SSI EFFECTS ON A STEEL BUILDING USING A BUILDING A CODE PROCEDURE AND A NUMERICAL MODEL

L. R. Fernández-Sola\textsuperscript{1} and J. Hernández-Torres\textsuperscript{2}

\textbf{ABSTRACT}

Analysis of soil structure interaction effects (SSI) on the dynamic behavior of structures has become more frequent on the last decades. The procedures included in several building codes, consider that SSI effects can be taken into account by computing the variation of the base shear due to SSI effects. This procedure considers that variations of all the response quantities on the structure are linearly equivalent to the base shear modification. The analysis of the dynamic behavior of a 10-story steel building with and without SSI effects (flexible and fixed base respectively) is presented on this paper. Modal response spectrum analysis is used to compare elastic behavior of buildings. SSI is included with the code procedure. In addition, the results of numerical models for the building with flexible base are presented. In this model, SSI is included in the analysis by using a set of springs in horizontal and rocking direction. A mat foundation is considered. A very soft soil with shear wave velocity of $V_s=80$ m/s is used. The dynamic stiffness of the soil-foundation system was computed considering the soil mass and stiffness. Results show that element forces computed with the code procedure and with the numerical models are different. Numerical models indicate that variations produced by SSI effects on the internal forces depend on the position of the element within the structure. Mode shapes and modal participation factors are different for the system with and without SSI effects. In addition, it is observed that the percentage of base shear absorbed by the bracing system and by the columns is modified due to SSI effects. This parameter is very important on the capacity design of braced frames.

\textsuperscript{1}Professor, Departamento de Materiales, Universidad Autónoma Metropolitana-Azcapotzalco, Av. San Pablo #180, Ciudad de México, Z.C. 02200 (email: lrfs@azc.uam.mx)
\textsuperscript{2}Graduate Student, Posgrado en Ingeniería Estructural, Universidad Autónoma Metropolitana-Azcapotzalco, Av. San Pablo #180, Ciudad de México, Z.C. 02200

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L.R. Fernández-Sola¹ and J. Hernández-Torres²

ABSTRACT

Analysis of soil structure interaction effects (SSI) on the dynamic behavior of structures has become more frequent on the last decades. The procedures included in several building codes, consider that SSI effects can be taken into account by computing the variation of the base shear due to SSI effects. This procedure considers that variations of all the response quantities on the structure are linearly equivalent to the base shear modification. The analysis of the dynamic behavior of a 10-story steel building with and without SSI effects (flexible and fixed base respectively) is presented on this paper. Modal response spectrum analysis is used to compare elastic behavior of buildings. SSI is included with the code procedure. In addition, the results of numerical models for the buildings with flexible base are presented. In these models, SSI is included in the analysis by using a set of springs in horizontal and rocking direction. A mat foundation is considered. A very soft soil with shear wave velocity of Vs=100 m/s is used. The dynamic stiffness of the soil-foundation system was computed considering the soil mass and stiffness. Results show that element forces computed with the code procedure and with the numerical models are different. Numerical models indicate that variations produced by SSI effects on the internal forces depend on the position of the element within the structure. Mode shapes and modal participation factors are different for the system with and without SSI effects. In addition, it is observed that the percentage of base shear absorbed by the bracing system and by the columns is modified due to SSI effects. This parameter is very important on the capacity design of braced frames.

Introduction

Earthquake analysis procedures included in several modern building codes around the world are based on the use of the response spectrum to compute the seismic forces on the structures. As it is well known, this approach represents the response of a structure with multiple degrees of freedom by the superposition of the responses of single degree of freedom systems (modes). Under these considerations, building codes [1-4] introduces the soil structure interaction (SSI) effects setting

¹Professor, Departamento de Materiales, Universidad Autónoma Metropolitana-Azcapotzalco, Av. San Pablo #180, Ciudad de México, Z.C. 02200 (email: lrls@azc.uam.mx)
²Graduate Student, Posgrado en Ingeniería Estructural, Universidad Autónoma Metropolitana-Azcapotzalco, Av. San Pablo #180, Ciudad de México, Z.C. 02200

an equivalent single degree of freedom system (ESDOF) with equivalent dynamic properties (fundamental period $T$ and damping $\zeta$) for the first mode. Some building codes consider in addition a modification on the ductility of the ESDOF system due to a change on the ratio between the strength reduction factor and the ductility demand on the structure [5-7]. With these modified properties, the structure will be subjected to a modified spectral acceleration demand. The base shear variation associated with spectral acceleration shift is used to compute changes of remaining response quantities (e.g. displacements, element forces, etc). This method uses modal shapes and modal participation factors computed without SSI effects.

The ESDOF approach is very useful and yields to good results in a lot of cases, for some structural responses (for example total base shear, overturning moment, absolute displacement of each story and story drift). Since just one degree of freedom is used, this procedure considers, in an implicit way, that modifications introduced by base flexibility in all responses along the structure will be linearly equivalent. However, there are studies that have shown that, in some cases and for some structural responses, the representation of the flexible base system with multiple degrees of freedom with an ESDOF may not yield in to good results [8-11].

The main difference between a fixed and a flexible base system is on the displacement components. Variation of period and ductility are associated to the increased flexibility of the soil-structure system. Soil-structure system is more flexible because when SSI effects are considered, the total displacement of the structure has two different components: the displacement produced by the translation and rocking of the foundation and the displacement produced by the deformation of the structure. When a ESDOF system is used, the identification of each displacement component is missed, since just one equivalent displacement is considered. In addition, foundation flexibility produces a change on the stiffness ratios among different structural elements, then the force distribution within the structure and the modal properties are modified too. Some design procedures are based on the distribution of element forces on each structural element. For example, in capacity design of braced frames, the balance of shear force on the frame and on the bracing system is a fundamental design parameter [12-14].

Differences of the magnitude and distribution of the element forces produced on a 10-story steel building with braced frames, computed with the ESDOF approach and with a numerical model are discussed on this paper. The numerical model is developed on a commercial software for structural analysis. SSI effects are included by a set of springs on the base whose stiffness are computed with the impedance function approach [15].

**Building and foundation characteristics**

Building was designed following the procedure described on the Mexico City Building Code (MCBC) [6] and the design procedure proposed by Tapia and Tena-Colunga for the capacity design of steel braced frames [12]. Design and elements dimensions’ details can be found on [16]. On figure 1, representative schemes of plain and elevation view of buildings are presented. Frames are designed with moderate ductility criteria ($\mu=2$) accordingly to MCBC. Capacity design recommendations are followed. Fundamental period of the building with fixed base is $T=0.991$ s. Soil properties correspond to a soft soil represented by a homogeneous layer with thickness of $H_s=22$ m and shear wave velocity of $V_s=80$ m/s. Foundation consists on a mat foundation overlaying
this homogenous soil layer. The foundation is embedded 5 m.

Base flexibility is introduced by using a set of distributed springs along mat foundation (figure 2). The constants of the springs are computed with the dynamic stiffness concept (impedance function) as presented by Gazetas [15]. This approach considers the influence of the soil mass and stiffness, so the dynamic stiffness of the soil-foundation system depends on the frequency of the excitation. Software DYNA6 [17] was used to estimate horizontal and rocking impedance functions. Only the value corresponding to the fundamental frequency of the soil-structure system was used. Given that the period of the soil-structure system with flexible base (\( \bar{T} \)) and base flexibility are mutually dependent, it is necessary to perform an iterative process to establish the definitive values of impedance functions.

Additional damping introduced by SSI is taken into account by using an effective damping ratio. Effective damping ratio was computed with the procedure included on MCBC [1]. Kinematic interaction is neglected. Since soil-foundation dynamic stiffness approach considers that all stiffness is lumped on a single joint, a geometric distribution of the stiffness on distributed springs is performed. Horizontal stiffness is uniformly distributed along 40 horizontal springs (Figure 2). Rocking stiffness is represented by the contribution of horizontal springs and the contribution of 16 vertical springs as shown in figure 2. Geometry of foundation is considered in this way. All joints of foundation are constrained with a rigid body constrain. More details of this procedure can be found on [16].
Design response spectrum considering SSI effects

As mentioned above, the response of a soil-structure system including SSI effects can be computed using spectral modal analysis using the dynamic properties of a ESDOF system ($\tilde{T}$, $\zeta$ and $\tilde{\mu}$). The expressions and approaches to compute the dynamic properties of the ESDOF system are slightly different among different building codes. On this work, the expressions of the MCBC [1] are used. Computed dynamic properties of the building with fixed base and for ESDOF system are reported on table 1. Fundamental period of the ESDOF system is larger than the one of the system with fixed base. The ductility demand on the ESDOF system must be smaller in order to keep the ductility demand on the structure within the design values. Damping of the ESDOF system remains equal to the fixed base structure one.

### Table 1. Dynamic properties of the structure with fixed base and the ESDOF system with SSI.

<table>
<thead>
<tr>
<th>$T_1$ (s)</th>
<th>$\tilde{T}_1$ (s)</th>
<th>$\mu$</th>
<th>$\tilde{\mu}$</th>
<th>$\zeta$</th>
<th>$\tilde{\zeta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.99</td>
<td>1.33</td>
<td>2.00</td>
<td>1.56</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
</tbody>
</table>

![Figure 3. Elastic and reduced response spectrum considering SSI effects for the soil profile considered accordingly to MCBC.](image)

Dynamic properties of the ESDOF system must be used to compute the design response spectrum. Elastic response spectrum must be computed using a damping factor of $\zeta$. Overstrength factor ($\Omega$) of the ESDOF system is equal than the one of the fixed base structure for all cases. The elastic response spectrum and the inelastic response spectrum with $\tilde{\mu}$ are shown on figure 3. Building codes establish that SSI effects must be considered only for the first mode in translation in each orthogonal direction. If an unique design spectrum is used, it must be computed as a combination of two inelastic spectrum, one for ductility of $\tilde{\mu}$ for the first mode and other for a ductility of $\mu$ for higher modes. The design spectrum with SSI effects is shown on figure 3 too. On this figure, the values of the ESDOF system period ($\tilde{T}_1$) and the periods of mode 2 and 3 on translation are shown.
Response of the structure with the code procedure and with a numerical model

Several building codes use an approximated method to take into account for SSI effects. This method considers that all structural responses are modified in the same proportion due to base flexibility. The response of the structure with flexible base is computed multiplying the response of the structure with fixed base by an interaction factor. The interaction factor is defined as the ratio of the base shear computed of the first mode with the response spectrum with SSI effects defined on the previous section ($\bar{V}_1$), and the base shear of the first mode computed without SSI effects ($V_1$). This procedure considers that all structural responses, with the exception of lateral displacements, are equally modified in all the structure. Values of spectral acceleration ($a_1$ and $\bar{a}_1$) and base shear for the fundamental mode with and without SSI and interaction factor ($\bar{V}_1/V_1$) are reported on table 2. Although the computed value for the interaction factor exceeds the building code limit of 1.25, for comparison purposes the computed value is used. So, building code procedure establishes that the element forces in all the structure must be increased by SSI effects by a factor of 1.303.

Table 2. Values of spectral acceleration and base shear for the first mode and interaction factor.

<table>
<thead>
<tr>
<th>$a_1$</th>
<th>$\bar{a}_1$</th>
<th>$V_1$ (t)</th>
<th>$\bar{V}_1$ (t)</th>
<th>$\bar{V}_1/V_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.218</td>
<td>0.284</td>
<td>380.75</td>
<td>496.13</td>
<td>1.303</td>
</tr>
</tbody>
</table>

Element forces were computed with a numerical model using modal spectral analysis. The design spectrum with SSI effects is used. Since potential additional damping introduced by SSI is already considered on the response spectrum, only the soil-foundation stiffness is modeled as described on previous sections. The element forces are analyzed in braces, beams and columns. Three types of columns and four types of beams are identified (figure 4). Columns placed on a corner of the structure (Corner), at the center of the building (Central) and the ones corresponding to the braced bay (Braced) are analyzed. Beams are classified as follows, beams arriving to corner columns (Corner), beams that are part of the braced bay (Braced), beams that connects the central columns (Central) and beams connecting one of the central columns with an exterior one (Internal).

![Identification of beams and columns](image)
The variation of the element forces due to SSI effects are shown on figures 5-8. On these figures, the x-axis corresponds to the ratio of the element force developed on the model with flexible base and the element force developed on the model with fixed base (SSI/FB). The y-axis corresponds to the story where the structural element is placed. This results means that if the SSI/FB ratio is larger than one (No change line), element forces are increased by SSI effects. In addition, value of interaction factor is indicated. If SSI/FB is equal to $\frac{V_1}{V_1}$, results computed with code procedure are equal to the ones obtained from the numerical model.

Variation of lateral force taken by the bracing system, the columns and the total brace-column system is shown on figure 5. It is clear that the increment is not constant within structure height. For upper stories, the increment on the lateral force on the brace-column system is smaller. In this case, the increment on base shear computed with the numerical model is larger than the one considered by the code procedure. This effect may be produced due to the difference on mass participation factors of the system with fixed and with flexible base. Since the first mode has a larger contribution for the flexible base systems, the participation factor of the first mode is larger. Since code procedure uses the modal information of the fixed base system, the base shear of the first mode can be underestimated. The variation of the SSI influence on structures height has been observed for concrete buildings [17-18].

![Figure 5. Ratio of lateral force absorbed by columns, braces and the total lateral system (columns + braces) for the system with and without SSI effects (SSI/FB).](image)

In addition, the variation of lateral force taken by the braces and on the columns is not equal. In general, braces develop smaller increments than columns. For lower (1 and 2) and upper stories (9 and 10) increase due to SSI effects is smaller. This effect produce that the balance of lateral force taken by columns and braces gets modified. For middle height stories (3-8), increment is very similar for both types of elements, having some stories were the increment on the braces is slightly larger.
Element forces modification on columns are shown on figure 6 (axial load $P$, shear force $V$ and bending moment $M$). Results were computed for different types of columns (figure 4), and for the average of all columns on the same story. It is clear that increments on axial loads are smaller than the one considered by the building code procedure. Axial load on central columns remains almost unchanged. On the other hand, axial load on corner columns experience the largest increments for upper stories (5-10) and is very similar along structure height. The increment on columns of the braced bay is the less uniform thru different stories. It is clear that axial load from fixed base model should not be directly multiplied by the interaction factor, since SSI effects must be included only for the effects associated with lateral forces. For example, axial force on central columns is almost unaffected by lateral forces while in corner columns, the axial force is highly influenced by lateral forces.

![Figure 6](image)

**Figure 6.** Variation of axial load ($P$), shear force ($V$) and bending moment ($M$) on columns for the system with and without SSI effects (SSI/FB).

Effects on shear force on columns had been discussed already. However, from figure 6 it can be seen that shear force variation depends on the column position. Columns on the braced bays experience the largest shear increments in almost all stories. As mentioned above, the increase on shear force for almost all columns (except central ones) is larger than the one defined by the code procedure for the first two stories. Variations of shear force, as well as for axial force, are smaller as the columns are placed on upper stories. Increments on bending moment on columns does ton follow the same trend as axial load and shear force, since the increment is not always smaller for upper stories. However, braced frame beams are the ones with the largest increments, as for shear force. In general, increments of bending moment are closer to the code procedure value on the lower stories, but are significantly smaller for corner beams on stories 4 and 6 and for central beams on the last three stories.
Results for element forces on beams (shear force $V$ and bending moment $M$) are shown on figure 7. As well as for columns, results were computed for different types of beams (figure 4) and for the average for all beams on the same story. The differences of the increment of shear force and bending moment for the different types of beams are larger than for columns. Central and internal beams (internal frames) develop smaller increments than corner and braced beams (external frames). As for the case of axial loads on columns, it seems that SSI effects have more influence on the elements of external frames.

For all types of beams and in all stories, increment of shear force computed from the numerical model are smaller than the ones computed from the code procedure. The beams that are part of the braced bay are the ones with largest differences along height. For both, shear force and bending moment, this set of beams is the one with the largest increments at ground floor and the smallest increments at the top story. Code procedure results are in good accordance for the braced and corner beams on the first 4 stories. These results show that...
the influence of SSI effects can be very different for the same type of element depending on the position within the structure. This may yield to differences on the ratios of forces developed in each structural element.

Increments of axial load developed by braces are shown on figure 8. Values of axial load on the braces are very similar than the ones computed with the code procedure for stories 2-4, but slightly larger. Braces on ground floor and upper stories develop smaller increments on axial load than the one computed with the code procedure. For braces on the top floor, the increment computed from the numerical model is half the increment computed with the code procedure. As for all the previous cases, increments on element forces introduced by SSI effects are not constant along structure height, and tends to be smaller for upper stories.

Conclusions

A comparison between the element forces variations due to SSI effects computed with the procedure included on MCBC and with a numerical model is presented. The procedure of MCBC is very similar to procedures included in other building codes (for example in ASCE 07). A 10 story steel building with braced frames is analyzed. Soil conditions correspond to a very soft clay of Mexico City and a mat foundation is considered. Results are presented as the ratio of the element force computed with and without SSI effects. Different types of columns and beams depending on the position within the structure are analyzed.

Code procedure considers that element forces in the whole structure must be modified by the ratio of the base shear computed with and without SSI effects (interaction factor). Results computed with the numerical model show that these variations are not constant along structure height. In general, as the elements are placed on upper stories, variations produced by SSI effects tends to be smaller.

It is shown that variations are different between different types of elements. For example, variation of lateral force taken by the bracing system and the columns are different. In general, the variation on columns is larger than the variation on braces. This effect modifies the ratio of lateral force on the frame and the bracing system, a parameter that has been identified as a fundamental parameter on inelastic performance of braced frames.

Variations of axial load on columns are smaller than the ones computed with code procedure. Central columns are the ones that experience the smallest variations and corner columns are the ones with the largest variations. Since SSI effects affects the lateral load on the structure, columns where the axial load is largely dependent on the lateral force (corner) experience the largest variations. Axial load computed from the fixed base case, must not be directly multiplied by the interaction factor.

How the shear forces and bending moments on beams and columns are affected, depends on the position of the element. In general, beams on the external frames are largely affected by SSI effects. Differences among different types of columns are smaller. Shear forces and bending moments on columns of external frames computed with the numerical model are larger than the ones computed with the code procedure. Since modeling the impedance functions as springs on the commercial software is easy, it seems like this is a better option to take into account for the
SSI effects rather than the code procedure.

Acknowledgments

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References

1. MCBC, Reglamento de construcciones para el Distrito Federal, Gaceta Oficial del Departamento del Distrito Federal, México, México, 2004 (In Spanish).
2. ASCE 7, Minimum design loads for buildings and other structures, ASCE Standard ASCE/SEI 7-10, American Society of Civil Engineers, 2010
3. NZS 3101-1, New Zealand standard code of practice for general structural design and design loadings for buildings, Standards Association of New Zealand, Wellington, 2006
4. NBCC, National building code of Canada, National Research Council of Canada, Ottawa, 2015
17. Fernández-Sola L.R., Martinez-Galindo G. Behavior of rc frames with hysteretic dampers considering dynamic soil structure interaction. 11th Canadian Conference on Earthquake Engineering. 2015