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CORRECTION FACTORS FOR OBTAINING MODIFIED RESPONSE SPECTRA CONSIDERING DYNAMIC SOIL-STRUCTURE INTERACTION EFFECTS

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ABSTRACT

The paper discusses dynamic soil-structure nonlinear models analyzed in a two dimensional space by means of OPENSEES. We discuss the current limitations of the NSR-98 Colombian code regarding the requirements to consider the ISSE and show that there are other combinations of soil-structure period ratio that are also important for the ISSE effects. A correction function is proposed to relate the spectral properties of the dynamic soil-structure with the acceleration at the bottom of the building and free-field, which serves as a parameter to identify which intervals with respect to the dimensionless parameter *r* (ratio between the period of vibration of the soil and the period of vibration of the structure) are necessary to perform the analysis of soil structure interaction, and propose a simple method for obtaining modified response spectra which take into account soil-structure interaction, noticing their differences with those proposed in the NSR-98 by their obligatory and alternative methods. Finally input files in Tcl (Tool Command Language) for modeling soil-structure systems in two dimensions are discussed as long as models of soil and structure for modal analysis separately, as well.

Introduction

The effects of dynamic soil-structure interaction (ISSE) change the dynamic properties to the structure under the assumption rigid base and the characteristics of ground motion around foundation (Avilés and Rocha 2004), in addition to its main effects such as increasing the period of vibration of the structure due to inertial interaction, the damping of the interacting system is generally increased, leading to lower design forces. On the other hand the ISSE causes the increase of secondary effects (P-Δ), which would produce an increase to sections of structural elements and consequently on the construction costs. This situation leads to better modeling systems and design optimization.

The ISSE effects are not considered many times for the design of buildings. The Colombian Code for Earthquake Resistant Structural Design (NSR-98) is very limiting when it comes to deciding when an interaction soil structure (ISE) analysis has to be done. It requires ISSE analysis

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when structural period is over 0.7 s and soil profile is S4 (12 m of soft clay with shear wave velocity less than 150 m/s). This criterion excludes other types of structures on other kind of soils (Agaton and Garcia 1999, Pineda and Ramirez 2005) for typical soils in Medellin city. The NSR-98 proposes an approximate method (Appendix A.2) to evaluate the ISSE, which is adequate there is enough information about all parameters involved in the phenomenon.

On the other hand other countries like Mexico some additional criteria are considered for ISSE analysis. Aviles and Rocha (2004) discussed the basis for the regulations to take into account the effects of soil-structure interaction at certain areas in Mexico City, which led to formulate the Technical Code for earthquake design.

Not to consider the ISSE effects may increase the uncertainty of structure performance. The design of structures in many countries around the world is usually based on obligatory or alternative methods like those proposed in the NSR-98. Those methods just take into account the effects of the ISSE for very limited number of cases like the ones mentioned above.

For the modeling process, the primary numerical tool to implement the FE simulations was the OpenSees software framework (Open System for Earthquake Engineering Simulation) (Mazzoni, McKenna and Fenves 2007) which has extensively been used worldwide for research in the field of earthquake engineering. As a compliment to this paper a contribution about modeling soil-structure interaction is provided through some files based on the scripting language Tcl (Tool Command Language).

Modeling Cases of ISSE

Ground Motions Used in the Analysis

For seismic dynamic analysis 3 records were used, those were taken from the seismic microzoning of the Aburrá Valley project (Microzonificación del Área Metropolitana del Valle del Aburrá 2009). It is not implied that this research concerns just to a specific place, instead those records were chosen in order to estimate the effect of earthquake excitation for near, medium and far seismic sources. Also the soils considered in the project do not belong to any specific place but are rather general and common soil profiles in many places.

Table 1. PGA y duration of earthquakes.

Ground motion	**PGA (g)**	**Duration (s)**
Near source	0.17	26
Medium source	0.1	54
Far source	0.07	54

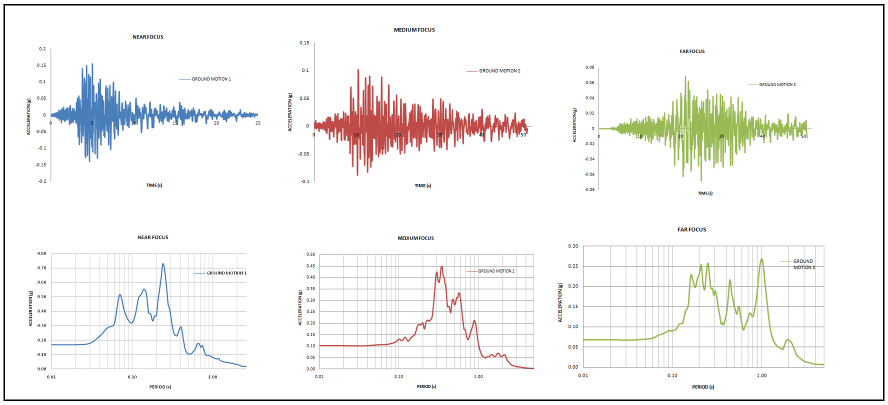


Figure 1. Ground-motions

Analyses Cases

Dynamic Soil-Structure Interaction is considered for cases in two dimensions subjected to motions showed in Fig.1 based on nonlinear models of soil (saturated clay soil under undrained behavior and a single layer) and structure (Concrete frame system on mat foundation with basement).

Soil

Soil profiles were analyzed for different shear wave velocity values (100-400 m/s) and thicknesses (10-50m).

Structure

Buildings as concrete frame systems of 7, 13 and 19 stories on mat foundations with basement also regularity both in plan and height are considered. A representative 2D frame of each building was analyzed.

In Table 2 the material properties, dimensions and characteristics of the reinforcement for the beams and columns for each of the buildings under study are listed.

Table 2. Dimensions and reinforcement structural elements

	Building		
	7-story	13-story	19-story
Number of bays-Bay Length-Story Height-Basement Height (m)	3-5-3-3	4-6-3-3	5-8-3-3
Columns			
Width-Height-Concrete cover	700-700-30	800-800-30	1000-1000-30

(mm)			
Longitudinal reinforcement ratio ρ %	1	1.5	1.5
Spacing stirrup (mm)	100	100	100
Beams			
Width-Height-Concrete cover (mm)	500-500-30	600-600-30	700-700-30
Longitudinal reinforcement ratio ρ %	0.7	0.7	0.7
Spacing stirrup (mm)	150	150	150
Slabs			
Weight/m^2 (kN/m^2)	10	10	10

Table 3. Concrete and steel properties.

γ (kN/m^3): Unit weight	24
ν : Poisson ratio	0.2
f'c (MPa) : Strength of unconfined concrete 7-story	27.5
f'c (MPa): Strength of unconfined concrete 13 y 19-story	34.3
fy (MPa) : Yield stress	412
Es (MPa) : Modulus of elasticity of Steel	200000
Ec (MPa) : Modulus of elasticity of concrete 7-story	24647
Ec (MPa) : Modulus of elasticity of concrete 13 and 19-story	27526

Spectral Correction Functions

In this section is presented how the results obtained by OpenSees were simplified and the procedures to propose a plot by which is possible obtain a response spectra taking into account soil-structure interaction effects.

First a modal analysis for soil and structure separately was carried out in order to compute natural frequencies of vibration and Rayleigh coefficients. Then a soil-structure analysis was performed, beginning with soil profile including absorbing boundaries (Lysmer and Kuhlemeyer 1969) and soil-structure interface (Olarte 2009). This system is subjected to static analysis. Also the building basement is embedded in the soil for completing static analysis.

Finally the complete system soil-structure is subjected to three ground motions through dynamic analysis (Mazzoni, McKenna and Fenves 2007). 315 cases were modeled, for each of them the acceleration history at base of building and free field were obtained and then the corresponding response spectra were calculated.

In order to understand the relationship between the response at the base of the building and free-field, the ratio between both spectra was computed (Base of building on free filed), also the abscissa was normalized with the fundamental vibration period of the building.

Based on the parameter *r* (Fundamental vibration period of soil Ts / Fundamental vibration period of building Te), the average values of relationship above (response spectra base of building on free filed) for each 0.25 of *r* is plotted, in which each curve corresponds to average values of *r*.

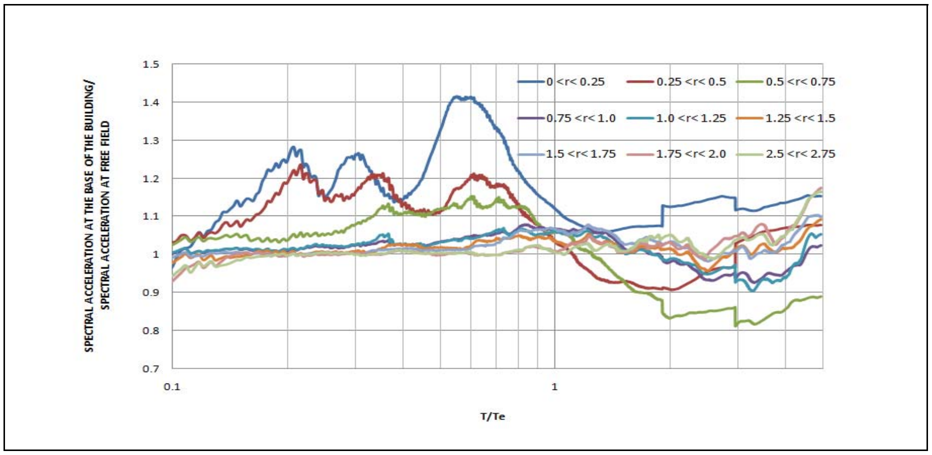


Figure 2. Ratio between the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building.

By Fig. 2 is possible to modify design spectra taking account ISSE effects by using the following information: design spectrum, fundamental vibration period of building and soil (they allow to calculate parameter *r*). With the *r* parameter is possible to obtain a curve from Fig. 2, which relates the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building and consequently the spectral acceleration at the base of the building is obtained.

Also the ratio between the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building for each ground motion are presented in Fig. 3

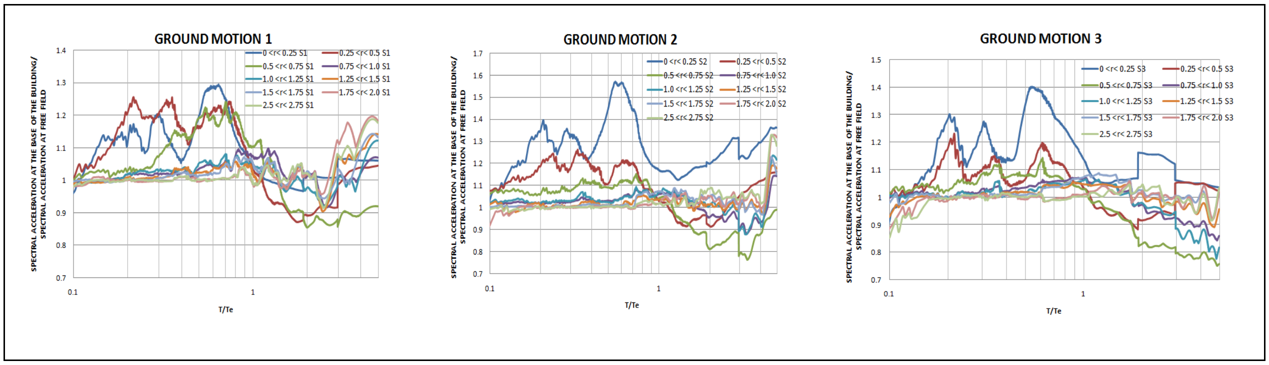


Figure 3. Ratio between the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building for three ground motions.

How Spectral Correction Functions Works

Like an illustration in Fig. 2 the use of the proposed functions is explained by two examples. Buildings (13 and 19 story) and soil (Height 50 m and shear wave velocity 100m/s).

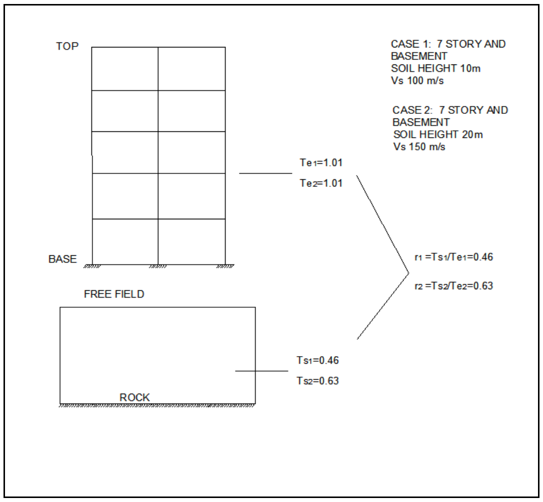


Figure 4. Information: natural vibration period of building and soil and dimensionless parameter *r*.

Previously the design response spectrum from the design code is obtained. Then the parameter *r* is computed with results from modal analysis, and then a curve is chosen from Fig. 2.

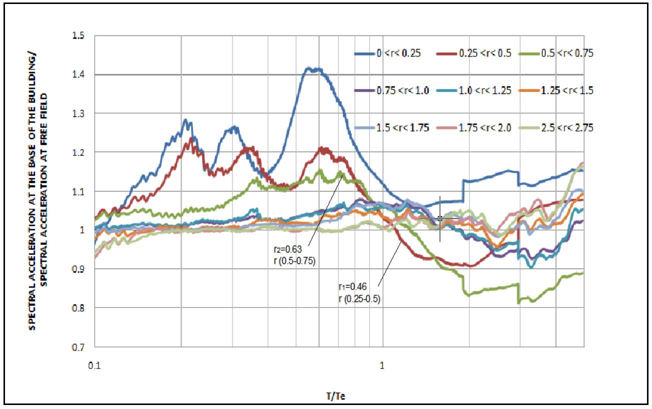


Figure 5. Curves of ratio between the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building for *r*1 and *r*2

Taking as many points as necessary from design spectrum in order to read in curve already chosen by parameter *r* on Fig. 5, values of the relationship between the acceleration at the base of the building and free field as values of period *T* are obtained.

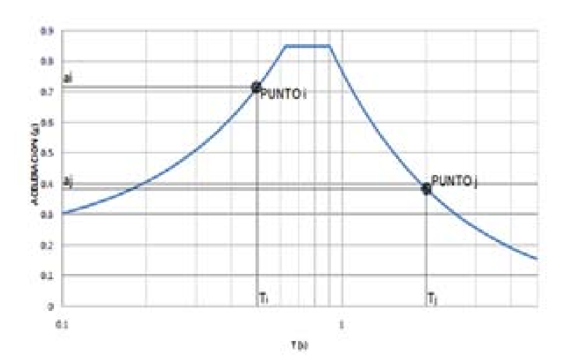


Figure 6. Points from design spectrum and their values of of ratio between the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building

Finally with acceleration from design spectrum and values of ratio between the spectral acceleration at the base of the building on free-field, values of acceleration at the base of the building are obtained, which are plotted with their corresponding values taken from the design spectrum, in order to obtain a design spectrum considering dynamic soil-structure interaction effects.

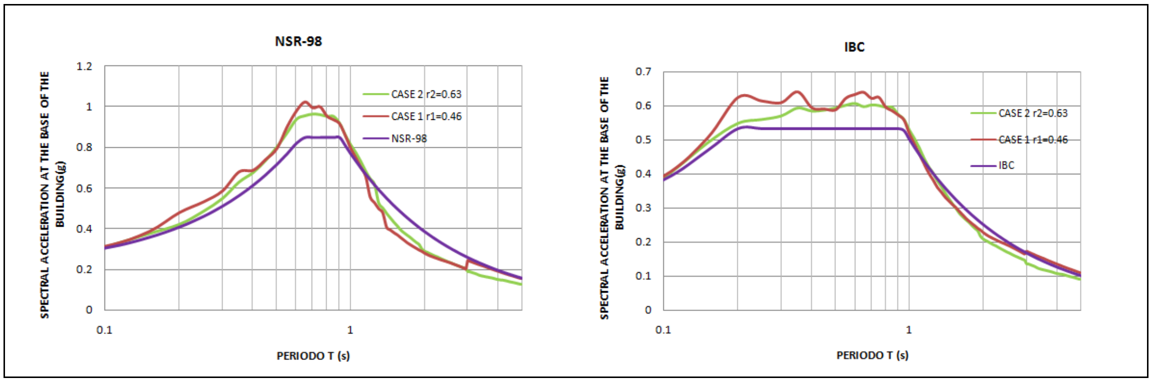


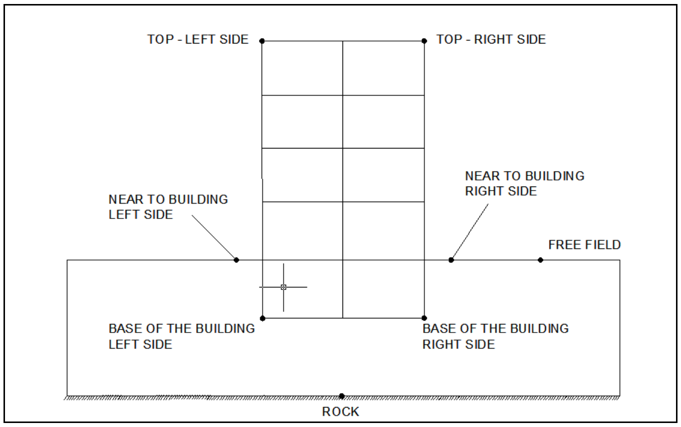
Figure 7. Design spectrum take into account soil structure interaction effects for cases 1 (r1 = 1.51) and 2 (r2 = 0.98) and design spectra NSR-98 and IBC.

Files for ISSE and Modal Analysis

In the files accompanying this paper are listed all the commands required in order to run OpenSees for ISSE analysis subjected to an earthquake, with the following limitations: one soil profile, finite elements have unit sides, except the ones from interface and boundaries, and one basement. Those limitations were selected to have a computational efficiency.

To execute the file called ISSE.tcl, it is necessary to know information about ground motion: time intervals, number of load steps between others. About soil and structure, it is necessary to know information about their geometry and parameters, which define their behavior. Finally is possible to divide the soil-structure interface and boundaries by entering the number for dividing each unit finite element (Olarte 2009).

The dynamic response for acceleration (g) and displacement (m) versus time at the points shown in Fig. 8 can be computed.



Also all lines required to run OpenSees for modal analysis in soils (saturated clays under undrained behavior with one profile) and structure (frame system with equal story height) are listed.

Conclusions

A simple way to consider the ISSE effect in order to modify the design spectrum by Fig. 2 is proposed, which related the spectral acceleration at the base of the building on free-field against the relationship between the period of design spectrum (period of a system of one degree of freedom) on fundamental vibration period of building.

The ISSE cases analyzed taking into account nonlinear behavior of the structure and soil, also rotational motion due to structure´s deformation and translational movement. However, it is not taken into account rotational motion due to rotation of the base of the building, due to limitations of software used.

This research is based on a parametric study in cases of Soil-Structure Interaction, therefore it was not considered necessary to analyze them for specific places. The focus is about to know when a structure is into the soil to the case without it. In addition to considerer the maximum number of known parameters and easy understanding for the engineering community

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