the fact that the static rigid body motion of the structure is:

$$\begin{bmatrix} K_{ss} & K_{sc} \\ K_{cs} & K_{cc} \end{bmatrix} \begin{bmatrix} v_s \\ v_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{… (2.5)}$$

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

$$\begin{bmatrix} M_{cc}^{(f)} & 0 \\ 0 & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{v}_c \\ \ddot{v}_f \end{bmatrix} + \begin{bmatrix} K_{cc}^{(f)} & K_{cf} \\ K_{cf} & K_{ff} \end{bmatrix} \begin{bmatrix} v_c \\ v_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{…. (2.6)}$$

Thus right hand side of equation (4.24) becomes

$$R = \begin{bmatrix} M_{ss} & 0 & 0 \\ 0 & M_{cc}^{s} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ 0 \end{bmatrix} \quad \text{… (2.7)}$$

Hence, the right – hand side of the equation (2.4) 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:

$$M\ddot{u} + C\dot{u} + Ku = -m_x \ddot{v}_x(t) - m_y \ddot{v}_y(t) - m_z \ddot{v}_z(t) \quad \text{…. (2.8)}$$

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.

3. PROBLEM STATEMENT

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. These responses were found by doing seismic analysis considering the Time History Analysis as using a long duration (Bhuj Earthquake). The details regarding PGA, total duration of quake, Peak acceleration are shown in the table below.

Table 3.1 Data for beams under dynamic loading

Earthquake excitation	**Peak acceleration m/s^2**	**PGA g**	**Total duration (sec)**
Bhuj	1.04 @ 46.005	0.106	132.515

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. This particular chimney was chosen as it has slenderness ratio 34.5 and it was found by Doris [24] that chimney with slenderness ratio between, 34.5 to 36.5 gave the best performance during earthquake. In the initial part the chimney was modeled as having fixed base in absence of soil structure interaction (SSI) and giving it free excitations of Bhuj. These earthquakes were applied as the result of conclusion drawn by Luco[16] that importance of soil structure interaction effects is highly dependent on characteristics of earthquake excitation along with the nature of soil.

In the later part, the soil interaction analysis was done based on considering different type of soils having different shear velocities, thus considering flexible base and non- linear Time History analysis were performed on the structure. The properties of different types of soils that were used in study are tabulated below.

Table 3.2 Properties of different type of soils

Velocity of Shear waves m/s	Velocity of primary waves m/s	Soil Type	Density KN/m^3	Poisson's ratio γ	Shear modulus G (KN/m^2)	Elastic Modulus KN/m^2
150	400	Soft Soil	16	0.49	36700	14.95×10^4
300	700	Stiff Soil	20	0.45	183500	25.836×10^5
600	1900	Dense Soil	22.4	0.35	322000	50.53×10^7
1200	4000	Rock	25.6	0.3	3758900	30.42×10^7

The value of E was calculated using $E_s = [\ \frac{V_p^2}{(1-\gamma)}\rho(1-2\gamma)(1+\gamma)\ ]x0.15$ where, *Vp* 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.

3.1. Computational Modeling

The analysis is carried out in SAP 2000, considering the soil structure Interaction (SSI) approach was based on "added model formulation" as explained in section 2. For analysis the chimney was modeled as a shell element consisting of 5052 elements and treating it as an elastic beam with properties varying along the entire height. The discretization was done by considering 16 sections between which the properties were assumed to vary linearly. The base was assigned as rigid base. 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.

4. RESULTS AND DISCUSSION

A rigid structure when subjected to ground motion moves back and forth with the ground in a rigid body motion. However the motion of flexible structure due to ground motion is different. Firstly, the flexible structure corresponds in number of natural modes. Peak responses for these modes occur at different time instances. The following graphs enable us to view the results of Time History analysis for different responses and understand the importance of Soil Structure Interaction (SSI) effects on seismic response of tall chimneys when it is struck by a long and a short duration earthquake.

It is observed from Table 4.1 below, that the time period for each mode decreases as the mode number goes on increasing. Moreover the time period for chimney is more for flexible soil in each mode. The time period goes on decreases as the soil goes on getting stiffer.

Also Fig 2 shows that the time period increases with increases with increase in soil flexibility. The % increase in time period is up to 9% for soft soil in fundamental mode and up to 80-85% for higher modes. Also it can be seen that the %difference in time period for flexible soils increases in a drastic manner from third mode as we proceed towards the higher mode (Fig 3). The time period for higher modes is shorter as compared to the fundamental modes. One of the interesting things that can be observed is that the time period goes on decreasing as the shear velocity increases i.e. for stiffer soils with higher shear velocity the time period values approach nearer to that obtained by fixed base assumption. Hence for shear velocity in excess of 600m/s soil flexibility can be ignored and base can be treated as fixed.

Table 4.1 % Change in fundamental period with consideration of flexible foundation with respect to fixed foundation.

Mode no	Type of soil (Vs Shear Velocity)	Fundamental time period (sec)		% Change in fundamental time period (*T*)
		Without SSI (Fixed base)	With SSI (Flexible base)	
1	150 m/s	3.74248	4.1278	9.3350
	300m/s		3.7464	0.1065
	600m/s		3.7448	0.0616
	1200m/s		3.7442	0.0437
2	150 m/s	3.74248	4.0402	7.3697
	300m/s		3.7464	0.1051
	600m/s		3.7448	0.0608
	1200m/s		3.7441	0.0429
3	150 m/s	0.796612	4.0389	80.2764
	300m/s		1.9960	60.0894
	600m/s		1.5536	48.7236
	1200m/s		1.3006	38.7485
4	150 m/s	0.796612	3.8975	79.5611
	300m/s		1.9580	59.3153
	600m/s		1.5536	47.5326
	1200m/s		1.3006	38.7482
5	150 m/s	0.54325	3.7471	85.5023
	300m/s		1.9580	72.2510
	600m/s		1.5183	64.2198
	1200m/s		0.8983	39.5216
6	150 m/s	0.54325	3.7471	85.5020
	300m/s		1.4977	71.8250
	600m/s		1.4977	63.7289
	1200m/s		0.8982	39.5206
7	150 m/s	0.410138	3.6433	88.7530
	300m/s		1.3010	68.4749
	600m/s		1.3007	68.4676
	1200m/s		0.7970	48.5402
8	150 m/s	0.410138	3.4553	88.1301
	300m/s		1.3010	68.4745
	600m/s		1.3007	68.4673
	1200m/s		0.7970	48.5397
9	150 m/s	0.325928	3.4381	90.5201
	300m/s		1.2620	74.1742
	600m/s		0.9649	66.2230
	1200m/s		0.7103	54.1164

Mode no	Type of soil (Vs Shear Velocity)	Fundamental time period (sec) Without SSI (Fixed base)	With SSI (Flexible base)	% Change in fundamental time period (*T*)
10	150 m/s	0.325928	3.2031	89.8246
	300m/s		1.2515	73.9562
	600m/s		0.8983	63.7177
	1200m/s		0.7103	54.1160
11	150 m/s	0.324463	3.1936	89.8402
	300m/s		1.2515	73.8996
	600m/s		0.8983	63.8804
	1200m/s		0.6413	49.4066
12	150 m/s	0.324463	3.0276	89.2831
	300m/s		1.2403	73.8402
	600m/s		0.8328	61.0395
	1200m/s		0.6413	49.4064

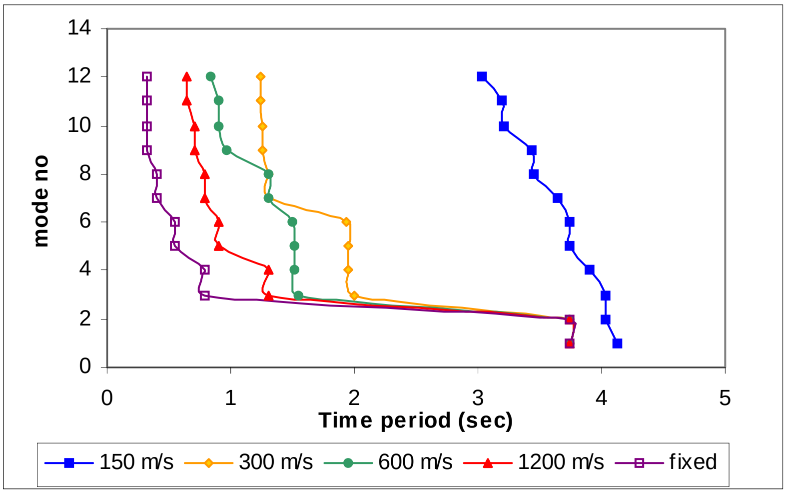

Figure 2 Comparison for modal time period for different types of soil

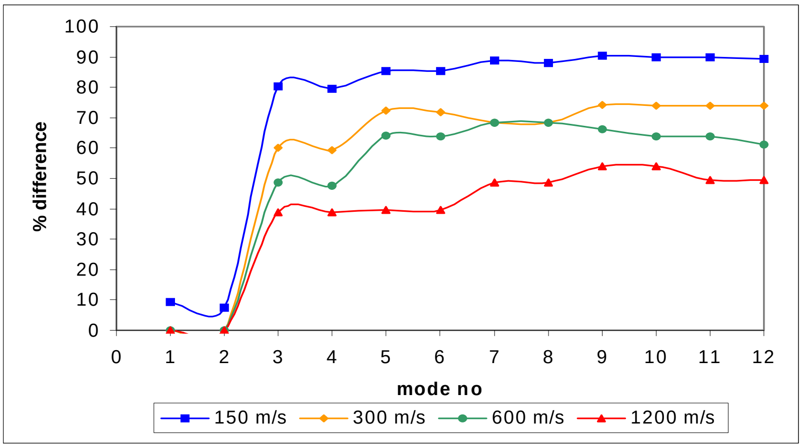

Figure 3 % Difference in time period for different modes

5. CONCLUSION

When a chimney was analyzed 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.

1) The effect of SSI is prominent for soils having shear velocity less then 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.
2) Soil flexibility decreases stiffness and increases natural time period of the chimney for all modes. As the soil gets stiffer its effect on mode shape reduces. This increase is up to 9 % for first fundamental mode and goes up to 80-85% for higher modes for soft soils. The effect of SSI is more prominent in first five modes.
3) The response of chimney is maximum at section 0.5h and h along the height of chimney for long duration earthquake.

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. So one should take care of these effects during the analysis and design stage to avoid future damages and destruction. 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 descritized by numerical values at discrete time intervals. Integration of this time acceleration history gives velocity history, integration of which in turn gives displacement history.

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