Natural Period of RC Buildings Considering Seismic Soil Structure Interaction Effects

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Abstract

The present article investigates the change in the natural period of RC frame buildings under the influence of soil-structure interaction (SSI). The structure is supported on pile foundation and the entire foundation-soil-structure system is modeled and analyzed in a finite element based software framework, OpenSEES. Established methodology is adopted for incorporating the effect of seismic soil-structure interaction and the inclusion of absorbing boundaries allows the model to simulate the phenomenon of radiation damping. Conventional Eigenvalue analysis cannot be used for obtaining the natural period of the SSI system as the modelling procedure renders the stiffness matrix singular. Therefore, time history analysis in conjunction with FFT analysis of the structural response are used to obtain the natural periods of the structure. Influence of different types of soil and foundation configurations on natural time period is studied for various structural configurations of the building frames. Soil type and foundation configuration significantly affect the increase in the natural time period of the building under the effect of SSI.

Introduction

During earthquake shaking, the magnitude of seismic force induced in a structure depends on the natural vibration characteristics. Primarily, the natural period of vibration is the significant parameter that determines the mobilized force level. This is also reflected in the definition of spectral acceleration coefficient (Sa/g) in the design guidelines, as a function of natural period of the structure. For the same structure, a variation in foundation-soil condition would result in the change of natural period and thus lead to further change in seismic force level. The present article investigates the change in the natural period of RC building frame under the influence of Soil-Structure interaction (SSI). The structure is supported on pile foundation and the entire foundation-soil-structure system is modeled and analyzed in a finite element based software framework, OpenSEES (Mazzoni et al., 2006).

Established methodology (Zhang et al., 2003; Kolay et al., 2013) is adopted for incorporating the effect of seismic soil-structure interaction and the inclusion of absorbing boundaries allows the model to simulate the phenomenon of radiation damping. However incorporation of the radiation dashpots requires the model to be unconstrained in the horizontal direction. Under such a situation, conventional eigenvalue analysis cannot be used for obtaining the natural period of the SSI system as the modelling procedure renders the stiffness matrix singular.

To overcome this drawback, the natural period can be estimated by obtaining the vibrational characteristics of the structural response. Time history analysis in conjunction with FFT
analysis of the response is used to obtain the natural periods of the structure. The SSI model adopted though unconstrained in the horizontal direction is able to simulate constrained behavior with appropriate loads and radiation boundary condition applied at the boundaries. In the present study, the effect of various soil and foundation configurations on natural period is studied for various structural-soil-foundation configurations of the RC building frames.

Modelling

Two-dimensional modelling of the structure, foundation-soil system has been carried out in OpenSEES. The modelled SSI system along with the adopted mesh is shown in Figure 1, and the modelling aspects are discussed in the following subsections.

![Figure 1. Representative illustration of the SSI model](image URL)

**Soil Domain**

A two dimensional plane strain model of the soil domain is considered having uniform depth. Four noded quadrilateral elements, with four gauss integration points, having bilinear isoparametric formulation has been used for the purpose of discretization. Reference low strain shear modulus of the soil has been considered to fix the largest size of the elements, based on the prescribed relationship by Kuhlemeyer and Lysmer (1973). Cohesionless soil of four types representing loose (SS), medium (MS), medium-dense (MDS) and dense (DS) has been considered in the study (Table 1). Pressure dependent constitutive behaviour (Yang et al., 2008) has been used for the simulation of the nonlinear characteristics of the soil. Plastic behaviour follows the nested yield surface criteria (Drucker and Prager, 1952) and the constitutive model can simulate response characteristics dependent on the instantaneous confining pressure. The constitutive model selected for the soil is a robust one capable of modelling typical characteristics of cohesionless soil such as dilatancy (based on the non-associative flow rules) and liquefaction (Elgamal et al., 2003). For the purpose of the present study, no water table was considered present in the soil profile and the bedrock is assumed to lie at a depth of 30 meters from the ground surface level and the horizontal extent of the soil domain is considered to be 8-10 times the length of the building frame in the considered direction.

**Structure Foundation System**

In the present study, the structure considered is a 2D RC building frame supported on pile foundations. A representative illustration of the typical plan and elevation of the building considered is shown in Figure 1. The typical floor-to-floor storey height considered is 3 m and
the bay width considered is also 3 m. Four different configurations have been considered for the structure, by varying the number of bays in the direction of the structural length, having lengths as 9 m (3 bays), 15 m (5 bays), 27 m (9 bays) and 45 m (15 bays). Four different configurations of height have been considered by varying the number of stories having heights as 9 m (3 stories), 18 m (6 Stories), 27 m (9 stories) and 36 m (12 stories). The structure is assumed to be located in the Zone V of the seismic zoning map of India given in IS 1893 (BIS, 2016a). The structure is to be supported on pile foundations and has been designed with the help of relevant Indian standards [IS 456 (BIS, 2000) and IS 13920 (BIS, 2016b)] after considering gravity and lateral loading as per IS 875: Part 2 (BIS, 1987), IS 1893: Part 1 (BIS, 2016a), and IS 2911: Part 1/Sec 1 (BIS, 2010). The assumed superimposed dead load considered is 3 kN/m$^2$ and the assumed live load considered is 3 kN/m$^2$. To represent the load of brick walls, a uniformly distributed load of 5 kN/m is considered to act on the beams of the frame. The details of the structural member sizes for frame building are shown in Table 2. The pile foundations have been designed for the four different soil conditions considered in the study. Two sets of pile foundations consisting of three piles and a single pile have been considered to take the load under each column. Distance between adjacent piles in a group is kept to be three times the diameter of the individual pile. The details of the pile group foundation and single pile foundation are shown in Tables 3 and 4 respectively. Elastic beam-column elements having two translational and one rotational DOFs have been used to model the frame and pile members of the structure-foundation system. The structure-foundation system is positioned in the center of the soil domain considered. The discretization of the pile has been made to ensure connectivity between its nodes and the soil nodes. The modulus of elasticity of the concrete material is taken to be 27386 MPa. The horizontal inertial forces are simulated in the structure by means of lumping the mass of the structure and the loads at the frame and pile nodes.

### Table 1. Basic properties and constitutive parameters of the soil

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>$\rho$ (t/m$^3$)</th>
<th>$\phi$ (°)</th>
<th>$\nu$</th>
<th>$v_s$ (m/s)</th>
<th>$G_r$ (kPa)</th>
<th>$\gamma_{\text{max}}$</th>
<th>$d$</th>
<th>$\Phi_T$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose (SS)</td>
<td>1.7</td>
<td>29</td>
<td>0.33</td>
<td>193</td>
<td>5.5×10$^4$</td>
<td>0.1</td>
<td>0.5</td>
<td>29</td>
</tr>
<tr>
<td>Medium (MS)</td>
<td>1.9</td>
<td>33</td>
<td>0.33</td>
<td>212</td>
<td>7.5×10$^4$</td>
<td>0.1</td>
<td>0.5</td>
<td>27</td>
</tr>
<tr>
<td>Medium-Dense (MDS)</td>
<td>2.0</td>
<td>37</td>
<td>0.35</td>
<td>234</td>
<td>1.0×10$^5$</td>
<td>0.1</td>
<td>0.5</td>
<td>27</td>
</tr>
<tr>
<td>Dense (DS)</td>
<td>2.1</td>
<td>40</td>
<td>0.35</td>
<td>257</td>
<td>1.3×10$^5$</td>
<td>0.1</td>
<td>0.5</td>
<td>27</td>
</tr>
</tbody>
</table>

**Note:** $\rho$ is the mass density of the soil, $\phi$ is the friction angle, $\nu$ is the Poisson’s ratio, $v_s$ is the shear wave velocity, $G_r$ and $\gamma_{\text{max}}$ is the reference low strain shear modulus at and peak shear strain respectively at reference pressure.

### Table 2. Details of frame members

<table>
<thead>
<tr>
<th>Storey Level</th>
<th>3 Storey Col Beam</th>
<th>6 Storey Col Beam</th>
<th>9 Storey Col Beam</th>
<th>12 Storey Col Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upto 3</td>
<td>300×300 200×280</td>
<td>350×350 200×350</td>
<td>450×450 250×400</td>
<td>500×500 250×450</td>
</tr>
<tr>
<td>3 to 6</td>
<td>-</td>
<td>350×350 200×350</td>
<td>400×400 250×400</td>
<td>450×450 250×450</td>
</tr>
<tr>
<td>6 to 9</td>
<td>-</td>
<td>-</td>
<td>350×350 250×350</td>
<td>400×400 250×400</td>
</tr>
<tr>
<td>9 to 12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>400×400 200×350</td>
</tr>
</tbody>
</table>

**Note:** All dimensions of frame members are in millimetre (mm)
Table 3. Details of the three pile group under frame members

<table>
<thead>
<tr>
<th>No. of Stories</th>
<th>Loose Soil SS</th>
<th>Medium soil MS</th>
<th>Med. dense soil MDS</th>
<th>Dense soil DS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pile length (m)</td>
<td>Pile dia. (mm)</td>
<td>Pile length (m)</td>
<td>Pile dia. (mm)</td>
</tr>
<tr>
<td>3</td>
<td>11.0</td>
<td>300</td>
<td>7.0</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>12.5</td>
<td>400</td>
<td>7.5</td>
<td>400</td>
</tr>
<tr>
<td>9</td>
<td>15.5</td>
<td>450</td>
<td>10.0</td>
<td>450</td>
</tr>
<tr>
<td>12</td>
<td>16.5</td>
<td>500</td>
<td>10.5</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 4. Details of the single pile group under frame members

<table>
<thead>
<tr>
<th>No. of Stories</th>
<th>Loose Soil SS</th>
<th>Medium soil MS</th>
<th>Med. dense soil MDS</th>
<th>Dense soil DS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pile length (m)</td>
<td>Pile dia. (mm)</td>
<td>Pile length (m)</td>
<td>Pile dia. (mm)</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>450</td>
<td>9.0</td>
<td>450</td>
</tr>
<tr>
<td>6</td>
<td>16.0</td>
<td>600</td>
<td>13.0</td>
<td>550</td>
</tr>
<tr>
<td>9</td>
<td>15.5</td>
<td>750</td>
<td>14.0</td>
<td>650</td>
</tr>
<tr>
<td>12</td>
<td>18.0</td>
<td>800</td>
<td>16.0</td>
<td>700</td>
</tr>
</tbody>
</table>

Soil Domain Boundaries

For SSI studies, modelling of the boundaries is very important to simulate the effect of radiation damping and the application of excitation input. Also, proper modelling of the boundaries allows truncation of the soil domain to a finite extent. In the present study, the vertical and horizontal boundaries have been modelled using Lysmer-Kuhlemeyer viscous dashpots (Lysmer and Kuhlemeyer, 1969) to arrest the waves at the boundary in the transverse and longitudinal directions and to prevent the same from reflecting back into the soil medium after being incident at the far-off boundaries. The ground motion input, for SSI cases, is applied in the form of equivalent nodal forces using the procedure outlined by Joyner (1975). For the structure with fixed base condition, it is appropriate to restrain the translational and the rotational degrees of freedom at the column bases to simulate the characteristics of rocky medium.

Seismic Input Motion

To carry out dynamic analysis of the structure soil system, it is a prerequisite to carry out static gravity analysis in a staged manner. This staged analysis procedure has been presented by Zhang et al. (2003). Staged analysis involves the incorporation of the radiation dashpots which requires the model to be unconstrained in the horizontal direction. Conventional Eigenvalue analysis cannot be applied to the SSI system as the modelling of the viscous boundaries render the stiffness matrix to be singular. In this situation, an alternative approach needs to be resorted for obtaining the natural period of the SSI system. Zhang et al. (2008) applied small amplitude motions and obtained the natural frequencies from the transfer functions between the input and the output. Similar methodology is adopted in the present study with suitable modification. White noise of very small PGA level (0.0005g) is selected. The time history of the motion and the distribution of the frequency content are shown in Figures 2(a) and 2(b) respectively. The white noise motion is applied on the SSI system and the response of the structure is recorded at the roof level of the structure. The natural period of the building is obtained from the Fourier amplitude ratio spectrum of the response obtained (by identifying the locations of the dominant peaks).
Figure 2. Seismic input motions (a) White noise time history (b) Fourier amplitude spectrum

Results and Discussion

Fourier Analysis
In order to verify the adopted methodology and its usefulness, the results obtained from conventional methods of estimating natural frequencies is compared with the adopted methodology. For the purpose of comparison, the first three natural frequencies of the structure are identified. Figure 3(a) shows the Fourier amplitude ratio (FAR) spectrum of the response obtained at the roof level of the 6 storeyed 5 bay building frame under fixed base condition and Figure 3(b) shows the comparison of the results obtained from the Fourier analysis with that obtained from conventional eigenvalue analysis. It is to be noted that the lowest value obtained from the Fourier amplitude ratio spectrum corresponds to the natural mode of vibration. It can be seen that a good agreement is seen between the results obtained from the two analysis methods.
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Figure 3. Fourier and Eigenvalue analysis: (a) Fourier amplitude ratio spectrum of response of 6 storeyed 5 bay building frame (b) comparison of natural period for 6 storeyed 5 bay obtained from Fourier amplitude ratio spectrum with eigenvalue analysis (c) Fourier amplitude ratio spectrum of free field soil domain for soil type SS (d) comparison of natural period of free field soil domain obtained theoretically and by Fourier amplitude ratio spectrum for soil type SS

Figure 4. Identification of the fundamental natural frequency of 6 storeyed 5 bay building frame supported by pile group foundation resting on (a) SS (b) MS (c) MDS and (d) DS soil

Apart from applying this procedure to the structure under fixed base condition, it is applied to a free field soil domain as well. Figure 3(c) shows the Fourier amplitude ratio spectrum of the response obtained for the soil domain corresponding to soft soil. For the purpose of comparison, first four natural frequencies have been identified. Figure 3(d) shows the comparison of the
natural period obtained from the present methodology and that obtained from the theoretical formula (Kramer, 1996). It can be seen that a good agreement is achieved between the theoretical and numerically simulated results. It is to be noted that the system behavior in FE model is relatively stiffer in the lower modes of vibration and relatively flexible in the higher modes of vibration. This can be attributed to the generation and lapse of confinement effect in the lower and higher modes of vibration respectively.

After the successful validation of the adopted methodology, time history analysis of various building frames under different soil-foundation conditions is conducted. Subsequently the FFT analysis of the structural response is performed to obtain the natural periods of the various building frames. Figures 4(a), 4(b), 4(c) and 4(d) show the frequency amplitude ratio spectrum of 6 storeyed 5 bay building frame under SS, MS, MDS and DS respectively. Moreover, the natural period of the building frame under fixed base condition is also obtained. Similar results are obtained for the various building frames under different soil conditions. The natural period of the building frame under the influence of SSI is denoted by $T_{SSI}$ whereas, the natural period of the building frame under fixed base condition is denoted by $T_F$. The ratio $T_{SSI}/T_F$ indicates the increase in the natural period due to the incorporation of SSI effects. The following section discusses the results obtained from the FFT analysis of the time history response of the building frames.

**Parametric Study**

The effects of width and height of the structure on the increase in the natural period is shown in Figure 5. Figures 5(a) and 5(c) show the increase in natural period of buildings on pile group foundation for loose soil (SS) and dense soil (DS) respectively. It can be seen that the increase in the natural period is highest for SS and lowest for DS soil. For any particular soil type, $T_{SSI}/T_F$ is highest for the structure with the lowest width (lowest number of bays) and the maximum height (highest number of stories). Figures 5(b) and 5(d) show the increase in the natural period of buildings with single pile foundation for SS and DS respectively. The observations made for building with pile group foundation are valid for that with single pile foundation on DS. However, for buildings with single pile foundation located on SS it is observed that the maximum increase in the natural period is corresponding to the tallest building with the maximum width (highest number of bays). However, as clearly observed for any particular building frame and foundation configuration, the increase in natural period is highest for SS and lowest for DS. Moreover, it can be observed that for any particular structure-foundation-soil condition, it is the structure supported on single pile that shows greater increase in natural time period as compared to that supported on pile group foundation. This indicates that the pile foundation configuration can significantly affect the behaviour of the superstructure-foundation-soil system considering SSI.

The influence of soil type and number of bays on the increase in the natural period is shown in Figure 6. Figures 6(a) and 6(c) respectively show the increase in natural period for 3 storeyed and 12 storeyed building frames supported by pile group foundation. It can be observed that the increase in the natural period is the highest for softest soil (lowest shear wave velocity, $V_s$). Similarly, the increase in the natural period is the lowest for dense soil (maximum shear wave velocity). It can be seen that for soil type SS, 3 storeyed building shows highest value of $T_{SSI}/T_F$ for highest number of bays, whereas, for 12 storeyed building $T_{SSI}/T_F$ is greatest for the lowest number of bays. Figures 6(b) and 6(d) respectively show the increase in natural period for 3 storeyed and 12 storeyed building frames supported on single pile foundation. The observations made for building supported on pile group foundation are valid for the building supported on single pile foundation. It can be seen that for soil type SS, 3 storeyed building shows the maximum value of $T_{SSI}/T_F$ for lesser number of bays, whereas, for 12 storeyed building frame
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$T_{SSI}/T_F$ is greatest for highest number of bays. For any particular structure-foundation-soil condition, it is the structure supported on single pile that shows greater increase in natural time period as compared to that supported on pile group foundation. Hence, it can be said that the increase in natural period is greatly dependent on the configuration of pile foundations.

Figure 5. $T_{SSI}/T_F$ relationship of building frame with number of bays and number of stories for building frame on (a) SS and pile group foundation (b) SS and single pile foundation (c) DS and pile group foundation and (d) DS and single pile foundation soil

Conclusions

From the present study, it can be concluded that SSI effects depend not only on the structural configuration but also depends on the foundation soil properties. Buildings supported on SS (loose soil) exhibit higher SSI effects as the increase in the natural period is higher. Apart from the soil properties, foundation configuration can greatly affect the increase in the natural period of the building from that of the fixed base natural period. Building frames supported on single pile foundation exhibit a greater increase in the natural time period as compared to those supported on pile group foundation.
Figure 6. $T_{SSS}/T_F$ relationship of building frame with number of bays and shear wave velocity of soil domain ($V_s$) for building frame with (a) 3 storeys and pile group foundation (b) 3 storeys and single pile foundation (c) 12 storeys and pile group foundation and (d) 12 storeys and single pile foundation soil

References


