ELASTIC SEISMIC RESPONSE OF MOMENT RESISTING FRAMED STRUCTURES WITH SOIL-STRUCTURE INTERACTION

Vishwajit Anand\textsuperscript{1} and S.R. Satish Kumar\textsuperscript{2}

ABSTRACT

The present study analyses effects of soil-structure interaction (SSI) on the elastic response of moment resisting framed reinforced concrete structures founded on embedded raft in an elastic half-space to accelerograms compatible to design spectra conforming to diverse geology. Most structures are designed to remain elastic under design basis earthquake and are expected to exhibit inelasticity but no collapse under maximum credible earthquake. Moreover machine foundations subjected to harmonic excitations are supposed to respond in an elastic manner during its routine use. Hence there is a need to understand elastic response of structure-soil systems. The effect of SSI is to increase natural period and damping of the structure-soil system. Structure-to-soil stiffness ratio is the most significant parameter influencing extent of inertial SSI effects and has been selected as a metric of SSI and smaller values denote closeness to fixed-base structures. It is observed that SSI leads to reduced design forces in structures subjected to either harmonic excitation or ensembles of spectrum compatible design basis earthquakes. The results are expressed as response spectra plots which are quite familiar to structural engineers.

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Introduction

When a foundation is subjected to vibrations due to either operating machinery or a seismic event, it is intuitive to comprehend that displacements in structure and ground will be inter-dependent. This process of soil response influencing structural response and vice-versa is referred to as Soil-Structure Interaction (SSI). SSI problems are coupled contact problems where stresses along the structure-soil interface cannot be determined without obtaining the displacement field along the very same interface [1]. It is an inter-disciplinary field lying at the intersection of diverse technical disciplines whose development started way back in late 19th century [2]. There have been contributions by Boussinesq, Steinbrenner, Reissner, Mindlin and Hanson to the field of static SSI. The era of dynamic SSI started in 1936 with Reissner and has witnessed contributions by Luco, Bycroft, Housner, Newmark, Veletsos, Whitman and many others. The interplay can be well conceived by understanding the following three phenomena by which soils and foundations affect the dynamic behaviour of structures [3,4]. First, the motion at ground surface is different from that at the bedrock level. Some frequencies in the originally

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band limited white noise ground motion get amplified while others get diminished. Secondly, seismic waves get reflected at the rigid structure-soil interface leading to a modified foundation input motion. Thirdly, inertial loads from the structure cause additional soil deformations resulting in a further modification of the base motion. The first one, called wave amplification effect, is present even in natural soil deposits without excavation or structure. Hence the other two, respectively termed as kinematic and inertial interaction, are considered to be the two components of SSI [5].

There has been a conventional belief that SSI poses beneficial effects on the seismic response of structures and hence ignoring SSI would result into a conservative design. It has been argued that SSI makes a structure more flexible, elongates its time period and enhances the system damping which would lead to reduced design forces. This belief has been justified by past researchers [6-8] who deduced a reduction in ductility demand at a slight increase in top structural displacement. This is the reason behind most of the present seismic codes, either allowing a reduction in design forces or advocating SSI to be ignored altogether. However there have been findings which prove that ignoring SSI leads to a significant underestimation of ductility demands [9,10]. Observations from past earthquakes, such as damage of pile supported bridge piers during 1989 Loma Prieta Earthquake [11] and collapse of Hanshin Expressway Fukae section during 1995 Kobe Earthquake [12], also support the detrimental nature of SSI. This lack of consensus among researchers on SSI effects has led to a dubious situation [13]. As a result, there has been lack of clearly laid provisions on SSI in seismic codes rendering it to be scarcely employed in design practice. Recent findings highlight the importance of SSI consideration in inelastic structural design and inadequacy of existing design guidelines in achieving desired ductility [14]. Stiffness degradation and strain hardening have also been found to affect seismic SSI response [15].

However despite of advances in inelastic seismic structural analysis, most of the structures are currently analysed and designed for elastic response. Most designs ensure elastic structural response under design basis earthquake (DBE) and expect structure to deter collapse by exhibiting inelastic behaviour under maximum credible earthquake (MCE). Further, machine foundations subjected to harmonic excitations are expected to remain elastic during its usual use. Hence there is a need to develop a procedure which is capable of predicting the elastic SSI response of a structure subjected to DBE and is convenient to be employed in regular design practice. Further since moment resisting framed (MRF) reinforced concrete structures form a major proportion of contemporary construction in developing nations, the present study assesses elastic seismic SSI response of such structures founded on raft foundations embedded in an elastic half-space. This article presents a set of response spectra which can be used in the design office to quickly assess SSI effects for a proposed construction.

Methodology

Review of SSI approaches

SSI problems have been solved using numerous approaches in literature. Experimental analyses have been attempted in the form of either shake table tests or dynamic centrifuge model tests [16-18]. However since experimental investigations are usually expensive and cumbersome, SSI problems have been widely analysed either numerically or analytically [19-24]. These approaches can be broadly categorized as linear versus nonlinear, discrete versus continuum,
frequency domain versus time domain and direct approach versus substructure approach [4]. While the first two classifications are based on nature of interface elements used, the third one is based on domain in which the solution is sought. The last classification, direct and substructure approach, comprises of fundamental differences in the solution strategies.

While direct method considers structure-soil system as a single entity, substructure method divides the problem into a number of substructures whose solutions are superimposed towards the end. Substructure approach turns out to be advantageous compared to direct method due to efficient computations, choice of varied modelling strategies and applications to parametric studies [4]. In substructure approach, kinematic and inertial components are characterized respectively by the use of transfer and impedance functions. Since kinematic component is predominant in the case of pile foundations and the present study considers structures founded on embedded raft, kinematic interaction has been ignored. Determination of impedance functions forms a critical step in substructure approach as they characterize force-displacement response. The initial attempts to compute impedance functions using boundary element methods (BEM) and finite element methods (FEM) were rigorous. Simple physical methods, such as lumped parameter models and cone models, were therefore developed which are accurate enough to be used in engineering practice. In the context of shallow foundations, impedance functions based on lumped parameter models are enlisted in literature [25-28].

**Present Methodology**

Real and imaginary components of impedance functions, as presented in Eq. 1, respectively represent stiffness and damping of structure-soil system. Their frequency dependence is characterized by dimensionless frequency \( (a_0 = \omega B/v_s) \). Dynamic stiffness \( (k_j) \) is expressed in Eq. 2 as a product of static stiffness \( (K_j) \) for surface footing, embedment correction factor \( (\eta_j) \) and dynamic stiffness modifier \( (\alpha_j) \) [25]. The radiation damping components \( (\beta_0, \beta_{yy}) \) are obtained directly from literature [27]. Frequency dependence of these functions has not been taken into account in the present study and they have been computed only at the fundamental frequency of the structure.

\[
S(a_0) = k(a_0) + ia_0c(a_0) \quad (1)
\]

\[
k_j = K_j\alpha_j\eta_j \quad (2)
\]

\[
\frac{T_{SSI}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_y}} \quad (3)
\]

\[
\beta_0 = \left\{ \frac{1}{\left(\frac{T_{SSI}}{T}\right)} \right\} \beta_i + \left\{ 1 - \frac{1}{\left(\frac{T_{SSI}}{T}\right)} \right\} \beta_s + \left\{ \frac{1}{\left(\frac{T_{SSI}}{T_x}\right)^n_x} \right\} \beta_x + \left\{ \frac{1}{\left(\frac{T_{SSI}}{T_y}\right)^n_y} \right\} \beta_{yy} \quad (4)
\]

Inertial interaction results into two major changes in system properties namely- elongated natural period and modified damping of structure-soil system. These are respectively given by Eqs. 3 and 4 [25]. Schematic diagram for obtaining elongated natural period \( (T_{SSI}) \) from structural period \( (T) \) is presented in Fig. 1. Radiation damping components are added to structural \( (\beta_i) \) and soil material \( (\beta_s) \) damping components to obtain total system damping \( (\beta_0) \). \( T_x \)
and $T_{yy}$ in Eq. 4 denote fictitious time periods obtained using mass of SDOF system $m$ and soil stiffnesses $k_x$ and $k_{yy}$. Coefficients $n$, $n_x$ and $n_{yy}$ depend on type of damping [29].

The dimensionless parameters governing extent of these inertial interaction effects are structure-to-soil stiffness ratio, structure-height-to-foundation-width ratio, foundation-width-to-length ratio, mass ratio (ratio of mass of structure to that of equal volume of soil) and Poisson’s ratio of soil [25]. Among these, the most significant parameter is structure-to-soil stiffness ratio given by $(h/v_s T)$ where ratio of structure height-to-period $(h/T)$ represents structural rigidity and shear wave velocity of soil $(v_s)$ is a measure of soil rigidity. This parameter can be considered as a metric for SSI effects where larger values correspond to stiff structures located on soft soils implying greater inertial interaction effects. The present study assesses effect of this parameter on elastic SSI response of MRF structures founded on an embedded raft under the influence of DBE. This is accomplished by analysing a set of single degree of freedom (SDOF) systems with different natural periods $(T)$, to sinusoidal as well as seismic excitations, while varying $(h/v_s T)$ in the range of 0.1 to 0.5 and keeping all other parameters unchanged. Hereafter $(h/v_s T)$ is referred simply as the stiffness ratio (SR) for brevity. Structure-height-to-foundation-width ratio $(H/B)$ and foundation-width-to-length ratio $(L/B)$ are respectively taken as 2 and 1. MRF reinforced concrete structures are idealized as SDOF system by lumping the structural mass at 70% of the total height in line with building codes [30] and past research [14]. Further, the natural period of fixed-base structure is taken as 0.1 times the number of storeys and each storey is assumed to be 3 metres in height. The weight of beams and columns is assumed equal to that of floor slab which is 0.2 metres thick. Mass density of concrete is taken as 2400 kg/m$^3$. Footing embedment depth is equal to one-fifth of structure height and complete soil-footing is assumed. The underlying soil medium is considered to be homogeneous with density of 1900 kg/m$^3$ and Poisson’s ratio of 0.3. Material damping in structure $(\beta_i)$ and soil $(\beta_s)$ are assumed to be 5% and 8% respectively of critical value. Once impedance functions are evaluated using selected parameters, the equations of motion under sinusoidal (amplitude $F_0 = 1$ and period $T_E$) as well as seismic (time history $\ddot{u}_g$ corresponding to design spectra [31]) excitations are formulated in Eq. 5 using D’Alembert’s principle. Equivalent stiffness coefficient $(k_{SSI})$ is obtained using Fig. 1. Newmark $\gamma$-$\beta$ method with $\gamma=1/2$ and $\beta=1/6$ (linear acceleration between time steps) is then employed to obtain peak of base shear corresponding to every SDOF system. This base shear is then normalized using weight of the structure to yield seismic coefficient which is then used to obtain response spectrum plots. This procedure is repeated for all accelerograms in a set to obtain design response spectrum as a mean of ordinates from each time history analysis. Time steps $(\Delta t)$ of 0.05 and 0.01 seconds are chosen for sinusoidal and seismic excitations respectively which
satisfy Eq. 6 and the computation is therefore capable of generating a stable solution. The detailed procedure is illustrated in Fig. 2.

\[
m\ddot{x} + (2\beta_0 \sqrt{mk_{SSI}}) \dot{x} + k_{SSI}x = F_0 \sin \left( \frac{2\pi}{T_E} t \right) \quad (5a)
\]
\[
m\ddot{x} + (2\beta_0 \sqrt{mk_{SSI}}) \dot{x} + k_{SSI}x = -m\ddot{u} + g \quad (5b)
\]
\[
\frac{\Delta t}{T} \leq \frac{1}{\pi \sqrt{2(\gamma - 2\beta)}} \quad (6)
\]

**Figure 2. Algorithm for seismic SSI response of elastic structures**

### Generation of design spectrum compatible acceleration time histories

Seismic SSI analysis is performed using synthetic accelerograms compatible to IS 1893 design response spectrum, shown in Fig. 3, for both rocky/hard and soft soil sites [31]. The present study considers structures to be located in seismically active regions (Zone V) with a zone factor of $Z=0.36$. Artificial time histories are generated using the computer program SeismoMatch 2016.
in order to achieve an average tolerance of less than 10%. Existing ground motion data from a similar geology, obtained from COSMOS VDC and K-NET websites, have been utilized in this context [32,33] and are reported in Table 1. These motions correspond to 15 sites in California and 24 sites in Japan for rocky/hard and soft soil sites respectively. The results are presented as plots of mean response spectra ordinates corresponding to accelerograms, in a certain geology.

Table 1. Details of existing ground motion data to obtain synthetic accelerograms

<table>
<thead>
<tr>
<th>Site</th>
<th>Earthquake, Date, Mag. (Mw)</th>
<th>Record Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocky/Hard Soil Sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Bear</td>
<td>1992-06-28, 6.4</td>
<td>Rancho Cucamonga</td>
</tr>
<tr>
<td>Landers</td>
<td>1992-06-28, 7.3</td>
<td>Littlerock, Rancho Cucamonga, Wrightwood</td>
</tr>
<tr>
<td>Loma Prieta</td>
<td>1989-10-17, 7.0</td>
<td>Gilroy, San Francisco</td>
</tr>
<tr>
<td>Northridge</td>
<td>1994-01-17, 6.7</td>
<td>Antelope Buttes, Lake Hughes, Littlerock, Rancho Cucamonga, Sandberg, Vasquez Rock Park, Wrightwood</td>
</tr>
<tr>
<td>Sierra Madre</td>
<td>1991-06-28, 5.6</td>
<td>Vasquez Rock Park</td>
</tr>
<tr>
<td>Whittier</td>
<td>1987-10-01, 6.1</td>
<td>Vasquez Rock Park</td>
</tr>
<tr>
<td>Soft Soil Sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hokkaido</td>
<td>1999-05-12, 6.1</td>
<td>Honbetsukai, Shibeccha</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>2004-04-11, 6.1</td>
<td>Honbetsukai, Shibeccha</td>
</tr>
<tr>
<td>Hokkaido</td>
<td>2004-11-28, 7.0</td>
<td>Akankohan, Akkeshi, Honbetsukai, Shibeccha</td>
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<td>Hokkaido</td>
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<td>Kyushu</td>
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<td>Hagi, Susa</td>
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<td>S. Honshu</td>
<td>1997-06-25, 6.1</td>
<td>Hagi, Susa</td>
</tr>
<tr>
<td>Tokachi-Oki</td>
<td>2003-09-25, 8.0</td>
<td>Akankohan, Akkeshi, Fujimi, Honbetsukai, Shibeccha</td>
</tr>
</tbody>
</table>

![Figure 3](image.png)

Figure 3. Design response spectrum (5% damping) for different geology in IS 1893 [31]

**Inertial SSI effects**

The two inertial interaction effects, namely elongation in natural period and modification in damping of the structure-soil system, are shown in Fig. 4. In Fig. 4(a), abscissa and ordinate respectively represent ratios of natural period ($T$) and SSI period ($T_{SS}$) to period of harmonic excitation ($T_{E}$). These ratios will be respectively termed as fixed-base period ratio and SSI period ratio, and are in tune with frequency ratio used in structural dynamics considering swap of terms.

**Results and Discussion**
in numerator and denominator. The dotted line in black implies no change in structural period. It is evident that considering SSI in analysis leads to an elongated period for the structure-soil system. The closeness of plot corresponding to $SR = 0.10$ to “no period change” line justifies the use of stiffness ratio ($SR$) as a metric of SSI and supports the fact that inertial interaction can be ignored in cases where $SR < 0.10$ [34]. Further, $SR$ values of 0.10 and 0.50 correspond to soil shear wave velocities of 300 m/s and 60 m/s respectively which are in the practically admissible range. Fig. 4(b) presents ratio of damping of structure-soil system to that of structure alone as a function of fixed-base period ratio. For all period ratios, SSI leads to increased damping in the system owing to radiation and material damping in the half-space. However the trend gets confusing at higher values of period ratio possibly due to inefficient radiation damping at higher excitation frequencies.

Figure 4. Inertial SSI effects: (a) Elongation in natural period, (b) Modified damping ratio.

Figure 5. Effect of stiffness ratio on elastic SSI response of structures under harmonic excitation

**SSI response to harmonic excitation**

Fig. 5 presents effect of stiffness ratio ($SR$) on peak structural response of SDOF systems, with natural period in range of 0 to 3 seconds, subjected to harmonic excitation. The results are expressed as a plot of peak base shear as a fraction of the total weight of structure ($C_{e.SIN}$) against period ratio. It can be noticed that choice of SSI period ratio as abscissa is preferable over fixed-base period ratio as the plots get properly aligned with peaks occurring close to unity. The slight
deviation is due to damping in the system. It is observed that larger values of $SR$, associated with predominant SSI effects, lead to reduced base shear. This is the reason behind some seismic codes suggesting a reduction in design base response arising out of SSI. The plots for $SR = 0.10$ and 0.20 are quite close and hence stiffness ratio of 0.10 is as good as a fixed-base structure.

Figure 6. Effect of stiffness ratio on elastic SSI response of structures subjected to accelerograms compatible to IS 1893 response spectrum for rocky/hard soil sites

Figure 7. Effect of stiffness ratio on elastic SSI response of structures subjected to accelerograms compatible to IS 1893 response spectrum for soft soil sites

SSI response to spectrum compatible accelerograms

Effect of stiffness ratio ($SR$) on response of structures subjected to ground motions compatible to IS 1893 design spectra [31] is reported in Figs. 6 and 7 respectively for rocky/hard and soft soil sites. The quantity $C_{e.EQ}$ is similar to $C_{e.SIN}$ except that they are obtained upon analyzing systems against earthquakes rather than sinusoids. The results are quite similar to that for the sinusoidal excitation with exceptions of peaks and valleys. However the plot is quite smoothened because of use of large number of ground motions. It is however worth mentioning that peaks and valleys are more prominent in Fig. 7 compared to Fig. 6 in spite of larger number of accelerograms used. The possible reason is that ground motions in soft soil are characterized by filtering out of some frequencies and thereby lower ordinates corresponding to those frequencies. Moreover peaks in Fig. 7 are located at a larger time period as compared to those in Fig. 6 due to the same reason. The suitability of SSI period ($T_{SSI}$) over structural period ($T$) is also evident in Figs. 6 and 7.
Summary and Concluding Remarks

The paper presents an outline of SSI and its significance in obtaining the correct structural response. Elastic responses of SSI systems, subjected to harmonic excitations and DBE, are obtained using the substructure approach. Analyses were performed on MATLAB R2015a using Newmark $\gamma$-$\beta$ method. The algorithm used in the study is also reported. Based on the results presented in the previous section, the following significant conclusions can be arrived at:

- Soil-structure interaction (SSI) makes an elastic structure more flexible. Both natural period and damping of the structure-soil system are higher than those of the fixed-base structure.
- Stiffness ratio ($SR = h/\nu_T$) is a suitable metric for SSI. Higher values of $SR$, characterizing rigid structures founded on soft soils, indicate greater magnitude of SSI.
- Considering SSI leads to a reduced base reaction in case of structures exhibiting elastic behaviour under design basis earthquakes.
- Ground motions on soft soil sites exhibit filtering out of various frequencies resulting into peaks and valleys in the response spectra.

Some of the conclusions may appear to be well-established but significance of the present study lies in the results expressed in terms of response spectral plots. Such plots can be readily utilized in design practice as a quick reference for assessing effects of SSI on a proposed construction. However it is not advisable to reduce design base forces in critical structures in view of detrimental effect of SSI on inelastic structural response [14]. Another point of merit is the methodology to obtain SSI analysis of structures.

References

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