# SOIL STRUCTURE INTERACTION IN THE ANALYSIS AND SEISMIC DESIGN OF REINFORCED CONCRETE FRAME BUILDINGS

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**ABSTRACT :**

The influence of soil-structure interaction in the analysis and design of a 6-storey and basement reinforced concrete frame building is investigated. Models simulating two different conditions: namely soil-structure interaction, and fixed-base behavior are considered. The influence of the soil structure interaction in the dynamic behavior of the structure is reflected in an increase in the vibration period as well as increase in the system damping in comparison with the fixed-base model, which does not consider the supporting soil. The influence of the soil-structure interaction in the seismic design of the structure is reflected in a decrease of the horizontal spectral acceleration values. The inclusion of the soil in the structural analysis provides results, stress and displacement values, which are closer to the actual behavior of the structure than those provided by the analysis of a fixed-base structure.

**KEYWORDS:** Soil-structure interaction, dynamic behavior of soil, seismic design, damping, vibration period, spectral accelerations

## 1. INTRODUCTION

The aim of this paper is to investigate the influence of soil-structure interaction in the analysis and design under the action of gravitational and seismic loads of an office building consisting of 6-storey and basement and structured as reinforced concrete frames. Special attention is paid to:

- The influence of soil-structure interaction in the dynamic behavior of the structure
- The implications of the soil-structure interaction in the seismic design of the structure.

The building is located in San Salvador, El Salvador.

## 2. SYSTEM CONSIDERED

### *2.1. Structure*

A six-storey and basement building is considered. The building has a plan size of 24.5 m wide and 34 m long. The basement is adjusted to the shape of the property and has an average plan size of 50 m wide and 52 m long, as shown in Figure 1. The building will be used for offices. The lateral and vertical load resisting systems are reinforced concrete frames. The basement is confined by retaining walls with buttresses, and internally is structured by frames, all of reinforced concrete. The frames are composed of columns, primary beams and secondary beams. The floors consist of pre-stressed slabs.

### *2.2 Geologic and subsoil conditions*

The geological conditions are composed of two formations: the first consists of acidic pyroclasts and volcanic epiclasts: brown tuffs, and the second consists of slag and lapilli tuffs.

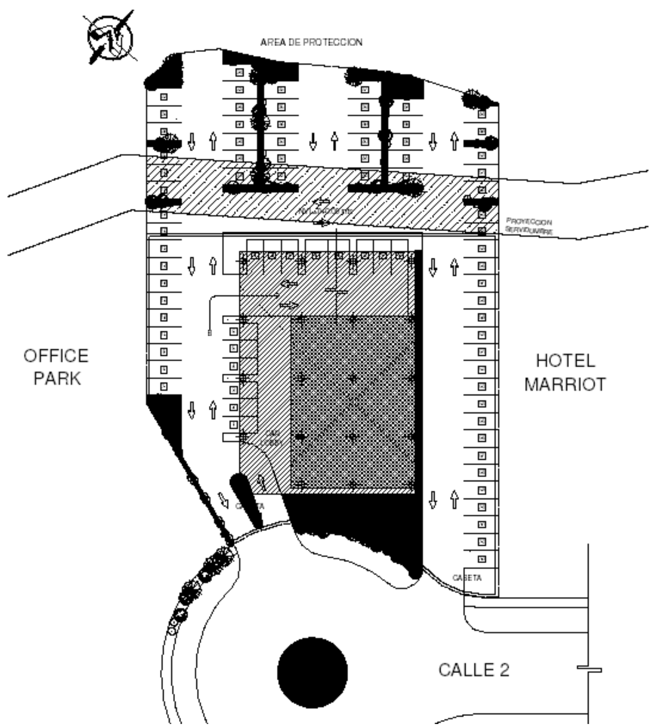


Figure 1. Plan view of the structure considered

The subsurface conditions are investigated through five seismic refraction tests on the ground surface, with the aim of identifying stratigraphy, presence and depth of hard rock and to measure the velocity of compression waves (P waves). From these measurements, shear wave velocities are estimated. No presence of the groundwater level was found.
The results are listed in Table 1.

Table 1. Stratigraphy and mechanical parameters of the site soils

| Stratum | Thickness | Vp | Vs |
|---|---|---|---|
| | (m) | (m/s) | (m/s) |
| Tierra blanca (White soil) | 5.53 | 455 | 223 |
| Slag | 9 | 1065 | 343 |
| Rock | > 18 | 2123 to 5338 | >426 |

### *2.3 Seismic conditions*

The site is located in the Seismic Zone I of the El Salvador National Regulations for Buildings, henceforth referred to as the Regulations. Based on the geologic and geotechnical conditions, the site can be characterized as type S2 for the definition of seismic loads according to the criteria of the Regulations. Table 2 summarizes the criteria for calculating seismic loads.

Table 2. Criteria for calculating seismic loads

| Category | Parameter |
|---|---|
| Site | S2 |
| Seismic Zone | I |
| Use | II |
| Vertical irregularity in flexible floor | Yes |
| Vertical irregularity in mass | Yes |
| Vertical irregularity in geometry | Yes |
| Basic structural system | A |
| Lateral load resisting system | Concrete frame with special design |

The parameters used to calculate seismic loads are presented in Table 3. To calculate the design spectrum, a 10% probability of exceedance in 50 years and a 5% damping for the structure are considered.

Table 3. Parameters for calculating seismic loads

| Parameter | Units | Value |
|---|---|---|
| To | s | 0.5 |
| Co | - | 2.75 |
| A | - | 0.4 |
| I | - | 1.2 |
| Cd | - | 8 |
| R | - | 12 |
| Inter-floor drift | m | 0.015h |

## 3. COMPUTATIONAL MODEL

Two numerical modes are generated using the computer program ANSYS. *Model 1* is generated to simulate seismic soil-structure interaction and includes the structure, foundation and subsurface conditions. The structure and foundation are modeled with finite elements, while the subsoil conditions are modeled with springs and dampers. *Model 2* is generated for comparison purposes and considers a fixed base condition.

### *3.1 Model of the structure*

The structure is analyzed assuming a linear visco-elastic behavior. A three-dimensional model of the structure is generated consisting of 490 nodes, 774 beam elements (beams and columns) and 921 plate elements (slabs and walls), as shown in Figure 2.

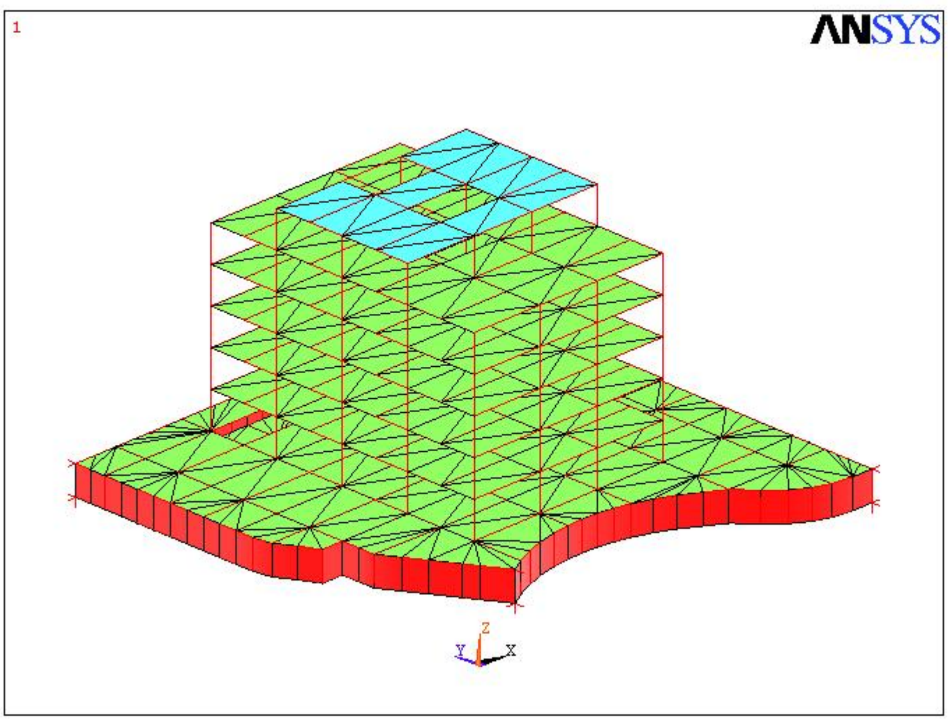


Figure 2. Finite element model of the structure

The material parameters used are listed in Table 4.

Table 4. Material parameters considered for the structure.

| Material | Density | Poisson's ratio | Young's Modulus | Material Damping |
|---|---|---|---|---|
| | [kg/m$^3$] | [-] | [N/m$^2$] | [%] |
| Reinforced concrete | 2400.0 (1) | 0.2 | $3.0 \times 10^{10}$ | 5.0 |

### *3.2 Soil-foundation model*

The soil-foundation, Model 1, is modeled with springs and dampers to reproduce bi-axial translational and rocking stiffness and damping parameters according to the formulation from Dobry and Gazetas (1985). Table 5 presents the values of stiffness and damping used.

Table 5. Mechanical parameters for stiffness and damping of soil-foundation system

| Direction | Number of elements | K | C |
|---|---|---|---|
| | | (N/m) | (N-s/m) |
| X | 8 | $1.27 \times 10^9$ | $1.06 \times 10^8$ |
| Y | 8 | $1.27 \times 10^9$ | $1.06 \times 10^8$ |
| Z | 4 | $6.67 \times 10^{10}$ | $3.57 \times 10^9$ |

### *3.3 Fixed base model.*

To assess the influence of soil-structure interaction, a reference model (Model 2) that does not include the mechanical parameters of soil-foundation is generated.

## 4. RESULTS

### *4.1 Modal analysis*

The characterization of the dynamic model is performed through a modal analysis. The modal frequencies and modal forms for Model 1 are presented in Table 6. The modal frequencies and modal forms for Model 2 are presented in Table 7.
A reduction in the modal frequencies of the structure by considering the soil-structure interaction with respect to those obtained for the fixed-base condition is identified.

Table 6. Modal frequencies and modal forms of Model 1: Soil-structure model.

| Mode | Frequency | Modal Form |
|---|---|---|
| | (Hz) | |
| 1 | 0.765 | 1. in x |
| 2 | 0.852 | 1. in y |
| 3 | 0.969 | 1. in z |
| 4 | 1.183 | Torsion z |
| 5 | 1.764 | 2o in z-y |
| 6 | 1.95 | 2o in z-x |

Table 7. Modal frequencies and modal forms of Model 2: Fixed-base model.

| Mode | Frequency | Modal Form |
|---|---|---|
| | (Hz) | |
| 1 | 0.823 | 1. in x |
| 2 | 0.943 | 1. in y |
| 3 | 1.19 | 1. in z |
| 4 | 1.249 | Torsion z |
| 5 | 2.136 | 2o in z-y |
| 6 | 2.314 | 2o in z-x |

***4.2 Damping in soil-structure system.***

The damping of the soil-structure system is a combination of the material damping values, of the soil radiation damping and of the inelastic behavior of the two subsystems: the structure and soil. It is difficult to identify the individual contribution of each component. An accurate estimate of the damping value for the entire system can only be done through experimental measurements. However, for the purposes of this study, the system damping is estimated through the method of half-power bandwidth method (Chopra, 2001), applied to transfer functions.
It is assumed that the rigid base undergoes a horizontal motion inducing the free-field motion due to vertical propagation of SV-waves in the overlaying soil deposit.
Because the ground motion consists of an unit acceleration amplitude, the calculated accelerations in the system constitute the transfer functions of the model, namely the ratio between the response and the excitation.
The transfer functions at the top of the structure are shown in Figure 3. The first resonance is associated with a frequency of 0.76 Hz, which coincides with the fundamental frequency of soil-structure model, f = 0.765 Hz, reported in Table 6.
As previously stated, the combined damping of the soil-structure system is estimated through the half-power bandwidth method. The results are shown in Table 8.

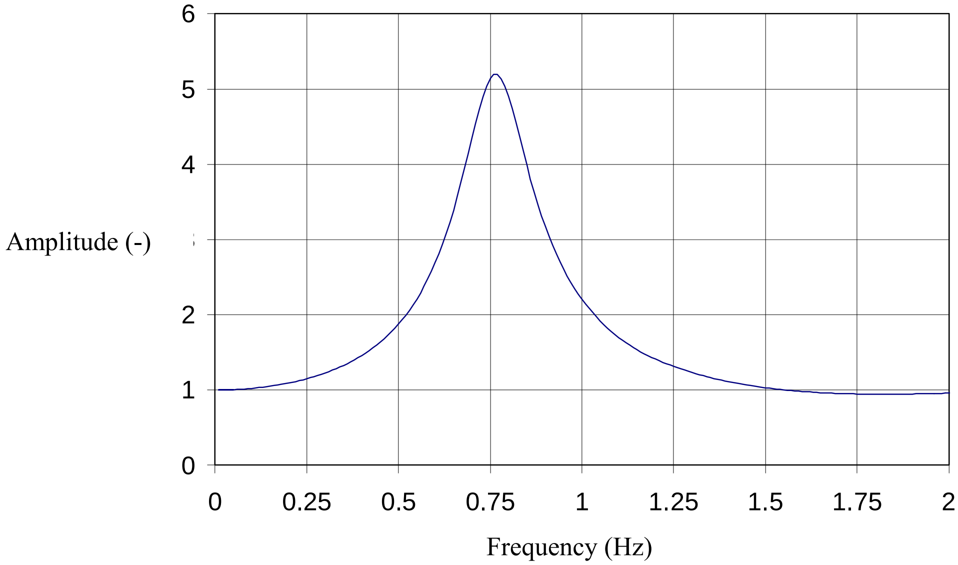


Figure 3. Transfer function on the roof of the building

Table 8. Dynamic parameters of the models analyzed

| Model | Fundamental frequency | Fundamental period | System damping |
|---|---|---|---|
| | (Hz) | (s) | (%) |
| Fixed-base | 0.823 | 1.215 | 5.0 |
| Soil-structure | 0.765 | 1.307 | 13.3 |

***4.3 Implications in the structural analysis and design***

It has been stated that the soil-structure interaction analysis implies an increase in the fundamental period as well as an increase in system damping in comparison with the fixed base reference model. As a consequence, the dynamic behavior as well as the dynamic loads to be considered for design purposes are modified. According to the Regulations, the design spectrum is defined by: the seismic zone, an importance factor, the subsurface conditions and the structural damping. Usually, a 5% structural damping is selected for design and it will be selected as structural damping for the fixed base model. The soil-structure model will be designed with a 13% structural damping.

Figure 4 shows the elastic design spectrum for the fixed base behavior (system damping $\beta$=5%) and for the soil-structure model ($\beta$=13%). Besides, the fundamental vibration periods for both systems are shown.

The values of horizontal acceleration for analysis and design purposes are taken from the design spectrum and are presented in Table 9.

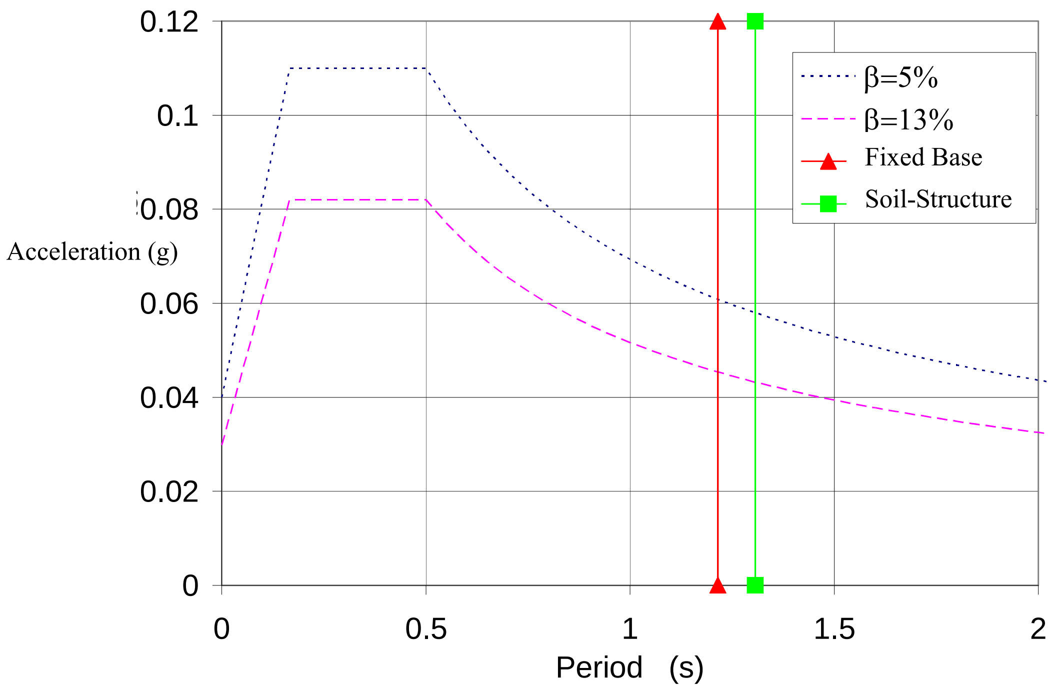


Figure 4. Design spectrum for different values of structural damping

Table 9. Design parameters for the two models

| Model | Fundamental period | System damping | Calculated Acceleration | Recommended acceleration |
|---|---|---|---|---|
| | (s) | (%) | (g) | (g) |
| Fixed-base | 1.215 | 5.0 | 0.061 | 0.061 |
| Soil-structure | 1.307 | 13.3 | 0.043 | 0.049 |

A conventional analysis considering a fixed-base model would provide a horizontal acceleration amplitude of 0.061 g. By considering soil-structure interaction, the horizontal acceleration amplitude is 0.043 g, which corresponds to 70.4% of the acceleration value for the fixed-base model. Following indications of the Regulation, the amplitude of the acceleration is reduced to 0.0488g, which is 80% of the value used for the static shear base calculation.

## 5. CONCLUSIONS

A design spectrum considering a critical damping of 13%, consistent with the structural behavior expected and according with the recommendations of the Regulations has been proposed.
The influence of soil-structure interaction in the dynamic behavior of the structure is reflected in an increase in the vibration period as well as an increase in system damping compared to the fixed base model. The increase in the vibration period is 7.6% compared with the fixed-base model. The increase in the system damping is 166% compared to the fixed-base model.
The influence of soil-structure interaction in the seismic design of the structure is reflected in a decrease in

the horizontal values of spectral acceleration. The reduction in the acceleration values for the fundamental period of the structure is 29.6% compared with the fixed base model. Following the instructions of the Regulation, it is recommended to reduce the spectral acceleration of the structure corresponding to the fundamental period by 20% over the acceleration value for the fixed base model.
The inclusion of the soil in the structural analysis provides results, stresses and deformations, closest to the actual behavior of the structure, in comparison with those provided by the analysis of a fixed-base structure. Mechanisms such as rocking can be investigated by including the stiffness parameters of foundation and subsoil. The increase in system damping is associated with a reduction in the elastic deformation of the structure due to the energy dissipated in the soil-foundation system. Besides, more economic designs are obtained by including the soil in the structural analysis and design, due to the reduction in seismic loads.

## 6. ACKNOWLEDGMENTS

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