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Towards improved earthquake preparedness: Site effects considering multiple seismic zones

Vers une meilleure préparation aux tremblements de terre: effets sur le site compte tenu de la multiplicité des zones sismiques

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ABSTRACT: Site response analysis is a key aspect in the quantification of seismic risk. Parameters defining the main dynamic properties that characterize a specific site mainly depend on the ground motion at the bedrock level and the soil features close to the ground surface. Integrating both, ground motion and soil features, within a probabilistic framework that considers the randomness of the mechanical properties of existing civil infrastructures is challenging, especially because of the computational effort involved. In addition, the dynamic properties of the soil tend to be affected at very low shear strains. These limits mainly depend on the duration and intensity of the ground motion. This study aims to apply a recently developed computational framework that allows for probabilistic considerations of the dynamic interaction between the ground and the surrounding structures during seismic events. Specifically, a set of ground motion records has been selected to propagate through random soil profiles. The resulting signals at the ground surface are transmitted to building models of varying heights, and their dynamic behaviour is evaluated. Then, using the cloud analysis approach, intensity measures, vibration periods of the degraded soil profile and structures have been used to search for the best-fit model that minimizes errors in predicting the influence of the site. The results of this study are expected to have significant practical applications in earthquake engineering and risk prevention.

RÉSUMÉ: L'analyse de la réponse du site est un aspect essentiel de la quantification du risque sismique. Les paramètres définissant les principales propriétés dynamiques qui caractérisent un site spécifique dépendent principalement du mouvement du sol au niveau du socle rocheux et des caractéristiques du sol à proximité de la surface du sol. L'intégration du mouvement du sol et des caractéristiques du sol dans un cadre probabiliste qui prend en compte le caractère aléatoire des propriétés mécaniques des infrastructures civiles existantes est un défi, notamment en raison de l'effort de calcul nécessaire. En outre, les propriétés dynamiques du sol ont tendance à être affectées par de très faibles contraintes de cisaillement. Ces déformations dépendent principalement de la durée et de l'intensité du mouvement du sol. Cette étude vise à appliquer un cadre de calcul récemment développé qui permet des considérations probabilistes de l'interaction dynamique entre le sol et les structures environnantes pendant les événements sismiques. Plus précisément, un ensemble d'enregistrements de mouvements du sol a été sélectionné pour se propager à travers des profils de sol aléatoires. Les signaux résultants à la surface du sol sont transmis à des modèles de bâtiments de différentes hauteurs, et leur comportement dynamique est évalué. En utilisant une approche d'analyse de nuage, les mesures d'intensité, les périodes de vibration du profil de sol dégradé et des structures ont été utilisées pour rechercher le meilleur modèle d'ajustement qui minimise les erreurs dans la prédiction des effets du site. Les résultats de cette étude devraient avoir des applications pratiques significatives dans le domaine du génie sismique et de la prévention des risques.

Keywords: Seismic risk, probabilistic model, dynamic interaction, cloud analyses approach.

1 INTRODUCTION

Soil-structure interaction is a fundamental factor in seismic risk estimation, where soil acts as a filter amplifying or damping harmonics based on its dynamic properties (Cruz and Miranda, 2021). Structures may resonate with the soil, leading to a rethinking of seismic risk paradigms, as observed during the 1985 earthquake in Mexico City (Beck and Hall, 1986). Therefore, understanding the dynamic response of the soil beneath a civil structure is crucial for seismic risk studies. Advanced nonlinear models, such as 3D finite element method representations, offer insights into this complexity. However, for computational efficiency, simplified 1D models like Kelvin-Voigt solids, which effectively approximate soil dynamics, are often used (Hardin and Scott, 1967).

This article employs a computational framework (Zapata-Franco et al., 2023) to analyse steadfastness in intensity measures (IMs) for predicting nonlinear building responses. This statistical property allows grouping results stemming from different building models without losing efficiency. This is of particular interest since new tendencies for seismic hazard characterization are evolving from 'Uniform Hazard Spectrum' to 'Uniform Risk Spectrum'. This enhanced approach is influenced by collapse fragility functions that should represent a large variety of buildings for consistent collapse probabilities across regions.

The framework has been originally developed for Reinforced Concrete structures, RC, which were modelled by considering Multi-Degree-of-Freedom systems. However, it has proven to be adaptable to a variety of structures, providing insights on seismic risk predictions (Vargas-Alzate et al., 2022). Particularly, in this article, simplified proxies built from Single-Degree-of-Freedom systems, SDoFs, have been employed to model RC buildings.

Bogotá has been chosen as a study site due to soft soil deposits and a comprehensive soil profile database, providing valuable data for seismic risk assessment (Pagliaroli et al., 2014). Regression analyses, comparing Scalar-based and Vector-valued IMs with building responses, indicate efficiency gains when grouping buildings by similar height ranges. This research provides insights into improving seismic risk predictions, particularly for cities with diverse building heights like Bogota.

2 PROBABILISTIC SOIL MODEL

A probabilistic soil model is generally used in geotechnical applications to consider the spatial and temporal variability of soil properties, and their effects on civil structures. These models rely on statistics and probability theory to simulate soil features such as strength and stiffness, which can vary with location and time. In this article, the probabilistic soil model presented in Zapata-Franco et al. (2023) has been employed. Figure 1 is a sketch of this computational framework. The variables represented within the soil profile scheme (shear modulus, density, damping parameter and layer thickness, G_i, ρ_i, ξ_i and h_i, respectively) determine the dynamic features of the modelled soil.

In summary, the probabilistic framework presented in Zapata-Franco et al. (2023) allows for:

i. Introducing a ground motion record at the bedrock level of a soil profile.
ii. Estimating the stiffness degradation and increase of damping in each soil layer based on the equivalent linear method.
iii. Calculating the resulting ground motion at the surface after propagation through the soil profile, taking into account the degradation of soil properties.
iv. Considering the resulting ground motion estimated in the previous step, by applying it at the base of one of the probabilistic building models.

These steps have been implemented after generating random samples of both soil profiles and structures, which are affected by ground motion records selected from a seismic database. These records have been acquired in seismic stations located on hard-soils.

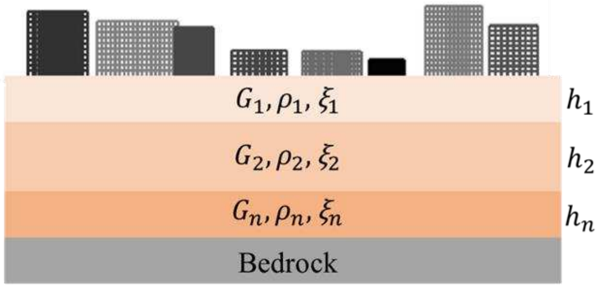

Figure 1. Schematic representation of the complete model.

2.1 Case of study: Bogotá Microzonation

This study focuses on Lacustrine soils that compose a critical deposit in Bogotá city, which is characterized by soft clays with high compressibility, interspersed with lenses of loose sand, volcanic ash, and peat up to 1m in thickness. The sediment width for this deposit varies from 50m to 500m.

2.2 Probabilistic generation of soil profiles

The probabilistic framework used in this research employs the Toro's model to generate soil profiles. (Silva et al., 1996). In brief, this probabilistic model consists of three main elements: i) a model describing the random stratigraphy at the site; ii) the median wave velocity profile; iii) a model considering both the deviation of the velocity from the median and its correlation with respect to the layer above. In the following, the elements of the Toro's model, applied to the lacustrine data for Bogotá city, are described.

2.2.1 Random stratigraphy at the site

For soil parameterization, 10 lacustrine profiles of the city have been employed (FOPAE, 2011). The random stratigraphy is characterized by using the "Layering Model" (Silva et al., 1996). This allows to consider that, often, as the soil layer deepens, it becomes thicker. Accordingly, the following power law is adopted:

$$\lambda(h) = C_3[h + C_1]^{-C_2} \tag{1}$$

where λ is the layer boundary rate (1/m) and h is the depth in meters. The estimation of the values C_1, C_2 and C_3 is carried out by using the capabilities of the Monte Carlo method to minimize multi-dimensional functions (Kucherenko et al., 2015).

2.2.2 The median wave velocity profile at the site

Due to the cumulative process associated to the creation of sedimentary deposits, it has been observed that a log-normal distribution adequately parametrizes the aleatory character of shear wave velocities (Toro, 2022). This parametric distribution has been adopted in the sampling process of the shear wave velocity. Note that, according to the Toro's model, the velocity is estimated at the layer midpoints.

2.2.3 Deviations of the velocity in each layer

Another important aspect observed in soil profiles is related to the spatial correlation between closer layers. The closer the layers the higher the correlation (Angelini and Heuvelink, 2018). This implies that widely separated layers tend to be less correlated. It has been assumed that the correlation between adjacent soil layers decreases with distance by means of the following model:

$$\rho_{i,j} = \begin{cases} i = j & \rho_{i,j} = 1 \\ i = j \pm k & \rho_{i,j} = 1 - \dfrac{k}{r} \geq 0 \end{cases} \tag{2}$$

where k is a number related to the position of a layer belonging to the same profile; r is a coefficient associated to the rate of correlation between adjacent layers. In this research, r has been fixed to 100/3.

2.3 Probabilistic simulation of soil profiles

Based on the description of the probabilistic features that soil profiles must meet, statistic models have been obtained via Monte Carlo simulations. The resulting soil profiles can be seen in Zapata-Franco et al. (2023). They all correspond to low shear strains.

3 SEISMIC HAZARD

3.1 Colombian seismic database

A compilation of ground motions recorded in Colombia between 1993 and 2017 has been considered, with a magnitude greater than 4.0 Mw. Accordingly, a total of 1992 records have been extracted from the SGC (SGC, 2020). From this set, 1236 ground motion recorded at hard soils have been used in this research.

3.2 Ground motion identification and scaling

In order to obtain a more precise representation of the seismogenic environment of Bogotá, the proximity algorithm developed in Zapata-Franco et al. (2023) has been employed. Bogotá has been regarded as a reference point, considering a radius of 400 km around the city. A set of 1023 ground motions recorded on hard-soils have been identified. 1000 of them have been employed to perform the calculations in this research.

There are several methods for scaling ground motions from a database (Haselton C.B., 2012). Typically, the aim is to have enough records leading the buildings to different performance levels. However, in current databases, there are often no strong ground motion records with high intensity values. This leads to excessive scaling, which may introduce bias in the structural response (Haselton C.B., 2012). To address this issue when using cloud analysis (Jalayer et al., 2015), the method proposed by Vargas-Alzate et al. (2022b) to select and scale ground motion records has been used. Figure 2 shows the total set of scaled ground motions acting at the bed rock level.

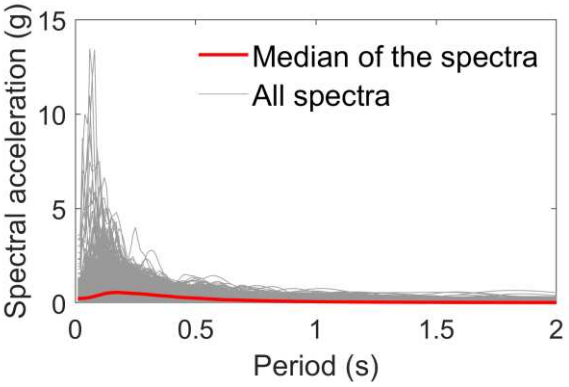

Figure 2. Spectra of ground motion records acting at bedrock level.

4 SEISMIC WAVE PROPAGATION

Seismic wave propagation leads to the degradation of soil stiffness and an increase in material damping in each layer. These alterations are dependent on the maximum shear strain experienced by the soil during seismic events. Several methods address this effect, one of the most widely used being the linear equivalent method (Kumar and Mondal, 2017).

This method iteratively estimates physical properties of a compatible soil profile using linear approximations, emulating the dynamic response obtained through computationally expensive non-linear analyses. The equivalent linear method considers stiffness degradation and increased material damping, utilizing normalized shear modulus and hysteretic damping curves. Reference curves from a geotechnical report (FOPAE, 2011) have been considered in this research to estimate the nonlinear response of probabilistic soil profiles. To do so, the ground motions have been scaled following the description presented in section 3.2. The resulting spectra of the ground motion at the surface, once applied the equivalent linear approximation, are shown in Figure 3.

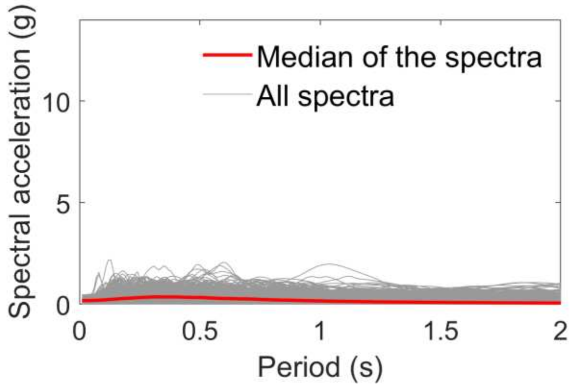

Figure 3. Spectra of ground motion records at the surface.

5 STRUCTURAL MODELLING

Simplifying structural models is crucial for efficient computations, allowing faster analyses of multiple buildings. The Single Degree of Freedom (SDoF) system is commonly used for dynamic calculations, offering easy time-history responses based on the fundamental period and damping. However, SDoF responses overlook stiffness loss due to plastic damage and the effect of higher modes. To address both issues, a proposed approach involves approximating the dynamic behaviour of Reinforced Concrete (RC) structures by averaging the time-history response of a set of SDoF systems within the interval (0.1T, 1.8T), where T is the fundamental period of the analysed building in the main direction.

The dynamic response associated with each oscillator has been estimated by means of the dynamic equilibrium equation for SDoF systems:

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = -m\ddot{u}_g(t) \tag{3}$$

where $\ddot{u}(t)$, $\dot{u}(t)$ and $u(t)$ are the spectral acceleration, velocity and displacement time history responses of the SDoF, respectively; $\ddot{u}_g(t)$ is the acceleration ground motion; m, c, and k represent the mass, damping, and stiffness of the system, respectively. Thus, the spectral time history response of a building in terms of displacements, $\bar{u}(t)$, is estimated as follows:

$$\bar{u}(t) = \frac{1}{p}\sum_{i=1}^{p} u_{(i)}(t, T_i) \tag{4}$$

where $u_{(i)}(t, T_i)$ is the response of the SDoFs with period T_i within the interval (0.1T, 1.8T).
Several engineering demand parameters (EDPs) can be extracted from the averaged time-history responses described above. For example, the maximum global drift ratio of a structure, MGDR, which is an EDP widely used in seismic risk estimations employing the capacity spectrum method (Freeman, 1998), can be estimated according to the following equation:

$$MGDR = PF_1 \frac{max\ (u_{(x,y)})}{\mathrm{H}} \tag{5}$$

where PF_1 is the load participation factor (Applied Technology Council, 1996); H is the height of the building. Regarding PF_1, it has been assumed that this variable is a function of the number of stories. In this research, $PF_1 = (\frac{7}{460}N_{st} + \frac{123}{115})$, where N_{st} represents the number of stories. In this manner, the higher the structure the larger PF_1.

Due to the probabilistic approach followed in this article, a set of fundamental periods has been generated to represent the analysed typology. Classical relationships between the evolution of this period and the height of the structure can be used (Goel and Chopra, 1997). For the case of study, it has been employed the following formula to relate the fundamental period vs the height of the structure (AIS, 2010):

$$T_1 = C_h * H^{0.9} \tag{6}$$

where C_h is a random regression coefficient which depends on the type of structure. This allows to consider possible uncertainties in the characterization of T_1. In the case of RC typologies, the average C_h is 0.047; it has been assumed a coefficient of variation equal to 0.12.

Three different structural typologies have been simulated. The difference between them is the number of stories. Thus, Low-, Medium- and High-Rise RC structures are composed of buildings whose number of stories varies from 2-6, 7-15 and 16-25, respectively.

6 CLOUD ANALYSIS

Cloud analysis requires to calculate the best fit curve between a set of IM-EDP simulations in the log-log space. In the following, the efficiency in terms of the coefficient of determination, R^2, has been calculated considering two approaches: i) using the ground motion records acting at bedrock levels to estimate IMs; ii) develop a multi-regression model that allows combining information provided by the soil profile and the IMs calculated in the previous approach. The IMs described in Zapata-Franco et al. (2023) have been employed to find the best correlated arrangements to predict the MGDR in both approaches. In addition to IMs, the following set of soil variables have been employed in the multi-regression model (Approach 2):

Table 1. Soil information variables.

Variables	Equation	Description
T_{S_L}	$\sum_{i=1}^{nlayer} T_{S_{L,i}}$	Fundamental period of the soil profile
$\bar{\xi}_L$	$\frac{\sum_{i=1}^{nlayer} \xi_{L,i}}{nlayer}$	Average linear damping of the soil profile
$\bar{\xi}_{NL}$	$\frac{\sum_{i=1}^{nlayer} \xi_{NL,i}}{nlayer}$	Average nonlinear damping of the soil profile
$\overline{Vs}_L$	$\frac{\sum_{i=1}^{nlayer} Vs_{L,i}}{nlayer}$	Average shear wave velocity of the soil profile
ΔT_L	$\lvert T_{S_L} - T_B \rvert$	Absolute difference between the fundamental period of the soil profile and fundamental period of the building (T_B)

6.1 Approach 1

After assessing the bivariate distribution between IMs and the MGDR, Zapata-Franco et al. (2023) show that AvSd is the best correlated IM to predict the MGDR. Accordingly, in approach 1 the authors focus on this IM for the statistical analysis. Results are summarized in Figure 4 for Low, Medium, and High-rise structures; results for a combination of the three typologies (All) have also been included.

6.2 Approach 2

The multi-regression model described in (Vargas-Alzate et al., 2022) has been used to identify the optimal combinations between IMs and soil parameters to predict the MGDR. Arrangements of three information variables have been assessed. Results are summarized in Figure 4 for Low, Medium, and High-rise structures; results for a combination of the three typologies (All) have also been included.

As Figure 4 indicates, for all types of structures, approach 2 shows higher regression coefficients than approach 1.

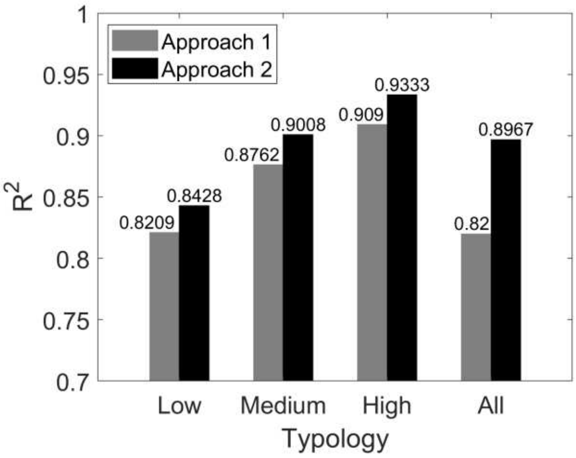

Figure 4. Regression coefficient Approach 1 and 2.

7 CONCLUSIONS

This article delves into the efficiency to predict the seismic response of simplified building models by considering inelastic responses of soils. These models are based on the average response of SDoFs around the fundamental period of each building. By employing the equivalent linear method to address the non-linear behaviour of soils, this study has integrated probabilistic soil profiles, structural models, and ground motion records into a Monte Carlo-based framework. Specifically, random samples of soil profiles have been generated and subjected to a set of accelerograms extracted from a Colombian database. The resulting motions at the ground surface have been employed to perform calculations on structural SDoF-based models.

At a first stage, it has been investigated the causal relationship between scalar-based IMs at the base of soil profiles and the resulting MGDR of structural models (Approach 1). The main conclusion is that AvSd is the most robust scalar-based IM for predicting the buildings response, when considering the interferences produced by the propagation of seismic waves through soil media. This conclusion holds when structural models are grouped by their number of stories or not. Note also that grouping buildings results in a significant increase in R^2, compared to a regression performed with the total amount of data. In general, the correlation increases when the number of storeys making up a subgroup also increases. This may be related to the fact that as the height of the buildings increases, the periods of both the structure and the ground profiles become more similar.

The objective of the second approach has been to analyse the increase in efficiency when considering vector-valued IMs. These IMs consider information of both the ground motion acting at the bedrock level and soil profiles. Again, AvSd has placed a central role in the regression analysis. This IM appears in all statistical regressions performed. In terms of the soil profile parameters, variables related to damping, velocity and period are the ones producing the highest increase in efficiency. These results highlight the importance of considering both structural and geotechnical factors to improve design and assessment of structures.

Future research should investigate the IM behaviour considering different soil types, seismogenic environments and structural typologies. Also, it would be usefully to extend the computational framework to 3D soil models.

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C - Risk analysis and safety evaluation

C - Analyse des risques et évaluation de la sécurité

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